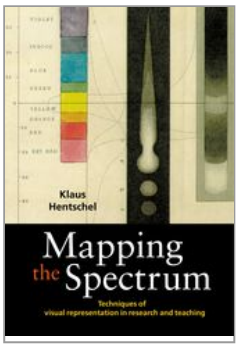

Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
Prof. Dr. Klaus Hentschel

Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

Title Pages

(p.i) Mapping The Spectrum **(p.ii)**

(p.iii) Mapping the Spectrum

OXFORD
UNIVERSITY PRESS

(p.iv) *This book has been printed digitally and produced in a standard specification in order to ensure its continuing availability*

OXFORD
UNIVERSITY PRESS

Great Clarendon Street, Oxford 0X2 6DP

Oxford University Press is a department of the University of Oxford.
It furthers the University's objective of excellence in research, scholarship,
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Oxford New York

Auckland Cape Town Dar es Salaam Hong Kong Karachi
Kuala Lumpur Madrid Melbourne Mexico City Nairobi
New Delhi Shanghai Taipei Toronto
With offices in
Argentina Austria Brazil Chile Czech Republic France Greece
Guatemala Hungary Italy Japan South Korea Poland Portugal
Singapore Switzerland Thailand Turkey Ukraine Vietnam

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Published in the United States
by Oxford University Press Inc., New York

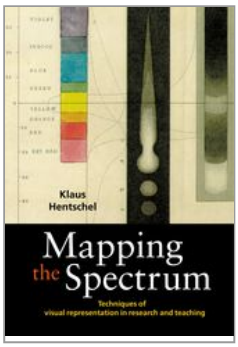
Reprinted 2009

Colour plates printed with the support from the
Georg-Agricola-Gesellschaft zur
Förderung der Geschichte der
Naturwissenschaften und der Technik e. V.

ISBN 978-0-19-850953-0

Cover illustration: The luminous, thermal, and chemical spectrum, as depicted in Robert Hunt’s
hand-coloured plate from 1844.

Printed and bound in Great Britain by CPI Antony Rowe,
Chippenham and Eastbourne



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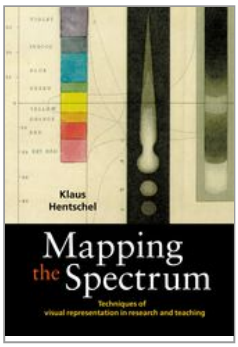

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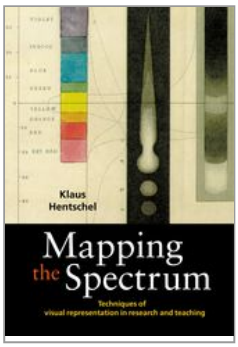

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Introduction

Klaus Hentschel

DOI:10.1093/acprof:oso/9780198509530.003.0001

Abstract and Keywords

This introductory chapter begins with a survey of the rapidly expanding study of visual representations in science, followed by a discussion of spectroscopy as a prime example of a visual science culture. It describes ten historiographic levels of analysis, which are then documented in the remaining chapters. The mapping metaphor is analysed, and the rhetorics of spectra are studied. The chapter concludes with acknowledgments and a list of abbreviations for the twenty-five archives consulted.

Keywords: historiography, visual science cultures, mapping metaphor, rhetorics of spectra

1.1 The study of visual representations in science

In the last decade much attention has been devoted to nonverbal communication and visual representation in science.[1] Pressed for an explanation of this upsurge in interest, both in sociologically oriented science studies and in the history of science, I would point to a confluence of several separate currents of research which call for more serious analysis of this dimension of scientific practice: (i) Several art historians have paved the way by bridging the gap between the fine arts and the sciences and by extending their studies into the realm of representations in the history of science.[2] (ii) There is a growing number of studies by historians and sociologists of science and technology on the interplay between nonverbal communication and cognition—on the way one thinks, so to speak, with the hands and the eyes.[3] (iii) There is a heightened awareness in each of these branches of the persuasive power of visual representations, which is backed up by a close examination of scientific controversies of the past and present.[4] (iv) Even in histories of photography there is a broadening of scope. Traditionally focused on such standard sujets as portraiture, landscapes, close-up studies of the early pioneers or technical innovations, they now sometimes incorporate early scientific applications as a major, and indeed fascinating, historical factor.[5] (v) Modern historians of cartography have started to reform their traditionally somewhat antiquarian approach. They now consider mapping as a process, and conceive of the resulting maps as systems communicating cartographic information.[6] (vi) Finally, there are several articulate and well-documented studies on the emergence and evolution of visual representations, especially in the geo- and biosciences, and also in astronomy.[7]

(p.2) The historical development of the graphical representation of data and objects had already been traced in some detail in a few isolated fields, such as statistics and botany, in the 1950s.[8] But Martin Rudwick's famous pioneering paper of 1976 on "The emergence of a visual language for geological science 1760–1840" pointed out particularly clearly that more was involved than development of progressively better and more suitable means of visualization. First of all, the use of visual representations in general is a contingent historical phenomenon, strikingly absent from some scientific traditions (Lagrange's analytic mechanics being an often-cited example), yet absolutely indispensable in others like the spectroscopic terrain surveyed here. Second, new modes of visual representations do not emerge as isolated innovations but within the context of larger cultural packages in which they are securely wrapped. These packages include components of theory as well as of practice, as becomes readily clear once we look at—or better still, try to use—older systems of representation, such as an astrolab or a navicula. They are absolutely 'opaque' to a novice who has never been introduced to their underlying ideas. Nor does such a theoretical briefing make them immediately 'transparent'.[9] A hands-on initiation into the artifice and the practical skills necessary to handle them is still needed in order to see the phenomena through them. Experimental procedures and scientific instruments must recede into the background in order for the residual phenomena to emerge as objects independent of human intervention. The same holds for their representation. The reader must become versed in the appropriate use of representational devices such as histograms or bar graphs, pie charts, curves, plot functions, stereograms, cartograms, nomograms, etc.[10] He or she must learn how to understand and read them. Initial resistance, misunderstandings, and controversies frequently occur in the history of science with the introduction of a new visualization technique. For instance, William Playfair (1759–1823), who first applied many now familiar graphical techniques to statistics, justified his use of a bar graph as follows:

> This method has struck several persons as being fallacious because geometrical measurement has not any relation to money or to time, yet here it is made to represent both. The most familiar and simple answer to this objection is that if the money received by a single man in trade were all guineas and every evening he made a single pile of all the guineas received during the day, its height would be proportioned to the receipts of that day, so that by this plain operation time, proportion, and amount would be physically combined.[11]

He was right not to assume that his new technique would be immediately perceived as transparent. It was slow to take hold. Only the next generation, in the second half of the **(p.3)** nineteenth century, became aware of Playfair's influence on the Continent.[12] This reluctance to adopt new visual techniques is by no means limited to statistics. Historians have noted it in eighteenth-century scientific journals as well. Experimental graphs, illustrating the functional

dependency of one observable upon another, are found in a number of isolated cases but “never became commonplace in that age”.[13] On the other hand, after such a technique has taken off, it remains alive and well for a long while, as the omnipresence of the pie chart in modern-day economics readily confirms. Once a technique has become established and its users fully accustomed to it, it often contributes substantially to the way problems are effectively handled and thought about. Exploded views of the inner workings of a complicated machine, first found in notebooks by Leonardo around 1500, are a good example; so are flowcharts used in engineering and programming. In fact, “graphs are especially suggestive when they re-evoke, stimulate, or revise the researcher’s visual-physical view of the process studied”. Rather than being perceived as a convention-ridden image, these nonverbal representations serve as “interactive sites” that the researcher is able to “see through” to the physical processes and materials selected or measured.[14] Eugene S. Ferguson and Walter G. Vincenti have shown how nonverbal thinking allows craftsmen, designers and inventors to develop mental images of their machine’s workings, how they can reason their way through its successive stages of operation and how such intuition enables them to spot the critical phase or come up with an improvement.[15] But thinking with (and in) pictures, e.g., drawing a diagram to organize thoughts rather than arguing in syllogistic form, is characteristic not only of the art of technology, but also of practitioners of other branches of science, such as mathematics, astronomy, geology, or botany. In Chapter 8, I give various examples of this ‘thinking’ with spectrum maps and spectrography—a thinking which often involved the search for patterns of lines belonging to a common series or band, or for homologies between different spectra. In reply to the likely objection that this pattern search was typical only of the nineteenth century, the following anecdote might be appended: When interviewed by Thomas S. Kuhn in 1967, the quantum physicist and chemist Friedrich Hund (1896–1997) explained how he had worked himself into the field of molecular band spectra, that is, before a systematic inventory in the style of Paschen-Gotze had been compiled for multiline spectra: “Well, I remember that I looked through much numerical data. I also remember that once I drew multiline spectra on sheets of millimeter paper about so long and stared fixedly at them.”[16] Needless to say, with the advent of Bohr’s atomic model in 1913, and more so, with the rise of quantum mechanics in 1925, such a study method rather became the exception. But before this break in theoretical conceptions (which made it possible to *explain* what could formerly only be *described),* the wild-goose chase for patterns was a quite common activity. As evidence of this I will later discuss Johann Jacob Balmer’s and Henri Deslandres’s searches for coherent descriptions **(p.4)** of series or band spectra, Lecoq de Boisbaudran’s and G.L. Ciamician’s search for homolo-gies between spectra of different elements, and GJ. Stoney’s and Arthur Schuster’s work on the optical analogues of harmonics or overtone series (see § 8.2–8.4).

1.2 Spectroscopy as a visual culture

I argue that spectroscopists during the second half of the nineteenth century were extraordinarily visually oriented, and this was by no means restricted to their main representational device, the spectrum map. The instrument maker and optician Josef Fraunhofer, the astronomer Charles Piazzi Smyth, the physicist Alexander Herschel, and his father, the pioneer photographer John Herschel, or the astrophysicist Samuel Pierpont Langley—all were interested in many different visual fields at once, and most of these scientists were accomplished draftsmen from the outset. Langley, for instance, became famous not only for his holographs of the infrared spectrum (to which we return on p. 79), but also for his highly detailed drawings of solar-spot observations by eye, during moments of exceptionally good seeing. In the case of Piazzi Smyth, his activities are as diverse as the tri-angulation of South African districts, landscape painting, day-to-day or tourist sketching, the lithography or engraving of prominent architectural sites, documentary photography of the Egyptian pyramids or the Tenerife Dragon tree, or ‘instant photographs’ of the clouds above his retirement home in Clova, Ripon.[17] His colorful records of solar and terrestrial spectra profited from his trained eye and his subtle mastery of the pen and the brush. Piazzi Smyth was conversant in most of the technical printing repertoire that the nineteenth century had to offer and was able to select the most appropriate one for each subject.[18] What led me to study his case more closely was his invention of symbolic techniques for representing spectra, just one more aspect of the fascinatingly broad scope of this truly artistic astronomer’s œuvre. He is a particularly vivid proponent of what I call the ‘visual culture of spectroscopy’ towards the close of the nineteenth century, a culture that spans across several disciplines, among them chemistry and astrophysics, physics and photography, and even medicine and engineering (for more on disciplinary issues see here § 10.1, pp. 420f.).

The longevity of such visual cultures as subsets of science with their integrated or associated predispositions for—or against—certain techniques of representation is documented in Peter Galison’s recent studies, in which he contrasts an image tradition and a logic tradition within twentieth-century physics. The former depends heavily on the use and construal of visual images (of mimetic reconstructions of natural events such as cloud formation, particle tracks, scattering events, etc.), while the latter relies on the quantitative, statistical analysis of large numbers of events as registered by electronic circuitry and detectors with apictorial, numerical output. Both of these research styles co-evolved during most of this century and survived several rather abrupt breaks with theoretical conceptions. It is only recently, with digitized image analysis, as recorded by charge-coupled devices **(p.5)** (CCDs), that these two competing styles began to merge: the electric output generated by these photocells can be manipulated in computer logic but ultimately still produces images similar to conventional photographs.[19]

Seen from this aspect, the study of spectra in general and spectrum analysis in particular has always leaned heavily towards the image side of the image-logic dichotomy. Successful research with spectra required refined pattern-recognition skills in order, for instance, to distinguish the spectra of different chemical elements or to detect the spectrum lines of trace elements in another substance. Spectroscopy thus provides us with excellent material for a case study of the mechanisms and problems encountered throughout the many stages of the learning process: How to distinguish between different basic patterns? How to make sense of the many subtle variations and superimposed effects (such as Doppler shifts, line broadenings, Zeeman splittings, etc.)? How to discriminate between artefacts of the representation at hand and ‘real’ effects at the very border of detectability? The data in spectroscopy were, first and foremost, spectral plates and maps plotting the distribution of lines and their relative intensities. Wavelength tables and lists, and classifications of line strengths and types were also used, of course, but only in conjunction with the maps, and rather for special purposes, such as metrology. What counted primarily was recognition of the *Gestalt* of a certain line grouping as it was depicted in Bunsen’s chart of characteristic lines or in Ångström’s map of the solar spectrum. The absolute placement of these lines in the Ångström wavelength scale, later recorded in tables to a precision of many decimal places, did not matter to the overwhelming majority of its practitioners. In fact, it is not easy to think of a contemporary scientific discipline with a heavier load of images for memorization. Thus it is no surprise that many traces remain of the procedure by which newcomers had to acquire these skills. One nice example is the huge wall-hanging posters that most of us have seen at school on the walls of our chemistry or physics lab. Because of its great importance during the late nineteenth and early twentieth century, spectroscopy achieved fairly broad dissemination down to the level of high-school education and popular science literature. One of the aims of this monograph is to study these modes of diffusion of knowledge and, in particular, the use of visual representations of spectra in this process. As we shall also see (on pp. 387ff.), along with the ubiquity of spectrum representations in the scientific workplace came a pedagogic move away from passive memorization to active drawing or recopying of characteristic spectra by the students, a point which I could document on the basis of numerous student notebooks preserved at one East-Coast college (Welles-ley) which—unlike most university archives—fortunately thought these student notebooks warranted their storage space.

The history of spectroscopy in general has already been treated by more than one of its own protagonists, but the agenda of the earliest studies was too much determined by polemical priority disputes, while the later ones were too often blatantly celebratory.[20] In 1900, the doyen of German spectroscopy, Heinrich Kayser (1853–1940), started publishing a multivolume series of handbooks designed to cover everything ever published in **(p.6)** the field.[21] This *Handbuch der Spektroskopie* certainly does fulfill its purpose as a compendious inventory, but it falls into the historiographic trap of streamlined Whig history, cutting short what has been declared as obsolete. Spectroscopy has also been repeatedly studied since the late 1960s by a few professional historians of science mostly interested in the interplay between spectroscopic results and the emergence of atomistic models of matter or spectrochemical applications.[22] Following the lead of Frank A.J.L. James, the most recent studies complement these internalistic perspectives with an approach directed at the cultural history of the field and connections to the institutionalization of new subdisciplines like astrophysics.[23] But to this day, whole research areas of considerable impact in today's science—such as quantitative spectroscopy, for instance—have still to find their historian. Altogether, this somewhat cursory attention does not adequately reflect the immense importance of spectroscopy in the natural sciences of the nineteenth and twentieth centuries. The spectroscope has served not only chemists, but also physicists, astronomers, and other scientists. It was utilized as a telescope, a microscope, a speedometer, a thermometer, a tape measure, a clock, and a chemical detector for such minute quantities as a teaspoonful of salt in a swimming-pool full of water. By the turn of the century, spectroscopy had become the dominant specialty, numerically speaking, in many institutes of physics, particularly in the United States where scientists had been concentrating on "manipulating light" since the nineteenth century.[24]

The amount of nonverbal, visual elements of the primary literature and documentation incorporated in the secondary literature is particularly disappointing: For instance, McGucken's standard history of nineteenth-century spectroscopy has only nine illustrations, seven of which depict spectra; but these are analyzed only in connection with the contemporary atomic and molecular models of matter. This negligence reflects two lamentable historiographic tendencies: (i) an overemphasis of theory, which leaves room for discussion of experiments only insofar as they somehow relate to the theoretical argument (as is the case with McGucken's book which concentrates on the search for series relations), and (ii) a myopia toward the many facets of nonverbal primary sources. As has already been pointed out by Martin Rudwick, this second point may have something to do with the text-orientedness of the historian of science, who is trained to work, analyze, interpret and deconstruct *texts,* and who in turn ends up writing a text about these texts. Many lack the training and practice for deciphering and analyzing nontextual components also embedded in these source materials. This contrasts sharply with the great attention that has been devoted within the last decade to nonverbal communication and visual representation in science, both within sociologically oriented science studies and within the history of science.

However, one can argue that in the history of astronomy, visual representations of the **(p.7)** constellations and celestial phenomena have always enjoyed considerable attention by historians of science.[25] For this branch of science, scientific photography seems to be particularly well documented, reflecting its enormous importance in the waning half of the nineteenth century.[26] Photochemistry, on the other hand, despite its defining role in the progress of scientific photography, has not received its due from professional historians of science. The only surveys we have in this area are written by some of the actors themselves, such as Robert Hunt and Josef Maria Eder,[27] but an in-depth historical analysis of the development of this field still remains to be written. In Chapter 6, 1 discuss the following main stages of this arduous research and development, which throughout that century resembled more an intricate art than a systematic science:

- explorations of the so-called 'actinic' spectrum, which could only be recorded by silver salts or other photosensitive substances (see here § 6.1–6.2);
- Hermann Wilhelm Vogel's discovery in 1873 that dye additives sensitized his silverbromide emulsions to red light over 5000 Å, which led to the development of 'orthochromatic' plates (cf. here p. 248);
- the availability of 'panchromatic' plates in 1904, which were sensitized further up to 7000 Å with dyes like dicyanine;

• further advances into the infrared with other dyes like cryptocyanine in 1919 (up to 8200 Å), neocyanine in 1925 (up to 9100 Å), and later derivatives, extending the range to 13 500 Å by around 1934 (cf. here p. 261).

The papers of George Harrison, William Meggers, and Kenneth Mees provide documentation for close cooperation between industrial research on photographic emulsions, at companies such as Kodak or Ilford, and researchers at the National Bureau of Standards, the MIT Spectroscopy Lab, or the Mt. Wilson Solar Observatory.

Unlike other studies on visual representations in the history of astronomy, which have a strong penchant for objects of special controversy (such as, for instance, Percival Lovell's infamous Martian canals, or Nasmyth's discovery of solar granulation),[28] this book will focus on the uncontroversial, accepted routine of the spectroscopist and the everyday practice of men and women who taught and published on the subject. Thus it proposes to contribute to the growing body of studies on scientific practice. It retraces interesting if not always spectacular cases that, taken together, should give a clear and representative image of the actual procedures followed in the observation, recording, and mapping of spectra. For this was by no means an enclave of a handful of specialists, but one of the busiest branches in the sciences, at least in the period from about 1860 to 1900. It attracted chemists and physicists, and reached far afield into such areas as blood analysis and steel production, to name just two early and important applications (discussed in § 9.8).

(p.8) The establishment of scientific photography notwithstanding, astronomers, chemists, physicists, and spectroscopists alike depended on others to get their drawings or photographs into print. And these too often completely obscure artisans are indeed historio-graphic aliens. We sorely need supplementary approaches from social history and labor history to shed light on the status, working conditions, and specific skills of engravers, lithographers, photographers, and other specialists involved in the transition of research data onto the published plate. 'Who were the guys?', a question posed a quarter of a century ago by the social historian of science Lewis Pyenson with regard to lesser known scientists, and which since has also been raised with regard to scientific instrument makers, is now a burning issue with respect to members of this printing culture, too. In Chapter 5, I survey the existing work on the material culture of the printing trade and then present a few specific cases (see here pp. 143ff.).

One of the finest recent studies perceptive of this aspect is Alex Soojung-Kim Pang's article on Victorian representations of the solar corona, which goes well beyond the historiography in other papers by systematically examining the interplay between observing practices, drawing techniques, and the subsequent technologies used in printing.[29] The present monograph continues this line of research in another area of representations, namely, the spectrum. Interestingly enough, spectra share several qualities with the solar corona, for instance, diffuseness; that is, it is not easy to observe and hence not easy to draw. In fact (as we shall see in Chapter 2), it took a long time for certain conventions to become established on how to draw or map a spectrum, and these conventions changed dramatically with the introduction of new printing technologies and with the interpolation of photographic techniques into both the recording and printing processes (see Chapters 4 and 6). Yet, the research contexts in which the corona and the spectrum were scrutinized could hardly be more different. Until the invention of Lyot's coronagraph around 1930, the corona was observable only during the rare times of solar eclipse at remote locations to which instruments and observers had to be transported on often strenuous scientific expeditions. Spectra, however, are usually observed in the laboratory, under controlled conditions, with fairly simple apparatus, and without the confining time constraints imposed on eclipse observers.[30] For the role that photography had gained by 1900, Pang's study of astrophotography provides an even better comparison case, because both stellar and spectrum photography require considerable care and experience to transgress the many technological limits of the contemporary photoengraving. As Pang documents for the case of astrophotography at the newly founded Lick Observatory, and as is shown here for spectrum photography, it was but a fine line between "improvement or correction of plates and doctoring", and considerable craft went into the correct choices of printing technique, contrast and tone, ink and paper.[31] But even with the most qualified of illustrators, things could go terribly wrong if their efforts were not carefully matched with the intentions of the spectroscopist who had originally supplied the sketches and drawings on which the lithographs and engravings were to be based. Even then, the lithographer and engraver were inevitably better placed to add the final touches to a plate on its way to press, as one spectroscopist ruefully notes in 1882: **(p.9)**

> as to the Royal Society's engraver who doubted my Oxygen lines: I have often had occasion to complain of the plates in the Transactions. A notorious case for instance is the plate illustrating Dr. Huggins' paper to the Society; the drawing is abominable and a disgrace to the Society, while the original drawing (which I have seen) is excellent + very clear indeed. But these things we cannot cure + must therefore endure.[32]

1.3 The mapping metaphor

As natural and indispensable as it may look to us nowadays, the use of visual representation is very much a historical phenomenon, strikingly absent from some scientific traditions as much as it is strikingly prominent in others. The introduction of a device as simple, in our view, as a scaled two-dimensional celestial map, for instance, does not occur before the fifteenth century. It is roughly at this time that the familiar geographic maps appeared: unlike the earlier symbolic *mappœ mundi,* representational devices now “mapped’ specific geographical positions according to a specific scale or projection. As Peter Whitfield, author of a recent catalogue with dozens of first-class reproductions of such maps, argues: “celestial maps as we know them […] were a product of the Renaissance sense of ordered space, the sense which also saw the development of perspective, terrestrial mapping and scientific diagrams.”[33] Whitfield points out that Ptolemy’s *Almagest* was not passed on to posterity with any illustrations (except geometrical figures). Even someone like Tycho Brahe did not feel the need to produce a star map, because to him “this was merely a demonstration aid which the non-specialist without instrument might use to identify what he saw in the sky”. Tycho preferred to invest his energy in compiling a reliable and precise tabular star catalogue. The introduction of representational techniques often derives from a transfer from one field, in which it has already become a familiar fixture, into another where it has yet to prove its utility. The rediscovery of Ptolemy’s projection method in the early modern period seems to be one such link between the history of central perspective, cartography, and stellar maps.[34]

> The structure of the star chart, the projection of a measured sphere, was dependent on the new language of cartography which appeared at the end of the fifteenth century. The key feature of that language, without which modern scientific mapping could not emerge, was the co-ordinate structure, the ordered space imposed by the grid of latitude and longitude, that was learned by Renaissance geographers from the revived works of Ptolemy. The new art of ‘cosmography,’ with its diagrams of the earth and the heavens, became a characteristic Renaissance pursuit. With the growth of map printing, all atlases from the later sixteenth century onwards included star charts of the northern and southern heavens, often with diagrams of cosmic structures, the geometry of eclipses, lunar phases and so on. The star chart, a scientific document just as the world map is, became a publishing genre, subject to the intellectual and commercial demands of the day.

(p.10) In § 5.3 I document the presence of similar transfers of printing techniques from cartographic maps to spectrum maps, many of which were actually printed at agencies specializing in the production of topographic maps, such as the Ordnance Survey and Johnston's printing house in Edinburgh, or the Swedish Military Lithographic Printing Agency. In the cases of several of the most outstanding engravers and lithographers involved in the production of nineteenth-century spectrum maps, I could likewise document active involvement in cartographic and architectonic branches of the printing business (see pp. 168ff.). Furthermore, both cartographers and spectrographers crucially depended on high-precision instrumentation, often delivered by the same superb instrument-makers.[35]

This affinity does not stop here, though. As will be discussed further in one of the concluding sections (10.10), an unidentified spectrum also shares much with *terra incognita:* Both have to be mapped for orientational purposes, as well as in order to truly 'know' them. In both cases it is not clear from the outset how to overcome their inherent amorphousness, which allows several nonequivalent ways of 'mapping' them. It may sound strange to use the expression 'mapping', familiar in the context of geography or genetics, but as we shall see, it crops up in many quotes about spectra. So it is quite definitely an actor's category, not some concoction of us latter-day historians.[36] Svetlana Alpers already pointed out the necessity of distinguishing between 'mapping' in a narrower and broader sense of the term:

> Used narrowly, mapping refers to a combination of pictorial format and descriptive interest that reveals a link between some landscapes and city views and those forms of geography that describe the worked in maps and topographical views. Used broadly, mapping characterizes an impulse to record or describe the land in pictures that was shared at the time by surveyors, artists, and printers, and the general public in the Netherlands.[37]

The identification of a deeply rooted "mapping impulse in Dutch Art" helped Alpers to integrate Dutch painting into the broader cultural context and mentality of this sea-faring nation in the seventeenth century. For us, too, it will serve an integrative function with respect to common attitudes, interests, and skill transfers between spectroscopy and cartography, between various scientific subdisciplines and certain branches of the graphic arts. Our case likewise ranks the 'testimony of the eye' above traditional authority, with a primarily descriptive mood reigning.

But there is no such thing as a unique visual description of any object. While the different cartographic conventions and projection techniques are well known, along with the debates over which to choose from among them,[38] it is less known that there is likewise a rich repertoire of modes of spectrum representations (cf. here pp. 2Iff.). Once a given mode is chosen, the spectrum map may be enlarged, or parts of it zoomed into closer view, **(p.11)** as soon as the interior has been explored and charted more thoroughly. They can be extended once new knowledge of bordering regions has been won, and then condensed again to regain a better overview and to avoid the danger of getting lost in the maze of details in a highly magnified chart. In fact, this parallel with cartography goes even further with respect to printing techniques (as we shall see in § 5.3).

Incidentally, cartographers tend to distinguish quite clearly between maps and atlases. An **atlas** is defined as a "very specific intermingling of written cartographic texts whose whole is more than just the sum of its maps: the atlas is a symbol of both its maker's professional status and the social worth of its owner (because of the greater financial capital involved in atlas production) and is also a metaphor for the encyclopedic sum of geographic knowledge".[39] Spectroscopic use of the two terms is much looser, however, with many self-described spectrum maps no less costly to produce nor less anxiously awaited by practitioners than so-called spectrum atlases. Ångström, Eder and Valenta, or Hagenbach and Konen presumably called some of their publications atlases in order to indicate a particularly broad spectral range covered or larger numbers of lines tabulated in the accompanying text. But other atlases (such as Higgs [1894]) are devoid of such accompanying tables. Size may also have been a criterion, with most atlases being in folio format or even grand-folio; but again there are exceptions, such as Uhler [1907], Mees [1909], or Löwe [1928], all of which are in small octavo. Besides these parallels to the cartographer's encyclopedic epitomes, there may also have been an—unconciously sought—elevation of status, some groping for recognition. But of much more importance than the name attached to the product of one's labors was whether it was accepted by the community as a standard reference work. Ångström's atlas achieved this just as much as did Rowland's map.

‘Mapping’ in and of itself is a widely used visual metaphor, signaling that a broad region of scientific objects is subsumed within the ‘empire of knowledge.’ Anthropologists use the concept of mapping to denote the production of a “mnemonic aid, especially visual, which all cultures utilize in some form or another.” The word derives from the Latin *mappa* which originally meant ‘table-cloth’ or ‘napkin’ and later also became the root of *mappœ mundi,* (i.e., medieval maps of the world). As Alice Jenkins writes in her analysis of spatial imagery in nineteenth-century representations of science, “the process of mapping is part of the harmonization of knowledge: ‘cartography’ creates order.”[40] Whether geographic terrain, brain tumors, cosmic radio sources, or the human genome, entering this keyword ‘mapping’ into any university library database will yield output from all these fields and more, spectroscopy being just a footnote. But the analogies, I claim, are much deeper than simply the way that scientists *speak* about their activities (which is Jenkins’s focus). They are also to be found in the way that these representations are *employed* in the various stages of scientific research practice (which is my focus).

Initially, just as in its counterpart the imperial chart, a new spectral region is mapped exploratively, for reconnaissance purposes, so to speak. Surprisingly often, this is done without any real understanding of what it is that is being mapped: Langley aptly described **(p.12)** his procedure as a “long groping in the dark”.[41] In fact, as has been pointed out with respect to early maps of radio sources, “the value of such a map was also independent of any particular conception of the sources. It would, however, facilitate further optical identification and thereby improve the likelihood of establishing the nature of the radio source”, or more generally, of the mapped object.[42] Exchange the word ‘radio’ with the word ‘light’, and the above quote is also valid for spectroscopic maps throughout the nineteenth century. Thus a substantial part of this book deals with this early, explorative phase of map-making, before there was any deeper theoretical understanding of what causes these spectra (the step-by-step deciphering of the spectral code is discussed here in Chapter 8).

In the next stage of map-making, the map is supposed to inform other experts working on adjacent or similar territory about the new conquests. Finally, the map assumes the function of unambiguously dispersing ‘secure’, certified knowledge in order to further the depletion of the new terrain’s resources or potential applications (similar to the initial logistical planning stages for the exploitation of a fully circumscribed and subjugated colony). Seen from this angle, Langley’s plot of the infrared spectrum, and his clarion call upon each new advance is the staking of a territorial claim at the farthest frontier: the infrared wavelength region beyond 10 000 Å: that is, beyond what photographers before him had reached is henceforth Langley’s land. Likewise, the region below 1850 A in the near ultraviolet, where Victor Schumann first succeeded in obtaining photographic spectra by evacuating his spectroscope and preparing gelatine-free emulsions (see here p. 71) is henceforth Schumann’s region, which name it still bears today. The Lyman region lies further beyond, and so on with many other examples throughout the full electromagnetic spectrum. This parallel between cartographic and spectroscopic mapping goes deeper, though. As we shall see (on pp. 168ff.), there were multifarious links between both activities. Indeed, if we replace ‘earth’ with ‘spectra’ in the following quote about geological maps, the first president of the Royal Geological Society might just as well have been referring to spectrum maps:

> Words following words in long succession, however ably selected those words may be, can never convey so distinct an idea of the visible forms of the earth as the first glance of a good Map. […] In the extent and variety of its resources, in rapidity of utterance, in the copiousness and completeness of the information it communicates, in precision, conciseness, perspicuity, in the hold it has upon the memory, in vividness of imagery and power of expression, in convenience of reference, in portability, in the combination of so many and such useful qualities, a Map has no rival.[43]

But the concept of mapping goes beyond the connotations of depicting, exploring, and offering orientation in unfamiliar terrain. Maps try to achieve more than a simple ‘representation’ of something that previously either had been observed directly or recorded indirectly. Maps are more than mere icons—in Peirce’s terminology those signs that bear a similarity to the depicted elements. They are also laden with symbols of various kinds **(p.13)** whose meaning is defined by convention. Think of a typical road map with its ‘key’ to explain symbols for various types of roads, railway tracks, rivers, churches, etc., and a ‘scale’ to indicate how to translate distances on the map into distances of the objects depicted. Sometimes a regular grid is superimposed onto the map so that each detail may be correlated with its respective longitude and latitude. Less often, indexical signs such as arrows point to features of special interest. All these features allow us to ‘read’ a map, not unlike how we read a book, as something “easily legible in a succession of fixations”. Thus in every map symbolic conventions are mixed with iconic elements. The systematic reason for this is that maps aim at something different from mere depiction or mirroring. As the art historian Ernst Gombrich put it: “Maps are normally designed to impart information about the invariant features of an area, in other words they leave ‘appearance’ on one side. […] In maps we want identicals to show as identical regardless of the angle from which we happen to look at them.”[44] Throughout this book, spectrum representations reiterate this inbuilt tension between icon and symbol, between capturing the full specificity of the observed feature and rendering what is typical about it, between representing and abstracting. For each of the many features of spectrum lines, such as line intensity, width, sharpness, wing shape, satellites, background intensity, and foremost color, an adequate rendering had to be found. And as we shall see, quite often no single best solution existed but rather several, often coexisting possibilities, which set apart the various practitioners of spectroscopy. It is a central aim of this book to illuminate the full breadth of this phenomenology of spectrum maps and their associated practices, but also to understand the reasons behind changes in these representational practices and their interplay with technological, experimental, and theoretical developments. On p. 45, for instance, when we look into the early history of representations of terrestrial spectra (as opposed to the solar spectrum), we shall see a gradual transition from a merely **narrational** description of flame or line colors (such as Talbot’s) via a **symbolic,** tabular vertical arrangement (such as Alter’s or Wheatstone’s) to an **iconic** horizontal chart (such as Masson’s). We shall also see, however, that this development is not a one-way track; on the contrary, a diachronic analysis of visual representations of emission spectra will reveal a meandering between preferences for iconic and symbolic types of representations (see Fig. 10.2, p. 440 for a synthetic summary).

1.4 The rhetorics of spectra

Each of these different modes of representing spectra carries with it a very specific rhetoric, something by no means limited to the verbal component of historical sources.[45] Mapping, in particular, involves selection and omission, simplification, classification, the creation of hierarchies and symbols. All of these procedures have or may have a rhetorical effect. Even the plainest spectroscopic map—apparently devoid of extraneous ornamentation—carries with it at least one agenda: to convince the users of its correctness and objectivity, its self-evident factuality. Henry Draper's first photograph of a solar spectrum is a striking example. He presented this product of a diffraction grating in photomechanical reproduction as "the **(p.14)** work of the sun itself, absolutely untouched". We shall see in § 6.7 whether this actually agreed with the manipulations of this image by himself and his printer. Draper's written comments on his spectrum plate were 'rhetoric' in the derogatory sense, even approaching intentional deception or trickery, but we should not limit our definition of rhetorics to such extreme cases. Even without this textual commentary, Draper's oversize plate in itself also carried rhetorics of its own (on the following, cf. Fig. 6.12 on p. 219). It displays the full spectrum strip in moderate magnification together with an enlarged section, presumably to show more clearly the high density and fine gradations of the recorded lines. A reproduction of the corresponding part from Ångström's lithographic atlas was supposed to underscore further that photography records far more lines than visual observation.

The rhetoric in many of the examples of visual representations presented in this book constitutes much more than simple accuracy and austerity of design. The choice of scale, frequency (or wavelength) range, mode of representation and printing technique, along with many other characteristics contributes to the overall appearance of the map and its influence or persuasive power. Samuel P. Langley's interesting dual representation of the infrared spectrum (see Fig. 2.36 on p. 79) shows that spectrum maps and atlases played a crucial role not only in scientific documentation but also in public presentation. His plot of the infrared part of the solar spectrum, which is nine times as long as the visible part, must have been impressive for students like Whiting's, who were shown this plot (cf. here the quote from one of her students' notebooks on p. 390): Here was a vast new territory to explore. We might compare this with early maps of North America when the Wild West was still largely unmapped terrain, or with subliminal but highly effective Eurocentrism at work in the mercator projection of world maps in a typical college atlas.

The persuasiveness of such a visual representation also has much to do with issues of accepted visual conventions and aesthetics, again largely unexplored areas as far as scientific images are concerned. In § 10.9, I reflect upon aesthetic assessments voiced by the historical actors with respect to graphs, maps, and other visual representations of spectra. I argue that from 1860 on, spectroscopy played a significant part in establishing a more visually oriented science culture, quite in step with other fields, which were drawing away from a rigid textual orientation at roughly the same time.[46] The nonverbal and nonnumeri-cal types of spectral representation used by teachers of spectroscopy played a crucial role in conveying the skill of pattern recognition. The Bunsen chart of the characteristic spectra of the alkaline metals (which figures so prominently in the research contexts of § 2.4, pp. 47ff., and §8.1) thus also serves as an icon for a didactic style: The pupils were made thoroughly familiar with these characteristic patterns in laboratory exercises designed for identification of the elements in the Bunsen-burner flame (cf. § 9.2). Such spectra were displayed on printed posters which, after 1860, suddenly began to appear in their thousands in chemical, physical, and technological laboratories and classrooms throughout the world. Emission line spectra of the chemical elements thus served as a spectrochemical alphabet, with the **(p.15)** spectra of unknown compounds analogous to words. These complex spectra, interpreted as superimposed images, then had to be analytically decomposed into their constituent elementary images in a visual process by which the lines of identified elements are subtracted from the complex compound spectrum. It was basically a mechanical alphabet—this analogy has come up repeatedly since the eighteenth century[47] but was never to become as productive in spectrum analysis as in the physico-chemical sciences. The same ‘letters’ later also resurfaced in the spectra of celestial bodies such as stars or nebulae, allowing one to ‘spell out’ their chemical constituents despite the immense distances involved.

Concerning the periodization of visual representations, Lorraine Daston and Peter Gal-ison have suggested a specific tripartite division of such sources in a deliberately cross-disciplinary fashion.[48] By studying a much narrower field in depth, taking into account not only the published images but, where possible, also the unpublished drafts or the larger pools of photographs from which the final ones were pulled, I attempt a systematic survey and analysis of these nonverbal sources. Starting with a brief survey of the earliest records of spectrum representations, a more detailed discussion fixes the beginnings at shortly after 1800, with both Wollaston and Fraunhofer finding indications of nontrivial substructure within the solar spectrum. This rich tradition of mapping the solar spectrum, both lithographically and photographically has its height towards the end of the nineteenth century. I trace the roots of spectrum analysis and qualitative spectroscopy to the older research strands of physical optics and chemical flame-color analysis and discuss the emergence of these fields as veritable research areas, stimulated by the publications of Bunsen and Kirch-hoff. I do not continue this particular historical line after the transition to Bohr's quantum theory in 1913, because the remainder of this story has often been told. Stellar spectroscopy, which only took off seriously in the 1860s (see here § 8.8, pp. 343ff.), and quantitative spectroscopy, which had an even later breakthrough in the late 1920s and 1930s, are consequently followed up somewhat further into the late 1940s, with some tabular summaries concerning their later rapid expansion. The overall dynamics of these areas of research, which is so strikingly different from the temporal development of visual representations, necessitate these differing time spans.

1.5 The structure of this book

During my earlier researches on the interplay of instrumentation, experiment, and theory in solar and terrestrial spectroscopy,[49] I was struck by the impressive variety of techniques used since 1800 to depict this phenomenon in all its subtlety and complexity. This diversity inspired me to go through atlases, maps, plates, and other illustrations in spectroscopic and astrophysical publications to study systematically the "emergence of a visual language" for spectra.[50] Following a generally diachronic vein, my aim is to combine a *historical* investigation of the changing modes of spectral representations with *systematic* considerations **(p.16)** about the interplay between research and printing, on the one hand, and research and teaching, on the other. Along the way, we encounter other branches that prove indispensable for dealing in a satisfactory manner with 'line matters'—to borrow the lithographer's term. For not only physicists, astronomers, and chemists were occupied with spectral representations, but also engravers, lithographers, photographers, printers, and other such artisans, and for each of these groups, questions of social identity have to be settled. For each we must know how they acquired their skills, what are their norms, their reputations, and how did they interact among themselves. As their social status changed over time, so did their everyday routine in the

wake of research and printing innovations that developed rapidly over the course of the nineteenth century. The goal of this study is to write the history of representations of spectra in as broad and balanced a way possible, focusing as much on the internal development of the scientific disciplines involved, as on the underlying material cultures. As much attention will be given to changes in the cognitive framework in which spectra were discussed, as to the visual skills needed to find the patterns considered relevant throughout the decades, and the manual skills needed to fix them as spectral characteristics identifiable and recognizable to any newcomer in the field. My sources are figures, plates, maps, and photographs from the published literature of several disciplines, especially physics, astronomy, and chemistry, but also from engravers and printers manuals, photography handbooks, correspondence between members of the various groups involved, and—where possible—sketches and drawings from laboratory notebooks. Among the fruits of my research in two dozen archives were quite a few documents allowing a step-by-step reconstruction of the different stages of the illustration process, leading from the initial observation through recording to final publication. For instance, in Fig. 6.11, the reader can examine Henry Draper's collodion photograph right next to his pencil drawing of the same region of the spectrum, and in the subsequent Fig. 6.12, compare a proof of Bierstadt's Albertype reproduction of it. All this material I found glued into one of Draper's laboratory notebooks, together with notes on the back-and-forth between researcher and printer (see here p. 213). But this full documentation of so close an interaction is admittedly highly unusual. In many cases a considerable amount of footwork was needed to come up with anything beyond the printer's or the engraver's last name—quite definitely, the social history of the printing trade, in particular, those branches connected to scientific illustrations, still deserves much more attention.[51]

Although in the early years of the nineteenth century depictions of the spectrum were quite rare, from about 1860 spectroscopic diagrams became quite frequent. An initial survey of which kinds of representation were dominant when is given in Chapter 2. It also outlines the gradual emergence of certain conventions in the mapping of spectra. In Chapter 3, 1 concentrate on the stepwise enlargement and narrowing in on interesting spectral segments, which was directly linked with progressive improvements in the scientific instrumentation used for observation and recording. I go into considerable detail about instruments of particular relevance to the production of spectrum maps (such as Fraunhofer's, **(p.17)** Henry Draper's, or Rowland's experimental setups).[52] The interplay between the chosen modes of representation and the available printing technologies is thematized in Chapter 4 with respect to engraving and lithography and in Chapter 6 with respect to photography.

In the 1870s and 1880s the growing importance of photography with the development of sensitive dry-plate processes and manageable techniques of photomechanical reproduction raises several other interesting points that are explored in Chapter 6. In contrast to the popular conception of photography as the most naturalistic form of visual representation, supported by the passionate rhetoric of its early ardent advocates (cf. § 6.2), 1 show in § 5.2 that at least until the mid-1870s, but to a lesser degree throughout the nineteenth century, the contemporaneous photographic and photomechanical techniques had crippling drawbacks which delayed full-fledged displacement of the traditional techniques of recording and reproduction for almost two decades, when the first photographic maps of the solar spectrum appeared (§ 6.9). During the transition period very often both traditional and modern illustrative techniques were used side by side, compensating each other’s weaknesses in a complementary fashion (cf. again § 6.4–6.8).

Having thus dealt with the different modes of representation in the first part, the book then turns to a discussion of the use of such spectrum plates and maps in research (Chapter 8) and teaching (Chapter 9). The discussion of the research applications centers around areas in which the search for patterns played a major role, namely spectrum analysis (§8.1), series, harmonics, and homology identification (§ 8.2–8.4), band spectra (§ 8.5–8.6), quantitative and stellar spectroscopy (§ 8.7–8.8). Chapter 9 presents the way spectroscopy was taught at high schools, colleges, and universities and its dissemination in popular treatises to other audiences like apothecaries, chemists, physicians, etc. Special emphasis is given to documenting the actual use of visual representations of spectra in lectures and laboratory exercises (§ 9.4–9.6). By means of a systematic comparison of the pertinent sections on spectroscopy and related issues in textbooks, laboratory manuals, and other material (§ 9.1), I am able to reconstruct the many levels of this education and pinpoint the crucial importance of nonverbal communication in acquiring pattern recognition skills, which were constitutive for spectroscopy during the nineteenth century. I also compare various local and national differences in the curriculum, picking out examples such as E.C. Pickering’s courses at MIT (in § 9.2), those offered at the Harvard Student Astronomical Laboratory (§ 9.7), or Sarah Whiting’s courses at Wellesley College (§ 9.5). The last is a particularly interesting case, because unlike most other institutions of higher learning this women’s college has preserved the lecture and laboratory notes of many of their students, some of which were later employed at the Harvard College Observatory as computers and aids in the classification of stellar spectra. While Whiting’s emphasis lay on transmitting the skill of spectroscopic pattern recognition, Lockyer’s teaching at South Kensington proposed to convey the skills needed for spectral mapping (§ 9.4). The gradual evolution in the selected topics and teaching methods is studied diachronically for the case of physics education at the Ecole Polytechnique in France roughly between 1860 and 1920, on the basis of preserved hectographed course manuals drafted by four generations of spectroscopists (§ 9.9).

(p.18) Both for the research and the teaching contexts, the aesthetic appeal of spectra on their viewers can scarcely be exaggerated. In § 10.9 I discuss this phenomenon with special regard to the language that spectroscopists used to describe fluted band spectra. Afterwards, I show how aesthetic motives also formed an important undercurrent in Louis Thollon’s endeavors at what I term ‘spectroscopic portraiture’, i.e., a rendering of the overall appearance, the *Gestalt* of a spectrum range; in § 3.5 we see how broader strata of the population perceived spectroscopy. Farmers, meteorologists, and military men, for instance, all were interested in weather forecasting applications of the so-called rainband in the sky spectrum, and we look at some reflections upon their experiences with the handy pocket spectroscope.

In a sense the end of the conventional depiction of spectra is marked by the rise of photometric methods of registration which had the great advantage of yielding direct information not only about the precise placements of the spectrum lines, but also about their profiles, which formerly could only be inferred from the earlier modes or representation. Because of the great importance of this new technique for twentieth-century research, the main body of my historical discussion ends with a brief chapter on photometric techniques (§ 7.4). Bohr’s atomic model of 1913, and quantum mechanics of 1925 totally transformed the approach toward spectra and spectrum analysis, by introducing theoretical explanations for what hitherto had only been described phenomenologically. Classical spectrum maps gave way to schematic term diagrams and photometric curves. Such radical breaks in the modes of representation also invite reflections about the most appropriate periodization (see the discussion of this point in § 10.8). How compulsory were the preferences for certain modes of representation? And how was the transition from one of these modes to the next made? In the final chapter, I summarize my findings concerning what I refer to as a ‘visual culture’ of spectroscopy from the late nineteenth century. Dominated by the search for patterns, visual representations were handled very much in the spirit of a morphologically oriented natural history. I then contrast the older and later modes of dealing with and representing the spectrum.

1.6 Acknowledgments

First and foremost, I have to thank the Dibner Institute for the History of Science and Technology in Cambridge, Massachusetts, most notably its directors, Jed Z. Buchwald and Evelyn Simha, for providing me with a Dibner resident fellowship in the academic year 1996/97. Their warm hospitality, the intellectual stimulus, and the helpful support from the technical staff at the institute facilitated concentrated work during the early phase of this project. Secondly, the American Institute of Physics funded a research trip to their archive in the Niels Bohr Library, which proved a rich source of both written and visual material. I am very grateful to the staff and its director Spencer Weart for helping me to make full use of their holdings. A substantial amount of time was spent in the archives at Harvard University and MIT, and I am indebted to the staff members for their enduring help with my many inquiries. After my return to Göttingen in 1997,I continued working on this book while teaching as assistant professor at the Institute for History of Science of the Georg-August-University. In particular, I would like to thank Elizabeth Eck, Ralf Haubrich, and Gerhard Rammer for their support. It would lead too far afield to list all the other institutions that I have visited or contacted—the list of abbreviations of the archives, from whose holdings I quote in the following, will have to suffice. Not included in the mentioned list **(p.19)** are the libraries from which I obtained the texts listed in the bibliography. The majority of the references were traced in the following libraries: Staats- und Universitätsbibliöthek Gottingen; Technical University, Berlin; Widener Library, Harvard; MIT Hayden Memorial Library and Burndy Library; Library of the Harvard/Smithsonian Center for Astrophysics (the latter four in Cambridge, Mass.); Library of Congress, and Library of the Naval Observatory, both Washington, DC, and finally the Niels Bohr Library of the American Institute of Physics at College Park, Maryland. The staff at Gottingen and at the MIT Humanities Library also had to bear with my numerous interlibrary loan orders for the remaining texts.

A substantial part of my study hinges upon access to relics of the past of yet another kind: historical instruments and their various material recordings of spectra, i.e., photographs, drawings, prints, and other forms of unpublished visual documentation. The most exciting set, relating to the work of Henry Draper, was made available to me by Deborah Warner at the National Museum of American History. I thank her as well as her colleague Peggy Kidwell very much for having shown me so many of these treasures in their instrument and photograph collections. The keeper of historical collections at the MIT Museum, Michael Yeates, was also very helpful in showing me the remaining visual documentation of MIT's physics and chemistry laboratories in the late nineteenth century. At Wellesley College Archives, Mrs Wilma R. Slaight and her colleagues were very helpful in providing me with materials pertaining to Sarah Frances Whiting's teaching of spectroscopy, a superb collection of student material. At the Royal Observatory in Edinburgh, Deputy Librarian Shona McEachern, her assistant Dawn Anderson, and the librarian A.R. MacDonald very kindly gave me access to the archival holdings relating to the work of Charles Piazzi Smyth, which includes his correspondence, notebooks, spectrum drawings, and photographic plates. Staff members at the archives of the École Polytechnique in Palaiseau near Paris kindly showed me various unpublished course manuals and practice session exercise lists, and librarians of the Observatoire de la Côte d'Azur and of the Lick Observatory Archives helpfully sent requested copies of materials and answered other questions.

Concerning the printing techniques used in the production of Fraunhofer's solar spectrum map, Mrs Marjorie Cohn, Curator of Prints and her colleagues at the Fogg Art Museum, Harvard University, were so kind as to examine this plate microscopically and to discuss the manufacture of the print with me in May 1997. The archivists at the Liverpool Record Office tracked down two obituary notices on George Higgs in local newspapers, and Professors Alan Bowden, David Edwards, and Martin Suggett in Liverpool kindly pointed me to further information about the man. The staff of the Massachusetts Institute of Technology Special Archives, in particular Ms Fran O'Donell, were very helpful in locating a set of Crew's spectrum photographs among their holdings and providing me with a reproduction; likewise, staff members of the Wolbach Library at the Harvard-Smithsonian Center for Astrophysics provided me with photographs of plates from Higgs's spectrum atlas.

Furthermore, many historians of science and technology have helped and supported me while I was writing this text, either by constructive criticism of selected parts of earlier versions, or by contributing good ideas and helpful hints as to what might be interesting to incorporate. While acknowledgment is given in the annotation wherever it was possible to nail down such help to specific points, let me just list those to whom I feel especially indebted: Bruno Belhoste, Hermann A. and Mary T. Brück, Olivier Darrigol, **(p.20)** Michael Hoskin, Kevin L. Johnson, Andreas Kleinert, Jost Lemmerich, Andrea Loettgers, Falk Müller, Kathryn M. Olesko, Donald Osterbrock, Alan Shapiro, and Roger Stuewer.

What would a book on spectrum representations be without color pictures? I am indebted to the Georg-Agricola-Gesellschaft for a generous grant which enabled me to include four color plates. I would also like to thank Sonke Adlung, Anja Tschortner, and Richard Lawrence for their help in preparing the manuscript for the press.

Parts of this book have already appeared in the form of journal articles. For the permission to reproduce these texts in extended and updated form in this book, I am indebted to Science History Publications (for parts of Chapter 6) Taylor and Francis (for parts of § 4.3 and 4.5) and Birkhauser Verlag (parts of Chapter 9).

Last but not least, I want to thank my wife, Ann, for all her support, ranging from assistance in archives to correction proofreading, translation of the French and German quotes, and revision of my English for this monograph.

1.7 Archival abbreviations

The following abbreviations are used for more frequently mentioned institutions. I am grateful to the archives and libraries whose unpublished sources I have cited for granting permission to reproduce the relevant passages and illustrations from among their holdings.

AASP:
Archives de l’Acadèmie des Sciences, Paris (Mme Christiane Demeulenaere-Douyére)
AEP:
Archives of the École Polytechnique, Palaiseau near Paris
AIP:
Niels Bohr Library, American Institute of Physics, College Park, Maryland
ANP:
Archives Nationales, Paris
ArP:
Archives de Paris, Direction des services (Mme Marie-Andrée Corcuff)
BNC:
Bibliothèque Nationale, Département de Cartes et Plans, Paris

BNE:
Bibliothèque Nationale, Département des Estampes et de Photographie, Paris
BNT:
Bibliothèque Nationale, Tolbiac, Paris
BöB:
Basel, Offentliche Bibliothek
CUL:
Cambridge University Library, Cambridge, England
DMM:
Deutsches Museum, München
HUA:
Harvard University Archive, Cambridge, Massachusetts
HUBL:
Handschriftenabteilung der Universitätsbibliothek Leipzig
JHUA:
The Johns Hopkins University Archive, Baltimore, Maryland
LAB:
Landesarchiv Berlin
LOC:
Library of Congress, Manuscripts Division, Washington, DC
MITA:
Massachusetts Institute of Technology Archive, Cambridge, Massachusetts
MITM:
Massachusetts Institute of Technology Museum, Cambridge, Massachusetts
NMAH:
National Museum of American History, Smithsonian Institution, Washington DC
RAS:
Royal Astronomical Society, London
RCW:
Royal Collection, Windsor Castle
ROE:
Royal Observatory Edinburgh
RS:
Royal Society, London
RSE:
Royal Society, Edinburgh
SAdK:
Stiftung Archiv der Akademie der Kiinste, Berlin
SPK:
Staatsbibliothek Preussischer Kulturbesitz, Berlin

SUBG:
Handschriftenabteilung der Staats- und Universitatsbibliothek Gottingen
WCA:
Wellesley College Archives, Wellesley, Massachusetts
WCSP:
Wellesley College Library, Special Collections, Wellesley, Massachusetts.

Notes:

(1) For overviews of more recent work on representation in science, see, e.g. Lynch and Woolgar (ed.) [1988], Mazzolini (ed.) [1993], Rheinberger [1994], and Pang [1997*b*].

(2) See, e.g., Edgerton [1984], [1991] chap. 7 on Galileo's representations of the Moon's surface, or Kemp [1990] on the history of linear perspective.

(3) See, e.g., Ferguson [1977], [1992], Vincenti [1990] as well as Latour [1986]. Cf. also Arnheim's [1969] earlier claims about intuitive thinking *(anschauliches Denken),* and Kaufmann [1980] for a concise survey of the various psychological theories of human cognition.

(4) See, e.g., Knorr-Cetina in Lynch and Woolgar (ed.) [1988], Dennis [1989], and Harwood [1989] on Hooke's *Micrographia,* Schaffer in Gooding *etal.* (ed.) [1989], Hetherington [1988] on various astronomical issues, Secord [1986] on the Cambrian-Silurian dispute, and Rudwick's studies of other geological controversies.

(5) See, e.g., Darius [1984] for an anthology of nice samples, Thomas (ed.) [1997] for some well-illustrated analytical essays, Schaaf [1979]-[1992] for pathbreaking studies on scientific photographers like John Herschel, Fox Talbot, and Piazzi Smyth, and Schaaf (ed.) [1994], [1996] for editions of pertinent primary materials.

(6) Compare, e.g., Crone [1953] with Woodward (ed.) [1975], [1987] for the change in introductory texts on the history of cartography; cf. Woodward [1974], Blakemore and Harley [1980] for historiographic surveys.

(7) I am thinking of Rudwick [1976] on the geosciences, Blum [1993] on American zoology, Pang [1994/95], [1996] on solar eclipses, and Pang [1997*a*] as well as his contribution in Lenoir (ed.) [1998] on stellar photography.

(8) On statistics see Funkhouser [1938], Royston [1956]; on botany see Blunt and Steam [1951], Nissen [1951], and recently Nickelsen [2000]; for more general surveys cf. also Nissen [1950], Ford [1992], Mazzolini (ed.) [1993].

(9) On the definition of ‘transparency’ in this epistemological sense see the contributions by David Gooding and Thomas Nickles, in Gooding *et al.* (ed.) [1989] pp. 14f., 216f., 302f. 31 Of.

(10) For a glossary of these and several other terms see Funkhouser [1938] pp. 364–8. For a critical survey from the point of view of a modern user of these representational devices, see Tufte [1983]. Cf. also Hankins [1999] pp. 52f. on the term ‘graph,’ and on nomograms in particular.

(11) Playfair (1801), quoted from Royston [1956] p. 242. Royston (as well as Shields [1938]) suggested that Play-fair transferred this idea of plotting graphs from the context of steam engine production. He had been employed as a draftsman by Boulton & Watt since 1780, which at that time was already using indicator diagrams to test the efficiency of their machines. For a contextual analysis cf. Brain [1996] chap. 1.

(12) On Playfair’s reception see, for instance, Funkhouser [1938] pp. 292ff.

(13) Quote from Tilling [1975] P- 194; cf. also Shields [1937]. The earliest examples found relate to thermometer and barometer readings recorded by Rømer and Lambert.

(14) See Krohn [1991] p. 197, and footnote 9 above on epistemological ‘transparency’. Cf. also Lynch’s or KnorrCetina’s shop-talk analysis, confirming this point that researchers ‘see’ their objects, rather than images thereof.

(15) See here footnote 3.

(16) F. Hund in an interview for the Archive for History of Quantum Physics (AIP), session of 26 June 1963, transcript p. 13. Unless otherwise indicated, all English translations in this book are by Ann M. Hentschel.

(17) On Piazzi Smyth’s wide-ranging talents and his emphasis on visual aspects, see Warner [1983], where he is portrayed as an ‘astronomer-artist’, as well as Schaaf [1979b], **[1980/81],** Thomas (ed.) [1997] pp. 88–91.

(18) See Smyth [1843/46] for detailed criticism of various published illustrations of nebulae by William Herschel (1811, 1814) and John Herschel (1834); he also comments there on his mezzotint techniques for rendering Maclear’s observations of Halley’s comet in 1835. Smyth’s paper is reprinted, with annotation and illustrations added, in Hentschel and Wittmann (eds.) [2000]. According to Warner [1983] p. 113, Piazzi had “apparent authority on the processes of engraving, aquatinting and mezzotinting”, and from 1845 on also in lithographing.

(19) See Galison [1997]; cf. DeVorkin [1985] and Smith and Tatarcwicz [1985] on the technological history of these devices, and Edgerton and Lynch [1988] on the aesthetics of digital image processing.

(20) See. e.g., Kirchhoff [1863] vs. Stewart [1863], Diacon [1867], Stokes [1876]. Kayser [1900], [1909], [1911], Junkes [1962], Dingle [1963], Brand [1995]. Cf. also James [1985*a*] for a critique of this Whig historiography.

(21) See Kayser [1900], [1902], [1905], [1908], [1910], [1912], [1924], [1930], [1932], [1934]. For the background of Kayser's handbook, see also his autobiography [1936]. About his life and work see Crew [1941], Freiesleben [1973], and here pp. 244 and 365.

(22) See, e.g., McGucken [1969], Sutton [1972], [1976], [1986], Maier [1964/81]; James [1983], [19856], [1986], [1988].

(23) See James [1981], [1995], Lankford [1981], [1997], DeVorkin and Kenat [1983], and James [1985*a*], Hentschel [2000] for historiographic surveys.

(24) See Forman *et al.* [1975], Weart in Reingold (ed.) [1979] pp. 300f., and Lankford [1997]. On Rowland's "school of light" specifically, see also Kargon [1986] and Sweetnam [2000] chaps. 1, 3, and 8.

(25) Pang [1997*b*] p. 155 makes this point in his useful literature survey on visual representation, citing Edgerton [1984], [1991], Winkler and van Helden [1992], Lankford [1981], Rothermel [1993] and others.

(26) See, e.g., Eder [1945], Lankford [1984], Schaaf [1990], [1992], Thomas (ed.) [1997] as well as other references here in footnote 163, p. 213.

(27) See Hunt [1844a], [1852], Abney [1874], [1878c], Eder [1884], Mees [1961]. The short remarks on the development of photochemistry found, e.g., in H. and A. Gernsheim [1955] chap. 23, for instance, are mostly based on these pioneering texts.

(28) See, e.g., Hetherington [1988] chap. 5 and further sources cited there on pp. 135f. Bartholomew [1976].

(29) See Pang [1994/95]; cf. also Becker [2000].

(30) On solar-eclipse expeditions, see Pang [1996]. On the coronagraph, see Hufbauer [1994].

(31) See Pang [1997] and here Chapter 4, § 6.7–6.8.

(32) Arthur Schuster to Charles P. Smyth, 14 July 1882 (ROE, 15.67, folder S); the plate in question is most likely pi. xxxiii illustrating Huggins [1868*a*].

(33) Quote from Whitfield [1995] p. ix; on the following see *idem,* p. 67.

(34) On this point see, e.g., Edgerton [1975] and Whitfield [1995] pp. 1, 61–3, quoted in the following main text. Strangely enough, Ptolemy himself designed and probably made a celestial globe, but never took the step of using his projection method to create a two-dimensional map. On another such transfer, see here footnote 11. p. 2.

(35) On the use of Ramsden's graduated circle and engineer's chain in the 1784 survey from London to Dover see Brown [1949] pp. 257–9; on Fraunhofer and Utzschneider's theodolites see Jackson [2000] and here p. 36.

(36) Just to give one example here: "The process of mapping infra-red spectra […] is, at best, a slow and tedious one. […] The work involves two distinct kinds of activity, viz. mapping the spectra, by means of a series of curves, and studying them." Coblentz [1905] pp. 4, 15.

(37) Alpers [1983] p. 147; cf. also here § 10.10 on 'Taking the mapping metaphor seriously'.

(38) See, e.g., Snyder [1993], Monmonier [1991] chap. 2, [1995] chap. 1 on the controversy over the Peters and Mercator projection.

(39) Edney [1993] p. 57.

(40) See Jenkins [1998] p. 190. Cf. also the *Oxford English Dictionary,* 2nd edn, vol. 9, pp. 348–51 on its etymology, with the first documentable use of 'mappe' in English dated to 1527.

(41) Langley [1882*b*]p. 587.

(42) Quote from Mulkay and Edge in Lemaine (ed.) [1976] p. 163. Quite in line with the analogy, Langley's infrared map does not distinguish between solar and terrestrial spectrum lines, and as we shall see on p. 268, Langley even had a hard time distinguishing between 'real' lines and the artefacts of his new instrument.

(43) George Bellas Greenough (1841), quoted by Secord [1986] p. 29.

(44) Gombrich [1975] pp. 127, 146.

(45) On the rhetoric of visual representations in science see. e.g. Lynch and Woolgar (ed.) [1988], or Latour [1986]; for cartographic examples cf. Harley [1989], Monmonier (1991] on "how to lie with maps". or Monmonier [1995] chap. 5 on the use of maps in the continental drift controversy.

(46) See, e.g., Felix Klein in Klein and Riecke (ed.) [1904] or Herbert Mehrtens, *Moderne Sprache Mathematik,* Frankfurt: Suhrkamp, 1990, pp. 60–84 on Klein's preference for mathematical models as visualization aids; or Suzanne L. Marchand, *Down from Olympus. Archeology and Philhellenism in Germany, 1750–1970,* Princeton University Press, 1996, pp. 142–51, on the increasing importance of *Anschauung* and visual aids such as maps, posters, and slides, in the teaching of the arts, classical history, and archeology (my thanks to Kathryn Olesko for pointing out this latter cultural parallel).

(47) See, e.g., Ferguson [1977] p. 835 or [1992] chap. 5 for examples of such sets of machine 'elements' used in the contexts of teaching and museums.

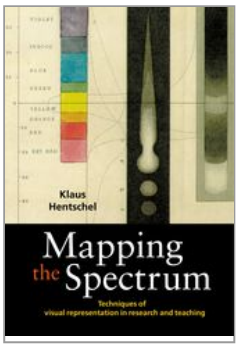
(48) See Daston and Galison [1992], Galison [1998], and here the discussion in § 10.8 on p. 450.

(49) See Hentschel [1993], [1996], [1997c], [1998] for the results of these studies dating back to 1990.

(50) This is, of course, an allusion to Rudwick [1976].

(51) The studies by Courboin [1914] and Dyson [1984] provide a useful orientation for engraving in the contexts of the French and British fine arts in the eighteenth and nineteenth centuries. See also Wakeman [1973] about Victorian book illustration, and K. and A. Hentschel [2001] for an in-depth case study on one Parisian engraver.

(52) The history of the various types of spectroscopes as scientific instruments is a quite neglected area of historiography—see Bennett [1984], Hearnshaw [1986] chap. 1, and Wolfschmidt [1998] for brief surveys, as well as Austin [1993], Warner [1993], for more detailed studies on particular types of spectroscopes.



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
Prof. Dr. Klaus Hentschel

Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

The Spectrum in Historical Context

Klaus Hentschel

DOI:10.1093/acprof:oso/9780198509530.003.0002

Abstract and Keywords

This chapter presents a historical survey of the analysis of spectra, starting with Leonardo da Vinci's observations of spectra from a glass of water. Newton's ‘new theory of light’ is treated along with his introduction of the prism as a research instrument. The long dominance of the Newtonian color scheme is discussed. Wollaston's and Fraunhofer's discoveries of dark lines in the solar spectrum are documented with hitherto unpublished material from the Fraunhofer papers in Munich and Berlin. William Herschel's thermography and John Herschel's maps of photographically obtained traces of spectra are covered as well as new instruments for exploring heat radiation, such as Nobili's and Melloni's thermopiles based on the thermoelectric effect.

Keywords: Leonardo da Vinci, Isaac Newton, Joseph Fraunhofer, William H. Wollaston, William Herschel, John Herschel, Leopoldo Nobili, Macedonio Melloni, thermography, thermopile

2.1 “The Phenomena of Colours”

The rainbow, or the natural decomposition of sunlight into its spectral components, has been a source of fascination for all human cultures.[1] But concerted experimental investigation of this phenomenon is of a much younger date, partly because reasonably clear glass or other translucent dispersive media are needed to generate a spectrum.[2] Glass of such quality was first manufactured in Roman times. In the first century AD the natural philosopher Lucius Annaeus Seneca first compared the colors of the rainbow with those created by con-ically shaped glass rods. During the twelfth and thirteenth centuries, interest in optics was revived again at Islamic centers of learning, soon to be followed by Christian ones. The Polish monk Witelo used translucent hexagonal crystals of quartz to examine color phenomena, covering three of the six surfaces in opaque wax. More commonly, water-filled globes were used. The German Dominican Dietrich von Freiberg, the English Franciscan Roger Bacon, the Egyptian astronomer and mathematician Ibn al Haitạm, and the Persian Kamāl al-Dīn al Fārisī all used such artificial raindrops to study the distribution of colors.[3] In the ninth century Venice became famous for its highly translucent, untainted *cristallo* glass—it is probably no accident that spectacles, or eyeglasses, were invented in Italy around 1300.[4] The technology of eyeglass production (initially convex lenses, 200 years later also concave ones to correct myopia) spread to other regions, notably the Netherlands where the telescope and microscope were invented around 1600. One of the first systematic experiments to include not only brief verbal descriptions but also a drawing of the spectrum was conducted by Leonardo da Vinci (1452–1519).[5] In one of his notebooks he described “rainbow colors” formed by the edges of air bubbles in a transparent glass of water. By observing these colors in direct transmission, Leonardo was able to exclude any influence of the eye in the projection of these colors onto the floor (cf. Fig. 2.1).

Prismatically shaped pieces of glass had long been known to produce colored light and were used for this purpose, for example, in Venetian lusters. According to the *Oxford English Dictionary,* the term ‘prism’ derives from the Greek πρἰσαα, meaning: “a thing **(p.22)** sawn”. In accordance with Euclid’s geometry it is defined as “a solid figure of which the two ends are similar, equal, and parallel rectilineal figures, and the sides parallelograms.” The first documented use of the term in optics is found in Henry Peacham’s *Gentlemans Exercise* of 1612, where he mentions a “most pleasant and delightfull experiment […] in a three square cristal prisme, wherin you shal perceiue the blew to be outmost next to that the red.”[6] In a German edition of Delia Porta’s (c. 1535–1615) *Magia Naturalis* which appeared in 1715, the term ‘Prisma’ was still treated as an unusual *terminus technicus* typeset in italics, carrying the definition “dreyecktes GlaB”.[7]

Thus it was only during the second third of the seventeenth century that these curious triangular pieces of glass —“fool’s paradise” as they were then also referred to because they “transform the colours of things into a thousand shapes”[8] —advanced from a curiosity, a mere toy, to a standard instrument of research. The Bohemian professor of medicine Jan **(p.23)** Marcus Marci (1595–1667),[9] for instance, used prisms to simulate the rainbow. Thirty-six of the theorems in his book *Thaumantias* from 1648 were devoted to the “iris trigonia”, the ‘prismatic rainbow’. He noticed the one-to-one correspondence between spectral color and angle of refraction.[10] But these acute observations were interpreted according to quite traditional premises rooted in the Aristotelian conception of color as constituting a specific mixture of light and darkness. White light was a simple substance, whereas the spectral colors were aberrations, or imperfections, possibly related to a change in the light’s density *(condensatio).* Consequently, Marci’s explanation for the appearance of the various colors in a beam that had passed through a prism was a difference in the degree of condensation, caused by the tapering thickness of the piece of cut glass.[11] Why color fringes appeared preferentially along the edges of lenses or prisms was settled by the supposition that there the ‘colored rays’ *(radü colorigeni)* were less often superimposed by the colorless and more intense image-generating rays *(specie objecti)*[12] A similar interpretation of color as a condensation phenomenon is also found in Giambattista della Porta’s treatise *De Iride et Colore* of 1593. Figure 2.2 shows rays of light, emitted from the Sun (G), traversing different thicknesses of glass, with violet emerging at R, blue at S, green at T, and red at V. (The parallelism of the refracted rays reveals Della Porta’s ignorance of dispersion!)

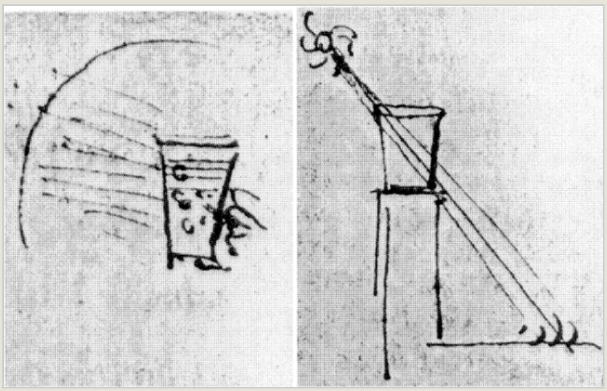


Fig. 2.1. Two drawings of spectrum observations by Leonardo. *Left:* spectrum observed in transmission through a water glass with air bubbles. *Right:* spectrum observed in projection upon the floor. From a Leonardo manuscript (RCW, no. 19150 r), reproduced by permission: The Royal Collection © 2001, Her Majesty Queen Elizabeth II.

(p.24) In his *Dioptrique* of 1637 René Descartes (1596–1650) used prism-shaped glass for his precise determination of the index of refraction of glass (cf. Fig. 2.3). A fine pencil of light was generated by means of holes A and L through two wooden props mounted at E and F. The glass sample was cut into the shape of a triangular prism and placed against the second prop. Because its face QR was flush against the prop, no refraction occurred where the light entered the prism, and the refracted ray along the line BI clearly indicated the refractive power of the glass: the higher its refractive index, the shorter the distance PI. The point of refraction R was quite close to the tip of the prism because that way the light ray was less likely to encounter inhomogeneities in the glass and would be less strongly absorbed. No scale is given in this illustration but the distance FL cannot have been much larger than 5 cm because of the inherent limitations in the contemporary production of homogeneous glass.[13]

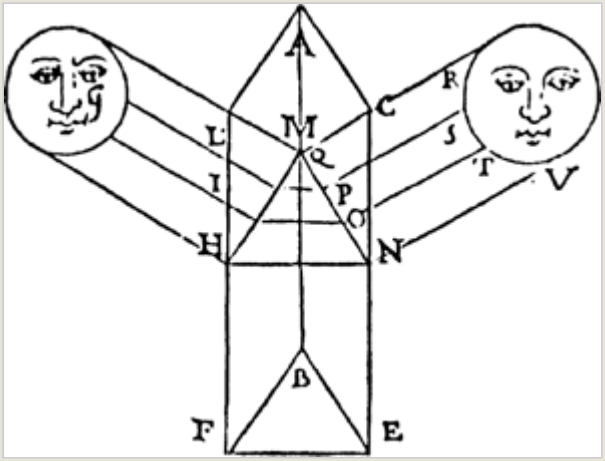


Fig. 2.2. Delia Porta's conceptualization of color generated by refraction through a prism ABCE. The density of the light is altered variously as it traverses different thicknesses of glass. From Della Porta [1593] p. 223.

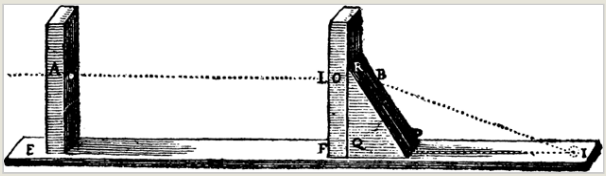


Fig. 2.3. Descartes's apparatus to measure the index of refraction. From Descartes [1637] p. 137 (reproduced in Descartes [1982] vol. 6, p. 212).

This experiment was designed to obtain just one value for the refractive index. Quite in line with this, Descartes also used a single index of refraction for water, namely, 187 : 120, for his famous calculations of the rainbow in another essay illustrating the fruitfulness of his treatise on method, *Les Météores,* which appeared in the same year. Nevertheless, he must have noticed that various colors were refracted slightly differently. This is confirmed by another illustration in *Les Météores* where he described a prismatic experiment (cf. Fig. 2.4) in which solar light is directed through a prism NMP and a spectrum HF is projected onto a surface perpendicular to the slit DE parallel to the second face of the prism. In this illustration, the divergence of the rays coming from both limbs of the Sun is greatly exaggerated: practically all of them hit face NM of the prism orthogonally, and the light refraction only occurs upon leaving the prism.

Descartes noted that no clear spectrum appeared if the opening *(I'ouverture),* or slit, as we would say, between D and E was too large. He inferred that, unlike normal light refraction, the spectral colors could only be formed along a dark border or edge. According to his mechanistic model of light, the spectrum colors were generated by a kind of spin imparted to the light particles hitting the border zone by E or D of the slit: those hitting the left end D rotated in one direction and thus exhibited one color (red) at F, while the others were turned **(p.25)** the other way round by the surface at E (and hence were transformed into blue-violet at H). The dashed middle ray hits neither border of the slit, but is nevertheless refracted to the point G. Thus the yellowish area near G was the effect of normal refraction of the Sun's rays. Descartes's mechanistic model of light was needed to explain why "darkness or a boundary to the light is necessary"[14] for creating the other colors of the spectrum such as red and blue-violet at the areas F and H, respectively. Color conceived as a superimposed rotation (*vertigo*) is also found in contemporary texts of other natural philosophers such as Thomas Hobbes (1588–1679), who may possibly have been inspired by Descartes's model of *tournoiement.*[15]

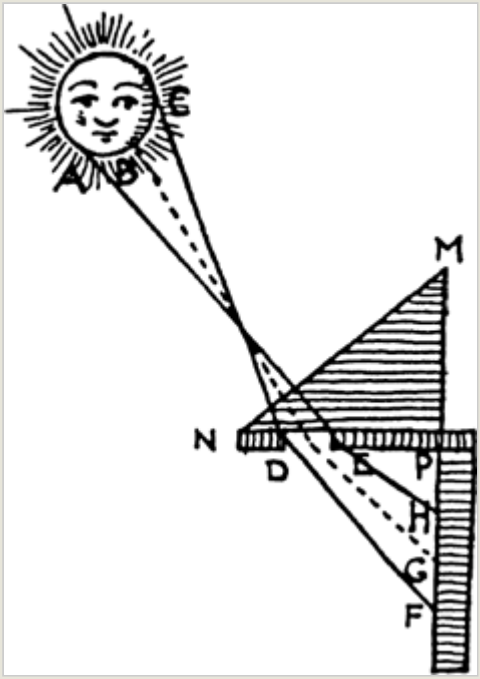


Fig. 2.4. Descartes s prismatic experiment with solar light. Coming from ABC, the ray is projected vertically onto face NM of the prism, refracted from the opposite face, and falls onto the screen PF. From Descartes [1637] p. 224 or [1982] vol. 6, p. 330.

While occupied with the "grinding of Optick glasses other than spherical" in the mid-1660s, Isaac Newton (1642–1727) became intrigued by the phenomonon which we now call 'chromatic aberration': even the most perfectly shaped lens does not focus all colors of a well-defined beam of light at the same spot, and this greatly reduces the definition of the image created by refracting telescopes. A first look at a bicolored thread through a cheap prism reportedly bought at a fair, already revealed to him that the blue rays were refracted more than the red ones. Newton then initiated a series of more systematic experiments, using a triangular glass prism inserted in a small hole in the window shutter of a darkened room, to "try therewith the celebrated *Phenomena of Colours*".[16] Having studied the **(p.26)** optical theories of Descartes and Hooke, he had doubts about the accepted modification theories of color, and his experiments amplified this skepticism. Quite in line with his general inclination towards an atomistic conception of matter, Newton conceptualized white light as a heterogeneous mixture of light globuli. According to his mechanistic model, which is documented in various manuscripts but not publicized until later, these globuli, distinguished by their different refrangibilities, stimulate the human eye to see specific colors. In his 'New theory of light and colors', which he first published in 1672, Newton was intent on restricting his presentation to propositions gathered from phenomena by induction. He thought he had shown conclusively that a white pencil of light contains rays of various colors that are separable by refraction in prisms, raindrops, or more generally, at the interface between two media of different refractive index. According to his mechanistic model, prisms thus act like separators, and colored glass or other colored matter act like filters, admitting only certain light globuli through while blocking others out. To please the inductivist Baconian spirit of the newly founded Royal Society, and also to immunize his findings against potential criticism, Newton omitted most of these

mechanistic assumptions, however, and decided to present the experiments in a way that made his theory emerge as an ‘inevitable’ outcome.[17]

The term ‘spectre’ conjures up notions of phantoms and unreal objects of thought. It was also used to refer to the apparitions exhibited in the then popular *camera obscura*—not unlike the darkened chamber Newton used for his investigations. Another root of the term ‘spectrum’ introduced by Newton to describe the colorful oblong image of the Sun produced by his prism *(colorum prismatis)* in his article on the ‘New Theory about Light and Colours’ of 1672 is the Latin verb *specto* for seeing or watching.[18] By varying the distance between a moveable screen and the prism, he verified that the rays continued to propagate along straight lines and not in some curved manner, as Descartes’s model of color deriving from a spinning motion of light globuli would have suggested. Placing an inverted prism right next to the first prism restored a circular image of the entrance hole on the screen. This indicated that the spectrum was not due to imperfections in the prism, in which case it would have elongated further.[19] When he generated a spectrum at least five times as long as it was wide with a good prism positioned up to twenty-two feet away from the screen, he was able to demonstrate that no further ‘division’ of the colors was possible after the ‘analysis’ of light in the first prism: Similar to a chemical reduction which, once completed, cannot yield anything more elementary, when light of a selected **(p.27)** color traverses two or more prisms in sequence there is no further alteration in the color—at least in principle, i.e., if the experimental procedure is followed rigidly and skillfully.[20] Not anticipating the many problems his contemporaries would have in replicating precisely this experiment, around 1672 Newton saw it as a particularly striking demonstration of the elementary nature of colored light and the composite nature of white light.

> Light is a confused aggregate of Rays endued with all sorts of Colors, as they are promiscuously darted from the various parts of luminous bodies. And of such a confused aggregate, as I said, is generated Whiteness, if there be a due proportion of the Ingredients; but if any one predominate, the Light must incline to that colour […].
>
> For, of the Rays, constituting the incident light, since those which differ in Colour proportionally differ in Refrangibility, they by their unequal refractions must be severed and dispersed into an oblong form in an orderly succession from the least refracted Scarlet to the most refracted Violet.[21]

This experiment flatly contradicted—and in Newton’s opinion refuted—the common conception of normal white light as elementary and colors as its derivatives. So Newton called this the ‘crucial’ experiment in his earlier optical papers, which claim he later retracted, however, because of its controversial nature.[22]

(p.28)

Not all of these colored rays could satisfy Snel's law of refraction with a given medium and one index of refraction (or as Newton put it, with one degree of refrangibility). Newton could resolve this apparent paradox by showing experimentally that each color on its own fulfilled Snel's law. The price he had to pay was varying the index of refraction with the color of each ray. For instance, in his calculations of the rainbow, it ranged between an approximated 108 : 81 for red rays and 109 : 81 for violet ones, as a consequence of refraction in water droplets.[23] As described most completely in Newton's second paper on light and colors from 1675, prompted by Hooke's persistent criticism, but also in prop. II, prob. I of book one of his later *Opticks,* he saw an analogy between the perception of light by the eye and the perception of sound by the ear. In his earlier *lectiones opticae* of 1670–72, he had divided the spectrum into five principal colors. Now he added orange and indigo, and argued that this doctrine of **seven primary and simple colors,** namely red, orange, yellow, green, blue, indigo, and violet, was also based on this harmonic analogy.[24]

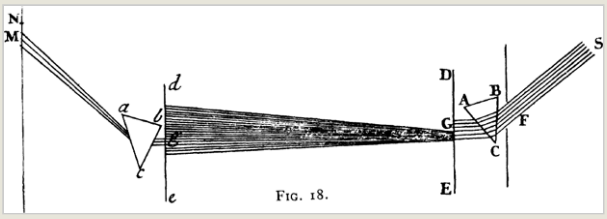


Fig. 2.5. Newton's *experimentum crucis* with two prisms in sequence. The light from a small circular opening F in the window-shutter is led through a condenser lens onto a fairly large prism ABC. The spectrum formed is projected onto a vertical screen DE and a small part of it is thrown onto a second screen at de, in which a small circular hole g admits rays from only one prismatic color onto another prism abc. The dispersed light is then projected onto the back wall MN and does not show any further dispersion, regardless of the color admitted through the hole in the projecting screen. Diagram from Newton [1704*b*] p. 47.

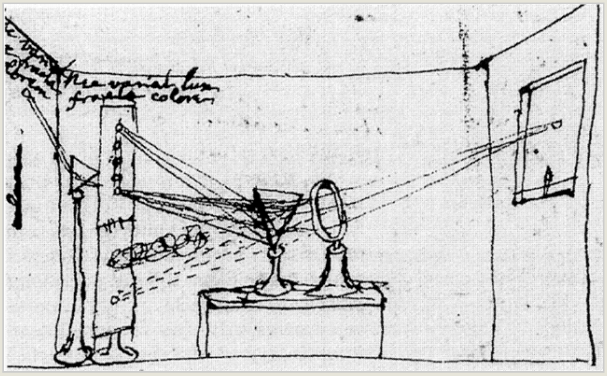


Fig. 2.6. A later variant of Newton's *experimentum crucis* from his correspondence (1721): The sketch differs from the schematic textbook presentation in that it depicts a condenser lens in front of the first prism instead of a second screen (DE with hole G) right after it.

(p.29) As Fig. 2.7 illustrates, Newton tried to interpret this color sequence as analogous to the diatonic scale in music: d–e (whole step), e–f (half step), f–g (whole step), g–a (whole step), a–b (whole step), b–c (half step) c–d (whole step). Accordingly, orange and indigo were semitones of smaller extension than the other primary colors in the spectrum.

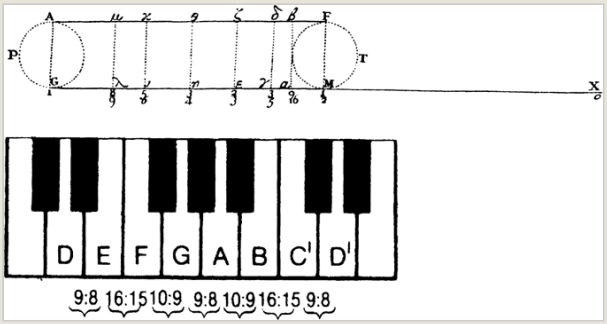
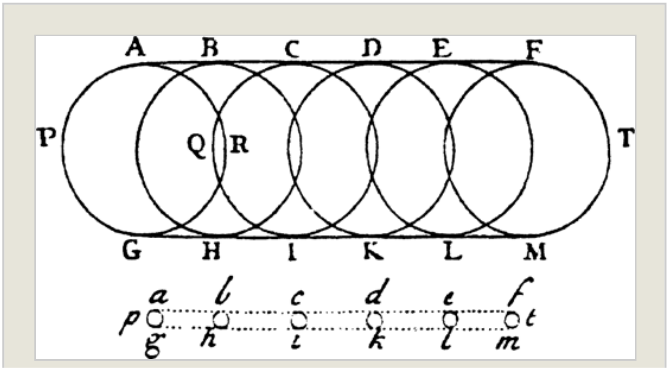


Fig. 2.7. Newton’s optical analogue to the diatonic scale. The relative elongation of the various color ranges according to Newton’s harmonic analogy (from Newton [1704b] p. 127), juxtaposed with a schematic comparison keyboard: the two halftones EF and BC correspond to the smaller intervals *μκ* and *δβ.*

Newton’s representation of the spectrum, which prevailed for the next 100 years, was a “parallelogram of light, with circular ends, in which the seven colours gradually shaded into each other without any interruption”.[25] Figure 2.8 shows how Newton’s parallelogram representation harmonized the continuous color change with a presumed finite set of primary colors. Superposed circles indicate the respective positions of the primary colors in the continuous spectrum. The smaller the circular hole is through which the solar light is screened, the less two adjacent circles overlap and the better the “heterogeneous Rays of compound Light” are separated.

Yet there is a strange inconsistency in this representation. A sufficiently small hole will cause the overlapping area between any two adjacent circles to vanish. But the spectrum exhibits intermediary colors between the primary colors, not white gaps. Although all these intermediary colors are interpreted as a superpositioning of two (or more) primary colors, the lower parallelogram representation fails to reflect this. In his *Opticks*[26] Newton did his best to smooth over this point and, astonishingly, none of his many followers seems **(p. 30)** to have noticed this incongruency between the conceptual and representational assumptions. In principle—if we ignore diffraction effects for a moment—this homogenization of the spectrum from a reduction in the size of the aperture can be carried on indefinitely. It would then actually imply an indefinitely large number of different rays rather than a finite set of primary colors. Although this point was made by one of France's foremost Newtonian physicists, Jean Baptiste Biot (1774–1862), in his treatise on experimental and mathematical physics,[27] many of Newton's epigones were quite evidently misled by the rhetorics of the parallelogram representation. To give just one example: the Göttingen naturalist Johann Christian Polykarp Erxleben (1744–1777) took Newton's visual scheme at face value:

> The colorful image is composed of as many circles as there are colors in it, one of which is red, another orange, etc., the last violet, which fuse into each other in the colored stripe. Each of these circles is an image of the Sun in light of a different refrangibility, so they cannot all fall on a single spot. But just because these circles or images of the Sun are so large, they fuse into each other and so one can make them smaller by holding a raised glass between the prism and the hole in the window shutter; then each simple [ray of] light separately assumes the form of small round disks rowed on top of each other.[28]



Erxleben even went about illustrating this idealized separation of the seven primary colors in a figure (see below) for his influential textbook, and it withstood Georg Christoph Lichtenberg's many revisions. Erxleben's unfortunate diagram bore the brunt of Johann **(p.31)** Wolfgang von Goethe's (1749–1832) derision, whose own alternative conception of light and color in his *Farbenlehre* is beyond the scope of this book.[29]

> In [Erxleben's] figure, now, the seven rays are placed nice and neatly on top of each other as seven circlets, just as though some one had once seen them like that; the connecting dashes that Newton had wisely always added are left out.

Newton's visual scheme continued to dominate visual representations of the spectrum throughout the eighteenth century. In 1808 the polytechnicien Jean Henri Hassenfratz (1755–1827) still depicted the absorption spectra of various colored glass plates and liquids interposed in a narrow beam of sunlight as overlapping circles of primary colors (cf. Fig. 2.10). Even though he declared in the introduction to his long paper that white light *actually* consists of an infinite number of colors, not just seven or three, his *visual representation* of his findings remained confined within the strictures of this Newtonian divisioning into primary colors.[30]

Fig. 2.8. Newton's parallelogram representation of the solar spectrum, a superpositioning of circles indicating the refraction of primary colors. The lower diagram illustrates improved color separation with smaller hole diameter. From Newton [1704*b*] p. 65.

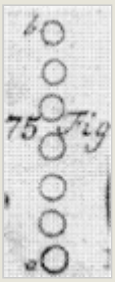


Fig. 2.9. To the right of Goethe's [1810*b*] § 246 comment, (Leopoldina edn, ser. I, vol. 5, p. 92): Erxleben's misleading representation of seven homogenized primary colors, from Erxleben [1772*a*–*c*] pl. VI, fig. 75.

Despite the persistence of Newton's visual scheme, around the turn of the eighteenth and nineteenth centuries his hypothesis about the seven primary colors came under renewed attack by advocates of a three-color theory.[31] It was even harshly censured for "the mystic number seven, the child of judicial astrology", being "devoid of foundation, and too plainly betray[ing] a tincture of the mysticism of the age".[32] Others, most notably Hassenfratz, were eager to point out that "la théorie de l'immortel physicien anglais" only intended to divide the spectrum into seven parts for practical reasons, and that Newton actually considered the spectrum as composed of an infinitude of different colors that fuse into each other in infinitely fine nuances.[33] All the same, the visual representations of the spectrum remained comparatively uninteresting, for no further structure was distinguished apart from the color sequence from red to violet. This changed only in the early nineteenth century, but as we shall soon see, the transition was gradual and the Newtonian heritage of analyzing the spectrum primarily in terms of color theory prevailed for quite some time. Nice evidence **(p.32)** for this thesis is provided by Johann Benedict Listing (1808–1882), a Göttingen specialist in physiological optics, who as late as 1866 still defended a standardized division of seven color regions in the visible part of the spectrum.[34]

The longevity of the Newtonian color scheme is a good example of a phenomenon which we shall encounter repeatedly throughout this study, namely the tenacity of representational forms despite drastic transformations in the theoretical and conceptual contexts from which they had emerged.[35]

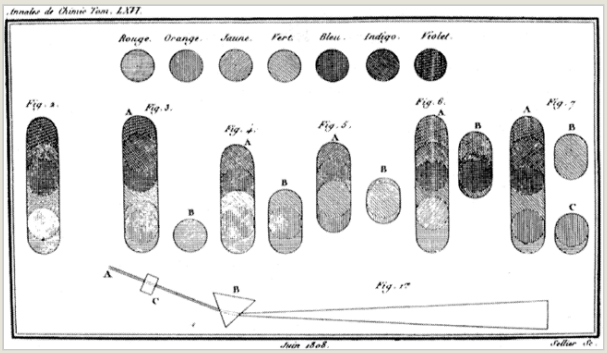


Fig. 2.10. Hassenfratz's absorption spectra of colored glass represented as superimposed circles or ellipses of the seven Newtonian primary colors of light (color code is along the top). From Hassenfratz [1808].

2.2 The dark lines

In 1802 a gentleman scientist observed dark lines in the solar spectrum. The retired physician William Hyde Wollaston (1766–1828), who financed his broad-ranging experimental researches from his discovery of a practical method for working platinum, made this observation while conducting an "examination of refractive and dispersive powers" of a flint-glass prism. He interpreted these lines as natural boundaries between four color zones:

> I cannot conclude these observations on dispersion, without remarking that the colours into which a beam of white light is separable by refraction, appear to me to be neither 7, as they usually are seen in the rainbow, nor reducible by any means (that I can find) to 3, as some persons have conceived; but that, by employing a very narrow pencil **(p.33)** of light, 4 primary divisions of the prismatic spectrum may be seen, with a degree of distinctness that, I believe, has not been described nor observed before.[36]

The lines which Wollaston designated A and B defined the boundaries of red, while D and E demarcated the violet from the blue (between C and D). The least clearly defined area, yellowish green, extended from B to C. Two more lines near C could not be ascribed any clear borderline position between the color zones, so Wollaston assigned them the lowercase labels f and g. In the position of minimum refraction in which, as Wollaston put it, "the colours are most clearly divided", he found that the intervals AB, BC, CD, and DE related to each other in the proportions 16, 23, 36, and 25, but these relations closely depended on the angle of incidence and on the type of prism used.[37]

For the first time, someone had noticed an internal structure in the spectrum other than the sequence of rainbow colors. This discovery had been triggered by the combined use of improved glass prisms and a very narrow slit.[38] How nontrivial this finding was is perhaps best illustrated by an anecdote reported many years later, after this observation had been repeated independently by Fraunhofer in Munich,[39] followed by hundreds of others. By 1823 several lengthy and detailed descriptions of how to generate and observe the famous phenomenon were available, yet even experienced optical experimenters seemed to have trouble, at first, in replicating Wollaston's and Fraunhofer's findings. Charles Babbage reported about a visit he paid to John Herschel in his mansion in Slough:

> Conversing with Mr Herschel on the dark lines seen in the solar spectrum by Fraunhofer, he inquired whether I had seen them; and on my replying in the negative, and expressing a desire to see them, he mentioned the extreme difficulty he had had, even with Fraunhofer's description in his hand and the long time which it had cost him in detecting them. My friend then added, "I will prepare the apparatus, and put you in such a position that they shall be visible, and yet you shall look for them and not find them: after which, while you remain in the same position, I will instruct you *how to see them,* and you shall see them, and not merely wonder you did not see them before, but you shall find it impossible to look at the spectrum without seeing them."
>
> On looking as I was directed, notwithstanding the previous warning, I did *not* see them, and after some time I inquired how they might be seen, when the prediction of Mr Herschel was completely fulfilled.[40]

(p.34) This episode is the more striking since Babbage did not even have to set up the instrumentation himself but was presented with the fully prepared phenomenon. What he lacked was thus not so much instrumental skill in producing the phenomenon as the knowledge about what exactly to look for. Knowing "how to see" the extremely fine irregularly spaced lines at right angles to the spectrum's color gradient was essential, given the low resolution of Herschel's home-made spectroscope. Lacking the experimental knack of a Herschel, it was a nearly insurmountable task to reproduce the phenomenon without knowing how to handle prisms, how they are mounted so as to ensure a symmetric passage of light through them, or how to construct a regular and sufficiently narrow slit.[41]

2.3 Early modes of representing the spectrum

The earliest representation of the solar spectrum deserving the term ‘map’ was drawn and engraved onto a copper plate by the self-educated optician and instrument maker Joseph Fraunhofer (1787–1826) in 1814/15.[42] (See Fig. 2.11 and color Plate I.) Fraunhofer had learnt this printing technique in his youth as a court glazier’s apprentice.[43] Like Wollaston, Fraunhofer also attached alphabetical labels to some of the most prominent dark lines in the solar spectrum (from A to H and a to b: see Fraunhofer’s early pencil sketch, Fig. 2.11), but he explicitly rejected the Englishman’s opinion that they were color boundaries and thus moved away from color theory.[44] Altogether, Fraunhofer counted a total of 574 lines between B and H alone, but in his published map he depicted only about 350 of them, taking considerable pains to represent accurately not only their relative positions and internal structure (the yellow D line is clearly depicted as a double line), but also to indicate their comparative intensities: compare the bold D or F lines with the very subtle lines right next to them in Plate I (cf. the analysis of the printing techniques for his map on p. 116). On top he added a curve indicating the relative intensities of the various spectral colors.[45]

PLATE I *(next page). Left:* Rare handcolored version of Fraunhofer’s 1814 map of the solar spectrum. From the archive of the Deutsches Museum, Munich, map collection, STO 1107, cabinet 39, shelf 03. *Right:* Published version of Fraunhofer’s map of the solar spectrum, carrying the inscription “ge-zeichnet u. geatzt von J. Fraunhofer” (drawn and etched by J.F.). Original length of both: 36.5 cm. (For detailed commentary on the printing, labeling and the additional intensity curve from Fraunhofer [1815*a*] pl. II, see here pp. 34ff. and 116.)

Captions of color plates II—IV (preceding pages)

PLATE II. *Above:* Lithograph (with superimposed colors by iris printing) of the flame spectra of various metallic compounds (cf. here pp. 42f., and p. 124 on the askew color borders typical of iris prints). From Miller [1845]. *Below:* Characteristic lines in the emission spectra of alkali metals and alkaline earths, with the solar spectrum at the top as reference (cf. here pp. 47f.). Chromolithograph by W. Creuzbauer’s printing house in Karlsruhe, original width 16.6 cm (cf. also fig. 2.18 on p. 47 for the black and white version and further commentary). From Bunsen [1860] plate V.

PLATE III. *Above:* Samples of eight handcolored drawings of various absorption spectra (cf. here p. 37), approximately original size. From Brewster [1822/23*a*] plate XXVII. *Below:* Chromolithograph printed on six stones with various greens to render different line intensities (cf. here pp. 125). From Kirchhoff [1861/62*a*] plate II.

PLATE IV. *Above:* The first three of Secchi's four classes of stellar spectra, engraved by P. Dulos, printed by Sarazin imp. (Paris). From Secchi [1870*a*] pi. II. *Below:* Samples of arc spectrum photographs obtained with Lippmann's process by Hermann Krone in Leipzig. 1892 (cf. here p. 208). Photograph from Deutsches Museum, Munich, Bildstelle.

(p.35) Already in an early pencil sketch reproduced below, but also in the black-and-white printed plate, Fraunhofer tried to convey the decrease in overall light intensity by means of shading near both ends of the spectrum (cf. Fig. 4.5, p. 116 for a close-up of the printed version).

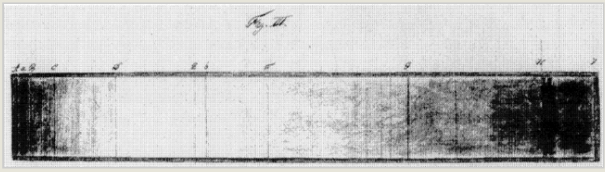


Fig. 2.11. Undated handdrawn pencil sketch of the solar spectrum, with all major lines labeled and darkening at both ends of the spectrum indicated by pencil hachure. originally 27 cm long. From DMM. Fraunhofer papers, folder NL 14-52.

In the main body of the text he simply cited refraction angles for some of the major lines. This dual documentation of qualitative and quantitative aspects was sufficient for the purpose Fraunhofer had in mind when he drew his map. He just needed markers for specific colors in the visible spectrum (using the Newtonian color terms) for his refractive index measurements of glass samples. Fraunhofer's angular measurements were taken with a precision theodolite, ruled on silver in 10 arc-second intervals, and an achromatic telescope. The two verniers helped provide a precision of one arc second so he could **(p.36)** determine the index of refraction to six decimal places.[46] In contrast to this, previous measurements of angular diffraction had been limited to an accuracy of less than 10 to 15 arc minutes because of the continuous change of the colors in the spectrum.[47] Fraunhofer's spectrum map must thus be seen in the context of the applied research done at the optical and mechanical manufactory of Utzschneider and Reichenbach at the former monastery in Benediktbeuern.[48] As Myles Jackson has pointed out, Bavarian makers of scientific instruments had profited from the Napoleonic occupation and the order by Maximilian IV to conduct an up-to-date geodetic survey of Bavaria employing the techniques of the Bureau topographique. Meanwhile their British competitors, who had dominated the field in the eighteenth century, were being hampered by high taxes on glass.[49] Fraunhofer's 'Optical Institute' supplied large amounts of bubble-free and striae-free achromatic glass for optical precision instruments such as telescopes and also responded to the high demand for such geodetic instruments as theodolites. It was ideally located to take advantage of an already experienced labor force. For glass making was not a foreign practice at the Benedictine monastery even before its secularization in 1803. The 48 people involved in the production of optical glass in Benediktbeuern included twenty polishers, two tube drawers, one heater, five turners, one glass pourer, one assistant optician, and numerous other skilled artisans.[50] Within this context of optical glass production, spectrum lines remained important for determining refractive indices and dispersion formulas throughout the nineteenth century.[51]

Once Fraunhofer’s discovery became more widely known through reprintings of his results and translations into English and French in 1823, the dark lines in the solar spectrum and the corresponding bright lines in flame spectra began to attract the attention of researchers, sporadically already in the 1830s, and extensively since the late 1850s. For such studies, Fraunhofer’s shorthand symbols were clearly not adequate. Nor were the vague color terms used in the early 1820s, such as, for instance, those in a paper on a monochromatic source of light by the Scottish physicist Sir David Brewster (1781–1868). Its spectrum is described as “a fine homogeneous yellow, which, when analyzed by the prism, exhibited faint traces of green and blue, but not a single ray of red or orange light”.[52] John F.W. Herschel’s report on “the colours of the prismatic spectrum exhibited by certain **(p.37)** flames” such as muriates of strontia (i.e., chlorides of strontium oxide) and of lime, copper nitrate, and boric acid, published in the same year 1822, is not any clearer, nor are Fox Talbot’s descriptions of “experiments on coloured flames” written four years later, in which he confined himself to a simple line count in the different color regions of sodium, potassium, and strontium salts held in the flame.[53] Both Brewster and J. Herschel had embarked on a study of the selective absorption of various media not so much out of interest in the spectrum per se. They were rather looking for perfectly monochromatic sources of light as a precondition for highly defined refractive index measurements. We have to remember that this research program was started shortly before Fraunhofer’s contributions became well known in England, and that this strategy of isolating light of a distinct color seemea very promising.[54] But Brewster must have felt the inappropriateness of verbal descriptions for colorful absorption phenomena. In a more detailed report from 1822 for the *Transactions of the Royal Society of Edinburgh* he appended a hand-colored plate of spectrum strips (red, yellow, green, blue, and lavender), with the respective absorption areas blackened out (see Fig. 2.12 and color Plate III).

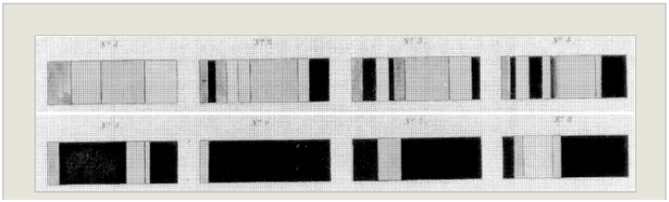
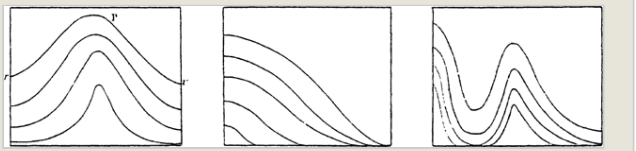


Fig. 2.12. The first eight of 12 absorption spectra as drawn by Brewster. Nos. 2 and 3 represent those of different kinds of blue glass, nos. 4 and 5 a combination of the former of greater thicknesses; nos. 6 and 7 represent the spectrum of light sent through a sky-blue paste and a very thick piece of green glass, respectively. From Brewster [1822/23*a*] pl. **XXVII**, reproduced in color on Plate **III.**

Even a black-and-white reproduction of this plate indicates by the uniformity of the shades of gray that no effort was made to represent the gradual color transitions in the continuous spectrum, nor to exhibit anything even approaching a dark ‘line’. Even the dark stripes are very wide and undifferentiated. But for Brewster this was no fault, because the only thing that mattered then was the extension of each of the various colored areas: the broader the blackened parts were, and the fewer the luminous areas, the better suited it was for his purpose of finding a monochromatic source of light. In the same year in which **(p.38)** his paper was published (1823), Brewster hit upon Fraunhofer’s publication and immediately translated and republished it in the *Edinburgh Philosophical Journal.* Interestingly, he deviated from Fraunhofer’s original title by adding “with an account of the lines or streaks which cross the spectrum”,[55] obviously still not quite decided about what to call the dark parts in Fraunhofer’s spectrum, as his earlier drawing suggests. Other commentators of Fraunhofer’s discovery compared his dark lines with the black stripes in interference patterns, thus hypothetically linking Fraunhofer’s discovery with Thomas Young’s and Augustin Fresnel’s discoveries in physical optics and their revival of a wave theory of light.[56]

The 1820s saw the introduction of another representational form of the observed spectrum as well. In his survey article on light, written for the *Encyclopædia Metropolitana* in 1827, John F. W. Herschel publicized his idea of describing the variation of light absorption with color in noncrystalline media, such as liquids and gases, by means of a curve. He plotted the amount of transmitted light as a function of refrangibility for various thicknesses of the absorbing material.[57]



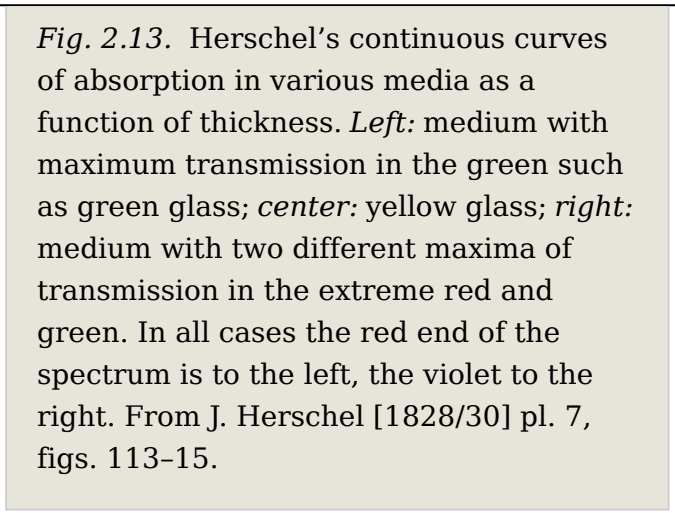


Fig. 2.13. Herschel's continuous curves of absorption in various media as a function of thickness. *Left:* medium with maximum transmission in the green such as green glass; *center:* yellow glass; *right:* medium with two different maxima of transmission in the extreme red and green. In all cases the red end of the spectrum is to the left, the violet to the right. From J. Herschel [1828/30] pl. 7, figs. 113–15.

The schematic representations obtained (cf. Fig. 2.13) were not based on measurements; they were rather a "geometrical picture of the action of the medium on the spectrum."[58] Nonetheless, they nicely illustrate the color intensification of absorbent media as their thickness is increased (left case with green glass), as well as the change in perceived color (dichroism) if the medium has more than one transmission maximum (right case). The center of attention for both Herschel and Brewster was the hotly debated question of which theory of light best accommodated the newly discovered effects of polarization, interference, and the observed dependency of refrangibility on color (dispersion).[59]

(p.39) Some observers continued to quote angular refractions or equivalently refractive indices until the late 1860s,[60] but these values (e.g., the angle 51°11′55" and the index $n_D = 1.33397$) were not only awkward to use but obviously dependent on the angle of refraction and material composition of the specific prism used in the experiment (see Fig. 2.21). Another recording method simply entailed counting the lines in the intervals delimited by the main Fraunhofer lines. This was done especially when the quality of a representation comparable to Fraunhofer's or later Kirchhoff's spectral map was at issue.[61] Given the thousands of spectrum lines revealed by a spectroscope even of only moderate resolution, which were available by the mid-nineteenth century, this task was far less easy than might be supposed. Especially when the observer wanted not only to count each line, but to locate it roughly as well, visual observation of the spectrum had physiological constraints:

> With the first attempts already, it became evident that it is extraordinarily difficult to indicate the number of lines in one part of the spectrum at the same time as their location. For at first glance, one sees only the stronger and very black lines, whereas when one looks at the colored stripes for a longer time until the eye has adjusted to a specific type of light, almost in every single segment of the spectrum on which the eye focuses, a large number of lines of differing light intensities becomes apparent, none of which or only individual ones of which, of a different quality, had been perceptible before. So if one combines observation simultaneously with measurement of the refractive angle, then many lines that the observer had been able to see quite clearly upon concentrated examination of the spectrum vanish because the eye must adjust itself in rapid succession to different types of light.[62]

Consequently, line counting and the measurement of relative distances between lines soon evolved into separate branches of spectroscopic research. The observer to whom we owe the above description of the eye's ability to adjust so quickly from one color region to another decided to concentrate first on the precise determination of relative distances between the main Fraunhofer lines and other characteristic lines. He then changed over to a detailed examination of the fainter lines in the much smaller intervals between the strong markers. Sections of the spectrum with very many regularly spaced lines lying close together essentially required little more than a line count. The data thus obtained were then transformed into sketches of a great number of small segments of the spectrum made to the same scale, to form a composite map of the spectrum.[63]

In 1854 a passionate amateur experimenter with home-made instruments, and inventor of several electrical gadgets including a proto-telegraph, also tried to distinguish the "physical properties of light produced by the combustion of different metals in the electric spark." This physician, David Alter (1807–1881)[64] of Freeport, Pennsylvania, drew up a **(p.40)** table of the seven Newtonian primary colors (from left to right) and listed twelve chemical elements (vertically, see Fig. 2.14). In the resulting 84 spaces he entered up to four vertical lines for the number of prominent spectral lines or bands (effectively somewhat like Roman numerals). So in a sense he simply counted how many such lines there were per color region for each spectrum.

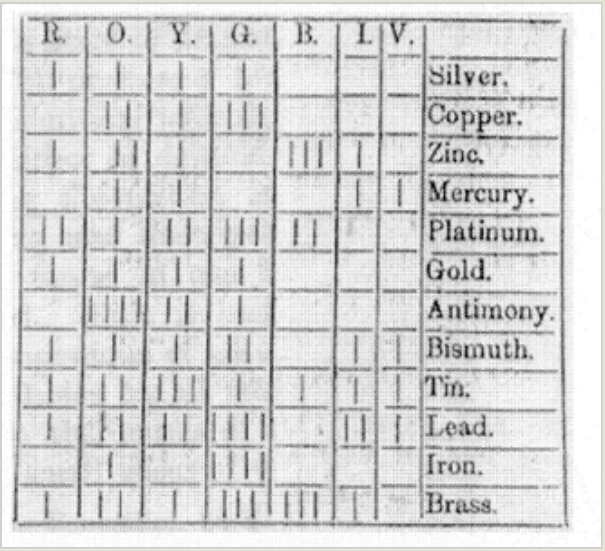


Fig. 2.14. David Alter's representation of spark spectra as a tabular line count in seven colors. From Alter [1854] p. 55.

His motivation for devising this recording approach arose from a desire to emend the limited verbal description of flame colors then in common use. Even the most refined vocabulary fell short when trying to discriminate between the color of flames or arcs of elements like silver and thallium: the arc spectra of these two metals both not only were green but happened to exhibit "the same shade of green." However, Tyndall identified two green bands in silver and only one in thallium, situated "midway between the two greens of the silver."[65] Thus a line or band count did improve upon the qualitative description. In the accompanying text Alter tried to specify the lines entered in his table further by adding descriptions like "faint yellow line", or "in the orange a very bright band, one of yellow and one of green—two faint bands in the blue which are not always seen". But these verbal descriptions remained diffuse and ultimately inadequate. While this sector-count representation, as I would like to call it, gave at least some information about the overall distribution of bold lines in the spectrum of the dozen elements examined, it was far from satisfactory in conveying their features. No effort was made to register the relative *intervals* between the lines, not to speak of their intensities. Authors positively struggled to express the subtle intensity distinctions: the "faintest suspicion of a line" as opposed to: "more decided line, fine line, decided line, more decided line, still more" or "strongest line" against one "almost as strong".[66] After 1860 Alter, with the support of a few others, tried to portray himself as a **(p.41)** "veteran spectrochemical analyst" or even as "the discoverer of spectrum analysis".[67] But a closer look at what he actually says in his publications about "coloured bands" reveals that he was still far away from finding a suitably unambiguous description for characteristic spectra of the chemical elements. Clearly, a better means of referring to a specific line within the spectral ranges of several hundred units of Å (in later nomenclature) was needed.

Sir David Brewster suggested an alphanumerical reference system to refer to the prominent lines *between* the few major lines that Fraunhofer had already labeled with upper or lowercase letters of the alphabet. About 200 stronger intermediate lines between these Fraunhofer lines were marked with natural numbers, beginning with 1 at the reddest end of each interval between two Fraunhofer lines: hence Dl, for instance, denoted the first dark line next to the yellow D line, while C26 denoted the closest dark line at the other side (towards the red end of the spectrum).[68] The many other fainter lines fared no better, though, in this notation system, which could be hardly more specific than: 'in-between line C26 and Dl'. The structural problem with this kind of labeling system was that the number of known lines was continually rising. So no matter how many lines were assigned 'names', there would always be lines 'in-between' that were not directly identifiable. To overcome this problem, Stokes proposed an alternate nomenclature to indicate the position of a chosen spectrum line with respect to any given pair of Fraunhofer lines. He divided the distance between any two Fraunhofer lines, say between lines D and E, into 100 equal parts and then indicated a position between D and E, 27/100 units away from D, as 'D 27 E', and a position 50 units from the interval G–H beyond the last visible line H as G H ½. The size of these units thus clearly varied with each interval between the Fraunhofer lines.[69] As this alphanumeric classification system was being suggested, however, the transition to a more strictly pictorial mapping of emission and absorption spectra was already underway.

Charles Wheatstone's (1802–1875) "table of bright lines" in the spark spectra generated from six different types of metallic electrodes is sometimes referred to as the first 'naturalistic' drawing of emission spectra. But unlike its reprint of 1861, Wheatstone's original contribution for the Dublin meeting of the British Association for the Advancement of Science in 1835 did not include any published drawing of the spectrum, just narrative descriptions of "definite rays, separated by dark intervals from each other".[70] The 'reprint' includes a figure structurally halfway in-between David Alter's table (shown above in Fig. 2.14) and spectrum representations common after 1860. This illustration, in which each spectrum is still represented vertically, not horizontally, must be seen in the context of the priority dispute over the discovery of spectrum analysis—a point unfortunately missed in most standard accounts of the history of spectroscopy.[71]

(p.42) In 1845 the professor of chemistry at King's College in London, William Allen Miller[72] (1817–1870), published the results of his experiments and observations of the flame spectra of metallic compounds like copper chloride dissolved in an alcohol solution before being brought into the flame. To better illustrate the "intricate spectra" thus obtained, Miller chose to supplement his paper with two chromolithographed maps, one of which is reproduced here as Fig. 2.15 and in color on plate III. Both consisted of five color zones (red, orange, yellow, green, and blue) whose borders also nearly coincided with the major Fraunhofer lines from B to F. The distribution of spectrum lines and bands was indicated by more or less strongly shaded regions. The presence of the Fraunhofer lines as orientational aids offered—at least in principle—a fairly accurate way to determine the relative distances and positions of the respective lines. Nevertheless, Miller cautioned against overestimating the precision of his prints, which had a total width of 15 cm and thus an average dispersion of c. 200 Å per cm: "No pretensions to accuracy are made in these sketches; they are simply intended to convey an idea of the general position and grouping of the lines. […] the comparison, though not rigidly accurate, being still very nearly so, and perfectly sufficient for my purpose".[73]

As Miller divulged to his readers at the outset, the purpose of his research had originally been to discover certain recurrent patterns in the “general arrangement of lines” in spectra of different but chemically related materials. Even though this aim, which is actually quite in line with the much later search for ‘homologous spectra’ (cf. here pp. 308ff.), was not met, Miller decided to publish his results anyway, if only to inform other researchers about which classes of substances did not work for such a research program.[74] Interpretation of his findings was thus relegated to the indefinite future—all the more reason at least to provide a sufficiently accurate phenomenological description of them. One indication that Miller did succeed in this much is the positive assessment of commentators even in our century. Despite the acknowledged inaccuracies, Miller’s plates were still “strikingly realistic pen and ink drawings”.[75] The London-based chemist was critized by his contemporaries, though, in particular for the low-temperature spirit flame he used, which was unable to produce the full spectrum of many of his samples, if at all. They were also disturbed by the fact that the alcohol solution superimposed its own spectrum on the examined spectra.[76] Thus, **(p.43)** when John William Draper (1811–1882),[77] professor of chemistry at the University of New York, published his report on the production of light by chemical action in 1848, that is, three years after Miller’s paper, his figure of the spectra of various flame spectra (with few exceptions) just makes use of rectangular stripes to indicate the different extensions of these continuous spectra mapped relative to the Fraunhofer lines in the solar spectrum. However, we do still see a rather symbolic depiction of what we today would identify as the two broad cyanogen band spectra (below G and between F and G), as well as interruptions of the continuous spectrum at regularly increasing intervals (in the spectral region B to E). In a blow-pipe spectrum, generated when additional oxygen is blown into the flame, thereby substantially increasing its temperature, Draper even noticed something that we would now identify as emission lines: “the spectrum was divided into five well-marked regions, separated from one another by inactive spaces; in short, I saw five distinct images of the blue cone, one yellow, two greens, one blue, and one violet.”[78]

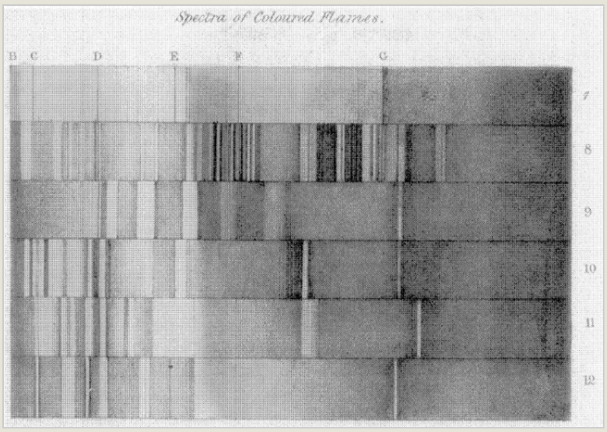


Fig. 2.15. W.A. Miller's representation of molecular flame spectra. No. 7: solar comparison spectrum with major Fraunhofer lines; no. 8: $CuCl_2$; no. 9: H_3BO_3; no. 10: $SrNO_3$; no. 11: $CaCI_2$: no. 12: $BaCl_2$. Lithograph by J. Basire. From W.A. Miller [1845*a*] pl. II (cf. also here Plate II (top) for the coloring of this plate by iris printing.

Altogether, a comparison of Draper's diagram (Fig. 2.16) with Miller's lithograph from three years earlier (Fig. 2.15) shows how far ahead of its time Miller's illustration was in the **(p.44)** mid-1840s. This more naturalistic visual representation of emission and absorption spectra, which includes the specific positions of dark and bright lines as well as a faithful depiction of their relative distances and intensities, was taken up by several other researchers in the succeeding years. In 1851, Antoine-Philibert Masson (1806–1860), who taught physics at the Lycée Louis-le-Grand and at the École Centrale des Arts et Manufactures, decided to embellish his description of metallic spark spectra with little black-and-white sketches of about 7 cm length. They essentially consisted of rectangular white boxes separated by stripes of different widths indicating the positions, color range, and to some extent the strengths of the main lines. Masson's 'tableau' actually is a very detailed projection of the various spectra recorded with the aid of a *camera lucida.*[79] Compared with Alter's table Masson's representation endeavors to provide more detailed information on the positioning of various lines within each rectangular box. It is much more iconic and less symbolic than its predecessor map. Had Masson followed up his iconography, he might have ended up with equivalents of Bunsen's plates displaying the characteristic spectrum lines of the **(p.45)** various chemical elements. But the fact is: he didn't. Like several of his contemporary physicist colleagues, he too was only interested in the nature of the electric spark, and not in spectra *per se,* which were nothing more than a noteworthy side-effect.

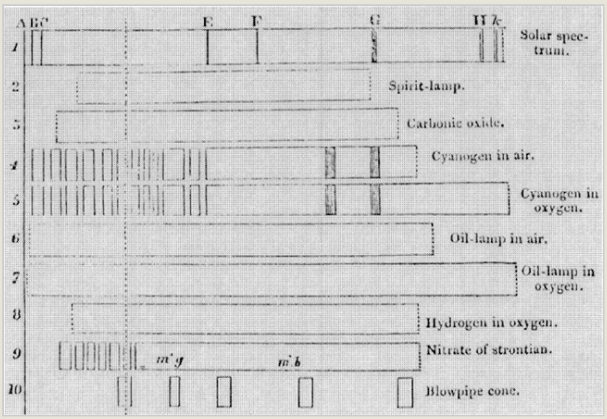


Fig. 2.16. J.W. Draper's diagram of continuous flame spectra (nos. 2–9) and of one discontinuous line spectrum of an oxygen enriched blow-pipe cone (no. 10), all drawn relative to the solar spectrum with the main Fraunhofer lines (no. 1). Woodcut. From J.W. Draper [1848] p. 107.

What we thus see in the early history of representations of terrestrial emission spectra (as opposed to the solar spectrum) is a gradual transition from a merely **narrational** description of flame or line colors (such as Wheatstone's) to a **symbolic,** tabular vertical arrangement (such as Alter's) to an **iconic** horizontal chart (such as Masson's), which then leads to the more extensive maps of larger spectral regions. Since many individual researchers are involved, working within their various 'scientific communities' or in isolation in private laboratories, and in many different national and local contexts, it cannot be expected that this transition be governed by any strict rules of the type 'no iconic mapping before 1854' or 'no tabular arrangement after 1851'. We are rather dealing with a gradual shift of preferences for one representational style over another, with considerable overlapping and a certain inertia especially with respect to the terminology used to denote them.[80] While in solar spectroscopy this transition to iconic depictions of the spectrum occurred already in the early nineteenth century (to a large extent from the immense impact of Fraunhofer's map on his contemporaries), in terrestrial spectroscopy a proper mapping of the relative distances between spectrum lines only became common in the mid-1850s.

2.4 The tardy emergence of spectrum analysis

There is a reason for the relatively late emergence of a 'mapping impulse' (to borrow a term coined by the art historian Svetlana Alpers) in the analysis of flame, arc, and spark spectra. It is true that such pioneers as Fox Talbot and Masson came quite close to discovering spectrochemical analysis. Talbot, for instance, had already pointed out that the two red tints of lithia and strontia flames, hardly distinguishable with the unassisted eye, could be readily kept apart if one looked at their spectrum.

> The strontia flame exhibits a great number of red rays well separated from each other by dark intervals, not to mention an orange and a very definite bright blue ray. The lithia exhibits one single red ray. Hence I hesitate not to say that optical analysis can distinguish the minutest portions of these two substances from each other with as much certainty, if not more, than any other known method.[81]

But despite such farsighted prophesies, prior to the late 1850s it was far from clear that each element had its own characteristic spectrum, and a lot of evidence actually seemed to speak *against* this assumption at the time. For instance, virtually all spectra exhibited a strong yellow line. Swan's findings seemed to suggest that different hydrocarbon compounds could not be distinguished by their respective spectra. Likewise, Masson's publications, which superficially look so much like an anticipation of spectrum analysis,[82] merely established **(p.46)** a set of four strong lines (which he called α, β, γ, and δ) as *common* to all eight spectra sketched in his 'tableau'.[83] To confuse things even further, some elements displayed completely different spectra in the flame than in the electric arc or spark. By no means all chemists had prisms at their disposal. Such were a more frequent item in physical cabinets, but physicists generally were not yet interested in problems of chemical analysis. Finally, even if they had been, it was far from clear at the time what the fundamental unit would be with which to correlate the various spectra. Chemistry was still grappling with the question of atomic structure, and many alternative models of the atom were intensely discussed throughout the nineteenth century. Supporters of Prout's hypothesis, according to which all atoms were composed of packets of light hydrogen atoms, were pitted against people like Lockyer who were looking for even smaller constituents of the chemical elements.[84]

The problem of too low flame temperatures was overcome in the middle of the 1850s with the invention of the Bunsen burner. The colorless flame produced by this gas burner yielded temperatures of up to 1800°C.[85] One of the first scientists to use this new device for spectroscopic analysis of various hydrocarbon compounds was the Scottish physico-chemist William Swan (1818–1894). His result was that for all spectra related to substances of the chemical type C_rH_s (e.g., wax, oil, tallow, turpentine) or of the form $C_rH_sO_t$ (e.g., ether, alcohol, and glycerine), the same five colored bands and half a dozen characteristic bright lines appeared, once the slit was adjusted to the blue base of their flames. Indeed, this spectrum was identical with the one from the blow-pipe, “though that little instrument gives it more neatly, clearly, and without the swamping effect on its best characteristics of the dense continuous spectrum derived from the more or less yellow light in the upper parts of most kinds of simple lamp flame.”[86] This surprising similarity in the spectra of dissimilar chemical compounds made Swan curious about how their common lines compare with those of sunlight. But his comparative plot (Fig. 2.17) showed disappointingly few coincidences: only in the case of the line α could he verify a precise coincidence.

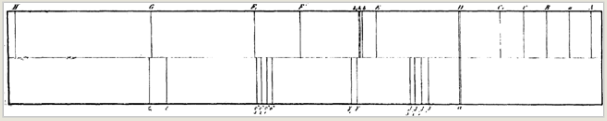


Fig. 2.17. Swan’s comparison of the solar spectrum (top) with the common lines of various hydrocarbon spectra (bottom). Copper engraving, 1857. From Swan [1853/57*b*] pl. I.

(p.47) As disappointing as Swan’s result of 1857 might have been, methodologically it was decisive. A systematic application of a hypothetical one-to-one correspondence between each chemical element and a characteristic spectrum generated in the high-temperature flame of a Bunsen burner triggered the sudden breakthrough in 1859. It was born of a fruitful collaboration between an analytical chemist, Robert Wilhelm Bunsen (1811–1899), who could prepare unusually pure samples, and a physicist well-versed in optics, Gustav Robert Kirchhoff (1824–1887), both of them at the university of Heidelberg.[87]

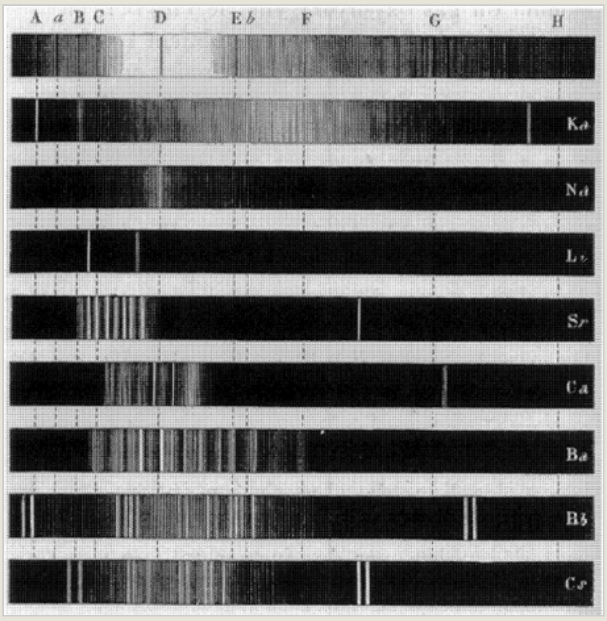


Fig. 2.18. The spectra of alkali metals and alkaline earths, including the newly discovered elements rubidium and caesium, as depicted by Bunsen and Kirchhoff, here reproduced in a later black-and-white version wood-engraved by Dulos and published in Secchi [1870] p. 230 (for the original color plate from Bunsen [1860] pl. V, limited to Ka, Na, Li, Sr, Ca, and Ba, see here Plate II). Only the characteristic lines of each spectrum are depicted, no scale is given, and the solar spectrum is added at the top for orientation.

Bunsen's celebrated color plate of alkali metal and alkaline earth spectra, which was promptly supplemented in 1860 and 1861 by the newly discovered elements of rubidium and caesium (see color plate II and Fig. 2.18 for a later black-and-white version), became a model of its kind: It was reprinted repeatedly in virtually every introductory text on spectrum **(p.48)** analysis, from the small-scale versions in sales catalogues of instrument makers to the wall-hanging poster size. I would venture to say, it was the most frequently reprinted scientific illustration in the second half of the nineteenth century. Thenceforward, the rapidly growing community of spectroscopists proliferated representations of other spectra not depicted in Bunsen's celebrated 1860 plate of emission spectra. For instance, Bunsen's map inspired his pupil Rudolph Theodor Sim[m]ler (1833–1874) to search for further applications of his teacher's method, and to plot the spectra of copper salts, manganese, and boric acid in a similar fashion.[88] But, along with countless others who may have had the same idea, he soon had to acknowledge that many metals (such as Mg, Al, Fe, Mn, Co, Ni, Cr, U, and Zn) and their compounds did not exhibit distinctive spectra when held in the Bunsen-burner flame or were dominated by much stronger, already familiar lines.[89] Bunsen's map likewise clearly served as a model for H.F. Brasack in Halle in his choice of the scale and mode of representation for his map of 14 metals published in 1866.[90]

Chemists like Alexander Mitscherlich in Berlin or Émile Jules Diacon (1827–1893) in Montpellier, were skeptical of the universal validity of Kirchhoff's and Bunsen's thesis that each element had its own unique spectrum.[91] But even they brought forward evidence to the contrary in a form that clearly followed the standards set by Bunsen's charts (see, e.g., Figs. 2.19 or 2.23). Spectra of chemical compounds like metallic oxides, chlorides, bromides, or iodides, were soon called **band spectra** to distinguish their channeled appearance from those of the Bunsen and Kirchhoff type, called **line spectra,** with isolated lines lacking obvious regularity in arrangement. Thereafter chemists continued to plot a considerable number of absorption spectra with broader bands distinguishing different absorbers.

2.5 Numerical scales in spectrum maps

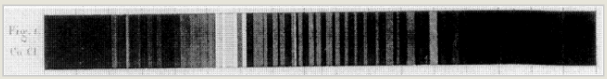


Fig. 2.19. The copper chloride spectrum depicted by Diacon. This copper engraving by Dulos (cf. here p. 143) shows the several broad bands with different ruling distances to indicate the various intensities. Its total length is 16.4 cm. From Diacon [1865] pl. I, fig. 1.

It is important to point out, though, that neither Bunsen's chart nor other lithographed maps of the early 1860s provided any numerical scale: they simply offered the solar spectrum **(p.49)** as a gauge, or other arbitrary lines as orientational aids.[92] In the second publication of 1861 by these two Heidelberg professors we learn more about how they had made their original drawings: Bunsen had certainly used a numerical scale as a guide. Their second spectroscope (cf. Fig. 2.20), which was a much improved design by the Munich optician Carl August Steinheil[93] (1801–1870), projected a custom-made transparent scale[94] that was inserted in the slit of a third collimating tube onto one face of the same prism that decomposed the light coming from the flame. By reflection off the prism surface, the image of this scale could be seen together with the flame spectrum. With this device two different spectra could easily be compared in addition, by means of a reflecting prism placed in front of the micrometric slit.[95] Thus instead of having to take angular measurements with reference to a graduated circle (such as in Fraunhofer's theodolite arrangement), angles were simply read off this scale.

But while such a scale was used as an internal reference aid, it was not considered unreasonable to exclude it from the published plate.[96] First of all, the choice of the origin for this scale was purely conventional. Bunsen happened to choose the value 50 for Fraunhofer's **(p.50)** D line, since this line was most easily identifiable in almost every spectrum.[97] The scale units, as seen through the eye-piece of the spectroscope, were even more arbitrary, because they were dependent not only on the unit chosen for the transparent scale γ, but also on the spectroscope's focal distance. Even if the scale γ and all the optical parameters could have been reproduced perfectly by other spectroscopes, two observers with different instruments would nevertheless still have disagreed on the numerical values of certain lines, because prismatic dispersion, and with it the relative distances between spectrum lines, depends crucially on the specific type of prism glass used in the spectroscopes.

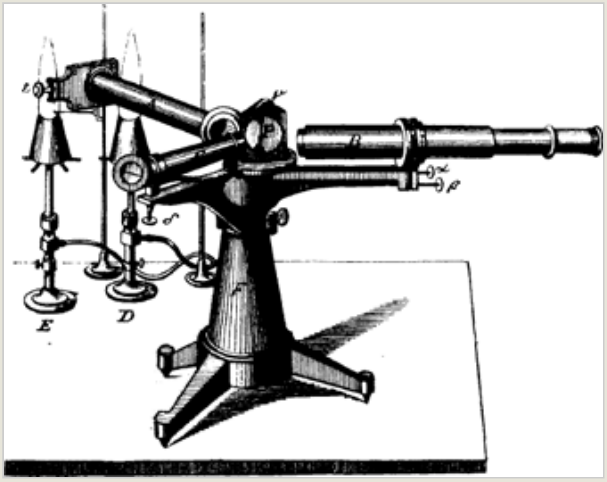


Fig. 2.20. Bunsen and Kirchhoff's second spectroscope, built by C.A. Steinheil in Munich. From Bunsen and Kirchhoff [1860/61*b*] plate. The scale at δ is projected onto the prism at *P,* whence it is reflected into the observing telescope *B.* The observer thus sees the scale superimposed onthe flame spectrum passing through tube from slit ε.

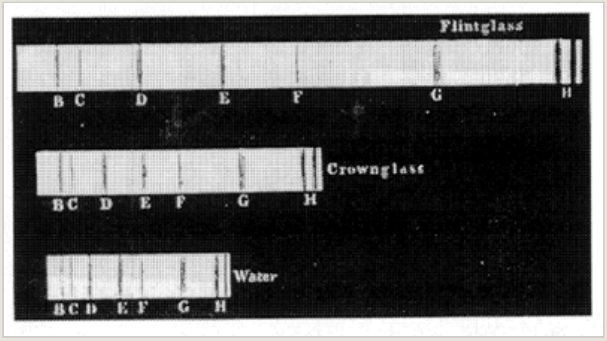


Fig. 2.21. Comparison of spectra generated by flint and crown-glass prisms. From Schellen [1870/72*b*] p. 229.

As Fig. 2.21 demonstrates,[98] a prism of flint glass produces not only a broader spectrum, but also relatively less red and more blue-violet than a prism made of crown glass. Thus, essentially: “Every prism gives a different map of the spectrum, nor when we find a band or line by the prism have we any means of fixing the absolute place, except by a reference to the normal or wavelength scale, or to one derived from it”.[99] As Simon Schaffer has argued, this “irrationality of dispersion” was quite instrumental in some of the debates on Newton’s crucial experiments in the late seventeenth and early eighteenth centuries. The continental scientists used different kinds of glass than the British, which precluded unequivocal comparisons of the refraction spectra obtained.[100]

There is another aspect to Bunsen’s chromolithographic representation of emission spectra beyond the omission of a scale. A controversy between Bunsen and two American chemists reveals particularly clearly how conscious Bunsen was of deviating—

(p.51)

> not without good reason[—]from the much more accurate means of measurement used by physicists in the determination of the refractive indices of transparent bodies, inasmuch as the chemist, for whom our apparatus is specially designed, does not require so much an exact knowledge of the absolute position of the single lines in the spectrum as he needs to be able to observe quickly and easily, especially when lines have to be recognized which only flash for a moment.[101]

Late in 1862, the chemists S.W. Johnson and O.D. Allen from New Haven had criticized Bunsen for incompletely and incorrectly mapping the spectrum of caesium. The two Yale chemists reported having found “without difficulty seven more lines” than the eleven depicted in the map published by Bunsen and Kirchhoff in 1861 and they additionally disagreed about the precise placement of some of the lines figured by their German colleagues.[102]

In reply to these charges Bunsen argued as follows: While a physicist's ultimate aim is to work towards numerically accurate *absolute* measures and *complete* catalogues of wavelengths, a chemist is interested in quite different information, namely the characteristic *Gestalt* of the spectrum lines of a given element. Therefore, in order to reduce the complexity of real spectra and to turn the given illustrations into a more easily recognizable pattern distinct from those of other elements, Bunsen had *purposely* omitted many of the weaker and less remarkable features: "we did not endeavour to catalogue the lines completely, but to represent as truly as possible the characteristic appearances of the spectra of the several substances. Owing to the difficulty of accurately distributing many shades of the same colour in chromolithographic printing, the weaker lines have necessarily been omitted in our drawings."[103] This self-imposed restriction to strong lines should not be understood as a defect, but as a virtue of Bunsen's mapping, because his goal was not comprehensive inventorization but a fixing of each element's most characteristic lines to allow its unequivocal identification. Bunsen's chart thus only depicted the basic fingerprint, so to speak, of each chemical element.[104]

To the extent that the limitations of chromolithography had hampered Bunsen's visual representation, this was a call for an alternate way of depicting spectra. Bunsen conceded this point by devising a quite different method of plotting the relative distances and intensities of spectrum lines and continuous spectra in the plate accompanying his rebuttal (cf. Fig. 2.22). The most prominent feature of the whole graph was the scale, printed as on a centimeter ruler, and gauged, as before, at $Na_D = 50$, with the prism placed at the angle of minimum deviation for all readings. Where Bunsen observed a spectrum line, band or, occasionally, a continuous spectrum with his spectroscope, he drew a black blob of proportionate breadth and length to symbolize the relative intensity of the spectral feature.

(p.52)

Fig. 2.22. Bunsen's symbolic plot of emission spectra and continuous spectra. The scale indicates readings from Bunsen's spectroscope, gauged at $Na_D = 50$ at the abscissae of the black spots; their ordinates represent the intensity of the features. Woodcut. From Bunsen [1863*d*] pl. V, figs. 4–5.

This partly iconic spectral coding was very simple to draw and, unlike chromolithographic plates, was easy to print as well. A simple woodcut would do the job (cf. here § 4.4), while otherwise several lithographic stages were necessary. This symbolic technique was used widely since,[105] particularly by chemists to render absorption spectra, which often exhibit broad absorption bands and other extended features that are thus easily captured. As late as 1881, William Marshall Watts (1844–1919), an experienced spectroscopist specialized in mapping the carbon spectrum and its various compounds, wrote: “There is no better plan of noting the peculiarities of a spectrum than that employed by Bunsen, in which each bright line is represented by a black mark on the paper whose height represents the intensity of the line.”[106]

Even though Kirchhoff and Bunsen recognized that, for prism spectroscopes, numerical scales were “arbitrary”, many others, especially chemists, were much less aware of this. In a whole series of experimental investigations, Alexander Mitscherlich (1836–1918), who had just submitted his dissertation to the University of Berlin, where his father Eilhart Mitscherlich lectured on chemistry,[107] corroborated his claim that the spectra of metallic compounds differ from those of the pure metals. His lithographed maps display the spectra directly above each other to drive home his point. His mode of charting the spectra combined characteristics from both representational techniques introduced by Bunsen: an iconic depiction of individual lines and their intervals, and a condensed comparative chart focusing on the distinguishing features in the spectra (cf. Fig. 2.23):

Mitscherlich’s spectrum charts are also a good illustration of the interplay between techniques of representation and original research: these comparative plots revealed recurring characteristic lines in the various compound spectra of a single metal. For instance, Mitscherlich claimed that the distances between the characteristic lines for barium varied with the atomic weights of the compounds (cf. the shift to the right of the two prominent lines in the spectra of BaF_2, $BaCl_2$, $BaBr_2$, and BaJ_2, with an increase in distance from 3 scale units to 3.9, 5.2, and 7.3 in the last four spectra of Fig. 2.23. According to their atomic weights, the relation between $BaCl_2$, $BaBr_2$, and BaJ_2 would have implied **(p.53)** 104/148.5 = 5.5 and 104/195.5 = 7.3, respectively). Mitscherlich also searched for similar relations by comparing the spectra of various metallic oxides. He found several local similarities but he eventually had to admit that his drawings provided only weak support.[108]

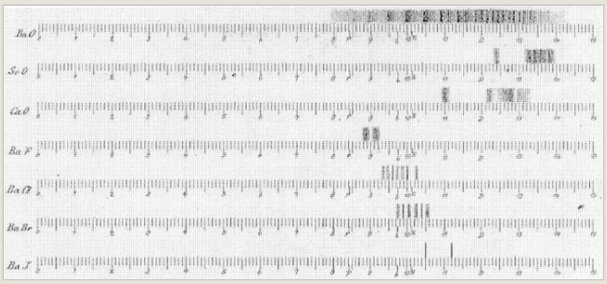


Fig. 2.23. The spectrum of barium oxide compared with those of strontium and calcium oxide, and with barium fluoride, chloride, bromide, and iodide, according to Mitscherlich. The numerical scale underneath each spectrum is arbitrary, whereas the letters D, E, F. and b indicate the positions of strong Fraunhofer lines. Stone engraving by A. Schütze (Berlin). From Mitscherlich [1864*a*] pl. VI.

Despite the failure of Mitscherlich's efforts to reveal essential clues about the structure and relationship of various elements, his systematic comparison of compound spectra followed the trend away from a merely qualitative depiction of the *Gestalt* of spectra towards a more precise, quantitative rendering of their line distributions. Bunsen's comparative and scaled black-and-white woodcut chart of metallic spectra and Kirchhoff's famous map of the solar spectrum, to which we now turn, sparked the transition toward representations of chemical spectra with an associated numerical scale, irrespective of whether or not it was deemed arbitrary. In 1861, right after the birth of spectrum analysis, Kirchhoff undertook to draw a map of the solar spectrum. The coincidence of bright emission lines and dark absorption lines now permitted a reading of the dark Fraunhofer lines as indicators of the presence of chemical elements in the solar atmosphere, suddenly giving this endeavor new relevance. To obtain maximum resolution, Kirchhoff used another Steinheil spectroscope with a four-prism chain designed according to his own specifications (Fig. 2.24).

How to convey the excitement he must have felt upon first seeing the solar spectrum in such unprecedented detail and intensity? One Munich instrument manufacturer exclaimed in 1862: "The splendor of Kirchhoff's solar spectrum is enthralling!"[109] A small sample segment from Kirchhoff's published map is reproduced here as Fig. 4.10 (p. 125). It included **(p.54)** chemical identification of some of the Fraunhofer lines that he could correlate with 463 emission lines of laboratory-generated spark spectra, with a juxtaposed numerical scale that ran from about 1000 (D) to 2250 (past F) in the map of 1861. The continuation of the map in 1862 extended this scale down to 381 (near A) towards the red end, and up to 2875 (near G)—note that Kirchhoff's scale runs contrary to the later wavelength scales. Why now include an arbitrary scale?

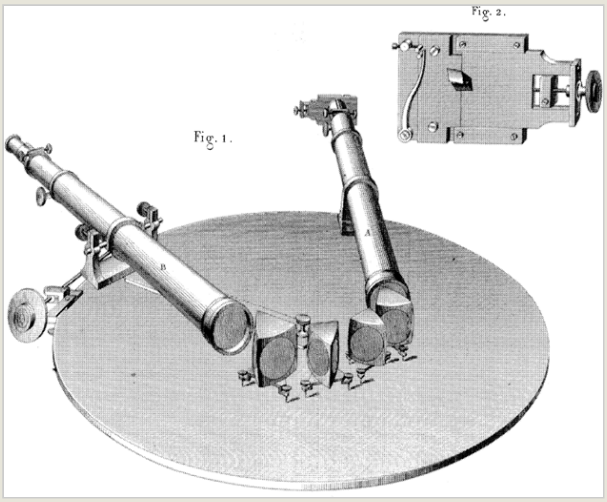


Fig. 2.24. Kirchhoff's four-prism Steinheil spectroscope. From Kirchhoff [1861/62*a*], pl. III.

> Above the drawing of the spectrum I have placed a scale divided into millimetres, and having an arbitrary commencement. This is, in the first place, useful for the purpose of obtaining an easy means of nomenclature for the lines. […] By means of this scale we are likewise enabled to specify with a greater degree of accuracy the positions in the spectrum where no dark lines occur. A relation between the numbers on the scale corresponding to the individual lines and the refractive indices of my prisms for these lines does not exist, because the prisms were sometimes placed more exactly than at other times at the angle of minimum deviation for the particular rays.[110]

Thus Kirchhoff's scale was nothing more than a convenient labeling system that had to be used in conjunction with his spectrum map. Orientation within the spectrum had been **(p.55)** made one step easier, but each observer still had to assess visually the similarity between the mapped groups of lines and what he saw in the ocular of his own spectroscope. A 'subjective' criterion still decided on the identification of a given line instead of some 'objective' one, such as a numerical coincidence of tabulated values with scale values read off the instruments. Despite this drawback Kirchhoff's scale was readily accepted by the scientific community. As an anonymous referee put it in his review of the English translation of Kirchhoff's memoir by Henry Enfield Roscoe (1833–1915) in 1862: "provisionally at least, Kirchhoff's scale is certain to be adopted. The whole science would be thrown into great confusion were different scales, each with its own zero, adopted by different observers, like the several systems of longitude; we earnestly deprecate such a proceeding."[111]

2.6 Prisms versus diffraction gratings

Aside from the differences between various types of glass prisms and prism spectroscopes, there was another "inherent defect in the prismatic spectrum":

> in the same spectrum, from the very circumstance of their greater refrangibility, those [rays] in the violet will be relatively more separated from each other than those in the red. […] The result of this increased separation in the more refrangible regions is to give an apparent dilution to them, while the lesser refrangible regions are concentrated. […] When, therefore, we obtain a prismatic impression on any sensitive surface, it is very far from representing the true character of the phenomena. The action which ought to be concentrated in a lesser space at the more refrangible region is spread over a greater, and with that augmentation an apparent diminution of the amount of action is perceived. This, of course, should make the maximum point vary, spread out unduly the violet end, and dilute the true effect. The different regions of the prismatic spectrum cannot be fairly compared with one another.[112]

This graduated ‘dilution’ of the prismatic spectrum is illustrated in Fig. 2.25. However, as Draper indicates here, there was an alternative way to assign a numerical value to a specific spectrum line which promised to yield a material-independent, ‘normal’ wavelength scale.

In a paper published in 1823, Joseph Fraunhofer had shown mathematically that a perfectly regular grid of lines would yield a spectrum by constructive interference of wave-fronts differing by integral multiples of one wavelength. He had even made some initial attempts to build such a diffraction grating, as they came to be called. They were made of wire wound along finely tooled screw threads to form a fine, regular grid. In a later design, closely parallel lines were scratched with a diamond onto a gold-plated glass surface. But these primitive gratings still could not compete against prisms.[113] Furthermore, the poor intensity of the resulting spectrum precluded their application in stellar spectroscopy; the **(p.56)** superposition of different orders of interference, and the appearance of pseudolines (so-called ghosts) beside prominent 'real' lines were further disadvantages of diffraction gratings. Nevertheless, improvements in ruling technology in the 1860s and 1870s, achieved by the instrument makers Friedrich Adolph Nobert (1806–81) in Pomerania, William A. Rogers (1832–98) at Harvard, and Lewis M. Rutherfurd (1816–92) in New York, changed all that. Diffraction gratings began to replace prism spectroscopes in metrological tasks requiring instrument-independent information about the 'normal' position of spectrum lines or other spectroscopic features. I cannot dwell here on the history of the production of these diffraction gratings,[114] but significant progress was made in the evenness of line ruling, the equidistancing of adjacent lines and the total width of a ruled surface S, which determines the resolution $\lambda/\Delta\lambda \sim n \cdot S/\varepsilon$ (n is the order in which one observes, typically the second or third). The small Nobert gratings in the late 1860s (used by Ångström, van der Willigen, Mascart, and Cornu) were replaced by Rutherfurd's in the mid and late 1870s, followed by Henry Augustus Rowland's concave gratings invented in 1882. The latter relieved the experimenter of collimator lenses or other optical components and thus simplified spectroscopic measurement considerably. They reached a theoretical resolution $\lambda/\Delta\lambda$ of up to 400 000, more than three times the resolution of the best prism gratings available, marking the high point of nineteenth-century diffraction grating technology.[115] Given certain preconditions (such as correct mounting and adjustment and, for a reflection grating, proper placement of the photographic plate opposite the grating, etc.), Rowland's concave gratings produced a normal spectrum at high dispersion and essentially free of ghost lines. They even provided the additional feature of considerable overlap among adjacent orders of the spectrum, which allowed internal verification of wavelength measurements by the coincidence method: a wavelength λ_1 in the order n_1 and a wavelength λ_2 in the order n_2 were coincident in the photograph if $n_1 \cdot \lambda_1 = n_2\lambda_2$. Because of all of these features, these concave gratings were widely hailed as a labor-saving device, and access to one of these **(p.57)** precision instruments became an essential prerequisite for spectrometric work at the research front. When Rowland reported on the possibilities opened up by his new technology at the Physical Society in London, James Dewar (1842–1923) commented:

> We have heard from Professor Rowland that he can do as much in an hour as has been done hitherto in three years. I struggle with a very mixed feeling of elation and depression. Elation for the wonderful gain to science and depression for myself, for I have been at work for three years in mapping the ultra violet.[116]

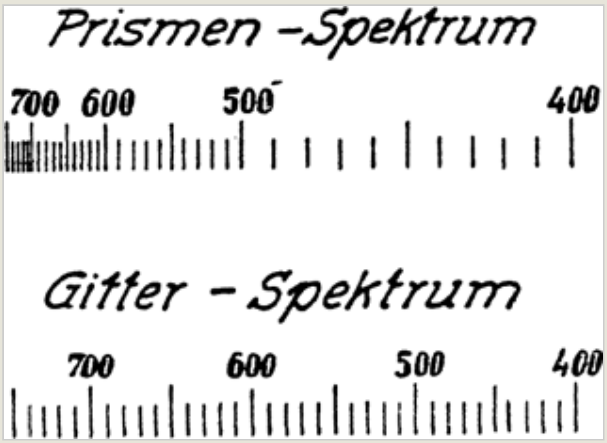


Fig. 2.25. Comparison of the scales of a prismatic and a diffraction spectrum. From Löwe [1925*a*] p. 7.

In cases where high-resolution diffraction gratings were not obtainable or not fully applicable to the specific spectral range under study, this normal spectrum had to be reconstructed from the data using a graphical method of conversion.[117] Thus we see that the visual mode of representation of spectra, in turn, generated a need for graphic modes of data analysis. Once ‘normal’ spectrum maps such as Ångström’s in 1868 became firmly established—“classically accurate and chemically expounded” as one contemporary put it[118]—older maps and spectral tables that had been plotted to other scales were converted into the new wavelength system. In 1868, for instance, both the Astronomer Royal George Bidell Airy in Greenwich and Josiah Willard Gibbs at Yale published formulas and tables for converting the ‘old’ Kirchhoff scale into the ‘new’ Ångström scale.[119] Likewise, in 1864 Leaner Ditscheiner in Vienna transposed the ‘old’ Fraunhofer angular refraction values into the new wavelength system and in 1869 Gibbs converted Huggins’s arbitrary scale, strongly criticizing Airy’s conversion of Kirchhoff’s scale as utterly useless for all scientific purposes.[120] The same procedure was later reiterated when Rowland’s system of wavelength normals replaced the older ‘normal maps’ in the 1880s.

It would be deceptive to think that with the introduction of the ‘normal’ wavelength system everything was stabilized: the half-life of each system of wavelengths, often associated with its own form of visual representation, i.e., the standard spectral map, remained incredibly short. To stay with the example of solar spectrum maps: Ångström’s map and wavelength values were superseded by Rowland’s “preliminary” wavelength standards, obtained with the best of his concave gratings. Rowland’s standards, in turn, were officially revised twice, the first revision appearing in 1928, and the second as late as 1966, not to mention the many minor corrections and alterations to his system under the ægis of the International Union for Co-Operation in Solar Research from 1904 on, and then, after World War I, under the guidance of the International Astronomical Union (IAU).[121] Closer examination **(p.58)** of Rowland’s laboratory notebooks in Baltimore reveals the considerable part played by known wavelength values in new measurements—if only as orientational markers and as an easy means of checking the basic reliability of the measurements.[122]

The emerging preference for maps generated by diffraction gratings displaying the normal spectrum, and line positions measured in terms of wavelengths, went hand in hand with a dispute over which *unit* to use for these wavelengths. French authors pled for the metric system and quoted their data in fractions of a millimeter, or equivalently, of one Å (defined as 10^{-10}m), in commemoration of the pioneering spectrum map published in 1868 by Anders Jonas Ångström (1814–1874).[123] Ångström’s access to a high-quality grating made by the Pomeranian instrument maker Nobert (see above p. 56) meant that he did not have to resort to prisms and could plot his spectrum directly from observation. Consequently, his map was the first of the ‘normal’ spectrum with the interstices between spectrum lines directly proportional to wavelength. He quoted wavelengths in units of 10^{-7}mm.[124] Ångström’s publication consisted of two volumes: the text volume included extensive wavelength tables, already attaining an accuracy of two digits after the decimal point, combined with detailed calculations concerning his wavelength standard as compared with a meter standard.[125] In a separate plate volume, six plates displayed the solar spectrum from B to H2 together with a wavelength scale in units of a ten-millionth of a millimeter and chemical identification for an estimated 5 % of the total 792 lines plotted on his map. At the time of publication, the accuracy of his line-position measurements was such that he could often do without most post decimal-point digits for rough identification. For instance, a wavelength of 5567 Å still clearly designated an unfamiliar new line that Ångström had observed in the spectrum of the aurora borealis.[126] However, rapid spectroscopic advances based on improved diffraction gratings soon required more decimal places to describe a line adequately, which made this labeling convention somewhat cumbersome. Simple inertia guaranteed the continued use of this unit by spectroscopists, who all used Ångström’s map and tables, as well as later ones based on his standards, but occasionally alternatives were suggested.[127] The

British inch, in particular, had some staunch advocates, who simply refused **(p. 59)** to quote “wavelengths in modern French terms, adopted by Ångström in the latter years of his life, vice the ‘inches’ of his renowned and heroic Scandinavian forefathers”.[128] But the British inch, measuring 2.54 cm, is considerably larger than the millimeter and wavelengths quoted in inches would only lead to smaller numbers with longer strings of post-decimal digits. On the other hand, it was advantageous if one decided to plot spectra not according to wavelength λ, but according to frequency $\nu = c/\lambda$, or equivalently, according to wave *number* $n — 1/\lambda$, essentially indicating the number of waves per unit length. A prominent spectrum line such as 5888.98 Å for the sodium D_I line in Ångström’s system thus translated into 43 085 in Piazzi Smyth’s wave-number scale.[129] Note that with the change from wavelengths to their inverse, the color sequence of the spectrum maps was also inverted: Ångström and his followers counted from small to large wavelengths, i.e., from the violet (left) to the red (right), while Charles Piazzi Smyth (1819–1900), Astronomer Royal for Scotland, plotted from low to high wave numbers, i.e., from the red (left) to the violet (right), “exactly suitable to Fraunhofer’s now expugnable order of lettering the chief lines of the solar spectrum from Red A as the beginning to Violet H as the end.” While prismatic spectra compressed the red end and diffraction spectra the opposite end of the visible spectrum (cf. here Fig. 2.25), a frequency or wave-number plot promised to achieve a “most desirable mean between the oppositely exaggerated views of Prisms on the one side, and gratings on the other”.[130] The wave-number (i.e., frequency) plot was particularly useful in the line-rich blue and violet regions because there it amplified distances between spectrum lines and thus decompressed line groups and bands “miserably cramped by the untoward qualities” of the wavelength scale adopted by Ångström.[131] Thus, all spectrum maps made by this Astronomer Royal for Scotland were labeled in his idiosyncratic scale of number of waves per British inch, despite repeated cautions by friends that this scale would adversely affect the popularity of his maps outside Great Britain.[132] Because of the prevalence of Ångström -based spectrum maps and the lack of fans of the British inch on the continent, **(p.60)** Piazzi Smyth’s convention remained somewhat idiosyncratic but it had another argument in its favor. The abscissa on his maps indicated wave numbers rather than wavelengths, and since wave numbers were directly proportional to frequency, his maps proved particularly useful to those more theoretically inclined minds who were looking for overtone series or other regular patterns in line and band spectra. (For more about this endeavor, which became quite popular in the last quarter of the nineteenth century, see here § 8.5f.)

Leaving aside these concerns about precision and theoretical adequacy of a spectrum scale, practical considerations also played a role. At least until the introduction of blazed gratings in the 1930s, whose grooves are cut in such a way as to concentrate the diffracted light in one preferred direction, diffraction gratings simply could not be used for many practical applications of spectroscopy, either because the intensity of the resulting diffraction spectrum was too low, or because the light source itself was too dim to allow examination with the less handy grating spectrographs. As late as 1921, both the director and the head of the research department of the Parisian municipal laboratory of chemistry complained about the available ‘normal’ spectrum atlases:

> Unfortunately, this spectrum comes from a grating and its appearance is very different from the spectrum provided by a standard spectrograph; the dissimilarity is so great that the operator is left in an inextricable dilemma, finding it impossible to attribute wavelengths to the principal lines of its spectrum.[133]

Thus, despite the undisputed state of perfection of ‘normal’ spectrum representations, a definite need for their prismatic counterparts remained, which other spectroscopists soon hastened to satisfy.[134] Seen from this angle, the story of spectrum representations is not a simple gradual replacement of one outmoded form of representation (i.e., prismatic spectra) with a newer one (i.e., grating-generated ‘normal’ spectra). The coexistence of different spectroscopic practices led to a parallelism in contemporary atlas types and plates. As the foregoing quote also shows, translating between the different images was by no means easy: considering the striking difference in appearance of a single line group in the two types of representations, I think it is fair to speak here of different ‘spectro-scopic domains’,[135] or different visual subcultures within a broadly framed visual culture of spectroscopy.

2.7 Extension of the spectral range and its interpretation

Thus far I have been discussing improvements in scientific instrumentation that led to an increase in accuracy of spectroscopic measurements. Let us now turn to another important research strand that is intertwined with the former: exploration of the spectrum at and beyond the red and the violet. This agenda dates back to the discovery around 1800 of new types of radiation in these invisible spectral regions.[136] It must be pointed out that it was by no means clear from the outset that, essentially, only *one* spectrum was involved, and a convenient framing concept such as electromagnetic radiation was, of course, only to emerge **(p.61)** with the work of Maxwell and Hertz in the second half of the nineteenth century. Prior to that, researchers often believed they had found a completely new type of radiation with its own spectrum, apparently overlapping neighboring ones that were thought to be produced by different entities. In the following I will concentrate on the exploration of what we now call the infrared spectrum. The research on so-called chemical rays (nowadays referred to as the ultraviolet spectrum) will be discussed in § 2.8 on the phosphorogenic spectrum and in § 6.4 in the context of the development of scientific photography.

2.7.1 William Herschel’s heat intensity curve

William Herschel[137] (1738–1822) is often hailed as the discoverer of infrared radiation in 1800. He himself was divided about how to interpret his results. At one point they seemed to suggest that the spectrum simply continued beyond the red end of the visible spectrum, and at other times they rather suggested a fundamentally new type of heat ray with qualities distinct from those of visible light. After empirically confirming the validity of the laws of reflection and refraction for these rays, Herschel initially opted in favor of a close similarity between heat rays and light. But their totally different properties of transmission and absorption in various media spoke against it: “we have a direct and simple proof, in the case of the red glass, that the rays of light are transmitted, while those of heat are stopped, and that thus they have nothing in common but a certain equal degree of refrangibility”.[138] The red filter thus acted as an auxiliary to separate the two types of rays present in natural radiation from the Sun. In addition, the diffuse scattering of light from unpolished surfaces was totally different from that of radiant heat: while thick black velvet scattered heat rays very effectively, it absorbed light nearly completely; on the other hand, gold-leaf paper scattered light rays very well, but ‘invisible light’ much less.[139]

In another well-known experiment, Herschel took three blackened thermometers and exposed one for five minutes each in different color zones of the spectrum, the other two thermometers remaining just outside the illuminated area to test for systematic errors. After recording the temperature readings systematically as a function of position, he found that the maximum of the heat spectrum was located outside the visible spectrum, beyond the red end (see Fig. 2.26). This was the more surprising since it conflicted with earlier determinations of the heating effect of various spectral colors.[140] Herschel's finding also implied that as the heat intensity curve rose against the refrangibility when moving, say, from the yellow region to the red end of the spectrum, the corresponding curve of visual intensity decreased in the same interval (see Fig. 2.27).[141]

This curve marks the transition from an earlier mode of inquiry into heat rays, mostly by means of mirrors and somewhat analogous to geometrical optics, to a research program **(p.62)** that could appropriately be called the spectroscopy of radiant heat because of the emphasis on its prismatic decomposition. As John Heilbron notes, this figure was also one of the first comparative visual displays of the results of quantitative measurements ever published.[142] Herschel saw the different placements of the maxima, but particularly the partially counterposing tendencies of the photometric and thermometric curves, as indicative of a fundamentally different entity, 'invisible light,' giving rise to these thermal effects.

(p.63)

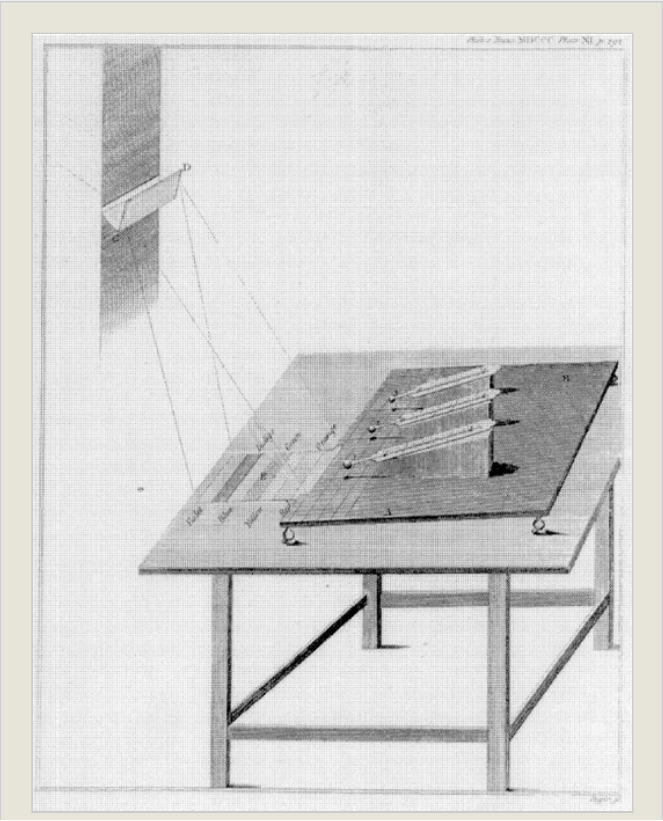


Fig. 2.26. Herschel's experimental setup with three thermometers, one on a projected solar spectrum and two placed beyond the spectral strip for comparison measurements. Copper engraving by J. Basire. From W. Herschel [1800*b*], plate xi, facing p. 292.

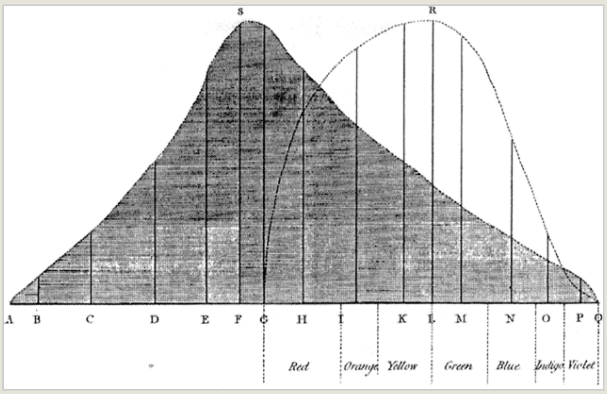


Fig. 2.27. Herschel's comparative plot of visual R and thermometric S intensity curves of the spectrum. From W. Herschel [1800d] pi. xx, facing p. 538.

> Now when these [two curves] are compared, it appears that those who would have the rays of heat do also the office of light, must be obliged to maintain the following arbitrary and revolting propositions; *viz,* that a set of rays conveying heat, should all at once, in a certain part of the spectrum, begin to give a small degree of light; that this newly acquired power of illumination should increase, while the power of heating is on the decline; that when the illuminating principle is come to a maximum, it should in its turn also, decline very rapidly, and vanish at the same time with the power of heating. How can effects that are so opposite be ascribed to the same cause? First of all, heat without light; next to this, decreasing heat but increasing light, then again, decreasing heat and decreasing light.[143]

His contemporaries were also undecided: John Leslie (1766–1832) and Christian Ernst Wünsch (1744–1828) believed that it was only a question of inadequately filtered optical rays, while Henry Charles Englefield (1752–1822), Thomas Young, and later also Jacques Étienne Bérard (1789–1869) took Herschel's view that there is thermometric action beyond the red end of the spectrum, although Bérard located the maximum within the visible part of the red.[144] The precise location of the maximum of the red region became the **(p.64)** subject of heated controversy,[145] which was only resolved in 1819 with Thomas Johann Seebeck's (1770–1831) demonstration that the maximum was dependent on the prism material.[146] Similarly, the heterogeneity of characteristic features and the polarity in their respective physical actions were the main arguments inducing researchers, John William Draper among them, to postulate yet another independent agency, namely chemical rays, at the other end of the visible spectrum.[147]

When Johann Wilhelm Ritter[148] (1776–1810) discovered the chemical action of invisible light on silver salts in 1801, he interpreted his finding, true to the Romantic natural philosophy then in vogue, as evidence of polarity in nature. He thought he had found the counterpart to William Herschel's heat rays at the red end of the visible spectrum: aside from the diametrical opposition with respect to its placement at the violet end, Ritter's rays were also associated with cold (vs. heat effects at the other extreme), with chemical reduction (or desoxydation, as Ritter called their chemical action), and with a stiffening effect on solids (as opposed to the loosening induced by heat rays).[149] Ritter's interpretation of his findings rapidly became known also in the English-speaking world via translations and abstracts. Even though Herschel was not influenced by Romantic natural philosophy, this argument nevertheless strengthened his own conviction about the ontological distinctness of heat rays: Aside from the better-known visible spectrum, we now had—or so it seemed to the majority of Herschel's and Ritter's contemporaries—two new natural kinds: heat rays and chemical rays.

2.7.2 John Herschel's thermograph

In early 1840, William Herschel's son, John William Frederick, developed what is called the **thermograph** technique for rendering heat radiation visible.[150] He thoroughly blackened one side of a very thin sheet of white tissue paper with the smoke of a candle, then exposed the white surface to the solar spectrum generated by a heliostat and two flint-glass prisms of 45° in the position of minimum deviation. Moistening the tissue paper with alcohol, he could observe that where thermic rays collected more intensely the paper dried more rapidly than elsewhere. Heat spots formed as a result, or thermic images of the Sun that "traced out their extent and the law of their distribution by a whiteness so induced on the general blackness which the whole surface acquires by the absorption of the liquid into **(p.65)** the pores of the paper."[151] These conspicuous and intense patches were only "transiently visible" with this technique, but there was enough time to jot down a good drawing of their features as they intensified and evolved over time, before the alcohol evaporated completely away. Later Herschel succeeded in fixing the image by adding a dye to the alcohol, residues of which remained on the paper in greater concentrations where the alcohol had evaporated away more quickly.[152] A photographic impression of the exposed spectrum intensifies just marginally towards both ends. The 'thermic spectrum' in Fig. 2.28, by comparison, builds up on one side only, in the infrared, with the exposure time increasing linearly from nos. 1 to 5. The big spot Y widens towards β, followed by the spots γ, δ, and the barely visible spot ε at the far left. Herschel's series of sketches was redrawn and published as a stipple engraving by James Basire for the *Philosophical Transactions of the Royal Society*.

At first, the contemporaries were unsure about how to interpret these results. From Herschel's correspondence we learn that he privately favored regarding these "heat spots" as evidencing a partial absorption by the terrestrial atmosphere of an otherwise unbroken **(p.66)** thermic spectrum. He thus imagined a continuous unabsorbed spectral range of radiant heat intermittently registered as a series of isolated spots.

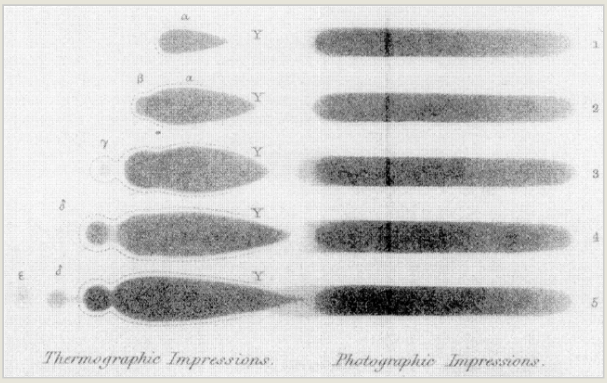
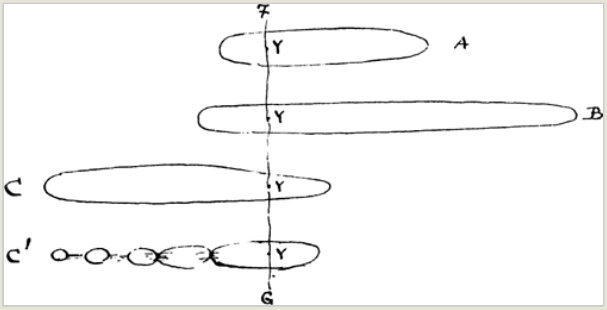


Fig. 2.28. J. Herschel's thermograph and photograph of the solar spectrum at five different exposure times. Stipple engraving by James Basire. From J. Herschel [1843*a*] pl. I, fig. 9.

> I have made some very curious thermographic experiments lately which lead me to think that not much more than half the Sun's radiant heat reaches the Earth's surface, being absorbed in the atmosphere[—]at least I interpret *the insulation* of *two* heat spots at a great distance beyond the spectrum—thus [then follows Fig. 2.29].[153]

Melloni suggested that Herschel had merely recorded the discontinuous thermal absorption of his flint-glass prism.[154] In March 1842, the American chemist John William Draper confirmed this "want of continuity" in the least refrangible part of the spectrum using the daguerreotype recording technique. He found not five but three strikingly dark zones beyond the red end of the visible spectrum which he called α, β, and γ, respectively. This **(p.67)** he considered its extremity beyond which no radiation could exist.[155] Later, these features were rediscovered and explored further with the aid of sensitive alcohol thermometers, thermomultipliers, phosphorescence techniques, and finally photography.[156]



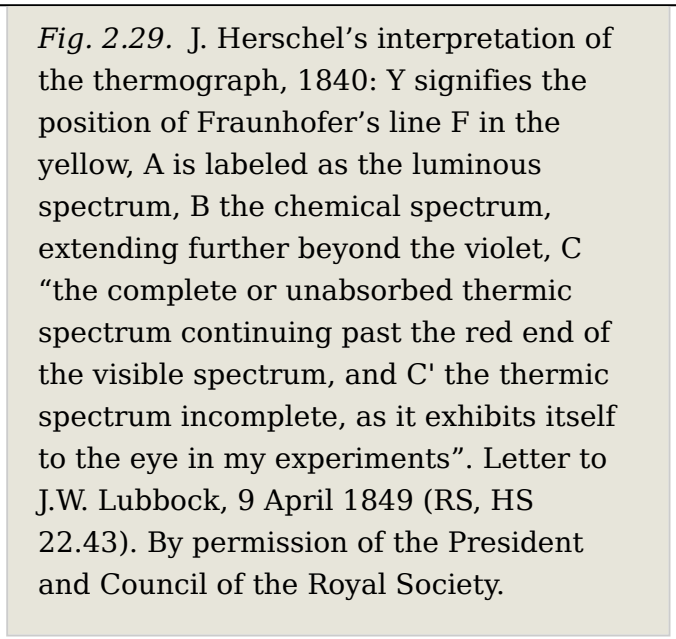


Fig. 2.29. J. Herschel's interpretation of the thermograph, 1840: Y signifies the position of Fraunhofer's line F in the yellow, A is labeled as the luminous spectrum, B the chemical spectrum, extending further beyond the violet, C "the complete or unabsorbed thermic spectrum continuing past the red end of the visible spectrum, and C' the thermic spectrum incomplete, as it exhibits itself to the eye in my experiments". Letter to J.W. Lubbock, 9 April 1849 (RS, HS 22.43). By permission of the President and Council of the Royal Society.

All in all, interpretation of these findings was far less straightforward than we may be inclined to think. It is hardly conceivable for us that these newer lines might be anything other than natural extensions of the visible spectrum beyond the red and violet. Some pioneer researchers (e.g., W. Herschel and J.W. Draper) did entertain this theoretical model for a while, but from the available evidence of the physical action on thermal, optical, and chemical detectors in the different spectral regions, most chose another interpretation: They postulated other types of radiation. According to both J. Herschel and J.W. Draper, solar radiation and the radiation emitted from luminous terrestrial sources was a heterogeneous mixture of visible, actinic, and calorific rays. The spectrum generated by a prism or a diffraction grating and photographed or explored by other means was understood as the superposition of three components: an optical spectrum more or less within the confines of Fraunhofer's lines A and H,[157] an **actinic or chemical spectrum** with its maximum beyond the violet end of the visible spectrum,[158] and a **thermic or calorific spectrum** with its maximum below Fraunhofer's line A.[159] The experimental problem facing these pioneers was how to disentangle these different components of normal radiation. Herschel had demonstrated chemical action of the solar spectrum far beyond the extreme red rays. Likewise Herschel and Melloni had both demonstrated the generation of heat in the visible part of the spectrum.[160] Evidently no clear-cut separation between the different ontological domains was feasible, because the various effects of the different types of radiation were not bounded by well-defined spectral limits but variant only in magnitude. In the following Fig. 2.30, the three strips illustrate the spectra of light, heat, and actinism positioned relative to the Fraunhofer lines in the optical spectrum. The middle strip is actually a redrawing of Herschel's thermograph of 1840 (cf. here Fig. 2.28), with its discontinuous features marked **(p.68)** α to ε, while the third, the actinic spectrum, clearly exhibits the gap in the yellow-orange region so typical of contemporaneous photographs. The dotted curved lines indicate the points of maximum and minimum effect for the three spectral types: The curve with its maximum at yellow refers to visible light, while the maximum at *α* refers to the thermal spectrum. The actinic curve is split into two, with one broad maximum in the violet region, and the other in the extreme red.

Traces of this spectral taxonomy so different from ours are found in the writings of well-informed and established scientists up to the 1870s.[161]

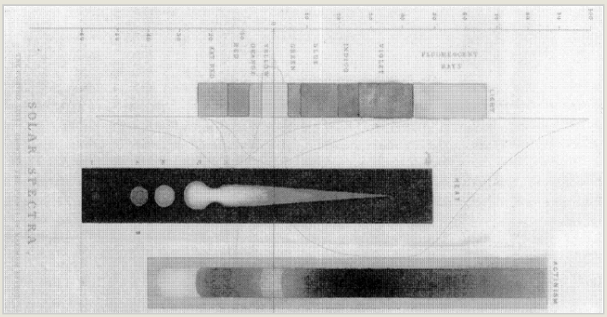


Fig. 2.30. The coexistence of three different types of spectra: luminous, thermal, and chemical. From Hunt [1844b], unnumbered handcolored plate, reproduced here in color on the dust jacket.

2.8 The phosphorogenic spectrum

Since the 1840s researchers had been aware of another spectral type in addition to the three distinguished in Fig. 2.30. It is labeled at the top of the figure as ‘fluorescent rays’. This “spectre phosphorogenique” was observed using substances like Canton’s phosphorus or Bolognian stone[162] as detectors. Although, like the chemical spectrum, the resulting image initially could not be fixed permanently, it could be made visible temporarily by projection onto a fluorescent fluid (such as quinine) in a flat glass container or onto a specially prepared screen coated with a powdered phosphorescent substance that was glued to the paper **(p.69)** with gum arabic.[163] Without magnification it was difficult to distinguish well-defined lines from the diffuse bands, and even more difficult to obtain accurate angular deflections while having to work in the dark. Consequently, the first published drawings of the phos-phorogenic spectra of calcium sulphide and barium sulphide published by Antoine César Becquerel (1788–1878) in the early 1840s show only a few luminous bands of considerable extension from the Fraunhofer line F onwards into the violet and beyond.[164] But eventually his son, Alexandre Edmond Becquerel (1820–1891), who succeeded him as director of the Parisian Museum d'histoire naturelle, made some progress.[165] He and others in his research tradition managed to “prove the existence of the same lines in the [solar] spectrum formed by these [phosphorogenic] rays as in the luminous and chemical spectra”.[166] This coincidence was an important argument in favor of the basic unity of the three—or four—different kinds of spectra, something which had already been suspected by the elder Becquerel in 1823 but which only became experimentally demonstrable around the mid-nineteenth century.[167]

In 1852, Sir George Gabriel Stokes (1819–1903), Lucasian professor of mathematics at Cambridge University, decided to follow up an idea of John Herschel's to substitute the fluorescent screen (prepared with quinine sulphate) with a phosphorescent one. Using a spectroscope, which incorporated a chain of three or four Fraunhofer prisms, he observed the action of the spectrum projected onto this screen and plotted "fixed lines of the solar spectrum in the extreme violet and in the invisible region beyond". While waiting to deliver a lecture at the Royal Institution in 1853, he was experimenting with electric light discharged from their powerful Leyden jars and dispersed by high-quality quartz apparatus when he made the chance discovery that quartz optics absorbs far less light towards the violet end of the spectrum than conventional glass prisms and lenses. These two innovations allowed Stokes to extend the known spectrum considerably beyond the Fraunhofer line H into the region invisible to the unaided eye. He found out that the extent of this new region amounted to no less than six to eight times the length of the visible spectrum. Accordingly he coined the term "long spectrum". Figure 2.31 illustrates his attempt to form natural groups of the many new lines observed. In continuing the labeling he was not at all **(p.70)** sure how the lines detected with his new visual method related to the lines and line-groups already spotted in earlier photographic work. So he decided not to use the capital letters employed by Draper in 1843, choosing instead lowercase letters, from *k* to *p* (in a later publication, up to *s*).[168]

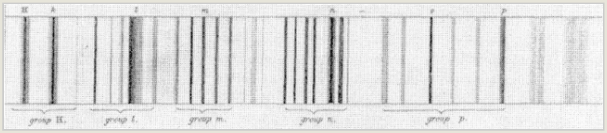


Fig. 2.31. Stokes's mapping of the extreme violet and the "invisible region beyond" the optical solar spectrum, ending at H. Steel engraving by J. Basire. From Stokes [1852a] pl. XXV. Cf. also Jamin [1858–66a] vol. 3, p. 483 for a woodcut illustrating an observer's visual impression of these faintly luminescent spectra seen in complete darkness.

This decision to resort to a new nomenclature illustrates very nicely the general problem of gauging empirical findings obtained with different types of instruments. Although both Draper and Stokes explored the solar spectrum in the same region of refrangibility, namely, beyond its violet end, Stokes simply did not recognize Draper's spectrum in what he saw with his technique. And who could guarantee that the rays detectable with his visual techniques really were the same as those that Draper had found with his photochemical method? As long as interpretation of these different types of rays remained unclear, there was no proof that the two types of spectra ought to be identical. Thus first explorations into uncharted spectral regions often led to incompatible, at best, untranslatable results, depending on the investigative technique being employed.

By a similar technique, Wilhelm Eisenlohr (1799–1872) traced the solar spectrum further into the ultraviolet region, as it came to be called by the mid-1850s. For wavelength measurements he used a diffraction grating which had been ruled on smoked glass. And in 1862 Stokes mapped the ultraviolet emission and absorption spectra of several substances recorded on screens made of uranium glass or a coating of uranium phosphate powder, this time reaching as far as the increasing opacity of air for shorter wavelengths would allow.[169] Three years later, E. Becquerel mapped the phosphorescence emission bands in 15 different solids relative to the main Fraunhofer lines of the visible spectrum with the aid of a standard spectroscope mounting.[170]

(p.71) Another important improvement was introduced in 1874 by the Genevan physicist Jacques-Louis Soret, who thought of placing a fluorescent substance like uranium glass in the focal plane of a standard spectroscope and observing the thus generated phosphoro-genic spectrum with another telescope slightly tilted with respect to the axis of the first.[171] In 1883 Henri Becquerel found out how to modify this technique for the infrared region of the spectrum. This was not so easy since infrared rays have the strange property of annihilating rather than augmenting the phosphorescence of substances like Balmain’s pigment or zinc sulphide. What he did was to expose the phosphorescent plate to intense blue light for about 15–30 seconds, and immediately afterwards to the infrared part of the spectrum for one to two minutes. Then for a brief time, he could see traces of the infrared spectrum lines in the form of dark stripes on the green phosphorescing screen. In this way he was able to draw a map of the near-infrared spectrum of half a dozen elements and six other substances.[172] Even though he could reach wavelengths up to 13 000 Å, Becquerel’s ocular measurements were very inaccurate because the light intensity of the zinc-sulphide screens was very low. As a result, many of his readings could not be verified by later researchers.[173]

At roughly the same time, J.W. Draper finally succeeded in photographing phosphoro-genic spectra. The basic idea was to bring the photographic plate into direct contact with the phosphorescent screen after the latter had been exposed to the spectrum for a while, typically a few minutes. This plate would then record each phosphorescent area and allow more precise readings at a later time. But the rapid dimming after exposure prevented Draper from obtaining good results. Even the Fraunhofer lines of the solar spectrum did not show clearly because of the inherent blurriness of his ‘phosphorographs’. His explanation for this was a lateral spreading of the luminescence on the photographic plate into the dark areas of the Fraunhofer lines. In 1888 Eugen Lommel (1837–1899) at the University of Munich finally overcame this limitation by following Henri Becquerel’s example and confining himself to working in the regions where exposure to the spectrum counteracted the luminescence of the phosphorescent screen.[174] However, as a cursory inspection of Fig. 6.16 (on p. 228) will confirm, this technique of phosphoro-photography could not compete in terms of line definition and sharpness with direct photography of other segments of the spectrum. Nor are any permanent traces left in this incursion into the ultraviolet region with Stokes’s fluorescent screens, which is but one step more direct. It was not until the 1890s that Victor Schumann (1841–1913) in Leipzig realized that the gelatine on the photographic plate was absorbing the ultraviolet rays. By devising special plates (later called Schumann plates) with virtually no gelatine content, he was able to remove one of the obstacles that had prevented photography from reaching below 1850 Å. Furthermore, he eliminated the absorption in air by constructing a vacuum spectrograph with lenses and prism made of white fluorspar. But it was a nerve-racking fight against air leaks in his spectrograph and other hurdles, and it was at the expense of his health that he obtained the first photographs of the hydrogen spectrum in the region around 1620 Å, which was later named **(p.72)** after him. He eventually even attained wavelengths down to c. 1000 Å.[175] The only other way to avoid the absorption of the ultraviolet part of the solar or stellar spectra beyond the cut-off below 2900 Å caused by atmospheric ozone was to photograph it outside the terrestrial atmosphere. That became possible after World War II with V-rockets.[176]

2.9 New instruments for exploring the heat spectrum

With the development of better thermal detectors, good progress was made in exploring the heat spectrum well beyond the red end of the visible spectrum. The first such invention was the thermopile, designed by Leopoldo Nobili (1784–1835) on the basis of the thermoelectric effect, which Thomas Johann Seebeck had discovered two years earlier. Accordingly, the change in resistance caused by a change in temperature of a pair of bars of antimony and bismuth effectively converted radiant heat into electric signals, which could be amplified and measured with a sensitive galvanometer.[177] In the hands of Macedonio Melloni[178] (1798–1854), who improved the sensitivity and reliability of this instrument considerably, the thermopile became a powerful tool. With it Melloni systematically measured the so-called ‘diathermancy’, or heat conductivity of various substances.[179] Melloni was also the first explorer of the heat spectrum to be thoroughly convinced that he was roaming in the outer fringes of the visible spectrum rather than in completely alien ranges of another kind of ray, as most of his contemporaries (in particular the two Herschels and J.W. Draper) had come to assume.[180]

In late 1871 a Russian physicist and physiologist also used the thermopile in conjunction with various prisms made of flint glass, rock salt, or filled with fluid carbon bisulphide, to map the heat intensity in the solar prismatic spectrum. Sergei Iwanowitsch Lamansky (1841-?)[181] was working in Heidelberg under Hermann von Helmholtz’s guidance at the time. His plot (Fig. 2.32) of the heat spectrum’s intensity as a function of frequency shows a **(p.73)** pretty smooth curve coming to a maximum beyond the red end of the visible spectrum (labeled ‘Ende’ in the figure), and then three successive dips in an overall rapidly decreasing intensity curve.[182]

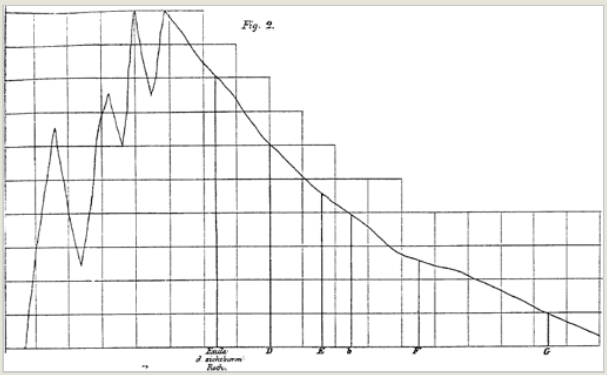


Fig. 2.32. Lamansky’s plot of the energy distribution in the solar prismatic spectrum as registered by a thermopile. From Lamansky [1872] pl. V. fig. 2.

The second important innovation was the ‘actinic balance’ or **bolometer** as it was soon called, which also made use of the sensitivity of electrical resistance to thermal change. The bolometer consisted of two identical blackened strips of thin metal and two identical bridge coils installed in a Wheatstone bridge (cf. Fig. 2.33) with a connected galvanometer. For high temperature sensitivity (in the order of magnitude of 10^{-6}°C per mm deflection of the galvanometer), one usually chose platinum, which has a high resistance-temperature coefficient, a small specific heat, and low heat conductivity. Besides having these suitable physical characteristics, this material could also be transformed into strips of the required thinness of 0.002 mm. This was done using so-called Wollaston wire of 0.1 mm diameter made of a silver sleeve around a platinum core of 0.0125 mm. After hammering the wire fiat, the silver sleeve was etched off to expose an extremely thin platinum strip.[183]

Briefly, measurement with such a bolometer proceeded as follows: By removing a screen, one of the two platinum strips was exposed to the thermal radiation of a predetermined part of the spectrum. Since the resistance of this arm changes, the deflection of the sensitive galvanometer needle directly indicated variations in the energy emitted by the relevant part of the spectrum. When a quartz prism was used to disperse the solar radiation—or **(p.74)** better still, a rock-salt or fluoride prism, which absorbs less of the incoming rays—and the spectrum was slowly guided across the platinum strip, the corresponding deflections of the galvanometer needle indicated the thermal energy as it was distributed throughout the spectrum. For the bolometer’s inventor, Samuel Pierpont Langley[184] (1834–1906) it was thus possible to plot the spectral maxima and minima of the solar heat radiation.[185]

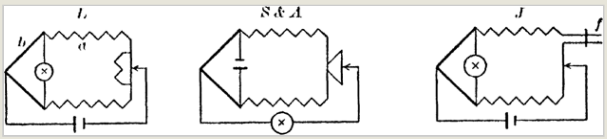


Fig. 2.33. Wiring diagram of Langley’s bolometer (L) [1881*a*,*b*], Snow [1892] and Aschkinass [1896] (S & A), and Julius (J) [1892/93]. From Coblentz [1908] p. 444.

This self-made man and, since 1890, head of the newly founded Astrophysical Observatory of the Smithsonian Institution in Washington, had at his disposal very large rock-salt prisms for the best possible dispersion. Most spectacular among them was his large 60° prism, which John Brashear in Pittsburgh had cut from one of the biggest natural pieces of rock salt ever found.

Traditionally, to get from the directly observable prismatic angular deviation of a certain spectral line to its wavelength λ, one used so-called dispersion formulas which describe the change of refractive index n with wavelength λ.[186] The simplest and thus most widely used formula had been suggested by Cauchy already in 1836:

$$n = a + \frac{b}{\lambda^2} + \frac{c}{\lambda^4},$$

with *a, b,* and *c* constants calculated by the least squares method. Alternatively, one could also use the so-called Redtenbacher formula:

$$\frac{1}{n^2} = a + b\lambda^2 + \frac{c}{\lambda^2},$$

the Briot formula:

$$\frac{1}{n^2} = a + b\frac{n^2}{\lambda^2} + c\frac{n^4}{\lambda^4} + k\frac{\lambda^2}{n^2},$$

(p.75) or the so-called Hartmann formula:

$$n = n_0 + \frac{c}{(\lambda - \lambda_0)^\alpha},$$

with an additional adjustable constant α depending on the prism material. It was usually defined at $\alpha \approx 1.2$ for average crown and flint glass or even simply set equal to 1 for purposes of approximation. The Hartmann formula had the advantage of being easily resolvable to compute the wavelength λ:

$$\lambda = \lambda_0 + \frac{c}{(n - n_0)^{1/\alpha}}, \qquad (2.1)$$

with λ_0 a constant for each spectroscope, which hence had to be measured only once. Moreover, eqn (2.1), with $1/\alpha$ set equal to one, allowed replacing the refractive index *n* by any directly observed quantity linearly dependent upon it, such as angular deviations, or micrometer readings.[187]

However, all these dispersion formulas were empirically derived from data taken from the visible part of the spectrum. As soon as researchers such as Langley or Schumann forged further into the infrared or ultraviolet, it was unclear to what extent one could rely on a naive extrapolation into unknown spectral regions, and which of these incompatible formulas beyond the visible spectrum one should choose. While taking measurements of the solar heat spectrum on top of Mount Whitney in September 1881, Langley “came upon a hitherto unknown cold band whose [angular] deviation indicated a (probably) very great wave-length.” Applying Cauchy’s formula to this band, subsequently designated Ω, Langley arrived at a troublesome result, “the formula declaring that no such index of refraction as I had measured was possible in the prism in question.”[188] No one knew the dispersion curves for prisms of rock salt, quartz, or glass in the wavelength ranges that Langley eventually reached (up to 5 μ = 50 000 Å). Because simple extrapolation from the dispersion curves plotted according to other dispersion formulas would not do either,[189] Langley was forced to use the only instrument that furnished a wavelength-scaled spectrum, a diffraction grating. But as mentioned earlier (cf. p. 56), concave gratings partially superimpose succeeding orders of interference: “overlapping spectra and feeble heat make the use of the grating too difficult”.[190] That is why he devised the following setup combining both prism and grating (cf. Fig. 2.34). As we shall see, this gave him a definite wavelength value for crucial lines or bands, independently of these interpolation formulas.

The incoming radiation was focused by a mirror M to pass through a slit S_1 and fall onto a small Rowland concave grating G. Depending on the adjustable position of a second slit S_2, a selected portion of the grating's spectrum was guided either by a flint-glass lens L_1 or by suitably oriented mirrors onto a big rock-salt prism P before reaching the bolometer B.

(p.76)

At any given angle of deviation off the Rowland grating, this arrangement caused two or three orders n_i, of the solar spectrum to be diffracted toward the prism with their wavelengths λ_i satisfying the relation

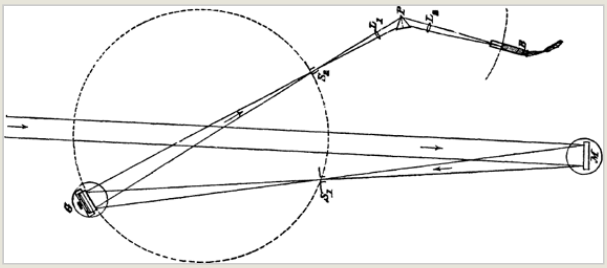


Fig. 2.34. Langley's experimental setup with both a prism P *and* a grating G to disentangle different orders of interference in the heat spectrum. From Langley [1883d] fig. 1.

$$\lambda_1 \cdot n_1 = \lambda_2 \cdot n_2 = \lambda_3 \cdot n_3 = \cdot \cdot \cdot \qquad (2.2)$$

This 'coincidence method', which Rowland had just introduced in conjunction with the development of his concave gratings,[191] thus linked a known wavelength, say, δ_3 in the third-order visible portion of the spectrum with perhaps hitherto unknown wavelengths δ_1 and δ_2 in the infrared.[192] However convenient for wavelength measurements, concave gratings also had their drawbacks. The bolometer could not simply be put near L1, because then it would register the integrated heat intensity of all orders of the spectrum diffracted in that particular direction. This is one of the main reasons why gratings found so little application in the early explorations of the infrared. In Langley's clever arrangement, however, this composite of rays of various diffractive orders is dispersed again by the prism into beams of radiation in three distinctly separate spectral ranges (i.e., ultraviolet, visible, and infrared). Only one of these is focused by the second lens L_2 and finally reaches the bolometer B. By slowly changing the position of the slit S_2 and scrutinizing the visible portion of the spectrum formed by the rock-salt prism for certain prominent features, such as the sodium D line, one can unequivocally identify certain wavelengths δ_2 in the order n_2, which (by means of eqn 2.2) then allows a precise gauging of unknown wavelengths δ_1 of the order n_1 in the infrared part of the spectrum. When this procedure is followed for a sufficient number of well-defined rays, an empirical dispersion curve can be drawn for the **(p.77)** prism at hand, which allows determination of all other wavelengths by standard methods of interpolation.[193]

With this empirical dispersion curve, Langley was able to gauge the dispersive powers of his rock-salt and fluor-spar prisms and thus to work with them directly. This was essential for the fainter lines and bands because of the generally weak intensity of spectra produced by gratings. But Langley had another problem: what his bolometer recorded in conjunction with its sensitive galvanometer was the heat intensity in a certain small section of the spectrum decomposed by his rock-salt prism. However, the red region in this prismatic spectrum was too compressed compared with a normal spectrum (i.e., proportionate to wavelength, cf. here Figs. 2.25 and 2.36). To get the proper heat distribution, he had to convert this intensity curve into one plotted as a function of the wavelength λ. In order to do this correctly, he had to make sure that the total amount of energy was the same in both representations overall as well as for each spectral region. This constraint led him to a suitable graphical conversion method that dates back to J.H.J. Müller's examination of the thermic action of solar heat rays in 1858 (on the following cf. Fig. 2.35).

In a two-dimensional coordinate system, the directly measured thermal energy distribution CD of the prism is plotted along the *x* axis. Straight above it is drawn the empirical dispersion curve EF (obtained from the prism-grating combination discussed above). Further to the left of the gauging curve, the x axis is divided into an arbitrary number of equal units (just four in the left part of Fig. 2.35) representing the normal wavelength scale. The corresponding points on the prismatic plot are found by drawing a horizontal line from each of the equidistant points on the y axis until it meets the gauging curve, and then drawing a vertical line down from each of these intersecting points until it reaches the *x* axis. Note that the nonlinearity of the gauging curve makes the points corresponding to the wavelengths of 0.4, 1.0, 1.6, 2.2, and 2.8 μ on the prismatic scale no longer equidistant: the large interval between 0.4 and 1.0 μ on the *x* axis has shrunk, whereas the compressed portion in the infrared part of the prismatic spectrum between 2.2 and 2.8 μ has expanded.

If one follows this procedure for a larger set of equidistant points than the four intervals depicted in the left part of Fig. 2.35, it is also possible to find the height of the thermal energy curve AB. The right part of the figure shows how the constraint of equal thermal energy for any two definite wavelengths is implemented in Müller's graphic conversion method. Several other persons were also involved in Langley's adaptation of this method, most notably Langley's assistant James Edward Keeler (1857–1900).[194]

The thermal energy is the gray shaded area ab of the prismatic plot, bounded by the two verticals at wavelengths λ_1 and λ_2 This surface area has to be equal to the gray shaded area cd of its corresponding normal energy curve. In practice, both a and c have to be **(p.78)** sufficiently small in order to get satisfactorily smooth curves—in the infinitesimal limit, the ratio of d : b is equal to tan ϕ, with ϕ being the angle formed by the tangent to EF at their point of intersection. It is important to note that the maximum of the heat-intensity curve will also 'shift' (from 1.0 to 0.5 in the above example).

A comparison of Langley's prismatic spectrum from 1883 (Fig. 2.36, top) with the normal spectrum constructed from it (bottom) shows how much the known optical spectrum was extended into the infrared region. The range that the visible part occupied shrinks from over 50 % of the prismatic spectrum to less than a fifth of the total range in the standard wavelength plot (then ending at 28 000 Å).

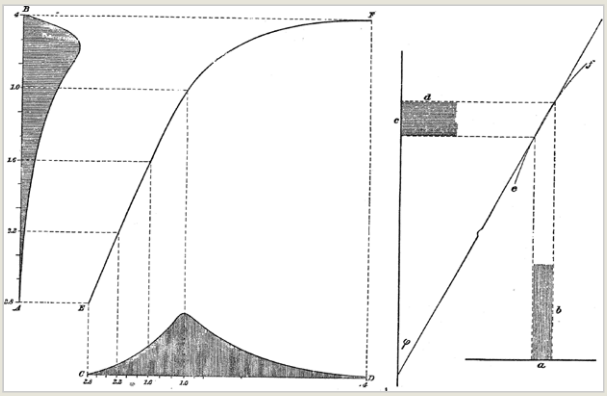


Fig. 2.35. Langley's graphic procedure for converting a prismatic spectrum into a wavelength plot (for details cf. main text). From Langley [1883*d*] figs. 3–4.

By comparing several such infrared spectra taken from solar light at various times of the day and thus through differing atmospheric thicknesses, Langley could also demonstrate that the major troughs in the spectrum, already indicated in Herschel's thermograph (see above p. 65), were due to absorption in the Earth's atmosphere. Later research proved that Langley's intricate way of determining the wavelengths of solar spectrum lines and bands was riddled with averaging uncertainties. Langley's estimates in the region 8500 to 11 000 Å deviated by about 4 Å, and for a few lines much more.[195] Nevertheless much territory had been gained since the first groping explorations of the dark thermal fringe of the spectrum.

(p.79)

Notes:

(1) The colorful story about the changing interpretations of the rainbow is told by Boyer [1959], with references to primary texts.

(2) The technology of glass-making goes back to the third millennium BC. But the early Mesopotamian and Egyptian cultures only had opaque types of colored glass, which were often used as imitation gem stones.

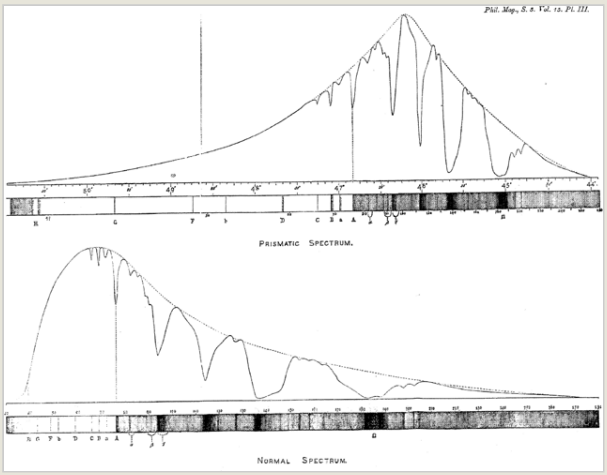


Fig. 2.36. Langley's graph of the solar spectrum into the infrared, up to 28 000 Å; above in the prismatic mode, and below in the reconstructed 'normal' mode. From Langley [1883*a*] pl. III.

(3) See Seneca's *Naturales Quaestiones,* book 1, part 7, § 1; book X of Witelo's *Perspectiva* (c. 1270, copied many times in manuscript and later included in F. Risner's *Opticae Thesaurus Vitellonis* of 1572); Roger Bacon's *Opus Majus* (c. 1266/67); and Wiedemann [1912] on Kamāl al-Dīn.

(4) See, e.g., Rosen [1956].

(5) On the following see the manuscript (RCW, no. 19149 r); cf. also Richter [1883], no. 288 for a translation of Leonardo's commentary.

(6) Quoted from the OED, 2nd edn (1989), vol. 12, p. 510, original spelling.

(7) See Delia Porta [1558*d*] p. 954. The respective passage is omitted in an English translation from 1658 of the same book (based on the second Latin edition of 1589).

(8) The quote is given in OED from a translation of Johann Amos Comenius, *The Gate of the Latine Tongue Unlocked,* London, 1656, §480, p. 139; Schaffer [1989] p. 73 also quotes Thomas White (1654) and Kenelm Digby (1669) about "Fools Paradises".

(9) This Czech physician, mathematician, and natural philosopher on the medical faculty of the University of Prague, was offered a chair at the University of Oxford in 1662 and membership in the Royal Society soon after its official founding; see, e.g., Kuba [1974], Marek [1998]. On Marci's influence on Barrow and Newton see also Rosenfeld [1932], Marek [1969] pp. 392ff., and Hall [1993] pp. 21f.

(10) See Marci [1648] p. 83 “Theorema XII: Lux non nisi refractione certa in medio denso mutatur in colores: diversaeque colorum species sunt partus refractionum” and p. 99 “Theorema XVIII: Neque idem color a diversa refractione, neque ab eadem plures colores esse possunt.” As is pointed out in Boyer [1959*b*] pp. 220f., Marci supposed the various colors were caused by minute differences in the angle of incidence (owing to the finite size of the Sun), whereas Newton demonstrated that they were due to small differences in the angle of refraction (with identical angles of incidence).

(11) See Marci [1648] p. 98: “Theorema XVII: radius magis fractus in medio denso plus potest radio minus fracto. Hoc est magis condensatur, magisque degenerat in colores … Radius magis fractus lucem continet magis defectuosam, hoc est coloris magis perfectum.”

(12) See Marci [1648] pp. 18, 88, and 98. As Boyer [1959*b*] pp. 22If. points out, he is thus one of the first theoreticians to conceive of white light as a composite, albeit not of the various colors, in Newton’s theory, but of two types of rays: photogenic vs. colorogenic. Apparently Marci came to this conclusion by noticing the difference between transmitted and reflected light off goldleaf and mica crystal.

(13) Substantial improvement had to await the early nineteenth century with Guinand’s and Fraunhofer’s technique of stirring the molten glass. See below, p. 34.

(14) See Descartes’s *Les Météores* [1637] p. 216 or [1982] vol. 6, p. 331. Cf. also Sabra [1967] chaps. I-4, Shapiro [1973] p. 190, and Hall [1993] pp. 5ff. for further details and the context of Descartes’s understanding of light.

(15) On Hobbes’s passages about *lumen pertubatum* see his *Tractatus opticus I* (first published by P. Mersenne in 1644), prop. **Ill,** corollary, p. 221 in the edition of Hobbes’s *Opera latina* by Molesworth, vol. V; cf. also Bcrnhardt [1977] pp. 10f., 16f. on the parallels between Hobbes and Descartes. Mariottc [1681] vol. 1 pp. 224–6 and pi. VIII also discussed Descartes’s model but favored Newton’s explanatory scheme (sec below).

(16) See Newton [1672*a*] p. 3075; cf. also his *Lectiones Oplicae* (1670–72). lect. 1, now republished with an excellent introduction in Newton [1984] vol. 1, esp. p. 50. According to his first paper *(idem,* p. 3080), he had purchased his first prism at a fair in Stourbridge, near Cambridge, in 1666 on returning home after the Great Plague. However, a historical analysis of Newton's early notebooks by Hall [1947], or [1980] pp. 156–75 indicates 1664 or early 1665 as a more likely date for his first experiments with a prism, whereas the central investigations of the heterogeneity of light came in 1666, when he had already procured further prisms: see also Cohen [1957], Schaffer [1989] pp. 76–9 on the prices of the prisms, and Westfall [1980] pp. 156–8, who also thoroughly discusses Newton's life and work.

(17) On this contrast between Newton's inductivist presentation and the actual development of his thoughts concerning light, see e.g., Lohne and Sticker [1969] § 5, Hall [1980], or the introduction to Newton [1984], As the many objections to his conclusions raised in the years after 1672 showed, this 'inevitability' was far off the mark.

(18) See Newton [1672*a*] p. 3076. He also continued to use synonyms, such as the "Phenomena of Prismes and other refracting substances" in his reply to Hooke (1672), reprinted in I.B. Cohen (ed.) [1958] p. 120. On the seventeenth-century usage of the terms 'spectre' and 'spectrum' see Lohne and Sticker [1969] pp. 18, 35, and *Oxford English Dictionary,* 2nd edn, 1989, vol. 16, pp. 167–70.

(19) For excerpts from Newton's undated treatise 'Of colours', see Hall [1980] pp. 164ff. and the facsimile in Schaffer [1989] p. 77 with a drawing showing the oblong form, but no mention of the later term 'spectrum'.

(20) Cf. also Marek [1969] p. 398 and Rosenfeld [1932] p. 330 on Marci [1648] p. 100 who had already stated explicitly but not grasped the full importance of the fact that the color of a spectral ray cannot be changed further by prismatic refraction: "Theorema XIX: Reflexio superveniens radio colorato non mutat rationem coloris."

(21) Newton [1672*a*] p. 3083.

(22) See, e.g., Newton's *Lectiones Opticae* (1670–72), lect. 3 or [1984] pp. 94ff.; [1672*a*] pp. 3078–9 and [1704*b*] vol. 1, part 1, prop. 2, exp. 6, pp. 45ff. Cf., e.g., Lohne [1968], Hall [1980] pp. 167f., Kaiser [1986] and Duhem [1906/08] chap. 10, § 3 on the concept of 'crucial experiments'. Schaffer [1989] has argued that difficulties in replication (lying in different types of glass used in England and on the continent) caused this controversy and slow acceptance of Newton's claims. On the other hand, Shapiro [1996] p. 60 contends, "Schaffer exaggerates the difficulty of replication and the unusual nature of prisms", favoring instead interpretational issues as the sticking point.

(23) See Newton [1704*b*] book I, part ii, prop. IX. prob. IV, pp. 168–78; cf. also Boyer [195%] p. 241.

(24) See Newton's *lectiones opticae,* published in Newton [1984], esp. pp. 50f. and 536ff. Newton [1675*a*] pp. 262f., and [1704*b*] pp. 125–8, where this division into which the eye would group the continuum of colors in the rainbow, was reportedly performed by an unidentified "Assistant, whose Eyes for distinguishing Colours were more critical" than Newton's. Cf. also the commentaries on Newton's optics and its context by Hall [1993]. esp. pp. 112ff., Gouk [1993], and Sepper [1994]. Precursors to this division of the rainbow into seven primary colors (Ptolemy, Dante, and La Chambre) are discussed by Boyer [1959*b*] pp. 62, 109, 227, 242. Most earlier authors had opted for three to five; cf. esp. Sayili [1939] on Aristotle's arguments for the three basic colors in the rainbow: red, green, and violet.

(25) Quoted from Brewster [1836] p. 385.

(26) See Newton [1704b] pp. 65f. on the diminishing mixture of the rays with decreasing diameter of the circles. His doctrine of seven primary colors was restricted to a short discussion on pp. 126f. and some speculative queries (nos. 12–14) at the end of his book, pp. 345f.

(27) See Biot [1816*a*] p. 410: "One must only assume that there are an infinite number of circles one after another, from the violet until the extreme red, instead of just a small number as have been drawn." Cf. also Lohne and Sticker [1969] and Zehe [1992] pp. 294f. for a helpful discussion of the practical limits of such homogenization which always depends on the spectral resolution of the instrument.

(28) Erxleben [1772*a*-*c*] § 370.

(29) Cf. also Fries [1824] p. 184 for a perceptive commentary on Goethe's critique. In the commentary to the Leopoldina edition, Zehe [1992] pp. 295f. agrees with Goethe's criticism of Erxleben's visual representation, but also points out that if Goethe had only wanted to, he could have seen reasonably good monochromatic solar images through colored media as observed by the Jena astronomer Karl Dietrich von Münchow [1816] p. 454, and by Hassenfratz [1808], whose experiments were known to Goethe. The aversion that this poet and naturalist felt toward Newtonian optics is well known.

(30) See Hassenfratz [1808] pp. 155f., 306f. On the broader historical context of color theory, and on Hassenfratz in particular, see Cantor [1983] and Shapiro [1993] pp. 284f.; cf. also Birembaut [1973].

(31) Wünsch [1792] opted for violet, green, and red, Young [1802] pleaded for a blue-green-red base, while Brewster [1822/23], [1831*d*] pp. 68ff., [1831*e*], [1834], [1855] pp. 117–24 favored blue, yellow, and red instead: see, e.g., Saillard [1983/84] and the sources mentioned there.

(32) Leslie [1804] pp. 416 and 347, who found it “strange and mortifying to observe the most objectionable part of that system” still in vogue 100 years after its conception.

(33) See Hassenfratz [1807] pp. 138, 163, in the context of polemics against Wünsch [1792].

(34) See Listing [1866], [1867] and Gissing [1910] p. 4: beyond 7230 Å, infrared; 7230–6470 Å, red; 6470–5850 Å, orange; 5850–5750 Å, yellow; 5750–4920 Å, green; 4920–4550 Å, blue; 4550–1240 Å, indigo; 4240–3970 Å, violet; and below 3970 Å, ultraviolet. Cf. also here p. 124 about his iris-print plate. On Listing, a son of a master brushmaker, cf., e.g., Tait [1883], Breitenberger [1993], and here p. 429.

(35) This agrees with similar findings by Kaiser [2000] on the persistence of Feynman diagrams in the period 1948–64; cf. here p. 440 for a more detailed discussion of this point.

(36) Wollaston [1802] p. 378. On the quite utilitarian context of Wollaston’s research see McGucken [1969] p. 2, Goodman [1976], Gee [1983] p. 140, Sutton [1988] p. 28.

(37) See Wollaston [1802] pp. 378f.

(38) According to Wollaston [1802] the slit width was only about 1/20th of an inch (as compared with Newton’s quarter of an inch hole), and its distance from the flint glass prism, “free from veins”, was 10 to 12 feet. The use of a slit as such was not a total novum, since Newton [1704] had already worked with a slit in experiment 11: see proposition 4 of book I in his *Opticks,* but Newton’s most famous optical experiments were done with a circular opening; cf. also Gee [1983] p. 96 on the importance of the sharpness, size and parallelism of the slit.

(39) Fraunhofer had used a slit of 15″ breadth 24 feet away from the prism (see below). According to Jackson [2000] p. 225, Fraunhofer was unaware of Wollaston’s research until John Herschel informed him of it in 1824.

(40) Babbage [1830] pp. 210f., original emphasis; Jackson [2000] p. 127 indicates that Fraunhofer had demonstrated his technique to Herschel personally during a visit in Benediktbeuern in 1824. This quote implies, however, that Herschel had succeeded with his replication before that visit, albeit not without difficulty. Some skills do travel by textual transmission, even though they are of course always much more easily acquired by personal interaction and deictic demonstration.

(41) The philosopher Schopenhauer is one famous example of such frustrated attempts to ‘find’ the Fraunhofer lines in the solar spectrum.

(42) See in particular the table of contents in vol. 5 of the Munich Academy’s *Denkschriften,* issued in 1817, which carefully distinguishes between copper engraving *(Kupferstich),* gravure *(Kupfertafel),* and lithography *(Steindruck),* all of which were used during this transition period in the printing of maps.

(43) For a while Fraunhofer even tried to make a living off printing visiting cards, using the gravure technique: see, e.g., Preyß [1989] P. 24 about this episode in Fraunhofer’s life.

(44) A comparison of Fraunhofer’s map and Brewster’s sketch (with commentary) suggests that Wollaston’s lines A, B, f, g, D, and E correspond to Fraunhofer’s B, D, b, F, G, and H—Wollaston had missed Fraunhofer’s C completely; cf. Brewster [1832a] p. 320.

(45) This curve was plotted from comparisons against an artificial light source superimposed onto the field of view in the observing telescope. The distance r of the reference flame image was variable, so according to Bouguer’s law, the intensity I in the spectrum was inversely proportional to the square of the distance of the comparison flame of constant intensity I_0 i.e.: $I_0 \sim I_0/r^2$ (see here p. 265).

(46) Leitner [1975] has shown that Fraunhofer’s estimate for his relative error at less than 0.1 % was correct for most of his measures (except for the line G).

(47) Two early reviews of Fraunhofer’s paper also emphasize this practical application of his discovery: see Schweigger [1817] p. 78 and Arago [1817] p. 97.

(48) See, e.g., von Rohr [1929], Roth [1976], Sang [1987], Preyß [1989], and Jebsen-Marwedel [1963].

(49) See Amann [1908], Jackson [1993], [1994], [2000] chaps. 2–3; cf. also Turner [2000].

(50) These employee numbers refer to the year 1811 and are drawn from entries in a family register of the Benediktbeuern parish discovered by Seitz [1927] p. 314; cf. also Roth [1976*b*] p. 183, and Jackson [2000] pp. 55ff. for other details about the labor force, and pp. 78ff. on the links to the tradition of secrecy and the centuries-old labor practice of the Benedictine monks.

(51) Cf., e.g., Herschel [1828] § 1117, 1121, Brewster [1832*a*] p. 319, [1836] p. 387, Powell [1839], Meyerstein [1856], [1861], J. Muller [1858], Mascart [1864*c*] pp. 263ff., van der Willigen [1864], Roscoe [1865*a*] pp. 613–18, 626–31, Gibbs [1870] pp. 45–50, [1875], and Chen [2000] pp. 49ff. on the details of the theodolites Fraunhofer and Powell used to measure refractive indices.

(52) See Brewster [1822/23c] p. 123; on Brewster's contributions to optics and his ardent defense of the particle theory of light against the wave theory, see in particular the pertinent papers in Morrison-Low and Christie (ed.) [1984], as well as Anon. [1881], Hunt [1886], Cantor [1983], Buchwald [1989] pp. 254–60, Shapiro [1993] pp. 331ff., and Chen [2000].

(53) See J. Herschel [1823], [1828*a*] p. 438, and Talbot [1826] p. 81: "In the orange was one bright line, one in the yellow, three in the green, a very bright one in the blue and several were fainter". Equally vague descriptions were given in John Herschel's letter to A. Quetelet: "On the colors of different flames and on the spectra they produce when they are analyzed by means of the prism" published in J. Herschel [1829], p. 254, unfortunately undated, but written in connection with his article on light for the *Encyclopædia Metropolitana,* completed in December 1827 and published in 1828 (according to Cantor [1983] p. 162).

(54) The context of absorption spectroscopy in Britain and the widely neglected earlier debates on absorption spectra in France between 1791 and 1816—in which visual representations play no significant role—are discussed in Shapiro [1993] chaps. 8–9.

(55) Fraunhofer [1823*c*].

(56) See, e.g., Arago [1817] p. 97, Schweigger [1817] p. 80. Cf., e.g., T. Young [1803/04*b*] pp. 646f. who already spoke of "intervening dark spaces" in the light of candles and various glasses, as "separated by a prism".

(57) The first such diagrams appear in Herschel [1823] pl. xxviii (immediately succeeding Brewster's plate), also reproduced and commented upon in Shapiro [1993] p. 333.

(58) Herschel [1828a] p. 431, § 490; cf. also Shapiro [1993] pp. 334f. on Herschel's mathematical reformulation of Bouguer's law and dichroism.

(59) See J. Herschel [1830] parts III-IV, pp. 439–582, and Brewster [1831*a*], [1832*a*] pp. 319f., [1833/34], as well as Shapiro [1993] pp. 339–54.

(60) See, e.g., Masson [1854] pp. 39, 44ff., 64ff., Esselbach [1856], Brewster and Gladstone [1860] pp. 155f, Mascart [1864*b*] pp. 237ff., van der Willigen [1864].

(61) See, e.g. H. Draper [18736] p. 402 or also Lockyer [1881a] p. 570.

(62) C. Kuhn [1853] p. 611.

(63) See *Ibid*., pp. 611ff. The map compiled at the Royal Observatory at Bogenhausen near Munich, where Carl Kuhn was staying on a leave of absence from St. Petersburg in the summer months of 1837 and 1850, was never published but only used for internal reference purposes.

(64) Alter had studied at the Reformed Medical College in New York City where he graduated in 1821. See. e.g., Alter [1928], Hamor [1934/35], and Hodge [1976].

(65) See Tyndall [1873*a*] pp. 153f. Compare also Herschel [1829] (his letter to Quetelet) and W.H. Miller [1833] for early examples of such clumsy verbal descriptions. Note the discrepancy with Alter’s inventory in Fig. 2.14.

(66) These shades of intensity, to which two further stages of “still more” are added, is found in Smyth [1877*c*] p. 42, who quite categorically pointed out that “drawings are infinitely more satisfactory records than verbal descriptions” ([1877*a*] p. 33).

(67) According to Hamor [1934/35]: “for the first time it is clearly stated that each element has a characteristic spectrum”; for criticism of this paper see, e.g., McGucken [1969] pp. 9, 13. Alter’s own priority claims appear in his letter to Edward Stieren, cited in Stieren [1867] p. 469 and Lorscheid [1868*a*] pp. 31–2; cf. Cowan [1894].

(68) See Brewster and Gladstone [1860] pl. IV, fig. 1; cf. also Schellen [1870/72*b*] pp. 253–7.

(69) See Stokes [1852] § 24. According to H.W. Vogel [1877*a*] p. 47, light from the blue sky only shows the spectrum clearly between B and h, while A is better discernible in evening light.

(70) Wheatstone [1835/61*a*] p. 11, where it is merely stated that “a table accompanied the paper”. Cf. the illustration in the 1861 ‘reprint’ of his paper: Wheatstone [1835/61*b*] p. 199.

(71) Suchas Roscoe [1868*a*] p. 383, Dingle [1963], Saillard [1988] pp. 28f., or Sutton [1972]. McGucken [1969] pp. 11–12 is the only one to note this modification and its timing.

(72) Miller studied at King's College, London. After graduation he worked for some months in Liebig's laboratory in Gießen, and in 1841 was promoted to assistant, and in 1845 succeeded J.F. Daniell as professor of chemistry. He was elected Fellow of the London Royal Society in 1845 and served in its Council 1848–50 and 1855–70 and as treasurer since 1861. On Miller, see C.T. [1871], Clerke [1897], Adams [1943], North [1974], and Becker [1994] pp. 85–98. On his role as expositor of spectrum analysis after 1860, see here pp. 367, 399ff.; on his collaboration with Huggins, pp. 344ff.

(73) W.A. Miller [1845*a*] pp. 85, 89; cf. also [1855] (3rdedn of his textbook in 1864), pp. 143ff. These color plates were actually not the first published diagrams of flame spectra (as has been claimed by Clerke [1897] p. 429), but certainly among the very earliest such representations.

(74) *Ibid.* Similar indications are also already found in W.H. Miller [1833] where he reports on a "series of equidistant lines [in the absorption spectrum of volatilized iodine] exactly resembling those produced by bromine;- a new and unexpected analogy between two substances which have so many other properties in common".

(75) See Brand [1995] p. 167.

(76) See, in particular, Lorscheid [1868*a*] pp. 28f.: "The illustrations of the flame spectra published by Miller are not very good. The inadequacy of his procedure did not allow greater accuracy." Roscoe [1868*a*] p. 383 explains this failure in Miller's use of luminous flames, which generate spectra not distinctive enough to the particular substance for use "as characteristic tests" of the metals in question.

(77) On J.W. Draper see, e.g., Anon. [1893], Fleming [1950], [1971], Hyde [1976], Trombino [1980], and Hentschel [2001*a*].

(78) J.W. Draper [1848] p. 111; cf. here Fig. 6.3 for his daguerreotype of the reference spectrum.

(79) Masson [1845–55*c*] pp. 300f. See also Masson [1854] p. 37: “exact drawings, taken in the camera lucida, of all the bright lines observed”. Cf. also *idem*, pp. 33f.: “no one has defined the colors of electric light well until now”. However, Masson reveals there that his focus lay less on the spectra themselves than on the electrical machinery used to create these electric sparks (“étincelles électriques”) in gases and fluids, and on the dependency of spark length (up to several decimeters) and intensity on the total charge applied and on the pressure of the gas or fluid.

(80) For instance, Simmler [1861] p. 8 still referred to an enlarged chromolithographic version of Bunsen’s comparative table of the alkaline spectra as a “chromatic wall chart” (“chromatische Wandtabelle”) even though hy then the tabular format had long since been superseded.

(81) See Talbot [1834/36] (I) p. 114. Note the strangely indirect and carefully worded conclusion, and also the fact that no drawing accompanied this statement nor did any other work along this promising line follow.

(82) In this respect, compare the controversy between James [1985*a*], [1986*b*], and Sutton [1986] about the prehistory of spectrum analysis, and footnote 87 below.

(83) See Masson [1845–55*c*] and [1854] p. 37: “In all the spectra one invariably finds four or five familiar lines, differing sometimes in intensity, but never absent”.

(84) Cf. Maier [1964/81], McGucken [1969], and Görs [1999] pp. 100ff., as well as H.W. Vogel [1883], North [1969], Dingle [1973], Meadows [1972] chaps. 6–7, and here p. 433 on Lockyer.

(85) See, e.g., Bunsen and Roscoe [1855–62*a*] part II, Bunsen [1859], Roscoe in Bunsen [1904] vol. 1, p. LII, Fuchs [1929]. On patent and priority disputes with the Berlin gas engineer R.W. Elsner see, e.g., Elsner [1856], Kisterner [1915], Feldhaus [1927], and Biltz [1928].

(86) Smyth [1879*b*] p. 234.

(87) For historical accounts of spectrum analysis see, e.g., Diacon [1865] pp. 8–10, [1867] chap. 3, H. Draper [1865], Kayser [1900] chap. 1, James [1983], [1986]. McGucken [1969], Brand [1995] chaps. 2-4, Hentshel [1997*d*]. For historiographic remarks on the tendency of Whiggish accounts to construct a fictitious ‘prehistory’ of spectrum analysis, see in particular James [1985*a*]. As Jochen Hennig (in prep.) has pointed out recently. Bunsen also knew how to work with prisms because of his prior work (together with Roscoc) on photochemistry.

(88) See Simmler [1861] P. 8: “to repeat the Bunsen-Kirchhoff experiments and to adapt their methods for other practical purposes”. See also *idem*, pl., rows 3–6. Cf. here p. 127 for details on the printing of this color plate.

(89) See *ibid.*, pp. 11ff. As was later realized, this had to do with the significantly higher ionization potentials of other elements, requiring higher flame temperatures to generate their spectra.

(90) Brasack [1866] (signed January 1864, but published only in 1866, probably because of delays in the engraving of the color plate accompanying his paper), p. 3: “I have become sufficiently convinced of how difficult it is to obtain a proper picture of the spectrum of a metal from such a drawing.”

(91) See, e.g., Mitscherlich [1862], [1863], Diacon [1863], [1865], [1867] pp. 62ff., 122ff. On A. Mitscherlich see here footnote 107.

(92) “um die Orientierung zu erleichtern”, according to Bunsen and Kirchhoff [1860/61*a*] p. 161; cf. also Brasack [1866]. Simmler [1861] p. 14 explicitly states that he used coincidences with known spectrum lines for fixing the position of the new lines in his map and plotted several of the reference lines in row 2 of his plate to provide his reader with the same guide.

(93) On Steinheil and his optical company, which was later continued by his sons Eduard (1830–1878) and Hugo Adolph (1832–1893) see, e.g., Steinheil [1855], Repsold [1916], Loher [1939], Knott [1893], Freiesleben [1976], and Brachner [1986] pp. 268–312.

(94) It was basically an ordinary millimeter scale that was drawn onto a glass plate blackened with soot and reduced photographically by a factor of about 15 and projected onto another glass plate by means of a camera obscura: see Bunsen and Kirchhoff [1860/616] footnote 1.

(95) See Bunsen and Kirchhoff [1860/61*b*] p. 376. Cf. also Bennett [1984] p. 3 on the considerable advances made with spectroscopes between 1860 and 1861, and Brachner [1986] pp. 282ff. about cooperation between scientists and the Steinheil company.

(96) Cf. also Kirchhoff and Bunsen’s justification for not doing so in [1862*a*] p. 2 ([1862*b*] p. 295). The scale of fig. 2 in plate I of this publication does not refer to the chromolithographed fig. 1 below it. but signifies an alternative way of depicting the strontium spectrum, which became more important in subsequent years.

(97) See *ibid.*, p. 290. Cf. also Watts [1881] pp. 317f., 320 for further details on the adjustments, and Lecoq de Boisbaudran [1874] or H.W. Vogel [1877a] p. 51 for different conventions: Lecoq set $Na_D = 50$; Vogel set $Na_D = 0$ and counted positively towards the violet and negatively towards the red.

(98) See also Brewster [1831*d*] pp. 70ff., Watts [1872] p. vi, H.W. Vogel [1877*a*] pp. 49f., and Zehe [1996]. Cf. also Lecoq de Boisbaudran [1874] p. 4 or Watts [1881] p. 325 for a comparison of the angular refraction of three flint-glass prisms from the same instrument maker. Duboscq in Paris.

(99) Langley [1883] p. 149. According to H. Draper [1873*b*] p. 402, wavelengths "as the proper indices for designating the Fraunhofer lines" were first actually used by John William Draper [1844*a*]. The first wavelength measurements in the ultraviolet were done by Esselbach [1856].

(100) See Schaffer [1989]; cf. Shapiro [1996], however, for a criticism of some of Schaffer's claims about the reception of Newton's *Opticks* [1704] on the continent. The expression 'irrationality of dispersion' is used in Preston [1890*a*] p. 191; cf. also Sears [1933] p. 55 on 'irrational' spectra from prisms as opposed to 'rational' ones generated by diffraction gratings.

(101) Bunsen [1863*b*] p. 246.

(102) Johnson and Allen [1863*b*] pp.] 99f.: "four red lines to the left of those given by Kirchhoff and Bunsen, […] a fine yellow line and two unimportant green lines not mapped by them"; the other red lines reportedly were "too near each other and too far to the right".

(103) Bunsen [1863*b*] p. 247.

(104) See also Thalén [1868] p. 10 for another spectroscopist's admission of having omitted most weaker lines in his maps, and Watts's [1881] p. 317 reiteration that for chemical analysis, often "very rough measurement only is needed; indeed, in most cases, the colour of the line or the general appearance of the spectrum is sufficient." For further commentary on the interplay between research goals and representational techniques in spectrum analysis, see here § 8.1, pp. 290ff.

(105) Cf., e.g., J.H.J. Müller [1847*a*] p. 661, Roscoe [1868*a*] pl., Watts [1872] pls. III-IX, H.W. Vogel [1877*a*] pp. 214ff. Cf. also p. 99 here, for Piazzi Smyth's development of symbolic techniques of spectrum representation.

(106) See Watts [1881] p. 318. Watts was assistant professor at the University of Glasgow, from 1866 teacher of physics at the Grammar School in Manchester, followed by the Giggleswick Grammar School in Settle, Yorkshire, where he advanced to the position of Senior Physics School Master.

(107) On Alexander Mitscherlich see, e.g., McGucken [1969] pp. 49ff., 103ff., and Schmidt [1994].

(108) See Mitscherlich [1864*a*] p. 485: “The spectra of barite and lead oxide are likewise extraordinarily similar to each other in individual sections. This similarity cannot be easily expressed in the drawings, whereas it is very conspicuous during observation.”

(109) See Merz [1862] p. 655: “Die Pracht des Kirchhoffschen Sonnenspectrums ist eine entzückende”. Cf. also Roscoe [1865*a*] p. 621 on Kirchhoff’s “very elaborate map”.

(110) Kirchhoff [1861/62*f*] pp. 4–5. Cf. below on Kirchhoff’s reservations about the quality of the lithograph.

(111) Anon. [1862] p. 54. Cf. also Roscoe [1868*a*] p. 386 on the discrepancy between Kirchhoff’s and Huggins’s spectrum maps of 1864. Kirchhoff had readjusted his prisms several times during the measurement to maintain the position of minimum refraction, while Huggins had not.

(112) J.W. Draper [1844*a*] pp. 52f. Draper’s plea for the use of the wavelength scale does not imply that he had also turned into an advocate of the wave theory, as McRae [1969] p. 364 has wrongly inferred: See Hentschel [2001*a*] about Draper’s late conversion in 1872.

(113) On Fraunhofer’s gratings, see in particular Glaser [1926*b*], Roth [1976] p. 190 for photographs of six Fraunhofer wire gratings, and Preyß [1989] p. 61 for a photograph of a Fraunhofer glass grating.

(114) See, however, Woodward [1881], Turner [1967], Turner and Bradbury [1966] on Nobert, Warner [1967], [1971], [1986] on Rogers and Rutherfurd; as well as Hentschel [1998a] chap. 3, and further references there.

(115) See Tolansky [1947] p. 93 for a more detailed discussion of the resolution of diffraction gratings, and Glaser [1926*a*] on the remaining defects in Rowland’s gratings. On Rowland’s life and work see, e.g., Ames [1901], [1916], [1935], Hentschel [1993*b*], [1999*c*], Sweetnam in Wise (ed.) [1995], [2000] and further references there as well as here p. 432.

(116) Quoted from John Trowbridge’s personal account in a letter to President Gilman of The Johns Hopkins University, dated 30 November 1882, and published in Reingold (ed.) [1964] pp. 272–4.

(117) See Langley [1883*d*] pp. 159ff. and rigs. 3–4, reproduced here as Fig. 2.35 on p. 78. Cf. also J. Müller [1859], H.W. Vogel [1877*a*] pp. 68f.

(118) A. Herschel [1900] p. 161 about Ångström [1868*a*].

(119) See Airy [1868], Gibbs [1867], as well as Stoney [1868] p. 17 where he recommends: “mark with pencil-dots upon Kirchhoff’s arbitrary scale each of the following positions of an absolute scale […to] make a reference to these exquisite maps much easier”. He used as a basis Ångström’s determination of the wavelength of 70 Fraunhofer lines published in Ångström [1863/64].

(120) See Ditscheiner [1864], [1866*a*], [1871], Gibbs [1869]. For later conversion tables in this tradition, cf. e.g. Stoney *et at.* [1878], Watts [1872] pp. xiii-xiv. and his later supplements, the ‘catalogue of metallic spectra’ as revised by a committee of the British Association for the Advancement of Science, and published in its *Reports* 1885–1888.

(121) Sec St. John *el at.* [1928], Moore, Minnaert. and Houtgast [1966] as well as. e.g. Kayser [1904], [1906]. Fabry and Pérot [1904], Eberhard [1903], Hartmann [1916], and Hentschel [1997c].

(122) See Rowland’s laboratory notebook (JHUA, ms. 6, ser. 4, box 36) [undated, circa 1885], showing averages of Rowland’s own measurements (left) and comparison values from H.C. Vogel [1879] and Fievez [1883] fol. 4, for wavelengths around 4900 A; or from Fievez [1883] and Ångström [1866] fol. 9, for wavelengths beyond 6500 A.

(123) From 1833 on, the son of a preacher studied mathematics, physics, and astronomy at Uppsala University, with Fredric Rudberg (1800–1839) as his Ph.D. advisor. After completing his thesis on conic refraction, Ångström became observer and assistant to Gustaf Svanberg in 1843, professor in astronomy in 1846, and in physics since 1858. On Anders Jonas [not Jons or Johan, as is sometimes asserted] Ångström see, e.g., Robinson [1870], Anon. [1874c], [1877], Thalén [1878], K. Ångström [1907], A. Beckman [1952], Maier [1970], and O. Beckman [1997]. His teaching activities are mentioned here on p. 434.

(124) See Ångström [1868*a*]. The lithographic printing of the map is discussed here on pp. 163ff. On Nobert, see Hentschel [1998] pp. 85ff. and other sources mentioned there.

(125) Unfortunately, in 1872 it was discovered that the earlier calibration of the Uppsala standard meter was incorrect, so that all of Ångström’s wavelength determinations were too small by about 0.013 %: see, e.g., Thalén [1885] pp. 18–20, [1899], Hasselberg [1906] pp. 192–6, and Widmalm [1993] p. 48.

(126) See Ångström [1869], [1875], A. Herschel [1875], Capron [1875], and Beckman [1997] pp. 22f.

(127) On the 1907 redefinition of the international Ångström (I.A.) in terms of the 6438.4696th part of the wavelength of the red spectrum of cadmium in dry air at atmospheric pressure and a temperature of 15°C see, e.g., Hentschel [1998*a*] § 5.4 and further references there. With the introduction of the SI system, the Ångström unit was replaced by the nanometer (1 nm = 10 Å).

(128) See, e.g., Smyth [1887] p. 460: “the Inch … is not only British, but nearly Earth-commensurable in the best way; viz, as the 500 millionth of the length of the Earth’s axis of Rotation; and it furnishes also a convenient series of numbers for the memory.” Piazzi Smyth’s loyalty to the inch was so strong that he later even tried to prove that various units of length of the Egyptian pyramids were based on the inch, an endeavor quite detrimental to his reputation as a scientist.

(129) Piazzi Smyth had actually resolved the D_l line into a close doublet with 43 085 and 43 088 waves per British inch—see Smyth [1880fc] p. 303.

(130) Quotes from Smyth [1887] p. 460 and [1880*b*] p. 288; cf. also Watts [1881] p. 327 on wave-number (frequency) maps as an “intermediate between a diffraction-spectrum and a dispersion-spectrum, the red end being less extended when compared with the blue end than in Ångström’s map, and more extended than in Kirchhoff ‘s.” Watts also describes the practical graphical interpolation procedures necessary to convert a wavelength-based map into a frequency or wave-number map.

(131) *Ibid*.; cf. also Smyth [1879*c*] p. 781 for his complaints about wavelength plots as “almost caricatures, rather than representations, of prism-observed phenomena”. He continued: the first 30 inches of Ångström’s wavelength map depict only 98 solar lines, whereas the last 30 as many as 522 “so that they have hardly any standing room”.

(132) See, e.g., W.H.M. Christie to C.P. Smyth, 5 May 1880 (ROE, 14.64, folder C): “I am afraid there may be a difficulty in getting foreigners to adopt the British inch. The difficulty in introducing your scale will be that observations so far have been expressed in wavelengths (tenth metres) + it will be necessary to have a ready means of converting these into wavenumbers.” Concerning Piazzi Smyth’s Winchester spectrum of 1884, a last minute intervention by James Gordon, librarian of the Royal Society of Edinburgh, resulted in the somewhat improvised addition of a wavelength scale in Å. It was drawn by hand by Smyth’s assistant Thomas Heath on the already finished lithographic plates: see H.A. and M.T. Brück [1988] P. 234.

(133) Kling and Lassieur [1921] p. 761 or p. 249T. The atlas they used was Buisson and Fabry’s [1908c] normal arc spectrum of iron.

(134) See, e.g., Lecoq de Boisbaudran and Gramont [1923] vo1. 2 for an example of a later prismatic atlas.

(135) Cf. § 10.4 for an elaboration of the concept introduced in analogy to Martin Jay's [1988] 'scopic regimes'.

(136) See W. Herschel [1800], [1801], and Ritter [1801], [1803]. For surveys see, e.g., Kayser [1900] chaps. 1, 5, part 7, and chap. 6, part 2c-d; Barnes *et al.* [1937/38], [1943/44], Barr [1960], [1976], Guiot [1985], Cesaro and Torracca [1988].

(137) Born in Hannover. Germany, William became an oboist in the Royal Hanoverian Foot-Guards, moving to England in 1757. Upon gaining international recognition as a telescope maker, he was awarded the Copley Medal of the Royal Society in 1781, elected a Fellow of the society in the same year, and finally appointed Astronomer to the King in 1782. On his life and work see, e.g., Barr [1961*a*], Millman [1980] part I. Ring [1987].

(138) W. Herschel [1800*d*] p. 522; cf. there pp. 509ft.

(139) See *ibid.* pp. 523, 533ff.

(140) Abbé Rochon [1783*a*] pp. 352ff., for instance, using sensitive thermometers made by Reaumur, had come to the conclusion that the maximum heating effect was in the orange-yellow color region, while Landriani [1776] pp. 43f. did not draw any definite conclusions.

(141) See W. Herschel [1800a-d]. On his struggle to find an interpretation, cf. e.g., Lovcll [1968]. Hubert [1999].

(142) See Heilbron [1993] p. 128. For surveys of early graphs in the natural sciences, see Shields [1937], [1938], Tilling [1975], and Hankins [1999],

(143) Herschel[1800*d*]p. 508.

(144) See [Berard] [1813] p. 315: "Mr Berard's experiments confirmed Mr Herschel's results with regard to the progressive increase in the caloric property from the violet to the red; but he found the heat maximum at the very extremity of the spectrum and not beyond it"—cf. also Biot [1816b] pp. 287f. and Cornell [1938] pp. 126ft.

(145) See, e.g., the heavy attacks by Leslie [1804] pp. 454ff., 559 on "a celebrated and most successful astronomical observer, who sometimes indulges a great latitude of fancy, and espouses opinions that are hardly consistent with the sober pretensions of science."

(146) See Seebeck [1819]. On Seebeck see also Poggendorff [1839/41], and Nielsen [1989/91]; cf. also Cornell [1938] for further references and discussion.

(147) See, e.g., Draper [1842*a*], [1844], [1845], and Hentschel [2001*a*] for references.

(148) The son of a protestant priest had been trained as an apothecary. He started studies in 1796 at the University of Jena, then one of the centers of Romanticism, and remained there until his move to Munich in 1805, where he had been nominated as a paid member of the Bavarian Academy of Sciences. On Ritter, who also pioneered the study of electrochemistry, see McRae [1975], Wetzels [1973], Kleinert [1984], and Guiot [1985].

(149) See esp. Ritter [1801/06] and the introduction to Ritter [1997] p. 36 for a tabular summary of the polarity between chemical and heat rays.

(150) According to J.F.W. Herschel's letter to James David Forbes of 3 March 1840 (RS, HS 25.6.1), the chosen term reflected Herschel's "absolute certainty that the chemical rays although discoloring salts of silver etc.—are no way conceived in the [effect?]" (remainder is cut off). On John F.W. Herschel see here footnote 31, p. 182.

(151) Herschel [1840*a*] p. 210 (from the postscript, dated 3 March 1840), and more fully described in note 1 of J. Herschel [1840c] pp. 51–9 and pl. II. As is documented in Jackson [2000] p. 125, J. Herschel had obtained in 1827 "some prisms from Utzschneider's manufactory among which is a large one of flint glass of the utmost perfection being like a piece of solidified water without a trace of a vein or imperfection of any kind" (quote from a letter to Faraday, 27 August 1827).

(152) See J. Herschel [1840*c*] and the entries in Herschel's diaries (RS, reel 28, box 2, 00156) of 3 and 8 March 1840: "perfected method of thermographing the spectrum". Cf. also Herschel [1843*c*], Rayleigh [1877], and Putley [1982] for early thermographs by Herschel and Tyndall.

(153) J.F.W. Herschel to John William Lubbock, 9 March 1840 (RS, HS 22.43), p. 2, original emphasis. Cf. also Herschel to Forbes, four days later on 13 March 1840 (RS, HS 22.44), where he mentioned three isolated spots, which he drew and labeled as in the publication of the same year, with the comment: "Of the spots γ and δ which are circular and well insulated I am certain; of ε there is some small doubt but I have several times got the same measure of it."

(154) See Melloni [1840]; cf. also J.W. Draper [1877*a*] pp. 87f. for his later criticism of these results based on the fact that Herschel apparently did not use a slit. Likewise, Rayleigh [1877] p. 351 had great difficulty accepting them because his attempts to replicate Herschel's thermographic experiment failed and his theoretical analysis based on Cauchy's dispersion formula suggested that "the heat spots δ and ε are decidedly beyond the position at which dispersion should cease". Abney's [1880*a*] pp. 664f. replication, however, yielded thermographs "very similar to those of Herschel with the exception of the spot *ε* —a spot, it may be remarked, the existence of which Sir John Herschel himself did not absolutely insist upon." The reason for Rayleigh's failure is obvious today: he used a bisulphide-of-carbon prism with thick glass walls which absorbed most of the infrared parts of the solar spectrum. Abney was aware of this problem and used flint-glass, quartz, and later also rock-salt optics.

(155) See J.W. Draper [1843*c*] p. 363 and pl. Ill on this "new system of Tithonographic spaces in the solar spectrum analogous to the Fixed Lines of Fraunhofer". See also J.W. Draper [1877*a*], [1881*a*] pp. 166ff. and his correspondence with C.P. Smyth in 1876 (LOC, J.W. Draper family contingent, gen. correspondence, folder Smyth) about his later priority claim. On Draper see here p. 196.

(156) See Fizeau [1847], Fizeau and Foucault [1847/78*a*], [1847/78*b*] p. 377; Lamansky [1872]: H. Becquerel [1883*e*] pl. I, and Abney [1880*a*] pp. 664ff., respectively. For Abney's reinterpretation of Herschel's findings in terms of infrared absorption bands, see also p. 257 here.

(157) Herschel actually thought he had discovered that "beyond the extreme violet rays there exist luminous rays affecting the eyes with a sensation not of violet, or of any other of the recognized prismatic hues, but of a colour which may be called *lavender-grey*": J. Herschel [1839] p. 208, original emphasis; cf. also [1840*c*] pp. 19ff., [1843*b*] pp. 107ff. In Hunt's [1844*a*] handcolored frontispiece plate (cf. here Fig. 2.30) they were denoted as fluorescent rays and rendered in light green.

(158) J.W. Draper preferred to speak of 'Tithonic rays'; see, e.g., J.W. Draper [1843], [1844*a*] pp. 65ff., app. 158ff., as well as J. Herschel [1843*b*] p. 131 for his critique of this new and "most fanciful" name for "an old idea, [namely] the notion of chemical rays as distinct from those both of light and heat [which are] perfectly familiar to every photologist". On Draper's arguments for the existence of an independent imponderable agent in the spectrum, see also Hentschel [2001a].

(159) The location of the maximum of the red part of the spectrum was the subject of heated controversy between Herschel, Leslie, Englefield, and others, which was only settled by Seebeck [1819] in demonstrating the dependency of the maximum on the prism material; cf., e.g., Cornell [1938].

(160) See, e.g., J. Herschel [1840*c*] pp. 16f., § 50f., as well as his letters to J.D. Forbes, 3 March 1840 (RS, HS 25.6.1) and to Talbot, 3 March 1840 (RS, HS 25.6.2).

(161) See, e.g., Smyth [1877*c*] p. 46, where he sets the ‘heat spectrum’ apart from the “actinic, or photographed” optical ones, and distinguishes “strictly optical, or eye-observed spectroscopy”. As is discussed further in Hentschel [2001*a*], John William Draper also hesitated until 1872 before definitely retracting his earlier views on the specificity of ‘Tithonic rays’.

(162) I.e., calcium sulphuret (or sulphide) and barium sulphuret. On the contemporary knowledge about such phosphorescent substances and their chemical preparations see, e.g., the entry ‘phosphorus’ in Ure (ed.) [1868] vol. 2, pp. 376–80 and E. Becquerel [1867/68] vol. I, part 1.

(163) For technical surveys of phosphorescence and fluorescence sec. e.g., J. Müller [1847*d*] pp. 641–55. Jamin [1858–66*a*] vol. 3. pp. 468–93, E. Becquerel [1867/68] vol. I, chaps. 1, 6. and 7, Eder [1886*c*] chap. 30, Kayser [1900] pp. 41–5, 646–51, and Harvey [1957] pp. 2081f., 3521”.

(164) See A.C. Becquerel [1842/44] vol. 2, pl. VIII, figs. 8–9, and pp. 168ff, E. Becquerel [1842] § 111 and plate, figs. 11f., 23–4. Cf. also Henry [1843] and Draper [1845], [1851].

(165) Researches of this type were later also taken up by the grandson, Henri Becquerel, who discovered radioactivity in 1896 while examining the action of X rays on fluorescent substances. See the entries on the three generations of Becquerels in *Dictionary of Scientific Biography*, vol. I (1970), pp. 555–62. On Edmond Becquerel, in particular, see Gough [1970], his Legion d'Honneur records (ANP, Leonore L0I6I075) and his personal dossier (AASP).

(166) See, e.g., E. Becquerel [1848*c*], [1866], and [1873] for his experiments on phosphorescence.

(167) See, e.g., A.C. Becquerel [1823] p. 139: “when one sees magnetism, caloric heat, and light generated at the same time as electricity, one is impelled to believe that all these effects are due to one and the same variously modified cause”, quoted as late as 1874 by Elie de Beaumont during the celebration of Becquerel’s 50th anniversary as a member of the Parisian Academy of Science: see the transcript (ANP. Léonore L0161076) among the supporting documents toward conferral of the rare title of *Grand-officier de la Légion d'Honneur* (Becquerel had already received the distinctions of *Chevalier de la Légion d ‘Honneur* in 1812, *Officier* in 1831. and *Commandeur* in 1865).

(168) See Stokes [1852] § 21 f. On his methods of observation and the context of his research see Stokes [1862] and his lecture on fluorescence in Stokes [1884*b*] pp. 277ff. and Chen [2000] pp. 137–41. Stokes’s *k* actually coincides with the *k* on Draper’s photographically recorded map. Stokes’s *l* cannot be found in Draper’s daguerreotype but is identified by him with Becquerel’s 1. The translation of Stokes’s original labeling into the subsequently adopted nomenclature is not trivial: see, e.g., J. Müller [1847–] p. 642 and here Fig. 6.10: Müller’s O is Stokes’s *p.*

(169) See Eisenlohr [1856] (who reached wavelength 3540 Å, in later nomenclature), [1854] for his introduction of the term ‘ultraviolett’ into the German literature, first cursorily used by Herschel [1840*c*] p. 20, but never picked up again until the mid 1850s, and Stokes [1862], who reached c.1850 Å. Cf. also Caneva [2001] p. 16 on the terminology, and Tousey [1962] for a concise survey of the succeeding steps into the extreme ultraviolet.

(170) See E. Becquerel [1842*b*] pp. 554f., [1859], [1866], [1867/68] vol. 1, pp. 247ff., vol. 2, pp. 79ff.

(171) See Soret [1874], [1877].

(172) See H. Becquerel [1883], [1884].

(173) Cf., e.g., Bergmann [1908] p. 116.

(174) See J.W. Draper [1881], Lommel [1888/90], and Fomm [1890] for a Ph.D. thesis prepared under Lommel’s guidance. On Lommel’s phosphoro-photography, cf. here p. 228; Lommel’s vita is covered in Rechenberg [1987]. Similar phosphoro-photographic work in the near infrared is discussed by Lehmann [1906] and Bergmann [1908].

(175) See Schumann [1889], [1893], [1901], and his moving letter to Ernst Mach, dated 26 December 1898 (SUBG, Mach papers) which delineates his unfortunate personal circumstances in pursuing this research. Cf. also Wiener [1913], Duclaux and Jeantet [1921], and Lyman [1914*b*] and here p. 431 on Schumann’s engineering training.

(176) On the first successful flight in October 1946, the solar spectrum was photographed down to 2100 Å at 88 km altitude using a very compact grating spectrograph: see, e.g., Baker & Smyth [1955] p. 45, and Tousey [1962] pp. 679f. for further references on twentieth-century ultraviolet spectroscopy.

(177) See Nobili [1830]. On Nobili, who had resigned positions as artillery captain in Modena and Brescia in order to become professor of physics in Florence, see Buchwald [1974]. On the natural philosopher and experimentalist Seebeck, see Poggendorff [1839/41], Frankel [1975]. Seebeck's collaboration with Goethe is discussed by Nielsen [1989/911. For further literature on later optimizations of the thermopile seeCoblentz [1908] pp. 398ff. and [1949].

(178) Melloni fled Italy in 1831 conducting most of his research in Geneva in the private laboratories of Auguste de la Rive, and in Paris. Upon his return to Naples he became director of a Meteorological Observatory on Mount Vesuvius and honorary professor of physics. See, e.g., de la Rive [1854], Guareschi [1909], Todesco *et al.* [1955], Barr [19616], Schettino [1987].

(179) See, e.g., Melloni [1833], [1834], [1847], and [1850]; on the inherent problem of the early thermopile, namely its too large heat capacity, and the remedy, see Rubens [1898] and Coblentz [1908].

(180) On Melloni's work and his conversion to the unitary concept of radiation in 1842 see, e.g., Cornell [1938], McRae [1969] chap. XI, Buchwald [1974], Schettino [1989], and primary sources cited there.

(181) According to the entry in *Poggendorff's Handwörterbuch*, vol. 3 (1898), p. 767, Lamansky studied in Giessen, Göttingen, Breslau, and Heidelberg. Following a research stay at von Helmholtz's laboratory, he became lecturer at the Academy in St. Petersburg, then taking a position in Warsaw. Around 1879 he worked in Mascart's laboratory in Paris, and two years later was employed as physicist at the St. Petersburg Central Observatory.

(182) On Lamansky [1872] and on other contemporaneous explorations of the near infrared spectrum, see also the historical surveys in Langley [1900] pp. 7–10, Kayser [1900] pp. 651ff., Barnes and Bonner [1937/38]. According to Brand [1995] p. 83, Lamansky's minima probably mark the 0.92. 1.1, and 1.4 μm combination bands of water vapor. Note also that in many reprints of Lamansky's figure, such as in Langley [1883*a*] p. 169. his figure was inverted in order to allow comparisons with the then more common wavelength plots.

(183) This procedure is described in Coblentz [1908] p. 417; cf. pp. 418ff. there, and D. Hoffmann in Hoffmann and Lemmerich [2000] on later improvements by Lummer and Kurlbaum, and others.

(184) The autodidact Langley had trained as assistant to John Winlock at Harvard Observatory in 1865, and became director of the Allegheny Observatory near Pittsburgh as well as professor of physics and astronomy at Western University in Pennsylvania in 1867. On Langley's work in infrared spectroscopy see, e.g., Barr [1961*c*], Kangro [1970] pp. 13–26, and Loettgers [2000]. Langley's early experiments with the bolometer have recently been replicated by Mahias Friedrich at the University of Oldenburg. For further biographical remarks and sources on Langley see also footnote 42 on p. 430.

(185) For descriptions of the bolometer, see, e.g., Langley [1881*b*], [1900] pp. 47ff., Coblentz [1908] pp. 438ff., Abbot [1958], R.T.G. [1901] p. 352. On the switch to autographic registration techniques, see here pp. 267f.

(186) On the following see Cauchy [1836] and Hartmann [1898]. Cf. also the survey on dispersion formulas by Carvallo [1900], Kangro [1970] pp. 23–6, and Chen [1998] for the contemporary theoretical and historical context.

(187) The latter property is proven in Hartmann [1898] p. 220. Langley [1883tf] only tests the formulas by Cauchy, Redtenbacher, and Briot, rejecting outright the first two as "impossible", and finding error margins in the latter of up to 20 % for wavelengths around 2 µ (= 20 000 Å).

(188) Quotes from Langley [1883*d*] p. 149. The Mt Whitney expedition also features in Langley [1882], [1884*b*].

(189) Coblentz [1905/06*a*] p. 135 criticized Julius's [1892/93] procedure for linearizing Langley's dispersion curve beyond 5 µ. This shows how essential Langley's gauging procedure for prism dispersion was.

(190) Langley [1883*d*]p. 150.

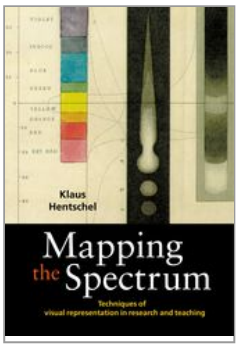
(191) See, e.g. Rowland [1882], [1883*a*], Ames [1889*a*], and Hentschel [1993*b*], [1998*a*] chap. 3, pp. 151f. for further references.

(192) Langley [1883*a*] p. 153, gives a specific example, with $\lambda_1 = 0.5890$ µ, $\lambda_2 = 1.178$ µ, and $\lambda_3 = 1.767$ µ. Subsequent diffraction in the prism deviated these three rays by the angles 47°4l', 45°54', and 45°08', respectively, which were thus clearly separated into three nearly homogenous beams.

(193) See Langley [1883*d*] pl. 2 or [1900] part II, pp. 217ff. and pl. XXVI-XXIX lor the empirical dispersion curves thus determined from Langley's large fluorite and rock-salt prisms. This interplay of gauging measurements of a few reference lines with a diffraction grating, and explorative measurements with prisms is also characteristic of Mascart's [1864] work in the ultraviolet, as well as of many later studies in the infrared, such as, e.g., Bergmann [1908] pp. 145ff. On the following see also J.H.J. Müller [1858b] pp. 41–3 and pl. II.

(194) Keeler had studied in Heidelberg and Berlin under Quincke. Bunsen. and von Helmholtz. and later succeeded Langley as director of the Allegheny Observatory before becoming director of Lick Observatory in 1898. His contributions are briefly mentioned in Langley [1883*d*] p. 161; cf. also Brashear [1900], Campbell [1900], Hale [1900], Perrine [1900], Hastings [1905], and Dieke [1973]. For details on the rather problematic bolometric measurements, see also Langley [1900]. Loettgers [2000], and here pp. 267ff.

(195) See Babcock [1928*b*] p. 326, and here § 7.3 for the step-by-step photographic exploration of the infrared spectrum in the twentieth century.



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
Prof. Dr. Klaus Hentschel

Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

The Interplay of Representational Form And Purpose

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DOI:10.1093/acprof:oso/9780198509530.003.0003

Abstract and Keywords

This chapter analyses spectrum maps from the iconographic and semiotic point of view. It studies representational techniques of making maps and of working with them, including enlarging comprehensive maps, magnifying interesting sectors, zooming, abstracting and condensing, and distilling out spectrum patterns especially for spectrum analysis. Rainband spectroscopy is covered as one early application for weather forecasting.

Keywords: iconography, semiotics, representational techniques, enlarging, magnifying, zooming, abstracting, condensing, distilling, rainband spectroscopy

The conquest of spectra was ongoing not only in the grand scale of things but also in the small. Along with the extension in range previously discussed, a step-by-step increase in resolution was another prominent development in the history of spectrum maps. This enlargement in scale affected representations of the full solar spectrum as well as specific segments of it for detailed study. In the following I will refer to these two modes of representation as ‘enlarging’ and ‘zooming’ (in § 3.1 and 3.2). For the sake of uniform discussion, I shall pick out a few characteristic examples from the area of solar spectroscopy. Two other modes of representation counteract these two trends; I have dubbed them ‘condensing’ and ‘distilling’ (see § 3.3 and 3.4). Because this chapter deals with spectrum maps from a systematic angle, the reader may want to consult the chronological summaries in Appendix 1 (on the solar spectrum) and Appendix 2 (on terrestrial spectra).

Before we start the discussion of the first of these ‘cartographic modes’—as they might be called in conscious parallel to recent discussions of specific types of map-making in the history of cartography,[1] I would like to caution against misinterpreting the following as a progressive linearized account. As we shall see in a moment, the transitions from Fraunhofer 1814/15 to Brewster 1833/62, Kirchhoff 1861/62, Ångström 1868, Vogel 1879, Fievez 1882/83, Thollon 1886/90, and Rowland 1886/88 certainly did imply a stepwise improvement in the overall resolution. If we gauge the latter in terms of the fraction of spectral range R over length L of the spectrum representation, then this range-per-length indicator R/L (an inverse of the average dispersion) fell from approximately 100 Å/cm for Fraunhofer’s map in 1814 to about 2.5 Å/cm for Thollon’s map (published in 1890). At first glance, this apparently relentless march of technological progress (cf. Appendix 1) looks suspiciously like streamlined history, stemming from a retrospective selection of suitable candidates out of a much bigger pool of research papers. It should become clear from the discussion of ‘Kuhnian losses’ accompanying each of these transitions (see pp. 84f.) that this is not the case. The enormous differences in the technical production and research goals associated with each of these different cartographic modes supports this point. Far from intending to construe any such Whiggish linearization of the complex history of spectrum maps, I would like to emphasize that the researchers were fully aware of the solar spectrum maps predating their own work. The fact that they cited and commented upon them in their introductions shows that the traditions described here were perceived and in a sense created by the historical actors themselves. Thus, the different cartographic modes of enlarging, zooming, condensing, and distilling discussed in this chapter are not just artefacts of my historical construction.

(p.81) 3.1 Enlarging comprehensive maps

As mentioned before, Fraunhofer was the first to publish a detailed map of the full visible spectrum of the Sun. His copper engraving was so exceptional that it took more than 15 years for someone else to decide to undertake a redrawing of the solar spectrum on a more detailed scale, and more than 45 years for substantially improved representations of that spectrum finally to be published. It was because of apparently unresolvable difficulties in correlating his own observations of solar and gaseous nitrous-acid spectra with Fraun-hofer's map that impelled David Brewster in the early 1830s to "enter upon the Herculean task of making a better map of the spectrum."[2] Instead of using Fraunhofer's theodolite, Brewster took a separately mounted five-foot achromatic telescope with an aperture nearly twice and a resolving power of about 200, i.e. roughly four times that of his predecessor.[3] In 1833 Brewster announced to the Royal Society of Edinburgh that he had delineated the full visible solar spectrum "on a scale four times greater than that employed in the beautiful map of Fraunhofer". Supplementarily to this five-foot-long drawing, some interesting portions were depicted on a scale twelve times greater than Fraunhofer's.[4] Brewster's main argument for this revision was a dramatic rise in the total number of dark lines resolvable in his more powerful optical system. Fraunhofer had drawn only about 354 lines (of the more than 560 lines observed by him), yet Brewster now counted more than 2000 "more or less marked" lines. Pursuing similar strategies several decades later, others raised this line total again: in 1862, Jules Janssen, for instance, reached 3000. Thus, at least until the 1870s, a simple counting of spectrum line totals remained a straightforward and quite common way of comparing two different representations.[5]

In retrospect, though, what was more important than the *quantitative* rise in the line totals was the *qualitative* identification of telluric absorption lines and bands within Brewster's solar spectrum. By carefully comparing the solar spectrum in different seasons of the year (from 1833 on), under different weather conditions, and with varying proximities of the Sun to the horizon, Brewster was able to achieve, as one contemporary put it, the "majestically mapped separation from the really solar dark lines in the sun's spectrum, of its low-sun, or terrestrial atmospheric lines."[6] Lines whose origin lay in absorption by **(p.82)** the Earth's atmosphere became broader in the morning and late afternoon or were only visible at these times. Such discrepancies between spectra caused by terrestrial absorption or gaseous emission and the prismatic solar spectrum provided additional motivation for Brewster to continue with his high-resolution inventory of the solar lines. In 1834 he was happy to announce that "after a little practice in the observation of the solar spectrum, I discovered most of the lines, which I had in vain sought for in Fraunhofer's map, as the counterpart of those in the gaseous spectrum."[7] But there were many decades delay before Brewster eventually finished his chart of the solar spectrum. When it was finally published in 1860, collated and arranged by J.H. Gladstone, its impact was small.[8] As we have already seen, just a year later, Kirchhoff published the first installment of

his solar spectrum map, which bore the first numerical scale—arbitrary though it was. It combined a better referencing system with higher dispersion and high-quality printing.[9] The Kirchhoff scale soon served as the standard reference system until Ångström's atlas was published in 1868, which marked a new step forward in the overall scale of representation reached.[10] While Kirchhoff attained a range-to-length ratio of ≃12.5 Å/cm with a total length of 264 cm, Ångström reached an *R/L* of 9.4 by expanding his atlas to 360 cm. The total length had thus increased by 30 %, but the *R/L* did not decrease by more than 25 % because Ångström had broadened the spectral range of his map at the same time.[11] Ångström's atlas, printed by the stone-engraving technique off a single lithographic stone, "and therefore as certain and secure as if engraved on a copper plate," as one commentator wrote,[12] had reached another stable plateau that was not surpassed for another dozen years.[13] It took Hermann Carl Vogel[14] (1841–1907) three years to complete his map of the solar spectrum. When this observer at the Potsdam Astrophysical Observatory finally published his map in 1879 **(p.83)** as a tint-stone engraving, it measured nearly 5 meters in length and had an *R/L* of 3.1. His painstaking measurements (visually, in the wavelength interval 5400–4800 Å, and partly photographically, below) gained added reliability by the inclusion of absolute wavelength measurements taken at the same site by two of Vogel's colleagues.[15] In 1883 the Belgian astronomer Charles Fievez[16] (1844–1890) published a high-resolution stone-engraved map with about 2400 lines in the wavelength range 6600–4600 Å and a total length of 594 cm. Such a high dispersion was achieved with "two of the most powerful spectroscopes yet heard of, a combination of a large Rutherfurd grating, having 17,296 lines to the inch, and two of the superlatively magnifo-dispersing "Christie" half-prisms from the Royal Observatory Greenwich."[17] Both maps had an *R/L* in the order of magnitude above 3 Å per cm, that is, nearly three times the resolution of Ångström's map, which they intended to supersede. Vogel covered the spectral range roughly from E to H, while Fievez concentrated his efforts on the range C to F, so their results were somewhat complementary. H.C. Vogel provided the motivations behind investing the considerable amount of time necessary for this revision work on the solar spectrum map in the introduction to his contribution. Spectroscopes had improved so considerably since Ångström's and Kirchhoff's time that by then even spectroscopes of medium dispersion could generate spectra at a dispersion equaling that attained by earlier maps. Added to that, the best instruments of the day revealed such an incredible wealth of detail that orientation among the forest of lines had become difficult with the available maps.[18] Furthermore, the ongoing identification of known chemical elements in the Sun's atmosphere by matching the dark Fraunhofer lines with the bright lines in terrestrial emission spectra also required the highest possible resolution. Often this was the only way to discriminate between neighboring or partially superimposed lines.[19] Finally, Vogel also mentioned his interest in slight temporal variations within the solar spectrum, and in comparisons between the spectra of special regions in the Sun, all of which **(p.**

84) required the sound basis of a ‘standard’ solar spectrum.[20] The end point in this sequence of lithographic maps of the visible part of the solar spectrum was reached in 1890 with the posthumous publication of Thollon’s high-resolution map of the region A to b. With an *R/L* of nearly 2 Å/cm, this expanded segment of the spectrum (from the red to the green) measured over 10 meters.[21]

After the Ångström unit had been established as an accepted standard of wavelength measurement, not only spectral maps, but also the wavelength values listed in the accompanying tables were scrupulously compared against their forerunners. Consequently, each map was built on its predecessors. We thus have a germane tradition of a certain mode of representation and not just a historical retrospective projection. This does not, however, turn our story into a linear path of continuous progress. First of all, the actors were painfully aware of fairly abrupt breaks with measurement practice each time a fundamentally new type of instrument was introduced.[22] Second of all, ‘Kuhnian losses’, that is, severe problems with translating lines in one map into those of its successor, were quite common. As Baden Powell complained in 1839: “In the course of my observations some doubt had arisen as to the exact identification of certain of the standard rays, according to Fraunhofer’s designation of them, owing to the very defective representations given of them in various optical treatises, which fail to convey the peculiar characteristics which mark the different bands.”[23] A similar complaint was raised even two decades later by a Norwegian, exasperated in his attempts to retrace the Fraunhofer lines in his own detailed drawing of the solar spectrum. What confused him most was the change in overall appearance when a cluster of closely neighboring lines is resolved by a more powerful observing telescope.[24]

At each scale of resolution, even something as familiar as the solar spectrum took on a strikingly different *Gestalt.* Not just inexperienced eyes were confused by this metamorphosis: When Kirchhoff prepared his map of the solar spectrum in the early 1860s, he totally dismissed Brewster’s and Gladstone’s map, intimating that it had no value because he could not identify any of their strange bands and markings with his own lines. As others confirmed, their two pictures are indeed, “at least for the red end of the spectrum, not even remotely alike”.[25] In this case, the marked incongruencies were caused by the different dispersive powers of their instruments: **(p.85)**

> Brewster and Gladstone worked with so small a prism or dispersion power, —generally only one prism,—that bands were intensified, fine lines invisible, to them. Kirchhoff on the contrary, used so many prisms, or such large dispersion power, that bands were invisible or resolved into their component fine lines to him, and the whole solar spectrum converted into little but lines and groupings of lines.[26]

Even worse problems arose when spectra generated by a prism spectroscope had to be compared with normal spectra produced by a diffraction grating because the line groups appear very differently in either case.[27] These problems were by no means confined to the early years. For instance, in a 'Report on Oscillation Frequencies of Solar Rays' compiled in 1878 by a committee of the British Association for the Advancement of Science, failures in the systematic correlation between Kirchhoff's and Ångström's maps were deemed quite serious. In the area of the line A, it is dryly remarked: "Kirchhoff records 57 rays less refrangible than 480.1, but none of them have been identified with these rays of Ångström ".[28] Likewise Piazzi Smyth complained that "in the violet regions the lines appeared to me so very much clearer, blacker, stronger, and both more numerous and more spread out than in [Ångström's] edition of them, that it was on that account often embarrassingly difficult to identify his few, thin, contracted lines and groups, amongst crowds of grander lines, all of them far more notable."[29] The conversion from lithographic to photographic maps also caused structural problems of comparison between both types of representation, because photographs often rendered lines faint that were actually quite bold when observed visually, and vice versa. Thus when H.W. Vogel needed a map to identify spectrum lines in the ultraviolet range, Cornu's lithographic map, though clearly more detailed and at higher dispersion, was less suitable than Henry Draper's small-scale photographic map.[30] While minutely comparing his new photographic map of the solar spectrum in 1891 with earlier lithographs, Charles Piazzi Smyth was worried about a strange change in the appearance of 'little d'. Ångström had drawn this line stronger and blacker than any other line between it and 'little e'. But later maps such as Vogel's and Rowland's (most of them based on photography rather than on visual observation) depicted this Fraunhofer line as much weaker, and in Piazzi Smyth's own map, little d "is either nonexistent now, or has become so faint and thin as no longer to deserve the honour of being distinguished by a Solar-spectrum letter name."[31] Did this imply that the solar spectrum had changed between 1863 and 1890? **(p.86)** Piazzi Smyth was consternated and intrigued enough about this possibility to urge all his readers to delve into the past history of representations of this particular region in the solar spectrum in search of clues about possible temporary variations in the solar spectrum, which was then generally conceived as unchangeable.[32] The endeavor to map the spectrum thus automatically created a demand not only for ever more refined and detailed representations, but also for systematic retention and cross-checking against older records. They were thus to be '*aufgehoben*' in the distinctly Hegelian triple-meaning of the word: at once to be preserved, lifted to new heights, and superseded.

What drove the dynamics of this enlargement by degrees? Why was it repeatedly felt necessary—in the average, every ten years, between 1814 and 1890—to invest one or more observer years in the meticulous registration of tens of thousands of micrometer readings (with many an observer being forced to stop because of the severe strain on the eyes)?[33]

The most important factor is technological progress in the spectroscopic recording instrumentation, once we go, say, from a single-prism spectroscope to a Steinheil four-prism spectroscope, and then on to a Browning multiple-prism spectroscope with automatic adjustment for the position of minimum refraction, or similarly from a Nobert grating to Rutherfurd gratings and finally to Rowland's concave gratings.[34] At each new stage, the available maps were no longer sufficient guides among the bewildering number of unfamiliar lines revealed by the best instruments of the day. But this is only an intermediary argument, because it does not explain why scientific instruments in turn were constantly being improved. I argue that research imperatives drove the dynamics towards spectrum maps of ever larger scale.

From 1860 onwards, spectrum analysis was a booming field. Growing numbers of practitioners needed to know the precise localization of characteristic spectrum lines of specific chemical elements (for more on this, see § 8.1, p. 290). In many cases, however, spectrum lines seemed to be common to two or more substances, or else they were too close together to be distinguished. In order to clarify such ambiguities, one practitioner expressed a generally shared demand: "the bright line spectra of the metals in question should be confronted with each other and with the solar spectrum under enormous dispersive power, in order that we may determine which of the components of each double line belongs to one and which to the other element."[35] Thus higher dispersions reduced the number of such ambiguous **(p.87)** cases of unresolved or merely accidental coincidences. At the same time, this clarification provided material for empirical verification of hypotheses about molecular or atomic structure. Some of the lines might actually not relate to the chemical elements *per se*, but to some of their hypostatized mutual building blocks, which would then explain why several elements seemed to share certain spectral features.[36] Likewise, the ongoing research on element identification in the Sun's atmosphere also required the highest possible resolution in order to discriminate between neighboring or partially superimposed lines. Thus after the substantial improvements induced by Rowland's concave gratings and substantially better sensitized photographic emulsions, William Huggins admitted that

> the accuracy of the earlier determinations of the spectra of the terrestrial elements is in most cases insufficient for modern work on the stars as well as on the sun. […] Increase in resolving power very frequently breaks up into groups […] the lines which had been regarded as single and their supposed coincidence with terrestrial lines falls to the ground. For this reason many of the early conclusions based on observations as good as it was possible to make at the time with the less powerful spectroscopes then in use, may not be found to be maintained under the much greater resolving power of modern instruments.[37]

To this ongoing endeavor of chemically identifying solar and stellar spectrum lines by precise coincidence with terrestrial emission spectra of the known elements was added another since the late 1870s that also required high-resolution maps: The search for patterns in spectra (cf. here Chapter 8), whether series lines or band spectra, or homologies between different spectra, demanded most rigorous and precise determinations of wavelengths (or frequencies), because numerical relations between these numbers were only as safe as the data.[38] Finally, particularly towards the end of the nineteenth century, growing interest in slight temporal variations within the solar spectrum that were possibly correlated with the solar spot cycle, and in surface features like the solar spots themselves required a sound basis in the form of a high-dispersion ‘standard’ solar spectrum against which these deviations could be gauged.[39] So we have a strong interplay between specific research objectives in various flanks of the spectroscopic research front on the one hand, and a recurrence of map enlargement on the other.

But the enlargement strand of representation discussed in this section ought not to be seen in isolation. It is intertwined with the three others (extension, zooming, and condensing) in a very significant way. I shall talk about this in the next sections, but before we move on, let us glance back at the people who undertook the arduous task of mapping the total visible spectrum in a resolution none before had ever attempted. Fraunhofer is in many respects a special case, an outsider with a very unusual upbringing: an autodidact, **(p.88)** in some respects, who was barred from regular membership in the Bavarian Academy of Science for many years because of social barriers. Kirchhoff, on the other hand, was clearly a leading authority in the field. He occupied a chair at Heidelberg University and in 1860 was a freshly elected member of the Prussian Academy of Sciences. All the later scientists who ventured to improve upon Kirchhoff's map, Ångström as well as Fievez and Thollon, were not leading authorities before their publications—they all were working in peripheral institutions which, if by no means unimportant, did not irradiate immediate influence on the scientific community at large.[40] Upon publication of his *Atlas of the Normal Solar Spectrum* in 1868, Ångström gained such authority, quite in contrast to previously, when his priority claim (against Kirchhoff) concerning the discovery of spectrum analysis had fallen on deaf ears. His atlas, together with his very precise determinations of the spectrum lines in terms of wavelength, measured in units of a ten-millionth of a millimeter (10^{-10} m), not only assured him a place in the hall of fame (the wavelength unit was later renamed Ångström in his honor—and he numbers among the venerated scientists in the inner court-yard of MIT's main building), but also superiority over his former arch-rival Kirchhoff, whose map became obsolete in direct proportion to the spread of Ångström's.[41] Similarly, both H.C. Vogel and H.A. Rowland won special acclaim for their achievements in the measurement and mapping of spectra. While Rowland already had reached the pinnacle of his career at The Johns Hopkins University in Baltimore, H.C. Vogel was still a lowly observer at the newly founded Astrophysikalisches Observatorium in Potsdam, with Kirchhoff and Auwers as codirectors. By embarking on this extensive examination of the solar spectrum in 1876, which he finished three years later, he also put his name on the disciplinary map with an achievement that was considered outstanding "with regard to both exactitude and abundance of lines."[42] In the year of its completion, in 1879, he was named full professor at the Berlin University, and three years later (after Kirchhoff's death) acceded to the directorship of this first German research institution devoted primarily to astrophysics.

Tab. 3.1 Interplay between research objective and representational type.

Research objective	→	Representational type
general orientation		condensed survey map

Research objective	→	Representational type
chemical analysis		display of characteristic lines
instrument resolution tests		detailed zooming of interesting areas
survey of the full spectrum		extensive map of the total spectrum

(p.89) 3.2 Magnifying interesting segments: zooming

David Brewster’s inventory of the solar spectrum also incorporated details of “some portions which were more particularly studied” on a scale twelve times Fraunhofer’s resolution. As Brewster himself wrote:

> On a comparison with Fraunhofer’s large map, the principal lines and features will be easily recognized; but it will be seen that every portion of the spectrum contains lines wanting in the earlier drawing, and that parts which Fraunhofer has marked by one line are resolved into groups of bright spaces alternating with dark lines.[43]

To facilitate comparison of the solar spectrum with terrestrial spectra, Brewster presented in magnification several absorption spectra (e.g., of nitrous acid and of strontium) observed under laboratory conditions.[44] When later observers improved upon Brewster’s map, many focused on one specific feature in the map, his discrimination of ‘atmospheric lines’, which are caused by the absorption of light by water vapor in the Earth’s atmosphere. The so-called rainband, around 5935 Å, for instance, could not be resolved with the instruments at Brewster’s disposal, so he simply rendered it as a diffuse shaded area. Just six years later, Ångström could distinguish 19 lines in this region, and between 1879 and 1882, in his observations with a Rutherfurd grating at the École Polytechnique, Alfred Cornu was able to resolve it into 170 components. Between 1887 and 1889 Ludwig Becker at the Royal Observatory in Edinburgh eventually succeeded in more than doubling this score, dissecting the band into 376 components. A similar stepwise increase in resolution occurred with the δ band, which Brewster had drawn as a big black area of about 2 cm width.[45] This conspicuous dark feature of his map must have challenged spectroscopists in the same way that the white expanses on the charts of geographic explorers intrigued cartographers from earlier centuries.

As spectroscopes improved in the period between 1860 and 1886, there was a dramatic evolution in the appearance of any given band spectrum. Let us look at various drawings of the A group near 7600 Å. What immediately strikes us in Fig. 3.1 is the considerable increase in resolving power in the two decades after Kirchhoff's pioneering observations. Although Thollon was still working with prisms (see here pp. 135ff.), all the later drawings included in this comparison are normal spectra generated by diffraction gratings ruled by Rutherfurd (nos. 3–4) and Rowland (5–6). The figure also indicates the difference in quality of the spectrum lines: notice the line splitting, first observed by Langley in 1878, as well as the differences in line definition (particularly with some of the lines in the middle of the group) and the overall shading (towards the head of the band). It is also noteworthy that as the resolution increases, the relative distances between the lines also keep changing, even when we restrict our comparison to the four normal spectra (nos. 3–6).

(p.90)

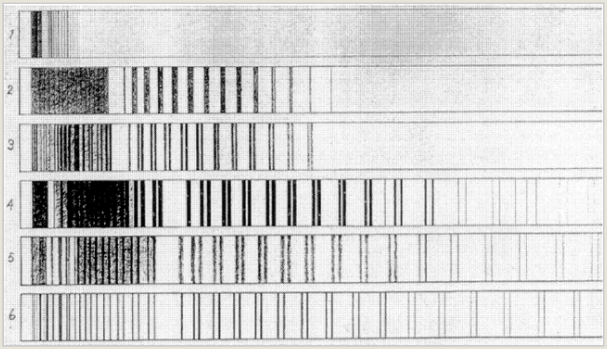


Fig. 3.1 Comparison of drawings of the A group by (1) Kirchhoff [1861/62], (2) Thollon [1890] pl. 1, (3) Langley [1878/79*a*], (4) Smyth [1882*d*], (5) Cornu [1886a], and (6) Lester [1904]. Compiled and redrawn by Lester [1904] pl. VI.

There were various reasons for wanting such selective magnifications of specific segments of the spectrum. Of course, regular band structures like the one in the foregoing figure aroused hopes of uncovering the causes behind such 'fluted' or 'channelled' spectra. The standard historiography of spectroscopy has emphasized—in fact, I would argue, exaggerated—this one aspect. I would like to stress here that several other motives were just as persuasive, and just as valid. For, this hope of deciphering nature's spectral language was a deceptive one, as we shall see in more detail in Chapter 8, when we return to this topic. The reason frequently given was much more positivistic and more in line with the rather empiristic attitude of spectroscopists of the nineteenth century. Like the geographer systematically filling in blank spaces on an otherwise complete map, spectroscopists also sought to rectify poor renderings of a particular section in existing representations. Consequently they drew attention to the necessity for a magnified representation of its immediate vicinity. In many earlier sketches, certain segments were regarded as significantly less reliable than the rest of the spectrum. For example, Brewster and Gladstone considered the blue interstice between the lines F and G to be "the least trustworthy."[46] In others, zoomed

sections allowed for interesting comparisons of seeing conditions over time or in different parts of the world.[47] And finally, the selected spectral range would sometimes **(p.91)** be taken simply as a suitable area for testing a spectroscope's quality. For instance, Lewis M. Rutherfurd proudly announced having resolved two red lines of potassium into double lines, and having decomposed a grand number of fine orange lines in the strontium spectrum with the aid of his six carbon-bisulphide prism chain. J.P. Gassiot found no less than 40 dark lines in the 6 Å interval between the two sodium D lines with his impressive chain of eleven such high-dispersion prisms.[48] Testing the resolution of his spectroscope was the declared motive also of William C. Winlock (at that time still at Yale University under the guidance of W. Gibbs) when he published his detailed 'chart' of the b group in 1880—independently, in fact, of Charles Fievez at the Royal Belgian Observatory, who also prepared detailed sketches of precisely this region in the same year.[49] Winlock's drawing gives us a good sense of the actual amount of additional information contained in a high-resolution drawing compared with the medium-scale standard maps of the total spectrum: while Kirchhoff's and Ångström's maps indicated 17 and 20 lines for that group, Winlock delineated no less than 37 dark lines, numbered consecutively b^1, b^2, etc., somewhat like Brewster's uppercase letters, to avoid confusion with Ångström's lines b_1-b_4. Thus here too, an interdependency exists between representational type and research goals, one that is quite similar to the relations already described for enlarged representations (see Fig. 3.1).

Developments in the technology of ruling diffraction gratings made these strides possible.[50] Given the great progress, if it was so easy to improve upon earlier representations of the spectrum with the available new Rutherfurd gratings, why not do a thorough job of it and produce a map of the whole spectrum at an improved resolution? Here is Winlock's somewhat defensive response:

> it would now be possible to enlarge Ångström's great chart almost as much as he improved upon Fraunhofer's first maps. But it would be an almost endless undertaking for a single observer to attempt a map of the whole spectrum, from the ultraviolet to the invisible red, brought to light by our most powerful instruments, and accordingly most physicists who have paid especial attention to solar spectroscopy have devoted themselves to a careful study of detached portions which appear of unusual interest.[51]

If we look at the vast amount of work Winlock had to do just to finish his detailed study of this minute portion of the spectrum, we see why, throughout the nineteenth century, it took an average of a decade and a half to proceed from one map of the entire solar spectrum to the next improved representation. Winlock recorded the b group not just once but repeatedly in a series of 23 measurements between 17 November 1879 and 7 May 1880. He used altogether eight different diffraction gratings (four by Rutherfurd, three by Rogers, and one by Brunner), which were then carefully compared. In the end, Winlock decided to base his published chart of the b group on five independent micrometer readings taken **(p.92)** on the same day, because this would minimize the discrepancies in the readings of lines whose intensity varied with the seeing conditions.[52] All the zooming discussed so far had been achieved by real improvements in spectroscopic resolving power. In principle it was possible simply to increase the size of the prism used. For single-prism spectroscopes the resolution is directly proportional to the length of the prism's base,[53] but large and perfect pieces of optical glass were hard to come by. In the case of prism spectroscopes, one strategy to circumvent this problem was to install a whole sequence of prisms, such as in Steinheil's precision spectrometer of 1861 or Browning's later prism chains that automatically adjusted to the position of minimum refraction (cf. Fig. 3.2). It is notable that both these instrument manufacturers were in regular contact with individuals at the forefront of spectroscopic research during this innovative period of instrument design in the early 1860s: Steinheil's man was the physicist Gustav R. Kirchhoff, whereas John Browning (1835–1925) in London cooperated with the astronomer Richard Proctor (1837–1888) and with the chemist William Crookes (1832–1919).[54] Once these basic innovations had been made, both Steinheil's and Browning's prism spectroscopes were marketed for many decades with only minor alterations.

The other strategy for increasing resolving power was to use high-dispersion fluid prisms. These were composed of five flat pieces of glass glued together along the edges and filled with a fluid of a very high refractive index, such as carbon bisulphide (CS_2). The faces of a large one could well measure 5 inches in width and 3 inches height, holding about a pint of liquid inside.[55] An additional advantage of these fluid prisms was their much better transmission of light compared to conventional prism chains.[56] But they tended to leak slightly—and thus inevitably gave off the foul odor of the liquid inside.[57] Even so, they were used often in research where minute shifts in wavelength mattered and where conventional prism chains could not be used because the sought features were too faint. Charles A. Young's observations of the corona spectrum during solar eclipses in the late 1860s are one **(p.93)** example; William Huggins's early research on Doppler shifts in stellar spectra since then or John Evershed's work on Zeeman splittings at Kodaikanal Observatory after the turn of the century are others.[58]

There was always a price to pay, however, for improved resolution of a spectroscope. In multiple-prism spectroscopes, each prism in a chain reduced the total intensity of transmitted light by about 10 to 25 %. The biggest problem with fluid prisms was that their dispersion was highly sensitive to slight changes in temperature. This meant that line positions could change by as much as 0.1 Å within a few minutes if the temperature changed by a single degree Celsius. The attainable accuracy of spectrometric measurements was thus limited. In the worst cases, sharp spectrum lines had a strange “woolly” appearance arising from local convection currents in the glass shell.[59]

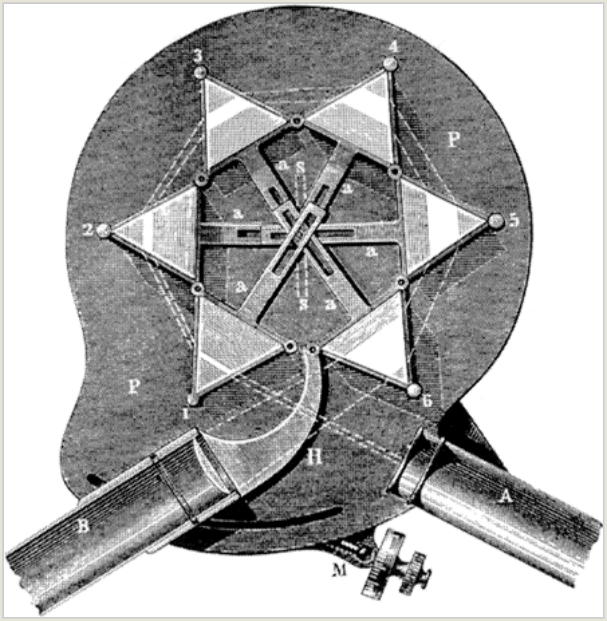


Fig. 3.2 Browning’s multiple prism spectroscope with a six-prism chain automatically adjustable to the position of minimum refraction. From Browning [1874] p. 7.

Another problem was the appearance of additional absorption bands caused by the dispersive fluid within the prism.[60] In the case of diffraction gratings, finally, a major portion of the light went into practically inaccessible **(p.94)** orders (at least until the invention of blazed gratings) so that their application was confined to fairly intense light sources.

Some spectroscopists, especially in France, resorted instead to a method of image augmentation by **lantern projection,**[61] which was somewhat similar to modern-day slide projection onto a screen. This method had become feasible with the availability of strong and stable sources of electric light, such as Léon Foucault’s electric arc, which was regulated by an intricate feedback mechanism.[62] This projection technique became quite popular in the mid-nineteenth century and devices like the *lanterne électrique* were marketed by the Parisian instrument maker Jules Duboscq[63] (1817–1886). Alternative light sources included the common Argand petroleum lamp or the bright oxyhydrogen flame, sold in France under the trade name *lampe Debray.*[64]

Using a bright projection lantern, such as the one seen on the far left of Fig. 3.3, a spectrum photograph on a glass plate measuring approximately 10 to 15 cm could be enlarged substantially on a screen. This projected image could then be easily inspected or redrawn. During the second half of the nineteenth century, this was a very widely used technique for increasing the scale of a spectroscopic photograph.[65] A somewhat related technique that was also quite popular consisted in examining spectrum photographs under a microscope on glass slides of about 5 × 1 cm.[66] But the high dispersion gained by these methods of optical augmentation had to be weighed against inherent disadvantages, which were frequently mentioned in the literature of the time. Eugéne Anatole Demarçay (1852–1904), for instance, employed the technique of lantern projection in his spectral mapping of 20 atomic and molecular spark spectra. He complained about the disproportionate widening of very faint lines and the occasional loss of detail through overexposure:

> Let me remark in this regard that the act of enlargement embellished the faint lines, as is normal, very noticeably. In some cases, the appearance of the spectrum was altered quite appreciably from what it is on the unenlarged direct negative. Even some very clear details on the direct negative occasionally disappeared (very distinct lines that are fused together, etc.). Thus these plates should be considered as affording no more than a quite accurate general idea, but a bit more boldly than the negatives, which were much superior to them in sharpness.[67]

(p.95) Henry Draper found the earlier work by Mascart and Alfred Cornu similarly wanting, who had relied on this enlargement technique.[68] Eleuthére Mascart[69] (1837–1908) had mapped the near-ultraviolet part of the spectrum after replacing the conventional glass optics of his spectroscope with prisms and lenses made of quartz or islandic spar, two substances with better transmission in that wavelength range.[70] Because these rays were invisible, he also had to attach a photographic plate to the observing telescope. “This kind of photographic ocular makes very small and very precise images, from which photographic enlargements can be taken or reproduced by sketching during examination with a magnifying glass.”[71] Thus, as Mascart himself implied, the disadvantage of this method was that the resulting photographic plate contained a dense concentration of many spectrum lines confined within a relatively small space—that’s where the magnifying glass came in. In order to gauge the precise location of each spectrum line, Mascart projected the spectrum together with a reticle, a fine regularly spaced grid, which helped him to determine the distances between the various lines on each plate. If even bigger dispersion was sought, these photographic glass plates could be used like slides and projected onto the wall in whatever magnification required. Mascart was conferred the Prix Bordin de l’Académie des Sciences for this highly successful method in 1866. His 1863 atlas of the ultraviolet region of the spectrum contained nearly 10 times as many spectrum lines as its forerunners.[72]

Another variant of the projection method involved projecting an image from the electric arc itself. As Fig. 3.3 illustrates, the electric arc, fed by a battery of 50–60 Bunsen elements, was positioned in the focus of a condensor lens which produced a parallel beam of light that passed through the slit onto a pair of 60° carbon-bisulphide prisms. The resulting spectrum was projected onto a screen 12 feet away.[73]

Its fairly large scale of 10 feet length and 18 inches height meant that it was well suited for demonstration purposes. But serious drawbacks arose when it came to quantitative measurements **(p.96)** and precise mapping of the spectral features: optical projection onto the screen involved unavoidable distortions of the image, and the unsteadiness of the light sources created additional problems. For these two reasons direct projection was mainly used for exploratory orientation and for popular lectures about what spectra look like and how they change when electrodes of different chemical composition are used.[74]

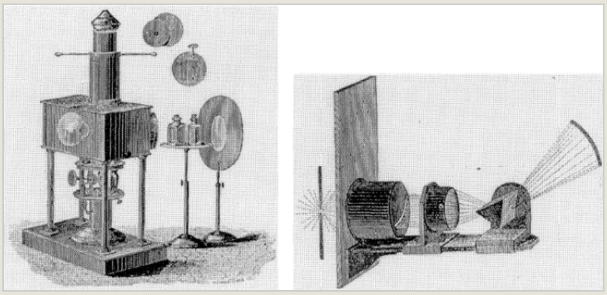


Fig. 3.3 Left: Wood engraving of a typical Duboscq lantern projection apparatus, and *right:* arrangement of condensor lens and prism. The electric arc is installed inside the apparatus on the left, and the various screws underneath are for adjusting the distance and position of the electric arc’s two electrodes. From Stein [1887] pp. 298 and 294.

If optical magnification by projection or by photographic enlargement does not work so well for technical reasons, wouldn't such a hand-drawn magnification lead to better results? How this idea worked in practice is illustrated by the following example. With his *Madeira Spectroscopic* published in 1882, Charles Piazzi Smyth went beyond merely supplementing lithographic plates of the spectrum, which he had observed during the preceding summer under the excellent seeing conditions of that tropical climate. He had conducted this "Revision of 21 Places in the Red Half of the Solar Visible Spectrum" with a Rutherfurd diffraction grating. To facilitate for his readers comparison against the results offered by his forerunners, he redrew the latter onto the same plate, magnifying each spectrum to the same scale. Marked improvements in spectroscopic resolving power since 1860 (cf. here Fig. 3.1, p. 90) made this quite a tricky business, also because of the various conventions and drawing techniques involved. Magnifying a spectrum map by a factor of ten or so meant that the breadth of each line had to be increased correspondingly. But for a strong line, rendered as a solid bold line in a medium-scale map like Brewster and Gladstone's, this magnification effected a "sometimes coarse, Cyclopean look thus imparted" (cf. here Fig. 3.4 line 1), **(p.97)** which Piazzi Smyth felt obliged to "palliate, or apologise for".[75] The Council of the Royal Astronomical Society rejected publication on the justification that it was superfluous to reproduce already existing published plates. They continued: The primary objection felt to the publication was that in the process of enlargement the breadth of the lines was so greatly increased that the character of the representation was lost; and it was even thought that on this account the reproduction was in some cases unfair to the author, as the change of scale made so great a difference in the appearance of the representation.[76] Other users of Piazzi Smyth's publication, which was eventually printed by W. & A.K. Johnston in Edinburgh, partly at his own expense,[77] were irritated as well: "Your microscope has rendered some of the lines so ponderous that all semblance of a slit is lost and they look like gaps indeed—of course I see your purpose in expanding their scale laterally".[78]

But the task of magnification implied more complications still, foremost subtleties in interpreting the intentions of the original engraver or lithographer. A good example is provided by Piazzi's puzzlement over the fact that in the 1860 spectrum map by Brewster and Gladstone each line in the preliminary band of 'Great A' is represented by a tight pair of vertically parallel engraved lines.

> Wherefore comes the question, What did they mean by that? If they really meant that they saw every one of those spectrum lines *double*, they would have eclipsed all subsequent observers up to and including Prof. Langley, of the Allegheny Observatory, in 1878, though he was the first of mortal men really to see and publish the fact of the most transcendent duplicity of those grand lines at the practical beginning of the spectrum. But the two earlier observers have totally omitted so many other features far easier to recognise, that I can only, in honesty as well as loyalty to science at large, conclude that they saw the now confessed double lines of Professor Langley as single ones; but saw them so pale, that they represented them on the copper plate by two thin lines close together, rather than by one thick, blacker and more decided one.[79]

This difficulty of discriminating between intended and unintended features in the representations of spectrum lines went to the heart of the matter of distinguishing spectroscopic fact **(p.98)** from representational artefact. Piazzi Smyth relied on contextual information, particularly the overall accuracy and detail, to *interpret* the published maps. So in his redrawing, all pre-1878 representations exhibit bold single lines, while the later ones are resolved into doublets (compare examples 1–4 with examples 5–7 in Fig. 3.4). But other conventions are at play as well in Piazzi's rerenderings: For instance, all the heavy lines have wavy edges to symbolize the somewhat diffuse boundaries of the dark Fraunhofer lines against their background. Another feature was diagonally shaded areas that were meant to denote dark spectral regions where individual lines could not be resolved. Taking up Bunsen's drawing convention for emission spectra (see here Fig. 2.22, p. 52), Piazzi also used different line heights as a means of differentiating between line width (i.e., horizontal extension) and intensity. The intensity of each spectrum line was represented as proportional to its height. Some very thin, hazy lines at the very limit of visibility were depicted as dashed or wavy vertical lines.

Proceeding in this manner, Piazzi Smyth wished to relieve his readers of the burden of going back to the original plates and “puzzling out every time *de novo* with a magnifying glass or a compound microscope, the meaning of vanishing traces of difficult lines and wrongly indicated shadows.”[80] But however exactly this systematic magnification in breadth may have treated the proportions of original line width and intervals in-between, it nevertheless failed to convey the most important quality of the earlier representations: resemblance with the overall *Gestalt* of the line group when examined through the spectroscope ocular. What Kirchhoff and his research student tried to convey in their 1861/62 map was not so much the precise width of each spectrum line in the A group, as the general impression of that spectral region. In the original scale, this was indeed successful. Given the technical and representational options, however, a simple enlargement of this drawing transformed the fine image into a monstrosity its fathers would have shuddered at seeing. At one point Piazzi himself admitted: “on the large modern scale, the old drawings would look rough, rude, and coarse”, but he pled for “physical truth’s sake rather than pictorial effect”.[81] Piazzi Smyth continued to use this technique in some of his later publications but I do not know of any other spectroscopists adopting it. While zooming in on certain sections of the spectrum was practiced throughout the nineteenth and early twentieth centuries for the various reasons mentioned at the beginning of this section, strict upscaling of older spectrum illustrations remained an idiosyncratic oddity, resulting in Smyth’s most extravagant and unmistakable set of spectrum representations.

What we gather from this is another *Gestalt* property of portraits: their non-invariance against an increase or decrease in scale. A screened image of a face, as in newspaper print, becomes unrecognizable when one comes too close to it and thus only sees the many dots out of which it is composed. Likewise its details can no longer be made out from too far away. This triviality explains why with each substantial improvement in spectroscope resolution, new portraits of the spectrum became necessary. A mere upscaling of the obsolete maps did not suffice; less because of new substructures not resolvable in the earlier maps, than because of the overall loss in *Gestalt* characteristics that enable recognition.

(p.99)

3.3 Abstracting spectra: condensing

Thus far I have been discussing approaches to spectral representations that essentially imply an increase in resolution over time. But there is a third strand that actually entails a drop in resolving power against foregoing maps. Since this voluntary loss of information, which I will call condensing, may appear counterintuitive, let me discuss two cases that belong in this category (for a third case see here § 8.4).

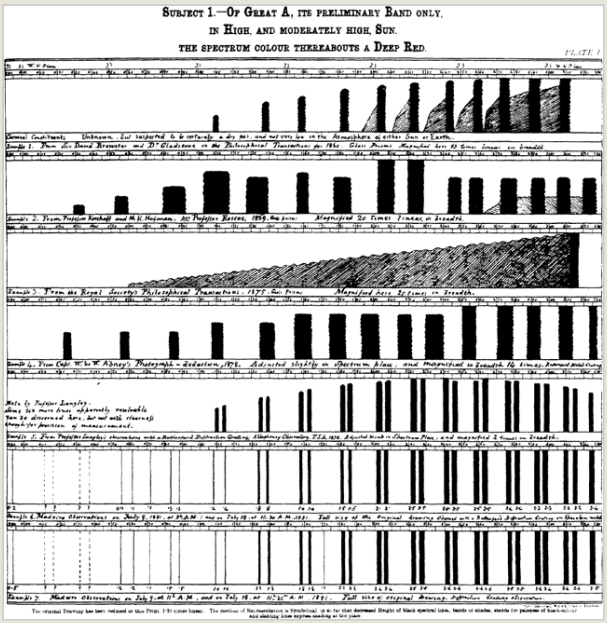


Fig. 3.4 Comparison of drawings of the A group by (1) Brewster and Gladstone [1860], (2) Kirchhoff [1861/62], (3) Hennessey [1875], (4) Abney [1878*b*], (5) Langley [1878/79*a*], (6–7) Piazzi Smyth (9 July 1881). Redrawn by Piazzi Smyth according to new conventions and magnified to the same wave-number scale (oscillations per British inch). Photolithograph by W. & A.K. Johnston. From Smyth [1882*d*] pl. I.

(p.100) (i) When Lieutenant John Bobanau Nickerlieu Hennessey (1829–1910), employed by the Great Trigonometrical Survey of India at Mussoorie near Bangalore,[82] set out to study the solar spectrum taken close to sunset, he did not take any big, cumbersome optical equipment with him, only a comparatively small spectroscope with three flint-glass prisms. Kirchhoff's instrument had had a resolving power of 40; Hennessey's could not attain more than 17. As a result, his spectrum image had only about three-tenths the extension of Kirchhoff's. When he tried to compare the spectra produced by his low-resolution spectroscope with Kirchhoff's map, he had trouble matching the two images:

> The want of intensity generally in the spectrum sun high as Mussoorie [6765 feet], combined with the smaller power of the instrument, made it exceedingly difficult, and in most cases impossible, to identify individual lines in Kirchhoff's map with corresponding ones under view; so that, after making every endeavour at identification, I was obliged to content myself with adopting the positions (sun high) assigned by him to the strong lines A, B, C, and D, and to place all the other lines of sensible intensity by means of differential measures and interpolation. Practically speaking, this amounted to the construction of a new map, so far as my wants were concerned.[83]

It might be argued that it was only to be expected that a comparatively inexperienced amateur as Hennessey was, would have difficulties of the sort expressed in the above quote; for he made spectroscopic observations on the side, in his leisure. But such problems were, in fact, far more common than this one example suggests. We find the same sentiment expressed repeatedly in print. And consequently, at regular intervals someone would sit down, redraw and publish a solar spectrum map at a lower resolution to fit precisely this need, that is, ready identification of certain groups of lines as they actually appear in a handy low-resolution spectroscope. For, the extraordinarily costly sensitive instruments were available to only a few elite institutions and, importantly, were not easily transportable and usually were left behind when observations were made at interesting places like hill tops with good seeing, or the remoter sites of solar eclipses. Hennessey's aim was a more limited one. He wanted to identify the differences in the spectrum of the high and the low Sun, for which purpose, he felt, a rather simple engraving on stone in one printing was sufficient.[84]

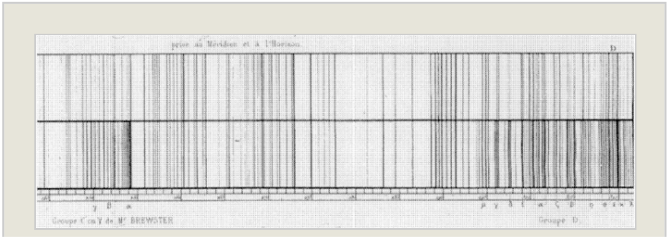
(ii) The sheer length of the big maps of the solar spectrum, especially those attained in the 1880s, made it impossible to survey the spectrum at a glance, and this apparently fed the need for more condensed representations. Gustav Müller (1851–1925), observer at the Astrophysical Observatory at Potsdam near Berlin, justified his medium-to-low dispersion **(p.101)** map of the solar spectrum, published in 1881 (that is, just one year after the publication of H.C. Vogel's big map of the solar spectrum), as follows:

> The charts of the Sun's spectrum by Kirchhoff and Ångström, as well as the spectral plates recently published by Vogel on an even larger scale, make it possible to orientate oneself from any line, even with the most powerful spectral apparatus, and to find its associated wavelength to the desired level of accuracy. It becomes more difficult to use these plates as a guide when using smaller instruments of lower dispersion to observe the solar spectrum. A considerable number of lines then vanish completely, groups of lines, which with more powerful instruments are easily resolved, appear fused into a single line, other lines unite into more or less blurry stripes. The appearance of the spectrum as a whole is changed so considerably by this that it occasionally takes some effort to determine a line correctly right off with the aid of the comprehensive spectral charts. This problem made itself repeatedly felt during spectral observation, namely during investigations I undertook to determine the influence of temperature on the refractive and dispersive conditions of various prisms. […] Perhaps other astronomers and physicists will also welcome such representations of the solar spectrum, and thus publication of the plates from my drawings may appear justified.[85]

Although Vogel’s stately spectral map, with a total length of nearly 5 meters, was not easily surpassed and certainly was regarded as the more important contribution, Müller’s smaller-scale representation of but 25 cm was also perceived as useful and quoted in later publications. Looked upon in terms of career investment, the 1881 publication had the advantage that Müller could figure as the only author. He is mentioned merely in passing in Vogel’s map and is not listed as a coauthor there, even though he had contributed considerably to the drawings and micrometric measurements of the photographic plates. After Vogel’s retirement, Müller was one of the candidates for his replacement at the Potsdam Astrophysikalisches Observatorium. The brilliant astrophysicist Karl Schwarzschild was preferred over him in 1908, but he eventually became director of Germany’s biggest astro-physical research institution after Schwarzschild’s untimely death in 1916.[86]

3.4 Distilling out the metaphysical

On the face of it, Daston’s and Galison’s periodization of atlases (cf. here p. 452) would rule out—or at least seriously question—anything like a metaphysical image in late nineteenth-century atlases. By then the time of the metaphysical supposedly had long since past. This is certainly true in the sense that we do not find any totally construed representations. In another sense, though, this is far less evident. Let me choose an example from the subclass of representations conveying the difference between the solar spectrum at high noon and close to sunset. In 1833 Sir David Brewster noticed that the solar spectrum looked distinctly different when studied at different times of the day. As we now know, he correctly inferred that these variations had to do with the effects of light absorption in our terrestrial atmosphere. Since then, observers drew comparative maps of the solar spectrum observed **(p.102)** at the meridian and on the horizon, or as observed at different altitudes. Pierre Jules César Janssen (1824–1907), for instance, published studies about the telluric rays in the solar spectrum from 1862 on for more than twenty-five years.[87] Long before he became director of the Meudon Observatoire d’astronomie physique in 1877, he had already examined the appearance of strong bands near the Fraunhofer lines C and D, using a five-prism chain, and drawn the so-called C, C′, and D groups for the plate accompanying his 1871 paper.[88]



His comparison revealed a substantial strengthening of all the terrestrial lines in the horizon spectrum because of the geometrically longer path taken by the Sun’s rays through the Earth’s atmosphere. But optimal viewing conditions of very dry air and observation of the meridian along the shortest line of sight could never completely eliminate these dark lines caused by atmospheric absorption. Thus Janssen concluded:

Fig. 3.5 Excerpt (group D) from Janssen's comparison of the solar spectrum between Fraunhofer lines C and D as observed at the meridian (top) and on the horizon (bottom). Copperplate engraved by E. Pérot. From Janssen [1871] pl. 1, fig. 2.

> The telluric lines are always visible in the spectrum. It is true that some lines seem to disappear when the Sun is very high, but this is but an apparent phenomenon that is easily explained. In fact, the intensity of a telluric line observed on the horizon is fifteen times greater than at the meridian. The result of this is that an insufficiently intense line on the horizon becomes invisible around noon; but this invisibility is only relative; it just occurs for lines at the limit of the power of the instruments.[89]

Thus, strictly speaking, there is no such thing as a 'pure' solar spectrum on Earth, since even at noon and under the best seeing conditions, a high-resolution spectroscope would still detect superimposed atmospheric absorption lines. This insight was taken particularly seriously by compilers of later solar maps at the highest attainable resolution. The atlas published by Louis Thollon from the Observatoire de Nice, in 1890 (already mentioned in § 3.1 in the context of enlarged maps) is a prime example. It displayed the solar spectrum **(p.103)** in four ways: (a) with the Sun at 106° above the horizon, (b) at 30° both in normal, and (c) in dry weather, and (d) omitting the telluric lines. As we can infer from the above quote by Janssen, the last row (d) does not represent anything actually observable in a spectroscope, be it ever so good quality, because this last representation is reached by elimination of all the lines shown to be of atmospheric origin. Stage (d) thus does not represent any real observation but a construed image of what an extraterrestrial observer should have seen. In our age of satellite telescopes this may not sound very alien, but it certainly did to Thollon's contemporaries. In this sense, the last row of Thollon's atlas is a distillation. All real observations can never be more than mere approximations of this 'metaphysical' image. If we take a closer look at an arbitrary section of his atlas (Fig. 3.6), we see how carefully this stepwise elimination of all the terrestrial impurities has been captured in the lithograph with delicate and fine strokes to trace the faintest of lines. The etcher has executed a step-by-step purification process leading us from the realistic spectrum of an observer immersed in the Earth's atmosphere to the realm of the sublime solar spectrum *per se*, the closest counterpart to Kant's *Dinge an sich* that I could find within my miniature world of spectra.

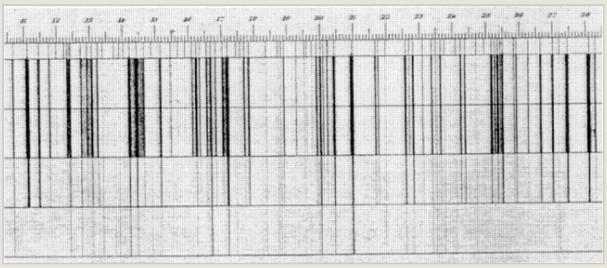


Fig. 3.6 Sample section of Thollon's comparative atlas of the solar spectrum (region A-B). Steel etching by C. Legros. The relatively dark scanning was necessary in order to bring out some of the faintest lines, which are barely visible even on the original plates. From Thollon [1890] pl. II.

Once on this track it is hard to leave it again, since suddenly we recognize similar features in other spectral representations as well. For instance, it is scarcely possible to prepare an emission spectrum of any substance in the Bunsen burner lacking any trace of the yellow D lines. Their extreme detectibility was celebrated. As was already well known to William Swan, only microscopic amounts of sodium are needed for the yellow D lines to show up clearly. Other lines—some originating from the air, as we now know—were equally common to the spectra of different elements considered pure in 1850.[90] Thus, mapping **(p.104)** terrestrial emission spectra not only entails careful plotting of all the lines belonging to the element or the molecule under study, but also recognizing and consciously omitting trace impurities that cannot be avoided in the chemical preparation of the sample. In this sense, charts of emission spectra like Bunsen's (Fig. 2.18) are also metaphysical images of an ideal rather than depictions of something actually seen in precisely that form. Hence, most of the hand-drawn representations of emission spectra have a touch of the metaphysical. In spectroscopy the 'metaphysical image' only vanished with the advent of photomechanical reproduction in the 1880s, when it was conceived as rendering typical spectra with all their associated impurities and defects. This is not to say that these photographs were not retouched, 'cleaned up', and otherwise manipulated, but the idea of what they were supposed to represent had changed.

3.5 The phenomenology of the rainband

There is a flip-side to this concatenation of the solar spectrum with atmospheric absorption lines. It relates to attempts to use these bands as an indicator of imminent rainfall. This meteorological application transgressed the strict boundaries set by the specialists and left its mark in various periodicals and even newspapers like the London *Times.* Many spectroscope advertisements and introductions to rainband spectroscopy were published during the early 1880s,[91] and the associated debates provide many clues about the differing perceptions of the spectrum among the general public. Such optical instruments were the first that many farmers had ever laid their hands on. This context of more popular usage of scientific instruments thus complements the previous section, in which we limited our discussion of the perception of the spectrum to scientists involved in more esoteric pursuits.

As mentioned in § 3.1 (on p. 82), Brewster's work from the 1830s began the discrimination between solar and terrestrial lines in the solar spectrum. His five-foot-long map of the solar spectrum, which was only published years later in 1860, already made a clear distinction between solar and atmospheric lines, although Brewster carefully picked his words to skirt any physical explanation: "in calling them *atmospheric*, nothing more is meant to be expressed by the term than the mere fact that these lines or bands become much more visible as the Sun's rays pass through an increasing amount of atmosphere".[92] Observations by the Astronomer Royal for Scotland Charles Piazzi Smyth, during a stay on Tenerife, further corroborated the possibility that absorption in the Earth's atmosphere might be responsible for the occurrence of these features and their variability. The results indicated that atmospheric lines vary with the altitude of the observing station (at sea level and on the peak of the Tenerife volcano). So did the observations by Jules Janssen, who was the first to resolve the fairly diffuse absorption bands on Brewster's map into their constituent lines, which he called 'raies telluriques' (cf. Fig. 3.5). In the mid-1860s, the Harvard chemist Josiah Parsons Cooke[93] (1827–1894) also placed himself in support of the hypothesis that **(p.105)** these telluric lines were caused by water vapor. But it took another decade before accumulated knowledge of these atmospheric lines in the solar spectrum could be put to practical use.

In the 1870s Piazzi Smyth and other observers noted striking variations in the solar spectrum near the sodium D line, such as were observed at Palermo before and after a sirocco in 1872, and shortly before heavy rainfall in Edinburgh in July 1875 as well as in Toulouse in May 1876.[94] It occurred to them that these variations might possibly be used to forecast rain, even in cases where the standard barometric method failed. Both Piazzi Smyth and Janssen had used small, easily portable direct-vision spectroscopes that looked like mini telescopes. Although only 4 inches long, they contained a five-prism chain mounted in such a way as to minimize the average deflection of rays while maximizing the resulting dispersion (cf. Fig. 3.7). According to the instrument historian Deborah Warner, the design of this type of instrument goes back to the French optician Giovanni Battista Amici in 1856. But better known modifications were proposed in the early 1860s by Jules Janssen as well as by the French optician J.G. Hofmann, who was also the first to market them.[95]

(p.106) The spectrum generated in such a breast-pocket spectroscope was about an inch long and half an inch wide. The Scottish meteorologist Hugh Robert Mill (1861–1950) described it as follows:

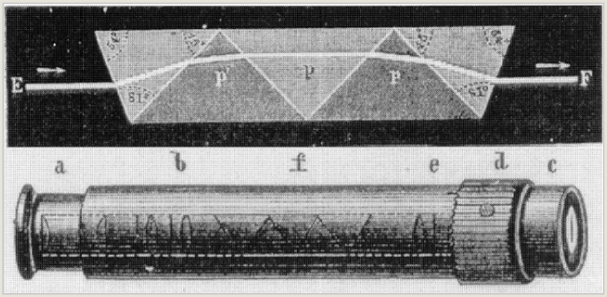


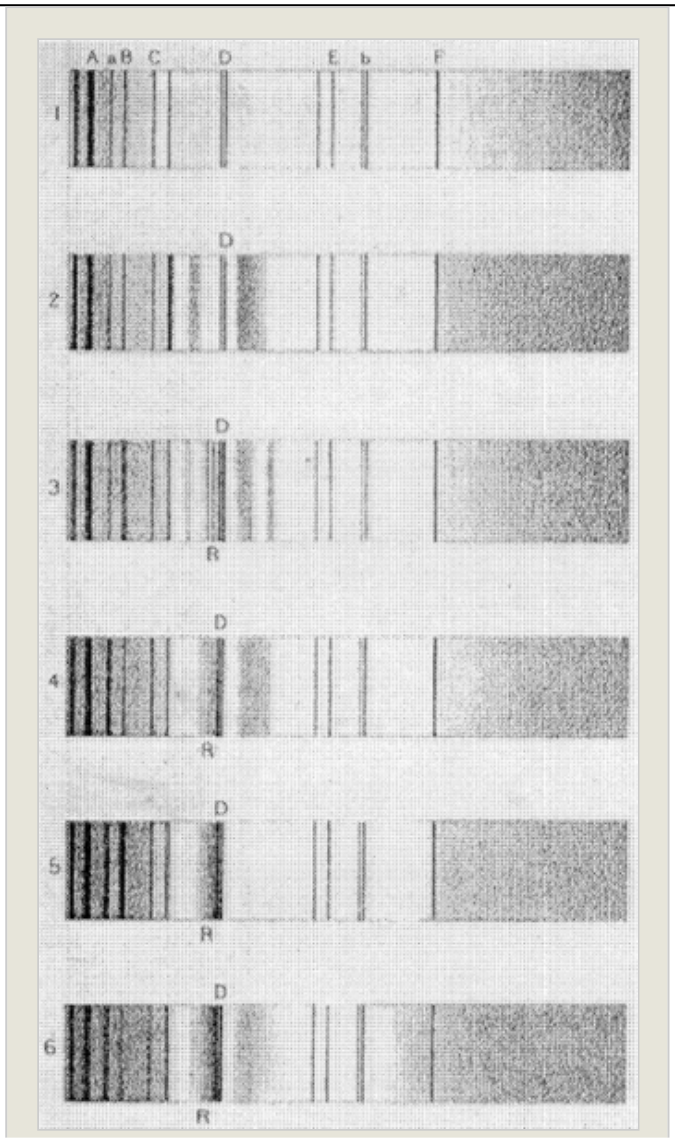
Fig. 3.7 Top: Diagram of the prism arrangement of a direct-vision spectroscope designed by Janssen: the sequence of three crown-glass and two flint-glass prisms minimizes the total deflection from the straight path, but the dispersive power of all five prisms is cumulative. *Bottom:* woodcut illustration of a rainband spectroscope marketed from the 1870s onward. Both from Schellen [1870/72*c*] figs. 48f.

> On one side a band of red, apparently 3/16ths of an inch wide, emerges from blackness and shades into a l/16th inch strip of yellow, which merges into a quarter inch space of green, passing an equal area of blue which dies away in hardly visible violet. Two or, in favourable circumstances, three black lines (α, B, C) are seen in the red, one (D) appears to separate the red from the yellow, a wide nebulous line divides the yellow from the green, several very thin lines appear in the green together with two thicker ones (E and b), and in the beginning of the blue there is a still darker line (F); besides which a glimpse may sometimes be had of other lines in the darker part of the spectrum beyond F. On looking directly at the sun many of the lines are split up into a number of very fine components, and the whole spectrum seems ruled with lines intensely black and geometrically narrow, most of which are invisible in diffused light.[96]

As cheaply made pocket spectroscopes flooded the market in the 1880s—often without even an adjustable slit and of very modest dispersion—observation of the telluric lines in the solar spectrum, and their variations with the seasons and the weather, started to gain popularity. In 1877 Piazzi Smyth coined the term ‘rain band’ for a group of dark spectrum lines on the red side of the sodium D line (that is, in the wavelength range 5895–5980 Å), and soon afterwards more calls to use the rainband for predicting impending rain were published in other journals.[97] By the middle of that decade several books had appeared to satisfy the demand of a rapidly expanding market for so-called rainband spectroscopes.[98] Instrument makers such as John Browning or Adam Hilger were among the first and enthusiastic promoters of spectroscopic meteorology,[99] and a heated debate over its merits was ongoing in the *Times* and the *Scotsman*.[100]

Capron illustrated his case for the rainband with a plate showing the variation in the solar spectrum seen with a spectroscope of only small to moderate dispersion. This plate is reproduced in Fig. 3.8 as a nice example of a technique often used in teaching spectroscopy: multiple depiction of the same spectrum under different observing conditions.

(p.107)



Not unlike the representations encountered in the previous section (for instance, Thollon's map, Fig. 3.6), the sequence of spectra given in the above plate is ordered successively, from an absence of the rainband in (1) and (2) to a strong presence in (5) and (6). The aim of this plate is to illustrate the substantial variation in appearance and intensity of the rainband as compared with the other solar lines and bands under different weather conditions.[101] The viewer is instructed not to be distracted by other features of the spectra, such as the quite prominent dark band to the right of the sodium D lines, which does not correlate with an increase in the rainband's intensity.[102] The user of Capron's manual had the task of deciding which among the several printed samples was most similar to the real spectrum **(p.108)** observed in his rainband spectroscope, that is, to match his visual field against a whole array of categories provided by the manual's author. Even this was a daunting task for anyone lacking prior experience with spectra. The difference between these black-and-white representations, naturalistic and multifarious though they attempted to be, and the colored spectrum as seen in the ocular of the little pocket instrument, devoid of any numerical scale, was still too vast. An inevitably dirty slit produced superimposed horizontal stripes and dust accumulating on the prism faces gave "a false obscurity to the spectrum".[103] In fact, with a simple low-dispersion pocket spectroscope, it was impossible to see the rain-band itself. Instead one sees an intensification and apparent widening of the D line towards the red, which is actually a result of the blurring of the sodium line from the hundreds of thin atmospheric absorption lines caused by the water vapor in the air: "The D-line proper is thus replaced by a brilliant yellow streak, and the rainband is seen as a black line clinging to its red side".[104] But even Capron admitted having met "persons (scientific and otherwise)", who simply could never see a rainband at all, even if they used a spectroscope with a higher dispersion. Yet others insisted that the horizontal

dust lines were rainbands, and "even well-practised observers differ very widely in strength estimates."[105] Capron advised observers experiencing difficulty in identifying the rainband to vary the observing angle, to distrust observations made too close to the horizon, and also to take into account the appearance of the main Fraunhofer lines: "when these are bright, clear, and sharp, rainband is usually absent; when they are obscure and seen faintly, rainband is generally present."[106] Mill likewise warned his reader not to expect too much in the beginning: "He need not look forward to 'seeing the rainband' at once; indeed the rainband has been wickedly defined as 'an optical illusion strengthened by long practice'. This is not exactly true, as we shall soon see."[107] The strong correlations promised by Capron between rainband observations conducted with due precaution, and actual rainfall were soon confirmed by Piazzi Smyth. He reported several readings of the spectroscopic rainband, "the blackest and most intense of the season", or looking "like a black ribbon in the sky", followed by "destructive floods" and a "perfect abyss of rainfall with thunder and lightning too".[108] Despite Piazzi Smyth's own proven success as a weather man, others disputed the reliability of such observations **(p.109)** in forecasting.[109] The primary reason for the persistent failure to use this indicator as an effective weather vane is general inexperience in observing the spectrum with its many variations unrelated to weather conditions. But another hotly debated question was how best to classify the varying intensity and width of the rainband and the other lines in the spectrum. The most common practice of simply judging it subjectively by eye, and recording it on a scale of, say, one to five, was problematic because it made reference to a "purely mental scale" without any "guarantee of the intensity which is represented by a certain figure one day being recognized as corresponding to that figure on another occasion."[110] Thus one early observer who endeavored to take daily spectroscopic observations of the rainband wrote to Piazzi Smyth: "may I venture to say that, if a coloured chart of the sky spectra, showing the different appearances of the rain-band from 0 to 10 according to your estimate was published, it would be of infinite assistance to observers, like myself, who have, at present, great doubts as to the reliability of their own estimates, and of course, the value of observations for

Fig. 3.8 The solar spectrum with and without the rainband (left of the sodium D doublet) under various weather conditions: (1) the solar spectrum in a clear blue sky; (2) spectrum on a hazy morning with a red sunrise, no rainband; (3) moderate low-sun bands and lines, rainband; (4) spectrum from a partly clearing rainy and windy sky, moderate rainband; spectrum observed with sun shining through saturated clouds, low-sun lines and strong rainband; (6) rainband pervasive and exceptionally strong between C and D, with the whole spectrum darkened. Lithograph by Stanford's Geographical Establishment. From Capron [1886] frontispiece.

comparison would be greatly enhanced if some such tranquille[?] standard was available."[111] Nearly every advocate of rainband prediction had his own advice to offer on how to circumvent this problem: Mill recommended a comparative scale in which the Fraunhofer lines E, b, and F were taken as reference standards for increasing width. C.S. Cook devised a mechanism by which diffraction fringes of variable intensity were projected onto the field of vision; and Louis Bell resorted to an even more involved photometric method based on the polarization of light after traversing five prisms.[112]

But what was most important was the practical skill acquired from routine recordings of the sky spectrum: thus Piazzi and his wife Jessica demonstrated the statistically significant success of the method of rainband observation in the hands of a trained spectroscopist. For years they kept a meteorological journal with daily, sometimes even more frequent readings of the rainband's intensity together with hygrometer readings and other weather indicators. However, these methods were all far too complicated or too demanding for anyone with just a passing interest in weather forecasting. It was no easy matter for a lay observer even to distinguish "between the appearance of the rain-band as shown by the whole atmosphere and by the layer fifty feet thick" between his or her observation post and a nearby white wall![113] Thus, rainband meteorology never succeeded in gathering a stable group of adherents and the market for these gadgets started to dry up again by 1890.[114]

(p.110) Looking back at the temporal evolution of representations of the solar spectrum, we see a pattern of extension, enlarging, zooming, and then condensing again or simplification. We certainly can distinguish between these four trends, each with their own specific functions: the exploratory excursions and enlarged atlases, the blown-up segments, and the condensed abstractions. But it would be inadequate to confine a discussion of solar spectral maps to any one of these four strands since, as I hope to have shown, they were inextricably interwoven in the contemporaneous practices of scientific research and popular exposition.[115] A similar complementarity of purpose and practice also governed the development of the various types of spectrum representations; in fact, as I will argue in one of the concluding sections (see here pp. 434ff.), this explains why several competing spectro-scopic domains could emerge and evolve partly synchronously.

Notes:

(1) See esp. Edney [1993] pp. 57f. for a fruitful approach incorporating conceptual differences in the information content, design, technical production, as well as broader social and cultural context of each of these cartographic modes.

(2) Brewster [1836] p. 389; see there p. 390, for the various prisms he used (including, *inter alia*, a fine Fraunhofer glass prism obtained from Talbot). In retrospect it is easy for us to understand why Brewster's efforts to find coincidences between the molecular absorption spectrum and the solar spectrum were in vain: the Sun's atmosphere is far too hot to contain any molecular constituents.

(3) See Chen [2000] pp. 58ff. for further details about Brewster's instrumentation, and *idem* pp. 123f. on enlargement as a typical trait of the visual tradition of optical measurements in the nineteenth century.

(4) See Brewster [1833/34*b*], [1836] pp. 389f. and Brewster and Gladstone [1860] p. 149; thus Brewster's efforts comprehended both enlarging and zooming. For detailed praise of Fraunhofer's map against later copies of it, see here p. 116.

(5) See Brewster [1836] p. 391 and Janssen [1862/63]. Cf., e.g., C. Kuhn [1853] who also estimated 3000 dark lines in the solar spectrum, about as many as then appeared in Kirchhoff's [1861/62] map. Cf. also Smyth [1880b] p. 286 on Ångström's map containing the "places and physiognomies of about 1 400 lines" while his own inventory of the full visible solar spectrum, compiled under optimal weather conditions in Lisbon in 1877/78, came to 2016 lines. In the ultraviolet, J. Müller's [1863] estimate of c. 80 lines was likewise soon surpassed by Mascart's [1864] count of more than 700.

(6) A. Herschel [1900] p. 161; cf. Brewster [1836] pp. 391f. In the late 1850s, Charles Piazzi Smyth also contributed to the exploration of atmospheric absorption bands by observing the solar spectrum at various altitudes (from 78° to 1° below the horizon) and heights (between 50 and 8903 feet) at Tenerife: see Smyth [1858c] pl. XXV, [1871b] p. Rl 16, as well as H.A. Brück [1983] pp. 29f. The later work on 'rainband' spectroscopy is discussed here in § 3.5.

(7) Brewster [1833/34*b*] p. 527; cf. also Chen [2000] pp. 57–60 for the context of Brewster's research, and pp. 52ff., 65ff. about Brewster's debate with Powell, who had increased the dispersion, by using prisms filled with carbon bisulphide, but not the resolving power.

(8) Among the noteworthy references to Brewster and Gladstone [1860] are Valentin [1863] pp. 6–8, Smyth [1882*d*], Becker [1890] p. 131, and a few other texts dealing specifically with telluric absorption lines and bands in the solar spectrum: cf. footnote 45 below.

(9) On the last see below Fig. 4.10, p. 125; on the substantial gain in information through higher dispersion see, e.g., Merz [1862]p. 655.

(10) In some cases, such as the famous corona lines 1474 on the Kirchhoff scale, this unit remained in use even after Kirchhoff's scale became obsolete in 1868.

(11) See Kirchhoff [1861/62] and Ångström [1868]. I use the ratio spectral range *R* to length *L* (or *R/L)* in units of Ångström per centimeter. The smaller the *R/L*, the higher is the resolution of the respective atlas or map.

(12) See Smyth [1877c] p. 39; "Ångström's normal solar spectrum; printed from stone also, but at one printing only [in contrast to Kirchhoff—see here p. 125], and from lines incised through a thin gum coating on the prepared surface of the stone, or rather into its very substance".

(13) Piazzi Smyth's Lisbon spectrum of higher resolution, mentioned in footnote 5 above, was only published in tabulated form. See, however, his notebook 'Solar-Spectroscope, April 1878-July 29, 1878' (ROE, 18.113) for his sketches of 22 segments between the preliminary band of Fraunhofer's line little a in the far red and some few lines beyond H_2. For instance, the region up to H_1 comprised 15 lines in Ångström's map, but 93 in Smyth's.

(14) H.C. Vogel had studied at the Dresden Polytechnical School and at Leipzig University (under Bruhns and Zöllner). He accepted directorship of the Bothkamp Observatory near Kiel in 1870 and changed to the newly founded Potsdam Observatory in 1874. See, e.g., Fowler [1908], Lohse [1907], Müller [1907], Herrmann [1975], [1976], [1981], T. Shinn in Joerges and Shinn (ed.) [2001] pp. 38f., and here p. 429.

(15) See H.C. Vogel [1879] (up to April 1877 the measurements were taken in the old Berlin observatory, before its relocation to Potsdam) and Müller and Kempf [1886].

(16) Fievez was trained at the École Militaire, and earned his 'diplôme d'ingénieur civil des Arts et Manufactures' in Liége. He served in the Belgian army from 1867 and worked in the chemical industry from 1870, entering the Observatoire Royal de Bruxelles in 1877; see Folie]1889/91*b*], Swings [1936]. Because the Observatory's director, Houzeau, wanted to establish a new department for spectroscopy, Fievez was sent to Meudon and Potsdam to acquire the necessary skills from experts like Janssen and H.C. Vogel. In 1885 he began lecturing on astrophysics at the Faculté des Sciences de l'Université de Liége, and in December 1888 was elected a corresponding member of the Académie Royale de Belgique.

(17) See Smyth [1882*d*] p. 3, who applauded this map as "one of the most advanced of the present day."

(18) See H.C. Vogel [1879] p. 135: “The larger and better instruments of modern times show such a great abundance of lines in some parts of the spectrum that it is only with effort that one can find one’s way in the mentioned plates.”

(19) For overviews on the increasing number of recorded chemical elements in the Sun see, e.g., Stoney [1868] pp. 15ff., Lockyer [1878*d*] chap. X, or Young [1881] pp. 87f. Kirchhoff [1861/62] had already identified iron, sodium, calcium, magnesium, chromium, and nickel, but he was still not certain about cobalt, barium, copper, and zinc. Ångström [1868*b*] confirmed cobalt, added hydrogen, manganese, and titanium; and many other elements such as cadmium, bismuth, and platinum were later added by careful comparisons of the solar spectrum with the arc spectra of these metals: see, e.g., Trowbridge and Hutchins [1887], or Hutchins and Holden [1887]. Rowland [1891*d*] pp. 522f. already lists 36 elements as definite constituents of the Sun, 9 more as likely, and 15 as definitely not in the solar spectrum.

(20) H.C. Vogel [1879]. Later, solar physicists and astrophysicists followed this line of research quite intensively: cf., e.g., Hufbauer [1991], Hentschel [1998a] and further references there.

(21) See here § 4.5, pp. 135ff., on Thollon’s map and his high-dispersion fluid-prism spectroscopes, as well as the brief notes in *Nature*, **21** (1879) p. 236, **32** (1885), p. 519.

(22) Thus, according to Trowbridge and Sabine [1887] p. 289, “the use of Rowland’s concave grating with its peculiar mounting must be characterized as a new method and a new departure in measurements of wave-lengths”. See also the quote in footnote 18 above.

(23) Powell [1839] p. 3. Cf. also Chen [1998] about Powell’s [1839], [1841] controversy with Brewster [1840] on the ‘true’ position of Fraunhofer’s lines G and H.

(24) See Broch [1853] pp. 313f.: “But since many lines that appear to the naked eye as simple bold lines resolve, upon observation with a telescope, into a number of closely lying weak lines and an innumerable quantity of hitherto invisible lines emerge at the same time, comparison with such a drawing is not easy.” Cf. also the commentary by Heusser [1854] who refuted Broch’s suspicion of changes in the Fraunhofer spectrum with geographic location or observational altitude.

(25) Compare Kirchhoff [1861/62] with Brewster and Gladstone [1860], based on observations made in the 1840s; the quote is from Smyth [1877c] p. 45.

(26) Smyth [1877c] p. 45.

(27) See, e.g., Cornu [1874/80*a*] pp. 422f., where he complained about the lack of similarity of his prism-based photographs with Mascart's earlier atlas (a normal λ plot) of the same near-ultraviolet region: "it is very difficult to reconcile the lines with the photographic proofs."

(28) Stoney *et al.* [1878] p. 40, cf. also pp. 44, 47ff., 52, 57, 61. 64f., etc. Watts [1872] made the most systematic effort to translate Kirchhoff's scale into wavelengths.

(29) Smyth [1880*b*] p. 287; cf. also, e.g., E.C. Pickering [1886] p. 224 for similar losses in the transition from engraved to photographed maps. On the reasons for producing such a table of inverse wavelengths, see here pp. 59 and 306.

(30) See H.W. Vogel [1880*a*] p. 196 footnote: "The comparison with Draper's photographic spectrum came more quickly to a finish, since in that one the lines are displayed in exactly the same intensity relations as are obtained in the spectral photographs. In Cornu's spectrum, some of the lines that appear strong in the photograph are weak, and vice versa; that [is] why a direct comparison is often difficult."

(31) Charles Piazzi Smyth: 'On two series of enlarged photographs; one in the visible, the other in the invisible of the violet of the solar spectrum; being an appendix to the R.S.E.'s whole visual solar spectrum of 1884' (RSE materials on loan at ROE), 17-page handwritten mss. inside the album case with solar spectra, sent to the Society on 9 May 1891, p. 15 and plate 49—cf. here also p. 235.

(32) Perhaps similar to those recorded after the volcanic eruption of Krakatao in the Indian Ocean in 1883: see *ibid.*, p. 3. Cf. also H.A. and M.T. Brück [1988] pp. 231ff., and Smyth [1877*c*] p. 46 for another such case: "Has the physiognomy of the big B line of the solar spectrum radically altered in the course of the last 40 years?" because Brewster and Gladstone [1860] had mapped this area quite differently, based on even earlier drawings.

(33) See, e.g., Kirchhoff [1861/62*a*] p. 63, or [1861/62*f*] p. 1. H.C. Vogel [1879] p. 136 also had to interrupt his observations because of the severe strain on his eyes and leave the remainder to his assistant G. Müller. Cf. also Bridgman [1957] p. 250 on Lyman: "He also suffered from a serious impairment of vision, which he ascribed to overstrain in measuring his spectroscopic plates".

(34) On the development of prism spectroscopes between 1860 and 1870 see Bennett [1984]. On the interplay of improvements in the technology of ruling gratings with advances in astrophysical and spectroscopic research see Hentschel [1993*b*] and [1998*a*] chaps. 2–4, 11.

(35) Quote from C.A. Young [1880] p. 353. Ångström's [1868] solar spectrum map, for instance, listed 70 lines as ambiguous.

(36) See, e.g, Liveing and Dewar [1881] as an example of a study examining such claims by Lockyer (cf. here footnote 90 on p. 314). They came to the conclusion that "however probable this hypothesis may appear, *a priori*, it must be acknowledged that the facts derived from the most powerful method of analytical investigation yet devised give it scant support" (p. 230).

(37) Huggins [1891] pp. 75f. This condemnation of earlier measurements included his own in [1864*a*].

(38) See, e.g., Schuster's [1882] p. 140 caution with respect to speculations by Lecoq de Boisbaudran and Stoney: "It requires a much more careful experimental examination […] to arrive at any proof of the reality of these analogies."

(39) See footnote 20 on p. 84 above.

(40) See in this respect, e.g., Lindqvist (ed.) [1993] and Nye [1986].

(41) The copy in Munich at the Deutsches Museum, formerly owned by the optical instrument manufacturer Siegmund Merz, carries the number 676a, which suggests a printing run of around 1000 copies for the first edition in Uppsala in 1868. One year later another edition was distributed from Berlin by the same publisher Dümmler, who had also printed Kirchhoff's map as a separatum.

(42) See Herrmann [1976], p. 55.

(43) Brewster and Gladstone [1860] p. 149 (cf. also footnote 4 here on p. 81). The succeeding text is mainly a detailed comparison of the two maps.

(44) See *ibid.* pl. IV, fig. 7, and fig. 11. Cf. also Valentin [1863] pp. 6–8 for a close-up examination of small segments of solar and terrestrial spectra.

(45) See Brewster and Gladstone [1860] pl. IV, fig. 7. Ångström [1868] pl. H: 'Raies atmosphériques'. Cornu [1884*a*], [1886*a*]; Smyth [1884*a*], Becker [1890] pp. 101, 127ff. and his first plate. See also Janssen [1862/63], [1866], [1871], Cooke [1866] as well as here § 3.5 on the meteorological applications of 'rainband spectroscopy'. Cornu's work on mapping the ultraviolet spectrum is discussed on p. 133, and § 9.9 sketches his lectures in optics.

(46) See Brewster and Gladstone [1860] p. 151.

(47) See, for instance, Cooke [1866] (also reprinted in Smyth [1882*a*) on the striking differences among four different observations between 17 November 1865 and 5 January 1866, which according to Cooke “fully accounted for the discrepancies in the representations which different observers have given of the D line” (p. 342); or H.C. Russell [1877], H.C. Vogel [1879] pp. 138f., and Thollon [1884] pl. 1, on the very different line counts between the two D lines from observations conducted in London, Kew, Sydney, and Nice.

(48) See Rutherfurd [1863*a*] and Gassiot [1864*b*] p. 185; cf. Bennett [1984*b*] pp. 3f. on the first demonstration of long prism chains at the International Exhibition held in London in 1862. Ditscheiner [1866*b*] describes the clever mechanical system for automatic adjustment of the position of minimum deviation. On Rutherfurd see here p. 209.

(49) See Winlock [1880] p. 399, and Fievez [1880]; cf. also Young [1880] on the E group, Cornu [1883*c*] on the section around D, Cornu [1884*a*,*b*], [1886*a*] on the bands near α, B, and A, and Smyth [1882*d*] on other bands.

(50) See, e.g., Hentschel [1993*b*], [1998*a*] chap. 3 and references there.

(51) Winlock [1880] p. 398. As mentioned above, however, both H.C. Vogel in 1879 and Fievez in 1882/83 took that trouble.

(52) See Winlock [1880] pp. 400f.

(53) See, e.g., Merz [1862] or Pickering [1868] on the comparative efficiency of different prism shapes and Tolan-sky [1947] pp. 87ff. on the inverse relation between resolving power and ‘resolving limit’, the latter defined as the power of the instrument to separate close components.

(54) In Browning and Crookes [1861] they even issued a patent for an “improvement in spectrum cameras”. Unfortunately, there seems to be no further record of their patent application no. 1181, issued on 9 May 1861, perhaps because it was too similar to an earlier design of a spectrum camera by Crookes [1856]. On Steinheil see here footnote 93 on p. 49; on Browning, whose instrument shop was located in The Minories no. 111, later at The Strand no. 63, see Anon. [1930], Williams [1994] pp. 15f., and Lightman [2000] pp. 667f. For a general survey of the development of spectroscope designs in the first ten years of spectrum analysis, see Bennett f 1984*b*].

(55) Such a prism was made for the chemist J.P. Cooke at Harvard in 1863 by Alvan Clark: see Cooke [1863], and Warner [1968] p. 70. Cf. here Fig. 9.9 for a simple fluid-glass prism construction, as well as p. 136 for Thollon's variant design. According to a letter by James Dewar to Charles P. Smyth, 3 June 1880 (ROE, 14.64, folder D), "the great secret of good fluid prisms is to use thick plate glass for the sides instead of the thin rubbish generally employed therein [which] invariably gets distorted."

(56) See, e.g., [H. Draper] [1885] p. 273, where it is estimated that Thollon's carbon-bisulphide prism, "while giving seven-eighths as much dispersion as six flint prisms, gives four times the light in the entire spectrum and eight times the light in the region near G."

(57) Cf. the anecdote reported by Mills and Brooke [1936] p. 25: "I remember that for our first trials we had one of the hollow prisms filled with bisulfide of carbon so much in use then, and which in consequence of a small leak smelt abominably. To this day this pungent odour reminds me of star spectra!"

(58) See. e.g., Young [1869], [1870]. and Warner [1968] pp. 49, and 64; Huggins [1868*a*-*c*], [1876] as well as here § 8.8, and Evershed [1909/10], [1913] and Hentschel [1998*a*] § 7.4–7.5, 10.2 there.

(59) See, e.g., [H. Draper] [1885] pp. 272f. for a description of the problem and Draper's countermeasures: installing a small propeller wheel inside the fluid prism to keep the liquid in constant agitation, and a thermostat to regulate the temperature of the liquid within ±0.1°C.

(60) See, e.g., Gibbs [1863], [1870] pp. 50–2, Gassiot [1863], Cooke [1865*b*] (who had ordered a chain of nine such fluid prisms from Alvan Clark in 1863), and Roscoe [1868*a*] p. 384.

(61) On the historical roots of this technique, going back to Abbé Nollet's 'microscope solaire et lanterne magique' in the eighteenth century see, e.g., Grandeau [1863*a*] part III: 'projections des spectres', Niewenglowski [1910] chap. 1; cf. also Bennett in Abney [1900] pp. 46–53 on how to make photographic lantern slides. Use of these devices in teaching of spectroscopy is discussed here on p. 397.

(62) See Foucault [1849], [1878] pp. 170–2 and Duboscq [1850]. A clear illustration of Foucault's regulator is also published in Schellen [1870/72*b*], p. 48.

(63) The son of a cobbler was an apprentice to the instrument maker J.B.F. Soleil. Becoming his son-in-law, he later took over the shop in 1849, directing one branch of Soleil up to 1883: see Brenni [1996]. Duboscq was awarded medals for his scientific instruments at the International Exhibitions in London 1852, in Paris 1855, and a gold medal in 1856; he was an elected member of the Légion d'Honneur.

(64) See Debray [1862], [1869], Miller [1855*a*] p. 153, Roscoe [1868*a*] p. 387, Queen [undated], Stein [1887] pp. 236–57, Welford and Sturmey [1888], Syndicat [1901] pp. 189, 216, 218f., as well Warner [1992] for other manufacturers esp. in the US.

(65) See, e.g., Browning [1874] pp. 14–15, 24f., [1878] pp. 34ff., E.C. Pickering [1874/76*c*] vol. II, pp. 250ff.

(66) The library of the Harvard/Smithsonian Center for Astrophysics, for instance, has an—incomplete—set of Higgs's photographic map of the solar spectrum on such microscope slides.

(67) Demarçay [1895] vol. *Texte*, p. 1; cf., *idem*, pp. 11f.

(68) See H. Draper [1873*b*] p. 402. On Cornu's use of the Oberhauser projection method, see below, p. 134.

(69) After his baccalaureate in Douai in 1856, Mascart taught as maître répétiteur at a lycée in Lille and in Douai. In 1858 he entered the École Normale in 1858, where he earned his 'docteur és sciences' in 1864. From 1861 to 1864 he was préparateur at the École Normale Supérieure, thereafter again teaching at various secondary schools in Metz and Versailles. From 1878 on, he was director of the Bureau centrale météorologique, and in 1872 he took the chair formerly occupied by Regnault at the Collége de France, where he had already been lecturing as professeur suppléant since 1868. He was furthermore a member of the Paris Academy of Sciences since 1884 (succeeding Jamin), becoming its vice president in 1903 and president in 1904. Cf., e.g., [Mascart] [1872], Janet [1909], Mascart's personal dossier (AASP), and his file for various promotions in the Légion d'Honneur (ANP. Léonore LI774034).

(70) For a contemporary survey of the spectral transmission of various types of glass and other materials see Eder and Valenta[1895].

(71) See [Mascart] [1872] p. 4. Since gelatino-bromide plates were not yet available, Mascart only had at his disposal dry collodion plates sensitized with silver iodide.

(72) See, *ibid*., p. 4: “The best drawings then available of this spectrum accounted for less than 80 lines and their positions had not been determined precisely.” Cf. the enclosure letter to his plate submission to the Paris Academy on 9 November 1863 in his personal dossier (AASP), which is nearly identical in wording to Mascart [1863*c*].

(73) See, e.g., Cooke [1865*a*], Lorscheid [1868*b*] pp. 105–10 as well as Grandeau [1863*a*] pp. 60–70, or Novák [1905/06]. In Philadelphia, James W. Queen & Co., soon also provided a ‘spectroscope for projection’: see Queen [undated]. According to Smart [1962], James Q. Queen (1815–1890) is first listed in the Philadelphia directory for 1839 as an optician. In 1860 he became associated with Samuel L. Fox and the firm became James W. Queen & Co. For a number of years there was a branch office in New York City. After his retirement, the business was continued as James W. Queen & Co. until 1893, when it was incorporated as Queen & Co.

(74) See, e.g., Lorscheid [1868*b*] p. 109: “The experiments just described, which are interesting to the extent that they can be performed before a large audience, are not to be compared, however, with the precise results one obtains with the standard spectroscope. They give an adequate idea of the importance and sensitivity of this method to those persons not intending to specialize in spectral analysis.” Cf. also Cooke [1865*a*] p. 243: “a simple and efficient method of exhibiting the phenomena to an audience”.

(75) See the ‘Notes explanatory and critical on the plates’ in Smyth [1882*d*] p. 7.

(76) See James W.L. Glaisher to C.P. Smyth, 22 May 1882 (ROE, 14.66, folder G). Cf. Smyth’s draft replies to Glaisher, dated 23 May and 27 April 1882: “As to the older authorities given in the plates & notes,- the prime object of the paper was to ‘review’ them, and how is the result of revision to appear if they are to be entirely left out; seeming to think they have never been brought together before; and that in the places where they have separately appeared serve of their labour under a vicious system of representation, which if excusable in their day, is not so now, and which I have therefore corrected in principles that I think will be found both true and easy for everyone to apply in future.”

(77) All spectrum plates in Smyth [1882*d*] were reproduced as photolithographs, but the title page bearing one of Smyth's landscape pencil sketches was 'woodbury-typed' from the original drawing—cf. also J.B. Johnston to Smyth, 16 August 1882 on Woodbury-type as "certainly the best mode of reproducing a drawing, where there are a number of shades." For the "photo-like reproduction, finishing paper and printing" of the 17 spectrum plates in 500 copies each, Johnston estimated costs of £25, 18s; for 300 copies the price would have fallen to £22, 9s and 9d. See the letter of 26 June 1882 (also in ROE, 14.66). For the last chromolithographed plate, "Colours, on spectrum principles", Smyth engaged "Messrs Johnston at my private expense throughout last winter to prepare the colour-system on them under my own eye [… until] after immeasurable alterations I thought their work possible"; draft of Smyth to Glaisher, 27 April 1882 (ROE, 14.66, folder G).

(78) See A. Hassen, Wainwright Brewery, St. Louis to C.P. Smyth, 30 December 1885 (ROE, 15.70, folder H).

(79) Smyth [1882*d*], pp. 6–7, original emphasis.

(80) *Ibid*., p.7.

(81) *Ibid*.; cf. here p. 127 for commentary on the drastic change in line width and intensity of line 2 in Fig. 3.4.

(82) According to Brown [1912], Hennessey joined the Trigonometrical Survey in 1844, was designated its deputy superintendent in 1869, superintendent in 1874, and deputy surveyor-general in 1883. During a leave of absence in 1863–65, he learned the new process of photozincography at the Ordnance Survey Office in Southampton, and established this process at the Indian headquarters, for rapid reproduction of their maps and survey sheets.

(83) Hennessey [1870] p. 4. Cf. also Hennessey [1875] p. 160 and pl. 25 for another map by the same observer, which differed in some details in the extreme red to D.

(84) Hennessey received three compound prisms made by the Dublin instrument maker Howard Grubb, at the behest of the Secretary or Council of the Royal Society. For a scathing criticism of the resulting plate which, nevertheless, ultimately supports the substantial funding of Hennessey's observations by the Royal Society, see Smyth [1882*d*] pp. 3, and 7, where poor Hennessey is charged with having missed "the true nature and construction of A's preliminary band […] to a degree that can only be relegated to the days long before both Professor Kirchhoff and Sir David Brewster, though really so much later."

(85) G. Müller [1881] p. 85; cf. H.C. Vogel [1879] and here p. 82.

(86) See, e.g., G. Müller [1916], Ludendorff [1925], R. Müller [1925], and Hermann [1974]; cf. also Einstein's letter to Hugo Andres Krüss of 10 January 1918, in which he criticizes the Potsdam tradition of mediocre talents ultimately achieving the highest positions in the institutional hierarchy of observers just by sitting out at their posts: *Collected Papers of Albert Einstein*, vol. 8 (1998), doc. 435, p. 605 (Engl. trans. p. 441).

(87) See Janssen [1862/63], [1871], [1888]; cf. also Cornu [1879], [1880], [1890], de la Baume Pluvinel [1908], Levy [1973] and Aubin (in prep.).

(88) See here Fig. 3.5, and compare it with the intentionally much cruder reproduction of Brewster's map by the same engraver, reproduced here on p. 114. Cf. also Smyth [1871*b*] p. Rl18 and [1877*c*] p. 44 on "M. Janssen's copper-plate engraved solar spectrum from C to D, one of the most carefully observed and beautifully engraved spectral drawings ever produced".

(89) Janssen [1871] p. 291. For similar statements, see Cornu [1883*b*] p. 61 and Smyth [1884/87].

(90) See Swan [1853/57*b*] and Masson [1845–55*c*], who actually concluded that he had found four brilliant lines common to all eight metallic elements he had analyzed spectroscopically. Cf. Gissing [1910] p. 21: "in all spark photographs of spectra, the lines due to air will show, and in most cases the sodium lines also will be present".

(91) For a brief survey with emphasis on the instrument market for rainband spectroscopes, see Austin [1993] and Peterson [1993].

(92) Brewster and Gladstone [1860], original emphasis, and their fig. 7 (also reproduced in smaller scale in Schellen [1870/72*b*] p. 254). See also Brewster [1833/34*a*], [1836] pp. 391f., Smyth [1871*b*] and Janssen [1882] pp. 885f. for accounts of the various historical contributions to this strand of research.

(93) Cooke studied at Harvard College from 1845–48, spent one year in Europe, especially in Regnault's laboratory in Paris, and then became instructor of mathematics. From 1850 he was professor of chemistry and mineralogy at his alma mater, where he instituted the first practical laboratory course. See Richards [1894]. Cf. also here p. 92 on his expertise in fluid prisms, and p. 377 on his great impact in teaching experimental methods.

(94) See Cooke [1866], Janssen [1866], [1862/63], [1865], CM. Smith [1875]. and Smyth [1858c] pp. 503ff. pl. XXXV, [1877*b*] p. 29.

(95) See Janssen [1862], Hofmann [1874], [1867] pp. 3, 208 where the date May 1863 is cited for Hofmann’s construction of the pocket spectroscope; for further details about Hofmann’s workshop, which was located at Rue de Buci no. 3 in Paris and later at Rue Bertrand no. 29, see Warner [1993] pp. 40f., Aubin (in prep.) and a collection of materials at Boston Public Library, call no. 7920A.25.

(96) Mill [1883*b*] p. 48.

(97) See Smyth [1877*b*] p. 30, [1880*a*] p. 195; cf., e.g., [1881], [1882] as well as Capron [1881], Cory [1883*b*], written for the Royal Meteorological Society, [1888], and Upton [1883], written for the US Signal Service.

(98) According to Capron [1886] p. 14 and his letter to C.P. Smyth, 2 January 1882 (ROE, 14.66, folder C), the London-based instrument maker John Browning had asked to reprint Capron [1881] as a brochure that was to be sent to any potential customer of his optical devices for four stamps. Other books include Mill [1883*b*], commissioned by the instrument maker A. Hilger whose pocket spectroscopes are recommended in it on p. 7, and Cory [1884], [1887].

(99) For instance, on 11 September 1877, Hilger in London, wrote an enthusiastic letter to Smyth, reporting about his clients’ and his own progress in recognizing the rainband, culminating in the hope that “every man shall have a Pocket-Spectroscope (ought to be of me) and Barometers of quicksilver will be out of use.” John Wood, optician and mathematical instrument manufacturer in Liverpool, likewise consulted Smyth for more detailed instructions on technical improvements, in response to numerous inquiries about the rainband spectroscopes. Negretti & Zambra in London solicited permission to reprint Smyth’s article in *Nature* to satisfy their clients’ interest in the matter (both ROE, 15.67).

(100) See Smyth [1882*a*], [1882*b*] p. 552 vs. Abercromby [1882], and the transcripts of the debates in Cory [1888] pp. 89–92, [1884] pp. 50–86, which is a reprint of various letters to the London *Times* in September 1882, and Cory [1883*b*] pp. 239–40.

(101) Cf. also Smyth [1858*c*] pl. XXXV and [1877*d*] pl. i, [1878a] p. 95 for similar examples of such a comparative map, and Smyth [1882*b*] p. 553 and Upton [1883] pl. 1 for more detailed charts of the rainband region with and without the bands. Further examples of this representational technique of comparative mapping will be discussed in § 8.7–8.8 within the research contexts of quantitative chemistry and stellar spectroscopy.

(102) Because this other spectral band varied with the height of the Sun above the horizon, Smyth [1880*a*] p. 195 called it the ‘low-sun band’. Likewise, Mill [1883*b*] p. 48 notes that “the nebulous line between the yellow and green is usually mistaken for the rainband at first, for it varies in intensity from time to time.”

(103) *Ibid.* Cf. also Piazzi Smyth’s Notebook ‘Great Spectroscope of 1876 … employed at LISBON on Sun-spectroscopy, July 1877’ (ROE, 18.105), entry under August and September 1877 for the astounding “variations of prism power on the rain-band near D”. These comparative plots of a single spectrum region under similar, optimal weather conditions, with just the prism exchanged, show how important the quality of the spectroscope prism was in being able to recognize the rainband. Smyth himself came to the conclusion that “in an Observatory, these small non-measuring spectroscopes should not be used even for the Meteorology of rain-bands; but a form of our present great spectroscopes with a prism of white flint, with small dispersion angle, but large size.” *Idem*, entry on 4 September 1876.

(104) Mill [1883*b*] pp. 48f.; cf. there pp. l0ff., and Smyth [1875*a*] p. 232 on the “abnormal intensification of D (or rather of some peculiar telluric lines so very near D as not to be separable from it in so small a spectroscope).”

(105) All quotes from Capron [1886] p. 11. He even conceded that his own statistics might also be affected by this problem of correctly gauging intensities.

(106) See *ibid.*, p. 12.

(107) Mill [1883*b*] p. 9.

(108) See, for instance, Smyth [1877*d*] (i) for his most dramatic report of rainfall forecasts during a steam-boat trip from Liverpool to Lisbon in 1877.

(109) See the letters to the London *Times* by Smyth [1882*a*], Abercrombie [1882], and the Duke of Argyle, all of which are reprinted in Cory [1884]; cf. the further literature mentioned in Mill [1883*b*] pp. 29ff., and Capron [1886] pp. 14–16. Cf. also Capron to Smyth, 8 October 1880 (ROE, 14.64, folder C): “The 6th [of October] gave a good example of the “rainband’. It was strong in the morning and we had a regular downpour en suite.”

(110) Mill [1883*b*] p. 49; cf. also Cory [1884] p. 23: “the use of a mental scale […] cannot be considered infallible”.

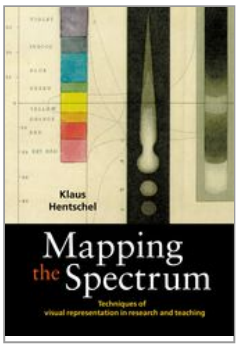
(111) Colonel G.E. Bulger to C.P.Smyth, 11 October 1880 (ROE, 14.64. folder B).

(112) See Mill [1883*b*] pp. 18ff., 50ff., Cook [1883], and Bell [1885]. Cook's method was inspired by the techniques used in Janssen [1871] to map the atmospheric lines, while Bell's developed the photometric methods of Gouy [1879], [1880]. Another method is suggested by Cornu [1883*b*].

(113) Hazen [1884] p. 209; likewise, Upton [1883] p. 5 also emphasizes that "satisfactory observations can be secured only by a skillful observer".

(114) The observers Mill [1883*b*], Bell [1885], and Upton [1883] allegedly had a 75–80 % success rate in predicting rainfall and had similarly good results in predicting dry spells from the absence of the rainband: see their respective tables and correlation charts. On the decline of rainband spectroscopy around 1890 see Peterson [1993] p. 95.

(115) Cf. also Pang [1997*a*] p. 191 for a quote from James Keeler's review of several recent lunar atlases: "Each atlas has, therefore, its own special value. The Paris atlas will be eminently useful for consultation in its place on the library table; the Lick Observatory atlas will find its chief use in the hand of the observer at the telescope."



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
Prof. Dr. Klaus Hentschel

Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

Line Matters

Klaus Hentschel

DOI:10.1093/acprof:oso/9780198509530.003.0004

Abstract and Keywords

Starting with the older techniques of copper engraving and etching, this chapter examines the radical impact of new techniques such as lithography, color lithography on up to six different stones. Woodcuts and other more schematic and symbolic techniques of recording spectra as well as the art of spectrum portraiture practiced by specialized draughtsmen are documented.

Keywords: engraving, etching, lithography, color lithography, woodcuts, spectrum portraiture, draughtsmen

A graphic representation inevitably emphasizes some features while neglecting others as irrelevant or atypical. Spectral maps, however, are governed not only by the observer's purposes but also by the particular printing technique chosen for such 'line matter'—to borrow the lithographer's term. Many competing techniques were available in the late 1870s, for example. They can be classified into three main categories:[1]

- relief printing (e.g., woodcuts),
- intaglio (e.g., copper or steel engraving and most early forms of photomechanical techniques—see here § 5.2), and
- lithography or other types of planographic or surface printing.

But the choice of any one of these techniques imposes certain constraints on the resulting print. While each has its inherent advantages, its own “potentiality for illusion”, it also has its specific limitations. Lithography, for instance, rendered halftones far better than intaglio prints. In particular, it provided the option of dispensing with the troublesome engraving techniques (such as cross-hatching) so laden with their own ‘syntax’ that the original is essentially ‘translated’ into their ‘language’.[2] Also, lithographs could be printed on dry paper and were cheaper than steel engravings, but high runs of the order of 1000 copies usually caused the stone to deteriorate perceptibly. Photomechanical reproduction techniques, in turn, programmatically promised to dispense altogether with intervention by artisans. But in reality, at that time the results were still far inferior to either lithographs or engravings of better quality.[3] In the following I introduce and contrast the different available techniques as I discuss the specific problem of adequately rendering spectral line intensities and band spectra.

4.1 Engraving and etching

In **copper engraving**, a technique known approximately since 1420, some variation in line intensity is provided by applying different amounts of pressure to the metallic burin or graver (cf. Fig. 4.1). It has its limits, though, because a single thick and solid line can cause too much ink to collect at one spot and make a mess during the intaglio printing process. Moreover, the lines in copper engravings are easily recognizable from their irregular **(p.112)** outline, or *taille.* Hence this technique is intrinsically inappropriate for spectral drawings requiring lines of even width.[4]

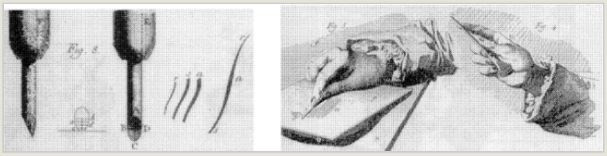


Fig. 4.1. Burin and its profile seen from two sides; resulting lines, and hand positioning for the ruling of lines in copper engraving. From Diderot’s *Encyclopédic* (1751) plates I, fig. 8, and **III,** figs. 4–5 of the section *Gravure en taille-douce.*

Another technique that was occasionally used in the early years of the study of the spectrum is **metal relief etching,**[5] whereby a polished metallic surface (usually a steel plate) is evenly coated with a mixture of heated wax, resin, and tar. The actual drawing involves scratching through the coating with a sharp steel-pointed needle to expose the metal. The plate is then washed in acid, which eats away at the exposed metal without affecting the coated areas. The resulting plate may be used for printing similar to a copper engraving. The lines on such a cold-needle etching are symmetrically shaped, and their profiles are u-shaped rather than v-shaped (cf. Fig. 4.2).

Fig. 4.2. Comparison of line profiles in engraving and etching. Left: engraved line and its profile, right: etched profile and resulting line.

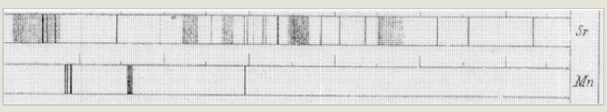
Because the waxed surface offers little resistance and the hand does not have to push the needle forward but guides it like in ordinary writing and drawing, it can render the draughtsman's intentions much more spontaneously than a copper engraving. Thus, according to one collector of imprints:

> The etched line is the only really truly even one. When finely drawn, it lends inimitable grace, matchless vitality. Broadly etched, it gains the character of monumental importance, of weighty force, unrivalled by anything else. The etched line is the line *par excellence*, and the etching is the ideal of black-and-white art.[6]

(p.113) The much more regular lines in **steel engraving** made it unsuitable for most artistic purposes. It was only chosen where this feature was either irrelevant or specifically sought. Diagrams of scientific instruments, graphs of mathematical functions, or schematic drawings of zoological specimens are some examples. In other words, it was a suitable technique for the majority of plates in the *Philosophical Magazine* or transactions of scientific societies of the mid-nineteenth century.

As in copperplate engraving, though, a pattern of crossed lines must serve for shading. The many how-to manuals I have seen usually recommend that such 'cross-hatched' lines not be at right angles. Its density determines the shade of gray produced in the print. Another technique used is 'stippling', which is the process of producing dots, either with what is called a 'point' (a sharp etching needle) for individual dots, or with a 'rocker' (a toothed plate) as a means of uniform shading. A 'roulette' is used to produce a series of short equal lines, or unequal strokes ('nibbling') to depict rough surfaces like tree bark.[7]

When William Huggins published his survey of the spark spectra of 24 different elements in 1864, the technique of steel engraving was chosen, presumably because highest priority was attached to conveying the accurate relative positions of the lines and bands in the spectra. But this choice had its drawbacks, as Fig. 4.3 reveals:



In a note about the two plates accompanying his paper, Huggins admitted:

Fig. 4.3. Shading details of the Srand Mn spectra. Steel engraving by J. Basire. From Huggins [1864*a*] pl. X.

> the spectra, as engraved, appear too faint. If great force had been given to the lines, by making them broader, they would, in several spectra, have occupied singly the space in which two or more lines have to be laid down. This deficiency in strength of some of the lines is more appreciated by the eye, in consequence of the shortness of the lines of the spectra […] In some of the spectra bands of unresolved light occur; these, in the Plates, are crossed with lines that they may be distinguished from groups of fine lines.[8]

Huggins's choice of this traditional technique, despite its deficiencies, is understandable when we consider that he and the chemist William A. Miller had compiled this data on spark spectra merely in preparation for studying stellar spectra, which is what they were really interested in.[9]

(p.114) The inherent limitations of shading by cross-hatching or stippling[10] is quite obvious in two other examples dating from 1851 and 1871: E. Wormser's drypoint engraving of Masson's nine tableaus of metallic spark spectra shows the dense line patterns used to depict the CO and CN bands in the blue and green regions—but this way of drawing them, all parallel to each other, inadvertently also makes these bands look much more intense than all the other lines in the spectrum. You can try to avoid this effect by choosing a constant tiny line interstice for all shaded areas supposed to signify unresolvable regions of high line density, adding another system of crossed lines with variable line distances to produce different shades of gray in the bands. However, as the area marked δ in the following redrawing of Brewster and Gladstone's map of 1860 shows (Fig. 4.4), the resulting pattern looks somewhat uneven and improvised:

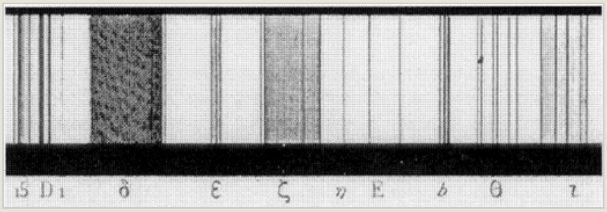


Fig. 4.4. Technique of cross-hatching to render different shades of gray. Steel engraving by E. Pérot. From Janssen [1871] pl. I, fig. 1.

Compared with Fig. 3.5 (on p. 102) by the same engraver, Ernest Jules Pérot[11], Fig. 4.4 is coarsely cross-hatched to signify the relatively primitive character of Brewster and Gladstone's map. In juxtaposition, Janssen's 1871 high-resolution map is engraved almost microscopically finely, with very frugal use of cross-hatching.

One could, of course, dispense with this second system of crossed lines altogether and just use very close vertical lines. But that representational convention inhered another ambiguity: did the map imply separate lines, perhaps just barely resolvable ones, or did it just mean to represent a relatively dark area of a very broad spectrum line? When Charles Piazzi Smyth examined various published spectrum maps in the early 1880s before undertaking to map the solar spectrum himself, he became increasingly irritated by the way in which engraver shading techniques broke his self-imposed rule that vertical lines be used exclusively to represent spectrum lines:

> Every modern spectrum being represented with its length horizontal, the important dark and so-called Fraunhofer lines therein are all necessarily vertical. When they are thick, black lines, they can, or should, be mistaken for nothing else; but when **(p.115)** they are sometimes thin, pale, and close together, they may very often be confounded with certain other vertically ruled lines, wherewith engravers so generally like to express shaded surface. Or, again, the latter kind of mechanical lines may be mistaken for the former optical ones, so as to be often misinterpreted, for an intention by the observer concerned, to assert that he had actually resolved what was, to other spectro-scopists, a single, into a double or treble, line; or a mere cloudy, shaded space, into many distinct, sharp, independent Fraunhofer lines: a falsity of the most reprehensible and mischievous kind.[12]

He likewise criticized the way in which Fraunhofer's line 'little c' had been engraved in the solar spectrum map by the Brussels astronomer Charles Fievez, as a "rare example with M Fievez of the bad method of vertical ruled thin lines to expreβ mere haze."[13] Consequently, Piazzi Smyth decided to adopt the following conventions for his own Winchester spectrum map, the first of which was specifically directed at eliminating this ambiguity of vertical lines, once and for all:[14]

> 1. A vertical line always stands for a veritable, seen and measured spectroscopic line or image of the slit, and for nothing else under the Sun.
> 2. Lines in any other direction than vertical, whether horizontal, or slanting at any angle and from either side are to be interpreted as nebulous shade only in vertical bars or bands at the place.
> 3. Greater or less [*sic*] height or depth, either of lines or of shaded bands, is intended to typify greater or less intensity of darkness and visibility of such lines or bands.
> 4. Cones of shade arranged on a vertical central axis indicate nebulous bands shaded off towards either side very gradually and delicately.

The last convention was especially needed at either end of the visible spectrum where the bright continuous background fades away, so the Fraunhofer lines no longer stand out as clear dark lines as they do in the middle range of the spectrum.

One of Piazzi Smyth's American correspondents concurred emphatically. His letter reveals the frustration caused by these ambiguities in line engraved spectrum maps:

> I am entirely with you (and can hardly understand that anyone can be otherwise) in your denunciation of the old-fashioned way of publishing spectral maps. I have myself often come across places where a doubt as to the nature of an apparent close aggregation of lines entered my mind – leaving one unsettled as to whether the author intended these parallel rulings for a dense band or merely to simulate the appearance of a gradual darkening of the space on either side of a thick line as the same is approached […] to the eye when viewed at a moderate distance.[15]
>
> **(p.116)**

Unfortunately, Piazzi Smyth's symbolic techniques of representation never quite became common practice among spectroscopists of his time, and so the uncertainties in interpreting spectra engraved in the second half of the nineteenth century persisted. Looking back at the beginning of that century, we appreciate even more the incredible skill with which the 'amateur' Fraunhofer had chosen a much less ambiguous mode of representation for his famous map of the solar spectrum in 1814 discussed above on p. 34ff. Not even its later revisions, made between 1823 and 1831, could reproduce the intricate way in which Fraunhofer managed to convey the brilliance of the yellow–green region of the spectrum against its violet and red ends. Fraunhofer had carefully etched the map, timing the corrosion of each trace in proportion to the intensity of the respective spectrum line. A bill that I found among the Fraunhofer papers in Berlin (see here Table 5.4 on p. 170, last line), reveals that for the black-and-white version of his map, to be published in the Memoirs of the Bavarian academy of sciences, he asked an unnamed printer to superimpose an Indian-ink wash on this etching to intensify the impression of darkness towards both ends of the visible spectrum (cf. Fig. 4.5); I have not seen this done in such sophistication on any other nineteenth-century spectrum plate. The resulting intensity gradient in Fraunhofer's map is so even that more than one print expert consulted mistook it for an aquatint. In that technique, named for its ability to imitate watercolor wash, powdered resin is dusted onto the polished plate in an amount appropriate for the halftone desired. Once a sufficiently smooth gradient has been achieved, the grains are fixed to the plate by careful heating. The fine dusting produces an exquisite chiaroscuro. This technique had been known already in the mid-seventeenth century but fell into obscurity again until its revival between 1770 and 1830, when it became particularly popular for landscape motifs.[16]

A contemporary of Fraunhofer, Baden Powell, confirms this unique quality of Fraunhofer's plate in a side remark to his report on refractions of the solar spectrum for the British Association for the Advancement of Science in 1839:

(p.117)

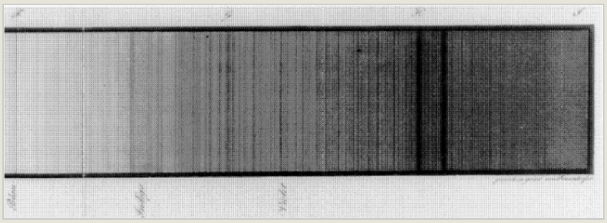


Fig. 4.5. Detail of Fraunhofer's spectrum map. Etching with an ink wash for the background shading. The text at the bottom right corner means 'drawn and etched by Fraunhofer'. From Fraunhofer [1815*a*] pl. 2.

> Among the larger maps of the spectrum, that in the Edinburgh Encyclopædia […] is professionally copied from Fraunhofer's, which is given in Schumacher's Journal […], and this, taken from that in the Munich Transactions […] This last appears to me superior in delicacy of representation, conveying by shading (which is by no means so good in Schumacher's print) an idea of the relative intensity of the different parts of the spectrum. Both preserve admirably the varied characters of the several groups of lines, and present a faithful picture of the actual object. All this, however, is almost entirely lost in the plate in the Edinburgh Encyclopædia, the execution of which is coarse, and the characters of the different bands ill preserved.[17]

In addition, a few handcolored versions of Fraunhofer's plate have been preserved.[18] But unlike the published plate of 1814, these color versions lack the Indian-ink wash of the shaded areas into the red and violet extremes of the spectrum, displaying instead the full range of colors in exquisitely subtle gradation: see color plate I. Whether or not this hand-coloring was done by Fraunhofer himself: These color plates indirectly also let us infer that the original illustration for the Munich memoirs was produced in a two-stage process: first a copper-etching of all the line matter such as labels, caption, and the curve, as well as the spectrum lines inside the box. Microscopic inspection of the spectrum lines with their different widths and intensities confirms that they were etched rather than engraved to guarantee evenness of line width as well as consistent variation in line intensity (i.e., depth of etched groove—cf. here Fig. 4.2 on p. 112 for a comparison with the *taille-douce* line profile). After this first printing stage was complete, the Indian-ink wash was added by hand. This involved two-stage procedure also explains the strange black frame enclosing Fraunhofer's solar spectrum—a feature absent in other spectrum representations. The fairly thick frame gave the printer a few millimeters leeway in positioning a screen protecting the areas outside it, so that he could then apply the Indian-ink liberally to guarantee a smoother gradient in the spectrum strip itself at the center. The ink-wash stage, which made the final result more expensive, was omitted for the few sheets destined to be hand-colored, as well as in the later reprinting for the *Astronomische Nachrichten*, where a French translation of Fraunhofer's paper appeared in 1823. The size, labels, and overall print quality reveal that it was printed off the same plate as the original version. The only difference to the Munich version is French translations of the color designations, which were added in parentheses.

Another quite efficient method for obtaining shadings is the **roulette technique.** The roulette was often used to make regular patterns with a distinct dark termination at one end that loses intensity towards the other end, such as occur in band spectra. The little metal wheel attached to a handle has evenly spaced grooves of the desired width and fineness along its rim (cf. Fig. 4.6 left). Fine examples of this technique are found in Lecoq de **(p.118)** Boisbaudran's atlas of luminous spectra from 1874.[19] The right half of Fig. 4.6 details one plate with the typical regular imprint produced by a roulette drawn along a ruler positioned parallel to the spectrum line.

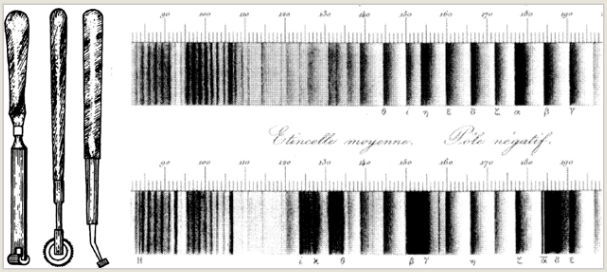


Fig. 4.6. Engraver's roulette (*left*) and sample use of the roulette technique in an atlas of band spectra (*right*). Engraving by Dulos. From Lecoq de Boisbaudran [1874] pl. 1.

Because Lecoq de Boisbaudran applied for the 1872 Prix Bordin awarded by the Paris Académie des Sciences, a gold medal worth 3000 francs, we are fortunate to have more complete documentation of the pre-publication versions of his atlas. Lecoq de Boisbaudran submitted seven 18-cm-long pencil sketches of each spectrum, as observed with his low-dispersion single-prism spectroscope. Figure 4.7 shows that he drew the spectrum lines and bands against a preprinted millimeter scale, carefully representing the width of the spectral features with the flat side of the pencil lead and varying the amount of pressure exerted to produce various shades of gray.

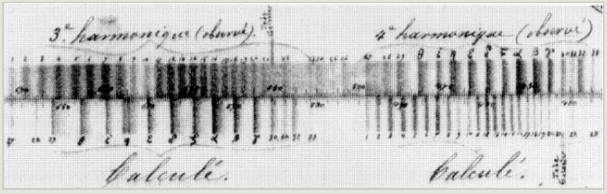


Fig. 4.7. Lecoq de Boisbaudran's pencil sketch of the band spectrum of air and nitrogen, near the positive pole. From AASP, file 'Prix Bordin 1872', sketch no. 6, reproduced by permission.

(p.119) As will be further discussed on p. 309, unlike the published version, many of these drawings include comparisons of his observations against spectral bands calculated under the assumption of an harmonic overtone structure. For, the Bordin prize had been offered for "analytical or experimental research that will have contributed the most toward establishing the theory of spectral lines", not for simple observation. However, as his accompanying text specified,

> the present work is solely observation and experimentation, it is completely independent of my theoretical researches on the constitution of luminous spectra. […] My goal being to facilitate for chemists the spectral analysis of principle mineral substances, […] I likewise sought to reproduce as exactly as possible the various spectral features: sharp or diffuse lines, shaded bands to the right or left, etc., etc. The lines are not represented as simple strokes except in a secondary scale graduated proportionally to wavelength and designed to facilitate rapid comparisons between spectroscopes of different dispersions.[20]

In the same letter, Lecoq claimed that the engraving of his drawings had been started five years previously, but it is not clear whether we may believe this, notwithstanding the conscientious effort invested in his spectroscopic portraiture (cf. also § 4.5 below).

4.2 Lithography

Lithography (literally: writing on stone, *Steindruck* as it was called shortly after its invention, or polyautography, as it was sometimes called in the Anglosaxon world) was invented in the closing years of the eighteenth century by Aloys Senefelder (1771–1834) in Munich.[21] In the earliest phase it was mostly praised as a cheap and comfortable technique for reproducing documents and prints generated by other techniques.[22] But with the appearance of detailed and practical technical guides around 1818, it became more generally accepted as a full-fledged alternative to copper engraving and etching.[23] Lithography freed engravers from earlier laborious shading techniques—although it did not eliminate them completely—and eventually replaced copper engraving as the favorite technique of nineteenth-century graphic artists. Paradoxically, early technical expositions, such as **(p.120)** Charles Joseph Hullmandel's (1789–1850) *The Art of Drawing on Stone*,[24] expose the extent to which techniques from copper and drypoint engraving like cross-hatching and stippling were also used in early lithography, even though the new technique offered quite different options. In one of the first publications on lithographic printing, the author praised not only its efficiency but also its ability to *imitate* other printing techniques such as woodcut or copper engraving.[25] As one historian of lithography put it:

> While lithography was setting itself up as a rival process to copper-engraving it was only natural that it should borrow some of its techniques from the established medium, but this influence probably lasted longer than it might otherwise have done owing to the technical limitations of the new process. When it was first invented lithography was hailed as a method of multiplying the pen or chalk drawing of any amateur. This was later found to be true only with certain reservations.[26]

Despite the greater simplicity of the new technique, one and a half decades elapsed before it was first applied to scientific illustration (foremost in anatomy and medicine). One reason for this shy debut was its reputation as a cheap medium in which the individual artisan's style and temper found greater expression. Copper engraving, by contrast, was regarded as 'incorruptible'.[27] In 1822 the editor of the *American Journal of Science* still considered lithography merely as an auxiliary, not a rival technique. He could not imagine it ever replacing the well-established and refined copper engraving, which "must still retain the preeminence which it possesses."[28]

In relief and intaglio methods, the physical contours of the printing face produce the motif. Lithography, however, is the first and most important method of planographic printing. It is essentially based on the mutual repulsion of water and grease and on the attraction of either of the two substances to their like or to a common porous ground, which is why lithography was sometimes also called 'chemical printing' (*chemische Druckerey*). The drawing is made by tracing grease onto the polished surface of a very fine-grained slab of argillaceous limestone.[29] Diluted ink is painted on with a brush, or drawn with a lithographic pen or crow-quill.[30] Alternatively, special crayons are used, as long as the color contains enough grease to repel water from the drawing surface. When the drawing is finished, the stone is washed with a mixture of twenty parts water and one part nitric acid to clean the remaining surfaces and to remove residual traces of grease. After a series of additional preparatory steps that involve gum arabic to prevent the grease from spreading, **(p.121)** the actual print is achieved by applying printer's ink, which is also greasy, to the whole surface—all parts impregnated with grease during the drawing stage soak in the ink, the other water-saturated parts do not. Thus it is possible to draw on a stone like on a piece of paper and then reproduce this drawing several hundred, even a couple of thousand times over. After the printing on a specially designed extrusion press is completed, the lithographic stone is repolished in preparation for the next drawing. Repeated use of the same slab is limited only by its overall thickness, which may not be less than about an inch in order to withstand the high pressures of the printing process.

The draughtsman could choose to use pen and ink, crayon or chalk, or other implements of variable width and hardness. The finely grained surface of the lithographic stone effects a microscopic pattern of dots of the appropriate width and density (see Fig. 4.8).[31]

Strictly speaking, it was not even necessary to write or draw on the stone directly. One could choose to draw on paper with any of the above-mentioned greasy inks, and then transfer the drawing onto the stone by contact pressure. This transfer method was rarely used for spectroscopic maps, though, because of the inevitable loss in overall intensity.[32] One straightforward procedure (as described by H.C. Vogel in 1879) is to take pens of different nib thickness or crayons of different hardness for each class of line intensity. Traditionally, lithographic draughtsmen used three different crayons, which allowed them to distinguish between at least three degrees of intensity. All observed details, fixed on a scale of visually estimated intensity and gauged in terms of line width, consequently had to be reduced to the finite number of lithographic intensity grades available.[33]

The spectroscopist's requirements for variation in line width and strength often well exceeded such a simple tripartite division, however. The intensity scales typically ranged between 1 and 6, but sometimes they could go as high as 9 or even 14 as, for instance, in the case of the solar map at medium and low altitudes made at the Edinburgh Royal Observatory in 1890 (cf. here p. 266). But when this map was finally printed photolithographically at about one-fourth the size of the original drawings, problems arose because the faintest lines came out as only intermittent traces: "It will be noticed that the faintest lines are far from continuous in the lithographs, but as it was found impracticable to make good this defect without altering the breadth of the lines, they are left untouched."[34]

Others experimented with pens specially designed to draw virtually continuously variable widths (cf. Fig. 4.9). Two pointed blades of metal joined by a milled-head screw form a double nib that holds the ink by capillary attraction. The separation of the two blades can be finely adjusted to produce lines of different breadths.

(p.122)

H.C. Vogel was one spectroscopist who preferred the flexibility such pens afforded over a fixed set of nib widths: “The lines were drawn in accordance with the breadth estimates using a ruling pen that had a regulating screw equipped with a scale. Weak lines have been drawn 2/3 the width of the spectral stripe, very faint ones 1/3.”[35] But there was also contemporary grumbling about the faultiness of drawing pens: “the nibs being so fine and weak that they partially close, and produce uneven lines by the pressure necessary to be **(p. 123)** used against the guiding edge.”[36] A ‘Mathematical Instrument Maker to H.M. Government, Science and Art Department’ described the gestural knowledge needed to draw with pens:

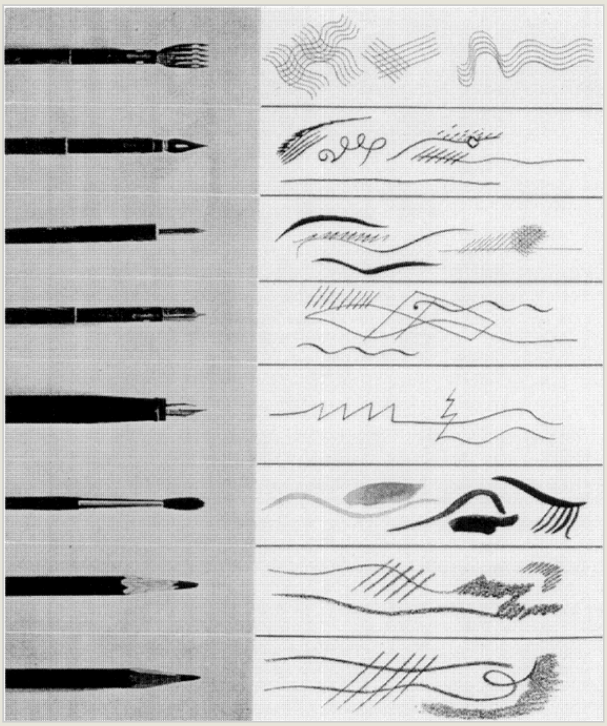


Fig. 4.8. Lithographic line patterns drawn with various implements. Counting from the top, 1: five-pronged pen, 2: waverly pen, 3: crow-quill pen, 4: relief nib, 5: waterman fountain pen, 6: hair watercolor brush, 7: conté crayon, 8: negro pencil. From Havinden [1933] p. 19.

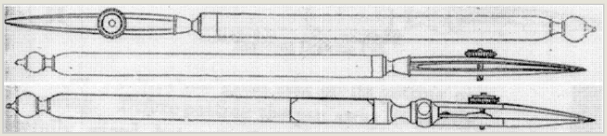


Fig. 4.9. Two different types of drawing pens. *Top:* Simple fine drawing pen seen from above and from the side; *bottom:* improved model with lifting-nib made entirely of steel, and forming a lifting-spring in itself. From Stanley [1866*b*] pp. 7, 9.

> In using a drawing pen of any kind, it should be held very nearly upright, between the thumb and first and second fingers, the knuckles being bent, so that it may be held at right angles with the length of the hand. The handle should incline only a very little—say ten degrees. No ink should be used except Indian ink, which should be rubbed up fresh every day upon a clean palette […] The ink should be moderately thick, so that the pen when slightly shaken, will retain it a fifth of an inch up the nibs. The pen is supplied by breathing between the nibs before immersion in the ink, or by means of a small camel-hair brush; the nibs will afterwards require to be wiped, to prevent the ink going upon the edge of the instrument to be drawing against. […] Before putting the pen away, it should be carefully wiped between the nibs by drawing a piece of folded paper through them until they are dry and clean.[37]

Irrespective of the amount of effort spent on the drawings, the published plates were generally pale and did not adequately reproduce the very fine visual differentiation in spectrum line intensity. Thus, within the scope of monochromatic prints, the observer's wishes were rather crossed than met at the printing stage.

In principle it was, of course, possible to color in black-and-white prints by hand. We have already mentioned Fraunhofer's plate, where this was done for a few choice copies (cf. here p. 117). For more than a handful of spectrum representations, however, following this procedure would have been practically impossible. In the early nineteenth century, coloring in by hand was a relatively frequent—albeit quite expensive—practice in higher-end artisan production.[38] Unless one was satisfied with a coarse indication such as on Hunt's plate from 1844 (see here Fig. 2.30, p. 68 and the dust-jacket illustration), for spectrum illustration it would normally not suffice simply to fill in clearly designated areas with a **(p.124)** few colors (somewhat like painting sets still popular today, where the hobbyist fills in the motif by matching color to preprinted number). The illusion of smooth transitions between the rainbow of colors had to be created while strictly respecting the color regions of the various spectrum lines.

Listing chose another option for his illustration from 1867 of the boundaries between the seven primary colors in the spectrum: *Irisdruck*, or iris printing. This technique produces a plate in full color from just two stones: one for the black-and-white line matter, and one called the tone plate. First the color imprint was made. Using the leather pad, the printer applied the different color inks in place directly on the stone, producing a sequence of stripes on the sheet, which the press would fuse into relatively smooth continuous color transitions. The black contour lines were then printed on top. Because the location and intensity of each color depended entirely on the printer's initial distribution of the various inks (typically blue, yellow, and red) on the tone plate, and on the exact amount of pressure exerted during the printing, Listing had to supervise the printing of every single sheet personally. Among the inherent limitations of this method was that the color boundaries were often not precisely aligned with the spectrum lines, but slightly askew (a good example for this defect is shown in color plate II-top). Nevertheless, Listing seems to have been quite pleased with the result: "I think that representing spectra chromatically truer to Nature by means of this iridotype affords a better result than has been achieved by earlier, in part quite costly reproductions."[39] But evidently, this was not a practicable procedure for higher runs. I was unable to track down a copy of the original plate, one of which Listing submitted to the Göttingen Academy of Sciences. But a smaller-scale version of it appeared in the *Annalen der Physik* in the following year,[40] printed at the Lithographisches Institut in Berlin. Since the *Annalen* were normally printed by Barth in Leipzig, this shows that iris printing was a highly specialized procedure. This plate was executed in Berlin by the "academic artist" Albert Schütze[41] (1827–1908), who had also stone engraved Mitscherlich's plate of various composite spectra in 1864 (see here Fig. 2.23 on p. 53) and the color plates in the German translation of Secchi's *Le Soleil* in 1872.[42]

4.3 Prints on more than one stone

Greater variation in line intensity and appearance as well as a more reliable rendering of the spectral colors could only be gained by printing the plate in a number of successive **(p.125)** runs off more than two stones. Chromolithography, as this process was called, became a specialty of German printers.[43] It played a considerable role in successfully disseminating knowledge in various other scientific disciplines as well, particularly in pathological anatomy.[44] Each plate of Gustav Kirchhoff's map of 1861 underwent six different impressions in different inks to render six intensity grades and seven different line widths. This degree of involvement approached the "printing in many plates", in eight or more layers, of turn-of-the-century chromolithography.[45]

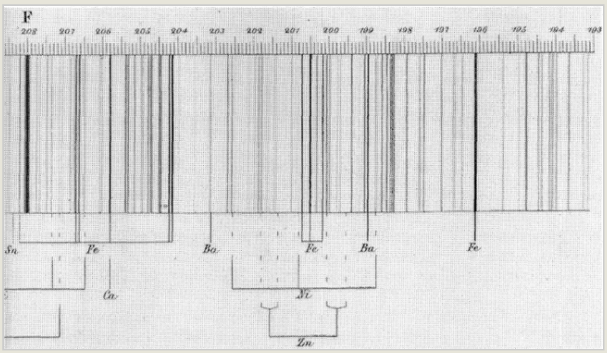


Fig. 4.10. Sample section of Kirchhoff's map of the solar spectrum from 1861, printed on six different stones using various inks from green and violet to black, and distinguishing seven different line widths. Chromolithograph by C. Laue. From Kirchhoff [1861/62*a*] pl. II, enlarged segment around Fraunhofer's line F.

Small segments of Kirchhoff's spectrum map are reproduced in Fig. 4.10 in black and white, and in Plate III (bottom) in color. The first stone, with the faintest, barely visible lines, was assigned a very pale ocre, and the last stone, on which only the most prominent lines were drawn, was inked with jet black. In-between were different shades of green, olive, brown, and violet. This sequence of printing from bright to dark tones was important because the latter fully covered the former, thus conforming to a viewer's expectations, who **(p.126)** is accustomed to seeing color as coloration, that is, as a filler of a circumscribed area. An inverted sequence would have reduced the vibrancy of the darker inks.[46] Another important element of the lithographer's trade was making a suitable choice of inks, which added significantly to the aesthetic appeal of the final result.[47] Kirchhoff's finished map certainly presents a much broader variation in line intensity and width, which is the main reason why it remained in use long after his arbitrary scale had become obsolete.[48] The lithograph was of such high quality that when an English translation of Kirchhoff's memoir appeared in 1862, the editor decided to reprint the maps from the same stones used for the original publication: "Impressions of the same maps, which are exact copies of Professor Kirchhoff's drawings, and masterpieces of lithographic art, have been secured for the English edition, and this will, therefore, resemble in every detail the German text."[49] These original stones were not available for the French translation, however. The editors of the *Annales de Chimie et de Physique* consequently had to take great pains to assure an adequate re-rendering of the fine gradations between the different line intensities. They commissioned one of their most specialized technical engravers, Pierre E.S. Dulos, to reproduce the plates with his recently invented *procédé Dulos.* This chemical printing technique did not have to resort to the usual engraving syntax for shading, such as cross-hatching, or closely lying parallel lines—which are so easily mistaken for unresolved spectrum bands.[50]

It was owing to the great care taken in the printing of Kirchhoff's plates that Dulos's map was received with such enthusiasm: as one reviewer wrote in 1862: "Just as the astronomer must have his charts and catalogues of stars in order that he may identify objects known to former observers, and interpolate his own discoveries, so the spectrum-observer must have this map of the spectrum at his elbow."[51]

This intricate sequence of printings on a single sheet to produce the spectral strips had its disadvantages, though. For one, Kirchhoff had to admit that the printed copies were not uniform; nor was the positioning of all the lines always totally accurate—all too often, one or several of the stones were slightly shifted relative to the others during printing. "The plates […] are printed with ink of six different tints from six different stones. Owing to mechanical difficulties it was found to be impossible to effect a complete coincidence between the separate copies and the original."[52] Slight displacements are also clearly visible in the color prints of Bunsen's map of terrestrial emission spectra. The dark background was printed on top of the colored layers—sometimes this black stripe was slightly off, so **(p.127)** that the colored layers beneath protrude at the margin. Not that this minor fault damaged the overall effect or hampered use of these maps in any way,[53] since one could always refer to the associated tables to get the precise wavelengths. But it shows once more the inherent limitations of the contemporary printing technology. Another disadvantage was less striking to the normal contemporary user of Kirchhoff's map but became bothersome much later in comparisons against spectrum maps drawn at a much higher dispersion (cf. here § 3.2). When Piazzi Smyth tried to magnify Kirchhoff's map to the scale of the most advanced spectrum representations of the early 1880s (see here Fig. 3.4, esp. line 2), he noticed that its depiction of the fine structure of spectral band Great A was "sadly disfigured and perverted out of its rhythmical symmetry by the abrupt steps of gradation from one tint-stone to another."[54] Hence this attempt at a naturalistic representation of the general aspect of the spectrum came at the cost of line-width accuracy. Consequently, for precision spectroscopy, there was a considerable advantage to printing off a single stone and in one run. Neither artificial relative displacements of some lines nor unintended changes in their relative line intensities could occur during the duplication stage. So spectroscopists were faced with difficult choices.

In close parallel to this Bunsen–Kirchhoff paradigm, one student of Bunsen in Heidelberg, the Swiss chemist Rudolph Theodor Simmler also opted for a multiple-stone printing for the plate in his dissertation of 1861. In illustrating the color characteristics of the spectra of various metals, the spectrum of copper, with its three different shades of green, proved particularly problematic to represent. To bring out the different tints in the print Simmler chose so-called Schweinfurt green as the basic color for the middle range of the spectrum and superimposed blue on the one side to get blue-green, and yellow on the other to get yellowish green. He also needed a stone for the red region, so there were four in all. But even after all this fuss, he had to admit that the result was but a poor approximation of the original's brilliance.[55]

Similar disappointment with the depiction of certain "peculiar bright lines" was expressed a few years later by Julius Plücker (1801–1868) in a paper about the spectra of ignited gases and vapors.[56] This was despite the fact that the lithographer had been of his own careful choosing, namely Aimé (Constant Fidele) Henry[57] (1801–1875) in Bonn. Well-known for his botanical illustrations of fungi, buds, and poisonous plants, some of **(p.128)** Henry's work appeared with his own descriptions and comments as separate books at his lithographic publishing house Henry & Cohen. Many other illustrations of his were published in the reputed *Acta* of the German Academy of Natural Sciences, the Leopoldina.[58] His vital role in the production of the Academy's publications eventually led to his nomination as honorary member and librarian. He was also an active member of the Botanischer Verein am Mittel- und Niederrhein and the Naturhistorischer Verein der Preu²Fischen Rhein-lande und Westfalens, and recipient of honors by various other naturalist organizations—he was thus clearly an illustrator of distinction.

This reputed expert in chromolithography used ten lithographic stones for a single color plate, in an attempt to convey the impressive range of colors in the various band spectra under examination.[59] When the German lithographer submitted his estimate for these plates, Stokes apparently tried to negotiate a cost reduction by limiting the number of stones for the colored plate, but the printing expert remained firm. Plücker then had to tell Stokes: "With respect to the reduction of price I have seen Henry on the subject who says, he cannot use a smaller number of stones (after all I saw in his laboratory I think he is right) and indeed as an artist and a merchant he would not like to have an incomplete or ill done work published in England."[60]

Aside from monetary considerations, a master lithographer such as was Aimé Henry, evidently also had to guard his reputation: He may well have considered this order for 1025 color plates, plus another two normal black-and-white engravings, as a golden opportunity to expand his printing and publishing business into the affluent London market. In that case he would not want to compromise on quality.[61] Other chromolithographed plates by A. Henry (mostly of botanical subjects) suggest that this amount of work was nothing unusual for him: he specialized in color plates, for which many inks were needed for but a single detail.[62] Not surprisingly, it also took much longer than estimated to complete the printing: In December 1864, Plücker and Stokes seemed to have thought the whole thing would be **(p.129)** over within three months. The exchange of the proofs and then the actual printing both took longer than expected, however, and in late March 1865 Plücker still had to beg Stokes to be patient for two or three more months.[63]

In a highly interesting article on 'Astronomical Drawing', Lady Margaret Lindsay Huggins admitted that "increased sensitiveness to variations in colour is no doubt promoted by the use of the spectroscope."[64] The epitome of this fixation on color is a contemporary chromolithography for Charles Piazzi Smyth's paper on 'Colour, in Practical Astronomy, Spectroscopically Examined'. Its third plate presents "25 very distinct and recoverable colours, with seven variations in degree of each". The 25 main colors were each printed off a separate stone, and screens of different densities were used to apply the seven tints: "lightest, lighter, light colour, full colour, dark colour, darker, darkest", which range from dilute to full color with black added to render the darker shades. The color terms Piazzi assigned to his 15 "pure, natural and original solar-spectrum colours" also reflect the subtlety of his palette: "ultra-red, crimson-red, red, scarlet, orange" in the Red group, "amber, yellow, citron, green, glaucous" in the Middle group, and "blue, indigo, violet, lavender, grey" in the Violet.[65] To these 'single-spectrum colours' were supplemented five color samples obtained by superposing two of the elementary prismatic colors, and another five examples of a "triple spectrum, very impure or artificially much mixed colours", all again in seven different degrees of intensity.

The process involving successive prints off different stones had to be carefully supervised, particularly to assure the precise positioning of the sheet on each stone. Usually marker pinholes were made at its four corners immediately before printing off the first stone. It then had to be taken out of the frame to let the ink dry. When it was remounted for the next impression, the pins affixed to the wooden frame of the printing press were fed through the same holes.[66] Despite such precautions, the number of misprints during the production of chromolithographed plates must have been considerable. Furthermore, as the Plucker example has just shown, unforeseeable delays must have been endemic to the process, so less costly and faster alternatives were sought. Piazzi Smyth opted for the following compromise: His three series of spectrum observations made at Winchester in 1884 were printed on paper with a preprinted stripe in one of 12 lithographic tints representing the various color regions of the solar spectrum. These 60 double-quarto plates for the *Transactions of the Royal Society of Edinburgh* were conventional photolithographs originally drawn with the help of assistants at the Edinburgh Royal Observatory, most notably **(p.130)** Thomas Heath.[67] Even though these charts could not portray the continuous change in spectral colors, each range was able to give at least an approximation of how the region might look when observed through the spectroscope. Symbolic recording of a spectral region against an associated scale could not capture the uniqueness of each spectrum, however. Piazzi Smyth avers: “no matter what strange, artificial and human devised scale any one may have been using he must also, if an observer, have had Nature’s inimitably beautiful and effective general indexing of the spectrum placed by colour before his eyes again and again; till those colours must, if he has a soul, have been impressed involuntarily and indelibly, on the tablets of his heart in thankful admiration of God’s glorious Creation.”[68]

4.4 Woodcuts and symbolic representations of spectra

Another possibility was to sacrifice color altogether and employ other means of representation. As we have already seen (on p. 52), Bunsen suggested a more symbolic coding of comparative line intensities, using the second (vertical) dimension on spectral plates. The length of a spectral line symbolized its intensity, while the shape of its tip (sharp or rounded) indicated the line’s profile.[69]

This technique became widespread, particularly for the mapping of laboratory absorption spectra at low-to-medium dispersions. A related intensity notation was developed by H.W. Vogel and other photochemists in their search for sensitizers of orthochromatic emulsions. Their relative sensitivities in a specific spectral region were symbolized by different degrees of shading superimposed on a numerical scale running from 2000 to 7000 Å.[70]

Piazzi Smyth also deviated from spectrum representation “in the literal method”, which attempts to mimic in black and white what can be seen in the spectroscope’s viewing field. He resorted to “a symbolic manner, wherein degrees of light are represented, not by degrees of black shade, but by height or quantity of a uniform shading—a far easier, more accurate, and practical method than the literal one, though not so acceptable to the public in general.”[71] As Piazzi Smyth describes, at both extremities of his Winchester spectrum of 1884, he drew diagonally dashed shaded areas

> running along the lower side of the otherwise white horizontal strip, and gradually rising in it as the spectral light falls; until, when that ceases any longer to be visible, the black shade has risen to the top of the horizontal white strip, and eclipses it from that place onwards. Hence at any intervening point between the full height of the white **(p.131)** strip near the middle of the spectrum, and its final extinction at either end, readers may judge of the degradation of the light, by the comparative heights of the black shade below and the white paper above it; or they may imag[in]e the sort of grey that would be produced over the full height of the strip, by smearing upwards, though but approximately, the amount of black contained in that part which is so coloured by the shade below.[72]

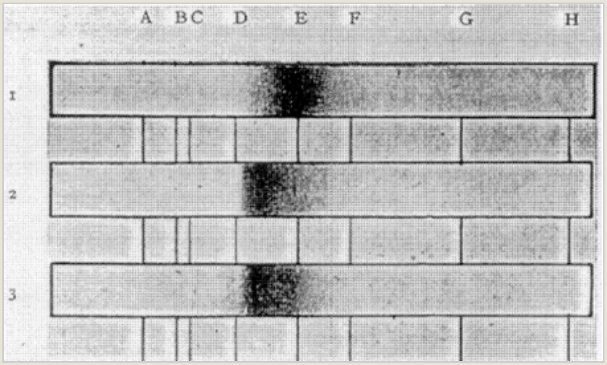


Fig. 4.11. A symbolic notation for the spectral sensitivity of three collodion emulsions, sensitized with (1) eosine, (2) erythrosine, and (3) rose bengal; capital letters at the top signify the positions of the main Fraunhofer lines. From H.O. Klein [1910] pl. III.

A loose sheet found in one of Piazzi Smyth’s notebooks nicely summarizes his main ideas. It was probably written for his assistant Thomas Heath, who actually prepared the final version of his spectrum maps for publication, to explain the convention of using the length of the spectrum line to represent its intensity on a scale ranging from 0.1 to 10. Lines greater than intensity 4 were drawn in full length but differing in thickness, lines between intensity 1 and 4 were shortened by up to one third, and lines below 1, lost up to two thirds of their length. Bands were always drawn in halftone, with diagonal shading lines (never vertical ones!) added where necessary.

(p.132) A graphic device opposite to the ones seen thus far was introduced in the mid-1860s. For a series of metallic emission spectra, white emission lines were depicted on a black background. Simply scratching away a uniform coating of printer's ink on the stone surface, in the manner of a scraped lithograph *(lithographe à manière noire)*,[73] created an adequate result. The even more basic traditional woodcut or its refined variant wood engraving—which made it possible to render textures and tonal values—were another alternative.[74] Given the comparative ease with which the printing block could be made and inserted into text, it is surprising that this format was not used more often, but I could track down only a few isolated examples of such woodcut diagrams.[75] More challenging than line intensity were other special features like the occasional emission line among the dark Fraunhofer lines or variations in the background continuous spectrum.

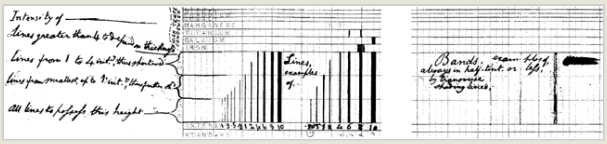


Fig. 4.12. Piazzi Smyth's conventions for the representation of spectral line intensity. From C. Piazzi Smyth's notebook (ROE, 18.113), loose sheet; undated, but post 1878, because it is drawn on a sheet presumably printed in preparation for the final drawing of the Lisbon spectrum map of 1877–78. By permission of the ROE Library and Archive.

> On good, correctly exposed negative plates, the space between the bright (in reality dark) lines does not appear uniformly black at all but displays striking differences in intensity. Some places give the impression that bright series of lines of exceptional fineness were weakening the darkness of the spectral base; other places, however, do not give even the slightest hint of line series and distinct, dark lines appear to be lying on the matt dark base. I had already noticed these dark lines, which would correspond to bright lines in the solar spectrum, on the more successful first exposures, and have been giving them special attention from the beginning. On the plates, spots in the spectrum that appeared conspicuously dark, and at the same time stripy, have been specially marked with dotted lines and little rings.[76]

Unobtrusive use of special symbols outside the general codex of representation can be found in other spectral atlases as well:[77] e.g., pointers in X-ray photographs or indices to capture special features that can only be inferred, for want of adequate iconographic means.

4.5 Spectroscopic portraiture

What representational techniques were used and which features were emphasized in first attempts to map new spectral regions? The case of the experimentalist Marie Alfred Cornu (1841–1902), professor at the École Polytechnique in Paris,[78] is of interest in this regard. When he published his ultraviolet extensions of Ångström's normal solar spectrum in 1874 and 1880, he was quite explicit about his objectives: to map the ultraviolet region up to the **(p.133)** limit of atmospheric absorption, that is, well into the uncharted range, in a mode of representation and at a resolution similar to Ångström's map of the visible spectrum.[79] Unlike Ångström, Cornu could not simply rely on micrometric measurements of directly observed line intervals, because the part of the spectrum he was studying was not in the visible range. He was compelled to use bromo-iodized collodion plates as a means of detection,[80] even though the resulting photographs were much inferior in quality to his final lithographed map. Because his predecessor, E. Mascart, had been working with glass optics, he had not advanced further than the line W at 3441.1 Å. Taking this into consideration, Cornu employed quartz and Iceland spar prisms and could thus extend his results up to line W at 2948.4 Å. His best photographs were made with a prism of Iceland spar, but unfortunately the dispersion n[λ] for prisms of this material was not known for this wavelength region. So Cornu had to gauge the photographs, as well as those obtained with a flint-glass prism, by means of a Nobert grating. Although the grating could not approach the resolution reached in Ångström's map, Cornu was able to determine the normal wavelength of 36 strong lines in the ultraviolet range. This set of reference lines then served as a gauging scale for the other lines in-between, which were determined by graphical interpolation. The actual drawing of the plate, at a scale of 1 centimeter = 1 millionth of a millimeter, proceeded as follows.[81] First, using a dividing engine, Cornu drew a fine grid of millimeter lines onto a piece of Bristol cardboard—the standard millimeter graph paper available was presumably too coarse for his purposes. Next he drew onto this grid the 36 strong lines determined with the Nobert grating. The other lines detected with the quartz- and islandic spar prism-spectroscope were then entered in-between these reference lines by interpolation. Cornu admitted that initially he had planned to determine all line positions on the photographs micrometrically but had abandoned this idea for two reasons: (i) The number of lines to be drawn was so great that it was not possible to identify them all unequivocally.[82] (ii) Even if this had been possible, the resulting precision would have been illusory: one cannot expect an accuracy of more than 0.05 Å of absolute wavelength, because it was a matter of no more than half a millimeter in a drawing on this scale. Instead he concentrated on accurately depicting the general appearance of each segment as could be inspected without strain after a magnification of 25 × to 100 ×. He thought that

> it was much more worthwhile to devote all my attention to reproducing the *aspect* or *effect* of each group of lines rather than to the absolute positioning of each individual one of them: in a word, that an error in the relative intervals within a group was much more detrimental than an equal displacement of the group as a whole.[83]

(p.134) This scale of enlargement for such ‘close-ups’ was obtained either by using a microscope with a magnification factor of 25–100 and a micrometrically ruled platform, or by employing Oberhäuser’s projection method,[84] whereby the photographic image is magnified by projection onto a white sheet of paper, somewhat similar to a modern slide projector. For the finest details Cornu first enlarged the photographic negative 12–25 times, and then repeated the above steps of microscopic and projective magnification. He ended up with a total length for his spectrum region between h and O of up to 3 meters, yielding an impressive 12 cm for the 35 Å interval between the H and K lines, and thus an average dispersion *R/L* of 3 Å/cm. Evidently, as already mentioned, the relative line distances seen on the correspondingly huge projection screens could not be transferred immediately to a sketch of the normal spectrum, because they had been generated by prisms of various refractions. Cornu drew an empirical dispersion curve for both prisms by comparing the positions of the 36 strong lines in the prismatic spectra with their positions in the normal diffraction-grating spectrum. An average curve between these points on a two-dimensional graph ($n_{\text{prism type}}$ as a function of the wavelength λ) then gave the gauging curve for interpolation of all the spectrum lines between the 36 markers.

In his drawings Cornu could use various inks to differentiate the line intensities, as well as fainter washes of Indian ink to indicate diffuser line contours or general darkening of the continous background spectrum. For the printed map, however, the engravers had to resort to the full arsenal of devices available to their colorless medium to render these intensity variations.[85] The result was one of the finest maps of the solar spectrum ever published in the nineteenth century.[86] Despite the high density of lines, this copper engraving brings out the microscopic spacing variations, shading of the continuous background, and many different grades of line intensity, ranging from the very bold to the barely visible (Fig. 4.13).

(p.135) Cornu’s map is thus a good example of a representation aimed at reproducing the overall aspect, the *Gestalt* (i.e., first and foremost, the collective appearance of the relative line groupings) rather than attaining the highest accuracy in the absolute placement of each individual line. The argument in favor of this preference of the subjective *effet* over objective *précision* constitutes the purpose of Cornu’s map: it was primarily intended as a visual guide, as a means of orientation for other researchers who, like Hartley and Adeney in Dublin, or Liveing and Dewar in Cambridge, were merely interested in the approximate positions of prominent lines in metallic ultraviolet spectra for purposes of chemical identification. With a research objective tuned to *Gestalt* recognition, Cornu’s focus in the following quote on the general *aspect* or likeness of spectroscopic lines and their groupings is by no means surprising:

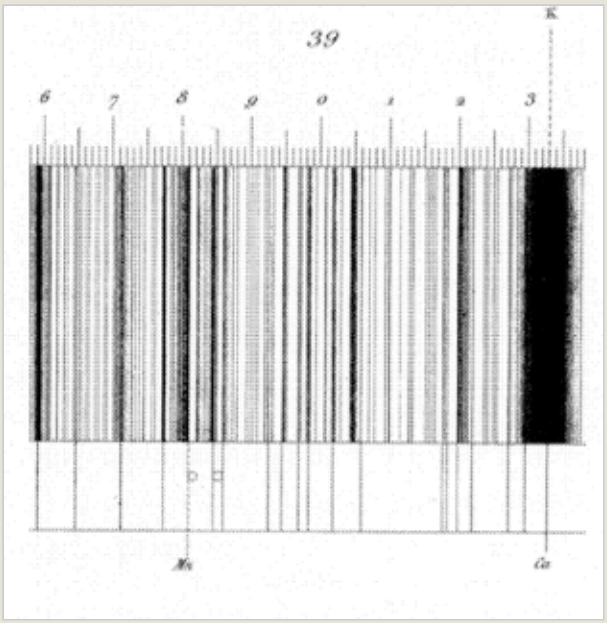


Fig. 4.13. Small section from Cornu’s map of the near-ultraviolet region of the solar spectrum around 3900 Å with the calcium K line to the right. The circles indicate brilliant lines which decreased in intensity between 1871 and 1872. Copper engraving by Dulos and Legros. From Cornu [1874/80*a*] pl. I.

> Apart from looking for the most reasonable classification of the lines, I sought to represent the general aspect of the groups as faithfully as I possibly could, in order to help physicists establish this concordance, which is of such capital importance in spectroscopic investigations. […]
>
> I began with the initial task of conveying the *effect* of the groups, either by intensifying the color of the ink, or by using a wash to represent blurred lines or regions with a darker background.[87]

Now one might argue that this spectroscopic ‘portraiture’, as this mode of representing the idiosyncratic features of each line might be called, is an exaggerated aberration. However, such a ‘feel’ for individual spectrum lines was evidently quite widespread and it was only consistent to search for subtle means of capturing such hardly quantifiable features. As a case in point, this is what Arthur Schuster wrote to a fellow spectroscopist about a particular blue line in the oxygen spectrum: “I have been often puzzled about that blue line. As you no doubt also have noticed there is an individuality about lines of a spectrum, which makes you feel, even without proof, which do and which do not belong together.”[88] The recipient of this letter himself had earlier lavished praise on certain “gigantic, as well as numerous thinner lines, all of them sharp-edged and well-defined, […] with almost a personality, in their most marked physiognomies”.[89] As we shall see in § 8.2, this perceptiveness toward line physiognomies and family resemblances among line groupings actually proved to be quite important in the search for series formulas, because it provided a selection criterion for matching groups of lines for incorporation into numerical or geometrical algorithms linking their respective wave numbers or wavelengths.[90]

As Ångström’s map served as a templet for Cornu, so did Cornu’s serve as a model for Louis Thollon.[91] (1829–1887). Thollon too proposed to sketch, with the best possible likeness, **(p.136)** the “physiognomy” of each group of spectral lines.[92] For his lithograph portrait—for which he was awarded the Prix Lalande in 1885 by the Parisian Académie des Sciences[93]—an increase in the spectroscope’s resolving power was crucial. In the late 1870s Thollon worked on fine-tuning his direct-vision spectroscope accordingly by means of an intricate multi-prism arrangement for minimizing the total angle of deviation while maximizing the dispersion.[94] His first arrangement from 1878, which employed eight glass prisms, attained an angle of 30° between the Fraunhofer lines B and H. After six-fold enlargement of this spectrum, it had a length of over one meter.[95] In the following year Thollon switched to a combination of two crown-glass prisms p and p_1 (index of refraction: 1.55, 80°) and one fluid prism p_2, filled with a mixture of ether and carbon bisulphide carefully prepared to have the same index of refraction as the glass prisms, and mounted as in Fig. 4.14:

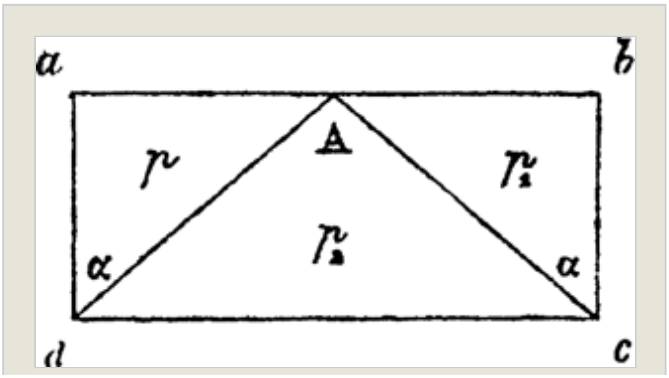


Fig. 4.14. Thollon's second prism setup for his spectrograph: block arrangement of two crown-glass prisms and one fluid prism. From Thollon [1880*b*] p. 751.

Because the prisms were positioned face to face without any air gap and were of the same index of refraction, this arrangement had considerably less loss of light from reflection. Reflection losses were now limited to the two sides *ad* and *bc*.[96] These new types of composite prisms thus had a clear advantage over both simple-prism and conventional direct-vision spectroscopes by generating less total angular deviation than the former and more dispersion than the latter. Translated into figures, while a conventional 60° flint-glass prism produces an angular distance of c. 20″ between the two sodium D lines, and a single carbon-bisulphide prism perhaps 45″, his new composite prism attained no less than 2'. When his Parisian optician and precision instrument maker Léon Louis Laurent[97] (* 1840) assembled **(p.137)** two such block prisms into a prototype direct-vision spectroscope, Thollon first realized what enormous dispersions were now within grasp: 12″ between the two D lines, equivalent to a prism chain of 16 carbon-bisulphide prisms or 30 glass prisms with a refractive index of 1.63.[98]

Thollon also developed a device that allowed him to record the details of the thus generated spectra far more efficiently. As shown in the foreground of Fig. 4.16, the entire prism block could be reoriented by turning a micrometric screw that was coupled to a rotatable platen carrying a long scroll of paper. While the observer focused on a spectral line by turning the micrometer screw V with his left hand, he could let a pencil trace a line on the paper by releasing lever M with his right hand whenever the line was coincident with a reference line in the center of his field of view in telescope O. Working from one end of the spectrum to the other, all the line intervals could be registered sequentially on the paper scroll, according to a scale chosen by means of the transmission gears between the micrometer and the scroll.[99]

Thus far, all of Thollon's developmental work on the spectroscope had been conducted in Paris in the physical laboratories of the Sorbonne, the École Normale, and the Collège de France. The next stage of his research project, a mapping of the full visible portion of the solar spectrum at this unprecedented dispersion, could not be carried out in the French capital, however, for the simple reason of weather conditions. For the greater part of 1879 Thollon worked in the private observatory of Prince Nicolas d'Oldenbourg in San Remo, Italy. "Aided, it is true, by the fine Italian Sun," as well as by his ingeniously contrived apparatus, he finished within less than three months a 10–15 meter-long drawing of the solar spectrum with approximately 4000 spectrum lines between A and H.[100] This map was presented to the Paris Academy of Sciences in late 1879 but was never published because, meanwhile, Thollon had embarked on an even more ambitious mapping project at the newly founded Observatoire de Nice.[101] Thollon had already had some dealings with that observatory as scientific consultant for its spectroscopic equipment. This prestigious site, with which France hoped to compete against the new observatories in Potsdam and Strasbourg, was where Thollon set his four prisms, two of them high-dispersion carbon-bisulphide prisms, in a special mounting that guided the light twice through each prism.

This arrangement yielded a dispersion of 700″ (or 30 mm on the map) between the two yellow sodium D lines, the optimum attainable with prism chains because of the significant loss in light intensity to each prism along the optical path. Only the big Rowland concave gratings (and later interferometric measurements) could achieve even higher resolutions.[102] **(p.138)** Because of the strong temperature dependency of his bisulphide-of-carbon fluid prisms, Thollon secured a constant ambient temperature by having water circulate within the table on which the spectroscope was mounted, and additionally by enclosing the whole instrumental setup (shown in Fig. 4.16) within a double-walled metal box suspended from the ceiling.[103]

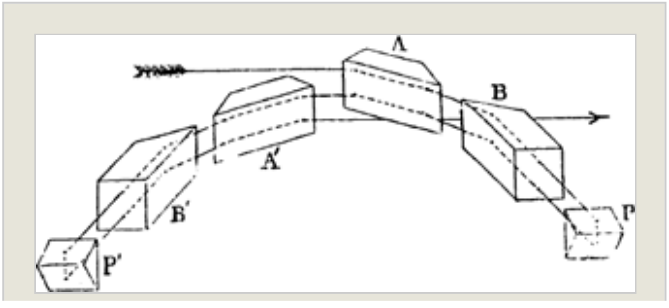


Fig. 4.15. Thollon's final spectroscope design: prism chain with four semi-prisms A, B, A′, and B′, and two normal prisms P and P′, forming the light path: A ′ B → P → B → A → A′ → B′ → P′ → B′ → A′. From Guébhard [1879] p. 225.

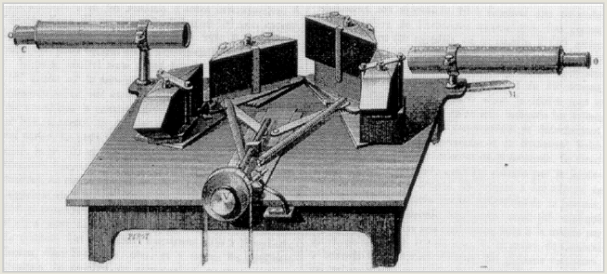


Fig. 4.16. Thollon's final experimental setup: prism chain with four semi-prisms (cf. the previous diagram) and two normal prisms, which reverse the path of the light coming from the collimator C at the far left; the observation telescope O can be seen to the far right. Turning the micrometer screw V changes the total dispersion while automatically readjusting all prisms in the position of minimum deflection. On the registering device in the foreground, see the main text. Engraving by Pérot. From Guebhard [1879] p. 224.

In a half-decade of assiduous labor, Thollon mapped 3448 lines in roughly one half of the optical part of the spectrum from the visible red to the middle green (from 7600 Å to 5100 Å), "with all possible fidelity, so that when looking alternately at the spectrum and at my drawings it is everywhere very easy to orientate oneself and to find all the details."[104]

(p.139) Unfortunately, he died before his *opus magnum* was finished, which was eventually published in 1890 at the expense of Raphaël Bischoffsheim, the financier of the Nice Observatory.[105] One decade later, Eugène Spée, who tried to continue along this vein by publishing an extension of Thollon's map from b to f, remarked:

> Thollon was both scholar and artist. […] An observer of rare precision and endowed with a remarkably skilled hand, he could reproduce the results of his observations with the truest accuracy. Struck, as he himself said, by the gaps revealed in the spectra published by his predecessors and contemporaries, and convinced of the importance and utility of a fine solar map, Thollon had conceived the grand project of doing, for the benefit of spectral analysis of the Sun, that which Argelander had realized for the study of the Sky, that is to say, of drawing a scaled spectrum in which, by the accuracy of their positionings and reliable reproduction of their external characteristics, all the lines would constitute secure enough fact that all those engaged in astrophysics could place upon it the greatest confidence.[106]

The increased resolution of his map was not the only feature with which Thollon tried to improve upon his forerunners. He gave a fourfold representation of the solar spectrum, with the Sun near the horizon; at 30°; in a normal and dry atmosphere; and finally, omitting the atmospheric lines altogether.[107] It was this feature that resulted in the continued use of his map, well after Rowland's photographic maps of the normal spectrum of 1886 and 1888 became available. The latter had dispersions of between 4.8 and 2.4 Å per cm, depicted nearly 20 000 Fraunhofer lines and were generally considered to be far superior to all foregoing lithographs.[108]

It is significant that both Cornu and Thollon were praised by their colleagues for their unique combination of scientific and artistic talent: "un savant doublé d'un artiste," as Spée put it. Thollon's beautiful drawings of the spectrum, which cost him six years of labor, plus another three for his engraver to transfer onto steel plates, marks the climax of the tradition of spectrum portraiture, which sought not only to plot the precise location of each spectral line, but also to portray "its thickness and blackness, and the character of its nebulous edges".[109]

Notes:

(1) See, e.g., Gascoigne [1986] § 1. Cf. also the critique of this standard taxonomy by Harris [1968]. who pleads for an alternative classification based on pairs of contrasting qualities used in forming the image (such as grease vs. water as the basis for all lithographic prints, light-sensitive vs. insensitive bases for all photographic processes).

(2) See, e.g., Hadon [1883] pp. 718f. According to Blanc [1874] p. 245, a good engraver ceases "to be a copyist to become a translator" who "translates truly into chiaro 'scuro the colouring of the picture": cf. *idem*, chap. II, and Jussim [1974] pp. 11 and 27ff. on a comparison of the 'syntax' of the major 'codes of prephotography'.

(3) See also Pang [1994/95] pp. 255ff. on the difficulty of choosing the right printing technique, for example, for representations of the solar corona during the transition period of the 1870s.

(4) On engraving *(gravure en taille-douce* in French, *Kupferstich* in German) see, e.g., Koschatzky [1975], pp. 96–8. On the history of engraving and etching in general see, e.g., Blanc [1874] chap. 2, Hind [1923] chaps. 1–2, 4–5, 7. The specific techniques of intaglio prints are explained, e.g., in Ripley and Dana [1871], Ziegler [1912*a*] vol. 1, pp. 13Off., Hill [1915] pp. 1–14, Gascoigne [1986] § 9–17.

(5) On the history of etching *(Radierung* in German, *gravure à l'eau forte* in French) see, e.g., Hind [1923] chaps. 3, 6, and 8, or Ziegler [1912*b*], vol. 1, pp. 13Off. For typical results see also Gascoigne [1986] § 10.

(6) Singer [1922] pp. 60f., quoted in Koschatzky [1975] p. 130.

(7) For examples see. e.g. Blanc [1874] part II, Ostroff [1969*a*] pp. 69ff. Jussim [1974] chap. 2. and here Fig. 4.6, p. 118.

(8) Huggins [1864*a*]p. 160.

(9) Huggins [1864*a*] p. 139: “for the purpose of accurately determining the position of the stellar lines, and their possible coincidences with some of the bright lines of the terrestrial elements”. Cf. here § 8.8.

(10) See, e.g., Hullmandel’s translation of Raucourt [1821], Smyth [1843/46*b*], pp. 71f., Ivins [1953*a*] pp. 51–70. Cf. also Goss [1993] pp. 222ff. on the use of hachures. parallel lines to indicate hill slopes, and three-dimensional effects in topographical maps.

(11) Unlike the unusually well-documented case of Dulos, I could find out only a few facts about Pérot: his address, Rue de Nesle no. 10, is listed in the Parisian *Didot-Bottins* for the 1870s and 1880s. See here footnote 35 on p. 147 in Chapter 5.

(12) Smyth [1882*d*] p. 6. On the transition from the vertical to the horizontal arrangement see here p. 45.

(13) See the box entitled “Fievez’ sun spectrum” (RSE material on loan to ROE) with 21 mounted spectral segments, cut out of Fievez’s [1883] plates by Charles Piazzi Smyth, with occasional marginalia. Quote from strip 17. On Fievez cf. here p. 83.

(14) These ‘general rules for the method of representation’ were printed verbatim under each of the 60 spectrum charts published in Smyth [1884/87]. For examples and further discussion of Smyth’s innovative, more symbolic techniques of representation, see here p. 99 and Fig. 4.12, p. 131 about the third convention.

(15) A. Hassen, Wainwright Brewery to C.P. Smyth, St. Louis, 30 December 1885 (ROE, 15.70).

(16) See Ostroff [1969] p. 69, Gascoigne [1986] § 17, and Ziegler [1912] pp. 190–201 for the most detailed description of the practical procedures, and Smyth [1841/46] for his praise of aquatint for astronomical illustrations (of comets). I am particularly grateful to the curator of prints at the Fogg Art Museum at Harvard, Marjorie Cohn, for having examined Fraunhofer’s original plate and discussing its various aspects with me in May 1997.

(17) Powell [1839] pp. 3–4. The three maps are Fraunhofer [1815*a*] pl. 2, fig. 5. [1823] pl. 2. fig. 6. and Brewster [1831*d*], pl. 433, fig. 16. Other reprints of Fraunhofer's map are to be found in E. Becquerel's [1842] plate, fig. 1. and in van der Willigen [1866], pl., fig. 1, the latter being the best redrawn reprint I have seen so I'ar.

(18) One of them is kept in the Goethe-Museum at Weimar (call no. GN 149F). It was sent to Goethe by Samuel Thomas von Soemmering in mid-March 1827 and is reproduced in Zehe [1990] p. 369. Cf. *idem*, p. 24 for an excerpt from Soemmering's letter: "So as not to appear with empty hands. I am enclosing a fully colored-in version of Fraunhofer's prismatic spectrum, because the prints found in the Munich Memoirs had been but ink-washed [*ausgetuscht*]" Another two hand-colored versions are kept at the DMM, map collection, and NL 14 (Fraunhofer), folder 52, obtained from the optical instrument company Sigismund Merz in the mid-1920s: see here color plate I.

(19) For contemporary applause of this atlas, which was printed by one of the outstanding engravers of the time see, e.g., Watts [1881] p. 318: "Very beautiful drawings of many of the ordinary spectra are given in Lecoq de Boisbaudran's *Spectres Lumineux*", or Twyman [1951] p. 34: "a series of twenty-eight beautifully reproduced plates".

(20) Lecoq de Boisbaudran, undated letter—before 1 June 1872 (AASP, file '1872 Prix Bordin').

(21) On the history of the terms, cf. Twyman [1970] pp. 3, 88, and Menz [1955] p. 12. According to the latter the term 'Lithographie' was introduced by the art and craft educator Joseph Mitterer (1764–1829) in 1805. According to more recent secondary literature, the discovery of lithography happened at the turn of the year 1798/99, whereas older literature still assumes 1796 or 1797. On its early history see, e.g., Senefelder [1818], Silliman [1822], Anon. [1874*b*], E.R. and J. Pennell [1898] (esp. on France and England prior to 1890); Blum [1993] pp. 49ff. and 162ff. on the US, Gandy [1940] (in particular on the later development in the US around 1900). Twyman [1970] focuses on Germany, France, and England up to 1850, Lemercier [1900] on France, Menz [1955] on Germany, and Graul (ed.) [1903], Schwarz [1988] on Austria.

(22) Cf., e.g., Menz [1955] p. 7 and pl. 2, or Soulier [1997] p. 162 or pp. 167f. for examples of early lithographic facsimiles of precious documents such as incunabula or Dürer drawings.

(23) See Senefelder [1818], Raucourt [1821], Engelmann [1822], Hullmandel [1824], and Jomard [1826]; cf. also Twyman [1970] part II. The rare and much less detailed earlier literature, such as W. Nicholson's '*Das Geheimnis der Lithographik* (1809) or H. Rapp's *Das Geheimnis des Steindrucks* (1810) indicate that lithography was a closely guarded secret, and at best an only partially understood novelty. For later but clearer descriptions of its techniques, see also Fritz [1901], Ziegler [1912] pp. 46–80, Hill [1915] pp. 15–22, Wengenroth [1936], Dehn and Barrett [1950], and Gascoigne [1986] § 19–20.

(24) First published in 1824, reprinted in 1833. See in particular pl. II and V, fig. 1, also reproduced in Twyman [1970] pl. 43–44; cf. also Anon. [1874*b*] for a critique of this "primitive style" adopted in early lithographs.

(25) See De Serres [1809], in the German version edited and commented upon by Gilbert in 1810: "The advantages of this type of printing are: that it has a character of its own, that it cannot be copied by the other types of engraving and printing, whilst all earlier modes can be imitated quite well by it; and above all, that it proceeds much faster than all the others."

(26) Twyman [1970] p. 119; cf. *idem*, p. 89, Mumford [1972] p. 31, Dyson [1984] p. 32, Gascoigne [1986] § 19.

(27) See in particular Soulier [1997] for a survey of early usage of lithography within the sciences, esp. p. 164.

(28) Silliman [1822] p. 170; cf. also Blum [1993] p. 52.

(29) Such limestone is found in Solnhofen and Kelheim near Munich in the Jurassic Alps (belonging to the upper oolite) which for a long time was the main source. A suitable quarry in Kentucky was discovered in 1819; see Blum [1993] pp. 49f. Raucourt [1821] pp. 29ff. also mentions some quarries in France, but according to Hill [1915] p. 15 stones from localities other than Solnhofen are all inferior in quality.

(30) On the latter two instruments, see, e.g., Stanley [1866*b*] pp. 8, 12.

(31) Cf., e.g., Engelmann [1822] pl. II. Hullmandel [1824] pl. I, and Twyman [1970]. pl. 38f. for early illustrations of the microscopic patterns on the stone surface. Raucourt [1821] pp. 28ff., 93ff. discussed the consequences of this texture for the printer's handling of ink, and Stanley [1866*a*] chap. II, various types of contemporary drawing pens.

(32) See e.g., Twyman [1970] p. 10 about the discovery of this transfer process. A plate by Alphonse Legros exemplifies such a transfer-print of a drawing on paper, in E.R. and J. Pennell [1898] between pp. 90 and 91. Blum [1993] pp. 183–5 illustrates a rare zoological application of this technique that yielded around 7000 copies.

(33) The advice about using three different crayon or pen nib thicknesses, respectively for the background, middistance, and foreground is given, e.g., by Twyman [1970] p. 89.

(34) Becker [1890] p. 135 footnote.

(35) H.C. Vogel [1879*a*] p. 143.

(36) Stanley [1866*b*] p. 10; the improved pen of Fig. 4.9 (bottom) being an effort to cope with this problem; cf. also Feldhaus [1959] p. 88.

(37) *Ibid*., p. 11. I am grateful to Geoffrey Cantor for kindly providing me with a copy of these pages; the University of Leeds has one of the very few library copies of this text.

(38) According to contemporary price estimates, coloring by hand more than doubled the price of the finished product even though it was done for a low wage almost exclusively by female workers: see, e.g., Nickelson [2000] pp. 71–3 on widows of engravers employed as illuminators by the Prussian Academy of Sciences in the late 18th century. See also Winkler [1975] p. 429, no. 415 for an example manufactured in 48 copies: fully illuminated, it was sold for 14 guilders; with less hand-coloring, its price was 10 guilders, and with none at all, 6 guilders, with 1 Bavarian guilder *(Gulden*, abbreviated fl) around 1805 worth about 3 kg of beef, *idem*, p. 436.

(39) See Listing [1866] pp. 171 and 175 on producing the plates by the iris printing method, “under my direct supervision at the local Lithographic Agency of Mr Honig.” According to the Göttingen *Adressbuch* for 1865, pp. 15, 44, G. Honig’s Lithographische Anstalt was located at Weender Strasse no. 6 in a house owned by him and his siblings.

(40) See Listing [1867] pl. V.

(41) The son of a master tailor had studied at the Academies of Arts in Berlin and Copenhagen. After initially working as portrait and genre painter, he turned to reproduction engraving and lithography. Entered in the Berliner *Adressbuch* as “Akademischer Künstler”, he was a well-known illustrator, being chiefly responsible, for instance, for the plates of the *Berichte der Akademie der Wissenschaften* between 1855 and 1882, and for the plates in various archeological publications by Carl Richard Lepsius (1810–84) and Eduard Gerhard (1795–1867). Anon. [1908], an obituary in *Vossische Zeitung*, and a necrology in *Biographisches Jahrbuch* of 1908 (p. 86) identify Schütze as the “main representative of scientific, esp. medical lithography”. In 1872 he also printed Rutherfurd’s photographic map of the solar map in a photomechanical reprint for Schellen [1870/72].

(42) See Secci [1870*c*]. Cf. J. Basire's chromolithograph for W.A. Miller reproduced here as Fig. 2.15 on p. 43.

(43) See Hullmandel [1824*b*] pp. 81f. Cf. here below p. 127 for an example of one Bonn-based lithographer executing a color plate for the London *Philosophical Transactions*, and Booth [1895] PP. 206f. on the possible reasons for this superiority of colored matter 'Printed in Germany'. Blum [1993] p. 263 mentions instances of color lithographs being produced more cheaply by draughtsmen in Frankfurt, Germany, for an American publication around 1890.

(44) On the latter cf., e.g., Putscher [1972] p. 54 who goes so far as to claim that, without chromolithography such as used extensively in the 230-plate atlas by Jean Cruveilhier (1781–1874), pathological anatomy would not have attained its central place in nineteenth-century medicine.

(45) See Gandy [1940] p. 5. On military topographical maps printed in four colors, cf. Goss [1993] pp. 221ff. Röll [1939] pp. 110, 113, mentions chromolithography off 15–20 stones.

(46) See, e.g., Winkler [1975] p. 432.

(47) See in particular Raucourt [1821] pp. xiii, 94ff., who developed what he called a "theory of the inks" covering the many different procedures and the constraints (such as room temperature) that the printer has to comply with.

(48) A desperate user of one copy of Kirchhoff's map at the Harvard Widener library tried to modernize it by entering the wavelengths in pencil in increments of 100 Å, to allow approximate interpolation of the intermediary lines; cf. also footnote 119 on p. 57.

(49) Henry Enfield Roscoe in the introduction to the English translation of Kirchhoff [1861/62*f*] p. iv. The lithographer C. Laue, is discussed here on p. 151.

(50) See Kirchhoff [1861/62*g*]. These 35 cm-long plates had to be folded twice to accommodate the octavo format of the *Annales*, so mere size does not explain why the French did not use the same stones, because the original plates are of the same length. On Dulos see here p. 143. A contemporary lament about the ambiguity between spectrum lines and the standard print syntax is found here on p. 97.

(51) Anon. [1862] p. 53.

(52) Kirchhoff [1861/62*f*] p. 4 footnote.

(53) When similar discrepancies between plate imprints for Kirchhoff and Bunsen [1860/61*a*] part II, were noted, Bunsen stated bluntly: "That does not substantially impair the use of these plates". Bunsen [1904], vol. III, p. 291.

(54) See Smyth [1882*d*] p. 7. He used Roscoe's reprint of Kirchhoff and Hofmann's plates made in 1869, but since it had been run off the original stones, the result ought not to have been too different—it is conceded, though, that these printers may not have been as versed in the technique.

(55) See Simmler [1861] p. 15: "At printing, Schweinfurt green unfortunately loses exceptionally much of its vibrancy and the illustration of the copper spectrum can give only a vague idea of the true brilliancy of this optical phenomenon."

(56) See Plücker and Hittorf [1865] p. 27, referring to the part of plate I displaying the cyanogen band spectrum.

(57) This son of a member of the French revolutionary army, Charles Albert Joseph Henry (1773–1816), and Anna Rebekka Mayer from Kleinbroich, was born in Douai, received practical training in graphic arts at the Lithographic Publishing House Arnz & Co. in Düsseldorf from 1817 on, and was then employed by them. In 1829 he moved to Bonn, where he founded the Lithographische Anstalt Henry & Cohen, which seems to have existed between 1833 and 1862, and was later renamed A. Henry & Co. Marrying Maria Anna Josepha Eiler, daughter of the district secretary Joseph Eiler, in 1842, he had three sons, Joseph (1843–1907), the bookdealer and municipal councillor Karl Johann Hubert (1844–1931), and the architect Albert (1846–73).

(58) A more detailed study on the joint venture publishing house, co-directed with M. Cohen and his son, "Verlag des lithographischen Instituts der Rheinischen Friedrich-Wilhelms-Universität und der Leopoldinisch-Carolinischen Akademie der Naturforscher, Henry und Cohen" in Bonn, is in preparation. According to the *Dictionary of Scientific Biography*, **10**, p. 12, the high quality of the *Nova Acta Academiae Caesarae Leopoldino Carolinae germanicae naturae curiosorum* was "partly the result of Nees von Esenbeck's bringing the artist Aimé Henry to Bonn." A bibliographic check yielded more than 40 publications appearing in this printing house between 1837 and 1861.

(59) This astonishingly high number of lithographic stones for a single plate can be inferred from a letter by Plucker to Stokes, dated 21 March 1865 (CUL, Stokes collection, Mss.Add. 7656, no. P 399). I owe many thanks to Dipl.phys. Falk Muller (Oldenburg) for calling my attention to these letters.

(60) Plucker to Stokes, undated letter (*ibid.* no. RS 2379; transcribed by Falk Muller).

(61) *Ibid.*; the mentioned total suggests that the *Philosophical Transactions of the Royal Society, London*, where the paper and its plates appeared in 1865, had a print run of about 1000 at the time. The remaining 25 copies were for Plücker's private use. Unfortunately, Henry's estimate for the elaborate color plate I is not documentable, but his estimate for the two normal engravings, plates II and III in a run of 1025 each was £10: see Plücker to Stokes, 2 September 1864 (no. P 398). According to May [1987] pp. 201–3, around 1850 a minimum middle-class income was around £300 a year, ranging between £1000 and £100; a great number of clerks and elementary schoolteachers received as little £60 per annum; at the same time a London townhouse might be let out for £45 a year.

(62) For instance, pl. 9 in Henry's set of plates for vol. 1 of Nees von Esenbeck's *System der Pilze*, Bonn (1837), had the following palette: yellow, dark orange, rust, hazel, dusty dark brown, grass green, bottle green, mossy green, pink, and slate gray besides the black contours on a white base.

(63) See esp. Plücker to Stokes, 2 September 1864 (*opcit.*, no. P 398) about the proofs: "they are much better than the former ones and may be still improved", and 21 March 1865 (no. P 399): "I have called at Henry's. Five stones are printed; there remain five the printing of which will require two or three months, as some colour[s] need a longer time. I was quite satisfied with what I saw. The stones will be preserved until the safe arriv[al] of the plates is announced."

(64) M. Huggins [1882] p. 359. I thank Mary T. Brück for having drawn my attention to this article.

(65) For these terms see Smyth [1879*c*] pp. 790–2 and pl. XXVIII, "printed by Messrs W. & A.K. Johnston, the [Royal Edinburgh] Society's able engravers, [having] kindly taken a deal of trouble and much anxious interest." His paper also contains interesting results concerning colors observed through colored media and on color blindness.

(66) This trick of the trade is described in a number of later printing manuals: see, e.g., Winkler [1975] pp. 429–31, entries 'Passer' and 'Nadeln'. Usually the perforations at the margins were carefully cut off prior to distribution or binding.

(67) See Smyth [1884/87] pp. 531f. and pl. 83 for the wavelength regions corresponding to the designated colors ultra-red, deep red, red, orange, yellow, citron, green, glaucous, blue, deep blue, violet, and ultra-violet; cf. also his notebook (ROE, 18.114), entry 3 for the period Oct. 1884-Febr. 1885, p. 168, and entry 4 of March/April 1885, noting that 53 of the 60 plates were finished, but "progress now slower on account of resumption of Star Catalogue Printing."

(68) Smyth [1884/87] p. 531; cf. also H.A. and M.T. Brück [1988] p. 236 for Ralph Copeland's encouraging response in a letter to Smyth (ROE) upon receipt of the printed Winchester spectrum; "I for one am very obliged to you for the colour, for it makes me feel quite at home with the spectra."

(69) See Bunsen [1863*b*] p. 247: "the ordinates of the edges of the small blackened surfaces […] represent the intensity of the several lines with their characteristic gradations of shade. […] For the sake of perspicuity, the continuous spectra which some bodies exhibit are specially represented on the upper edge of the scale."

(70) See, for instance, H.W. Vogel [1877*a*] pp. 214, 238, 262ff., Eder [1884], [1886], and here Fig. 7.5, p. 263 for Mees's photographic wedge spectrograms.

(71) Smyth [1877*b*] p. 33 and [1877*a*] pp. 28f.

(72) Smyth [1884/87] p. 529.

(73) See, e.g., Koschatzky [1975] pp. 179f.

(74) See, e.g., H.W. Vogel [1877*a*] pp. 122f., 166 for simple woodcuts, and Kainen [1959] on Thomas Bewick's (1753–1828) crucial role in the technical development and popularization of wood engraving.

(75) See, for instance, the representation in Huggins [1864*a*], the plates in Roscoe [1868a], H.W. Vogel [1877*a*].

(76) H.C. Vogel [1879] p. 169.

(77) E.g., small circles in Thollon [1890], triangles in Spée [1899].

(78) Cornu had studied at the École Polytechnique from 1860, entering the École des Mines two years later. He became *répétiteur* and *professeur á'Ecole Polytechnique* in 1864 and 1867, respectively, furthermore member of the Paris Academy of Sciences in 1878, of the Bureau des Longitudes in 1886, and corresponding member of seven other scientific academies. A specialist in optics, Cornu was most famous for his precision measurements of the velocity of light, for which he also received the Prix Lacaze of the Paris Academy of Sciences. Cf., e.g., Burgess [1902], Mascart [1902], Anon. [1902], Bassot and Poincaré [1903], Poincaré *et al.* [1904], S.P.T. [1905], Anon. [1904], Herivel [1971], his personal dossiers (at AASP and AEP), and his file concerning promotions by the Légion d'Honneur (ANP, L0593033). His teaching at the École Polytechnique is discussed here in § 9.9.

(79) See, e.g., Cornu's letter of 15 April 1878 to the Paris Academy of Sciences, quoted in the 'pochette de la séance du 19 Avril 1878' (AASP), enclosing his submission of a corrected version of the first plate of 1874, together with the second plate, finally published in 1880.

(80) See Cornu's [1889] detailed recipe for sensitizing the plates with his ferrous sulphate developer. It also mentions various technical tricks which Cornu did not make public at the time of his experimentation. The paper was only published because Victor Schumann translated some notes Cornu had sent to him personally.

(81) See Cornu [1874/80*a*] pp. 432f.; for the interpolation formula, see Cornu [1874/80*b*] appendix; and Cornu [1883*a*] for a description of his custom-designed high-dispersion spectroscope, built by J. Duboscq.

(82) See Cornu [1874/80*a*] p. 433: "one no longer knows how to assign them from the experimental record without mixing them up and without making errors in the finer details."

(83) Cornu [1874/80*a*] p. 433, original emphasis.

(84) Cf., e.g., Stein [1877] pp. 449ff. According to A. Brachner in DeClercq (ed.) [1985] pp. 120 and 146, the German instrument maker Georg Oberhäuser (1798–1868) moved to Paris in 1822 in reaction to a depressed market in scientific instruments.

(85) See Cornu [1874/80*a*] p. 433: "effort to render the effect of the groups, either by intensifying the color of the ink or by applying a wash to represent blurred lines or regions with a darker background: amplified positives were a great help to me as a guide." On the engravers of his map, Dulos and Legros, see here pp. 143f.

(86) Cf., e.g., the praise in Hartley and Adeney [1884] p. 63: "splendid map", and here p. 147 about the engravers.

(87) Cornu [1874/80*a*] pp. 422 and 433, original emphasis.

(88) A. Schuster to C.P. Smyth, 16 January 1882 (ROE, 15.67, folder S).

(89) Smyth [1880*b*] p. 289.

(90) See here pp. 293ff. It was only with the discovery of the Zeeman effect in 1896 and the subsequent finding that series lines usually exhibited the same type of Zeeman splitting in magnetic fields, that a stricter criterion for series attribution had been found, but by then the series formulas had already been figured out empirically.

(91) This specialist in high-dispersion spectroscopy provided in 1879 experimental verification for the Doppler-Fizeau shift caused by solar rotation; see Janssen [1887], Anon, [1887*b*], Levy [1976].

(92) See Thollon [1879*c*] p. 1305: “I applied myself toward reproducing with the utmost care the physiognomy that my instrument’s enormous dispersion lends to each line”. Cf. here p. 102 for a comparison of the dispersion of Thollon’s map with other spectrum maps.

(93) Although conferral of this prize (worth 540 francs) to Thollon by a commission composed of Faye, Lœwy, Mouchez, Wolf, and Tisserand (rapporteur), is mentioned in the Proceedings of the Paris Academy, no records of any submitted material have been preserved (AASP, folders Prix Lalande, 1885 and 1886).

(94) See Thollon [1878] pp. 595ff. for his geometrical proof that each ‘prism couple,’ joined at their bases, was positioned at minimum deviation once the angles *i* and *e* of the light were equal to the normals of the outer prism faces.

(95) See Thollon [1878] p. 331.

(96) Thollon [1880*b*] pp. 750–2 compared the light loss in an Amici prism and in Thollon’s block arrangement: 57 % loss for the former, and 37 % for the latter. On the temperature dependency of these fluid prism dispersions, see here p. 93.

(97) Laurent had worked in the optical instrument shop of G. Frommet for 14 years before joining his father-in-law Duboscq’s instrument shop in 1870 and taking over the central position of ‘constructeur d’instruments d’optique et de précision’ there in 1872. See, e.g., Poggendorff, vols. III and IV. On his spectroscopes for Thollon, see esp. Guébhard [1879] p. 223, Laurent [1879], Thollon [1879*a*] p. 81.

(98) See Thollon [1879*a*] p. 81 which includes small drawings of the B, b, and D groups of the solar spectrum, illustrating the apparent distance of approximately 18 mm between the two D lines and the many other lines seen in-between (cf. here p. 91).

(99) See Thollon [1879*c*] p. 1307 for a brief description (unfortunately without a diagram) of this “registering procedure, which has extraordinarily shortened and facilitated my work” and Guébhard [1879] p. 224 for the drawing reproduced above.

(100) See, e.g., Guébhard [1879] p. 223 who mentions a total length of 15 m, while other abstracts mention 10 m.

(101) According to Müller [1992] pp. 131–6, the Nice Observatory was constructed between 1879 and 1886. Its dome of 26 m diameter was the largest in Europe, and its main refractor with an objective lens 76 cm in diameter was for a time the largest in the world. According to Levy [1976], the spectroscope was completed in 1883.

(102) See Spée [1899] pp. viii–ix. According to Guébhard [1879] p. 224, three such fluid prisms twice traversed by the light had a dispersion equivalent to 31 ordinary flint-glass prisms with a 60° refractive angle and a refraction index of 1.63. Cf. also Thollon [1883] pp. 108–11 and the illustration of Thollon's high dispersion direct-vision spectroscope manufactured by A. Jobin in Syndicat [1901] p. 137.

(103) According to Ranyard [1890] p. 211. For contemporary praise of Thollon's spectroscope see, e.g., A. Schuster to C.P. Smyth, 14 July 1882 (ROE, 15.67, folder S).

(104) Thollon [1879*c*] p. 1305.

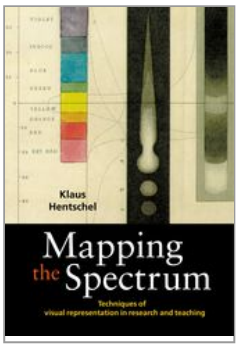
(105) See, e.g., Janssen [1887] p. 1048 on Thollon's own ambitions for his solar map: "with it he had wanted to make a towering monument to Science. But towards the end he sensed that it would be difficult for him to realize this project completely."

(106) Spée [1899] text vol., p. vii.

(107) Of the 3202 dark spectral lines listed in Thollon's accompanying table, 2090 were of purely solar origin, 866 of atmospheric absorption lines, and 246 were labeled 'mixtes'. See Thollon [1886/90] text vol. cf. also Spée [1899] text vol., p. x, and here § 3.4.

(108) See Spée [1899] p. xiii: "a quite large number of lines seen as single with Thollon's spectroscope were found to resolve into two, even into three, in Rowland's tables"; cf., *idem*, p. xvii: "Mr. George Higgs of Liverpool, while working with a concave grating of four-inch diameter and a degree of curvature of ten feet, has obtained photographs of the D group numbering 25 to 30 lines. Thollon's drawing bears only fifteen." See also Kayser [1936], typescript p. 132, where he cursorily sums up Thollon's work as follows: "[… in] Nice, where I looked up the astronomer Thollon, who at that time was occupied with the large atlas of the solar spectrum,—a very creditable enterprise, had it not immediately been surpassed, by a wide margin, by Rowland's photographic atlas."

(109) Ranyard [1890] p. 211 praises Thollon's work as "portrayed with conscientious accuracy."



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
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Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

The Material Culture of Printing

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DOI:10.1093/acprof:oso/9780198509530.003.0005

Abstract and Keywords

This chapter discusses the material culture of printing spectra in the 19th century. The social setting of print experts, their wages, and total numbers in various countries (especially France, Germany, England and the USA) are also taken into consideration. Photomechanical printing techniques widened the possibilities and deeply changed the practice and economy of spectrum mapping, but only in the late 19th century. A frequent transfer of skills from topographic map-making to spectrum map production is revealed. The chapter closes with a section on the economy of the printing trade.

Keywords: material culture, topographic maps, spectrum maps, photomechanical printing, skills, economy of printing

5.1 The social setting

Let’s go back some two decades to the period 1860–75, that is, safely before the ‘intrusion’ of photography into the business of spectral map production on a larger scale, and reconstruct the whole sequence of tasks involved, from the first visual observations to the distribution of a finished spectral map. The scrupulous visual examinations of the spectrum, and the micrometric determinations of relative line distances were mostly made by observers, whom we would today call ‘scientists’.[1] They were often wealthy, highly motivated amateurs like Joseph Lockyer, whom we associate with these maps today. I say ‘mostly’, since there were limits, some of them physiological. Gustav Kirchhoff, for instance, confessed in a footnote to his ‘Examinations’ that the first installment of his map of the spectrum was not complete, “as the remainder requires a revision, which I am unfortunately unable to undertake, owing to my eyes being weakened by the continual observations which the subject rendered necessary”.[2]

I am not certain what he meant by ‘revision’, whether he was referring to new observations or just to recalculation and rescaling of his observations in preparation for the drawing. Either way, the second part of his map acknowledges observations by Karl Hofmann (1839–1891), one of Kirchhoff’s students.[3] Hofmann also signed Kirchhoff’s map with ‘del.’ *(delineavit)*, which signifies that he actually drew the figure that was printed. While Hofmann had majored in mineralogy and later became a noted geologist in Hungary, Ångström’s assistant Robert Thalén (1827–1905) remained in the field. He was not only the coauthor of some of Ångström’s maps, starting with the continuation of Kirchhoff’s **(p.141)** map into the violet published in 1865, but later published independently as well.[4] Several other examples of such collaborations between unequal partners also spring to mind, such as the one between Sir William and Lady Huggins and between this gentleman scientist and the chemist William A. Miller. Especially in the Kirchhoff/Hofmann case, where the collaborator has sunk into total oblivion, we are not far removed from Stephen Shapin’s ‘invisible technician’ for the earliest prototypes of air pumps, whose operation certainly could not have been assured solely by a single heroic experimentalist.[5]

But in our case, even more people are involved. With the observations already in hand, the research results must first be sketched and then engraved. As we have already seen with the example of Cornu, the first drawing of the spectral map was frequently done by the observer himself, although sometimes this task was delegated to an assistant: Ångström’s famous map bears Robert Thalén’s signature in the lower left-hand corner even though it was not a co-authored publication (unlike their later map of 1875 of the band spectra of metalloids).[6]

The next stage in mapping the spectrum, however, the actual engraving of the map on a copper plate or drawing it on stone, was usually not done by the observer, as only very few among them were skilled in this manual art.[7] The preparation of the plate was done by a professional copper engraver or lithographic draughtsman, and in many cases the printing process involved yet another person or institution, although for low runs the same lithographer could be engaged for this.[8] Far from seeing themselves as mere executors, at the end of the production line, engravers and lithographers considered themselves interpreters, translators of the scientists' sketches and drawings into printable material for the ensuing reproduction process.[9]

As Alex Soojung-Kim Pang has shown in his study on Victorian representations of the solar corona, "engravers had to be monitored and corrected, especially when working at one or more removes from original pictures, but the engraver's skills had to be allowed to operate if copying was to be successful."[10] The same applies to representations of spectra. The commissioned engraver or lithographer virtually never observed the object directly and **(p.142)** thus had to rely fully on the sketches, drawings, and accompanying lists, tables, and other notes provided by the spectroscopist. Obviously, friction at this interface in the traditional division of labor was inevitable, and complaints from both sides abound (see here p. 227, for instance). This friction was the main source of a scientist's distrust in 'translations' of such drawings and depictions into engravings and lithographs. Despite repeated efforts by the experts to inform their readers about the various drawing techniques, along with their associated strengths and weaknesses in the final print,[11] knowledge about these "essentials of illustrations" was not as widespread among professional scientists as one would have liked. This is set against the all-too-frequent circumstance that the draughtsmen had never laid eyes on the object of study. Compounding this ignorance was their tendency to fall back on the conventions and customs they had acquired during their training—as one contemporary put it: their "hand lapses voluntarily and unavoidably into accustomed modes of action."[12] The historian of photography Larry Schaaf recently gave the nice example of the Dragon Tree of Oratava. A pencil sketch by M. Ozone from an expedition to Tenerife is compared with an illustration in Alexander von Humboldt's *Atlas Pittoresque* (1810), with later reprints of it (1832) that make the tree resemble the Central European elm, and finally with photographs by Charles Piazzi Smyth (1858). The latter sarcastically noted:

> On comparing this [pencil] drawing with my Teneriffe photographs, the editors of the MacGillivray edition [1832] must surely have assumed that I had put up the camera before an altogether erroneous tree. […] It is instructive, as connected with the language of drawing, to trace the gradual growth of error and conventionality as man copies from man. Errors are always copied, and magnified as they go; seldom are excellences reproduced. After a few removes, the alleged portrait of nature is only a caricature of the idiosyncrasies of the first artist.[13]

Throughout the nineteenth century, independent lithographers and lithographic printing agencies (Lithographische Anstalten) competed for customers in a quite large market, with the trend moving away from the family or small-scale enterprise towards bigger commercial firms.[14] Institutions that needed large numbers of illustrations on a regular basis for their publications often hired their own engraver or lithographer on a full-time basis or else maintained stable business relations with outside contractors. Their printing context in eighteenth-century France has already been looked at: The business relations between engravers and the Académie Royale de Peinture et de Sculpture is described quite well in François Courboin's study, which was awarded the Prix Bordin by the Académie des **(p.143)** Beaux-Arts for 1914. But nothing similar has yet been done for their scientific sister institutions.[15] The Parisian Académie des Sciences, for instance, was also a regular patron of a variety of artisans; yet in this case often the only documentation of them is an inconspicuous signature on a plate in the *Mémoires* or another publication partially funded by France's central institution of science.[16] Any personal dossiers on these craftsmen were not considered worth keeping for posterity, and the internal records of the institution's financial and administrative committees contain only scant information about pecuniary compensation for individual plates, apparently limited to cases beyond the normal course of business.[17] Thus, even though the high repute of the Academy's publications rested to no small degree on the skill of their engravers and lithographers, these professionals remained in obscurity. Being specialists in scientific illustration, their names are not even listed in the many reference dictionaries of engravers and printers compiled by historians of art and art collectors.[18] For unlike their colleagues from the fine arts, they were classified as 'artisans', not 'artists'.

Let us take a closer look at a specific case. The Paris Académie des Sciences engaged a certain Monsieur Dulos as one of their engravers around 1850 and he remained in their employ until his death. Yet there are few institutional traces left of him apart from a few vague mentions in the Academy's administrative files.[19] According to the *Didot-Bottin*, the Parisian city almanach, Dulos's address in the 1860s was "Rue des Mathurins–St.-Jacques, no. 11." A Paris map of 1867 indicates that this road is now called rue du Sommerard (in today's 5th 'arrondissement' or municipal district) quite close to the College de France in St.-Germain—at that time the 15th arrondissement). By 1870, he had moved to nearby "Rue de Seine, no. 34" in the same district (in today's 6th arrondissement), very close to the Académie des Sciences on Quai de Conti.[20] Strangely enough, none of these city address entries divulged this expert's given names, not even publications about his path-breaking innovations in printing technique (see below) were forthcoming in this regard. So I had to hunt them down in the Parisian marriage registry. Between 1795 and 1862, only one male person surnamed 'Dulos' was married in Paris, namely Pierre Edel[e]stand Stanislas Dulos, son of Jean Dulos, who married Lucie Legrand in the Catholic church of St. Sulpice (in the neighboring 6th district) on 26 January 1850. The groom's address was 15, rue Pavée St.-André-des-Arts (which was a small and narrow street in the old 1lth arrondissement on **(p.144)** the left bank). Further hunting in the Parisian death registry revealed that he was born on 1 June 1820 in Dax, Landes, and died on 15 April 1874 in his apartment in Paris.[21] He died a widower, leaving two children: Jenny Louise, born in 1852 and married to the civil engineer Pierre-Valéri Dalbouze; and Pierre Émile, born in 1857 and thus still a minor at his father's death so that he was placed under the guardianship of his older sister and her husband.[22] Dulos's middle name 'Edelestand' hints at a Jewish background, although the church where he was married, the second biggest in Paris, suggests that he was fully assimilated and a baptized Roman Catholic. Furthermore, the surname indicates eastern European origins: Dulos is a fairly common name among Czechs. Its rarity in France meant that, unlike many of his fellow tradesmen, our engraver could afford to dispense altogether with his initials. Pierre Dulos had at least one sibling, an elder brother Pascal (born 1818). Both brothers received the same professional training in the industrial arts at the local École Nationale des Arts et Metiérs in Angers, Département des Landes. Pascal Dulos was matriculated there between 1834–37, and a detailed listing of his grades still exists. For Pierre, who entered the same college one year later in 1835 and graduated in 1838, the same document is unfortunately missing, but we can assume that, like his brother, Pierre too received instruction in the applied crafts as well as in mathematics, mechanics, physics and chemistry, technical and architectural drawing, calligraphy, and some courses in French and English.[23]

The assumption that this Pierre Dulos is our man is further corraborated by an inventory of his estate taken six days after his death at his home in St. Germain des Près.[24] Aside from a set of the *Mémoires de l' Académie des Sciences*, the deceased also owned copies of *Cosmos, Annales de Chimie et Physique, Bulletin de la Société de Photographie, Société des Anciens Élèves des Écoles Nationales d'Arts et Métiers*, and various other books on chemistry, mineralogy, physics, electricity, and mechanics. Many if not all of these c. 150 books were presumably illustrated with engravings by his own hand.[25] Among his clients (listed by name in one of his accounting journals) we find the physicists Fizeau and Pouillet, the chemist and gerontologist Michel Eugène Chevreul, and the mining engineer and mineralogist Désiré Pierre Baudin.

(p.145) According to the legally certified inventory of Dulos's property and estate, drawn up on 21 April 1874, his furniture and household effects were valued at 12 956.50 francs. Bills for finished engravings totaling 1862.20 francs were still outstanding. Additionally, the notary priced Dulos's finished or almost finished engravings and other prints at 12 673.31 francs, quite a substantial sum at the time, being about ten times the annual salary of a low-level employee.[26] Interestingly, two years before his death, Dulos had taken out a loan in the amount of 30 000 francs in order to start work on engravings commissioned out to him by the Ministry of Public Works (see below p. 169). This sum was most likely at least twice Dulos's yearly income and more than the annual salary at 25 000 francs that the star engraver Alphonse Legros earned as professor at University College, London.[27]

This little excursion into the social history of an engraver and lithographer reveals that despite enjoying a good reputation for his engravings in spectroscopy and related scientific topics, Dulos did not work exclusively on scientific illustrations. His reputation was based on an innovation in printing technique. Dulos developed a refined process based on the properties of capillarity for transforming drawings or lithographs into line engravings *(gravures en taille douce).* A drawing with lithographic ink, for example, is traced onto a silver surface, usually a silver-coated copper plate. Then a layer of iron is electrolytically deposited on top and the ink is washed off with turpentine or benzine to expose the silver along the traces. A film of liquid mercury is subsequently spread onto the printing face, which is attracted to the silver and collects in the slight depressions, where it beads to form convex protrusions. Thus a relief is obtained. Once the excess mercury has been removed with a fine brush, it is possible to print from this plate using a plaster or wax cast. Copper galvanization of this cast fixes the contours originally delineated by the mercury, to yield a resistent matrix for intaglio engraving *(gravure en creux).* By experimenting further with this technique, Dulos found that the cliché metal could be replaced with a more practical fusible alloy of "métal Darcet"[28] and only a small part of the highly toxic mercury, or alternatively with a copper amalgam.

Relying on the property of silver to attract mercury more easily than copper and to attach itself more firmly there, Dulos adapted his technique to tackle bolder outlines, such as those made with a blunt lithographic crayon: After the crayon drawing on a copper plate is complete, the plate is silvered and the drawing removed to leave the copper exposed only along the lines. The plate is then dipped into a mercury sulphate solution, and the sulphuric acid in the sulphate combines with the copper to form copper sulphate, leaving the mercury to bond with the silver plating. After some minutes of reaction, the mercury's passage away from the exposed copper areas toward the silver preserves the lateral walls of the cavities created by this process.[29] Sample plates produced by this *procédé Dulos* show how exquisitely Dulos's technique handled various shades of darkness, so perfectly, indeed, that plates with certain *gravures en relief*, printed by Dulos's techniques, were not **(p.146)** infrequently mistaken for line engravings, even by the local experts.[30] It also came in handy for the most difficult jobs, such as for the French translation of Kirchhoff's paper on the solar spectrum in 1863/64.[31] Unlike the English translation, the French version did not have the original chromolithographed plates available (cf. here Fig. 4.10). So with its ability to reproduce fine gradations of line intensity, the 'procédé Dulos' was just the right technique to use for black-and-white reproduction of the exquisitely colored originals (see Fig. 5.1).

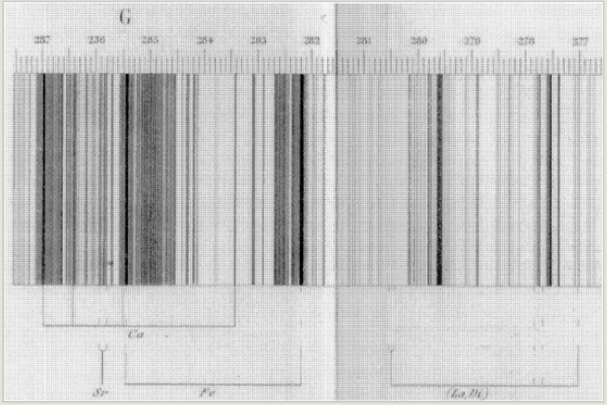


Fig. 5.1 Section of a reprint of Kirchhoff's 1861/62 plates of the solar spectrum around Fraunhofer line G. Printed by the 'procédé Dulos'. No cross-hatching or screening was used to produce the many different shades of gray. From the *Annales de Chimie et de Physique,* 4th ser. **1** (1864), pl. **III.**

Dulos's *capilligraphie*, as his *technique de gravure chimique* was also called,[32] definitely profited from the unusually close link between this 'graveur de l'Académie des Sciences' and the science of his day. Capillarity was a big topic in France dating back to Laplace's interest, along with electrochemical techniques such as electroplating. The *procédé Dulos* brought fame to its inventor, who held the title of 'Ancien Élève des Arts et Métiers' besides that of 'chevalier de la Légion d'Honneur', most likely for his longstanding employment as cartographer for the French War Ministry.[33] The estate listings of **(p.147)** unfinished copperplates for regional maps of France reveal more than their monetary value. These estimates varied according to the state of completion of the plates. One bearing the black contour lines was priced at c. 100 francs. If those for the blue, red, and yellow impressions were also ready, the estimates rose accordingly. The maximum value of a virtually finished map was 700 francs.[34]

Ernest Jules Pérot[35] continued Dulos's cartographic work on the French seaports around 1874, while Charles Désiré Antoine Legros assumed some of his other scientific illustration work into the next decade.[36] The latter, a son of a 'maître de construction' was born in 1843 about 200 km south of Paris in Nevers. He received a thorough training in calligraphy and orthography, drawing, mathematics, and practical skills in the 'atelier d'ajustage' or workshop at the École Nationale d'Arts et Métiers in Aix-en-Provence, where he was enrolled in 1859. Graduating in 1862, he was ranked 28th in a class that had shrunk from 101 at the beginning of the school year to 79.[37] He first started work as an independent draughtsman ('dessinateur') in Lyon.[38] When Pierre Dulos died, the transition was evidently a smooth one, since Dulos and Legros had already collaborated together on one of their finest spectrum plates: the first plate of Cornu's near-ultraviolet spectra, which appeared in 1874. It was based on Cornu's data, tables, photographs, and possibly also a final drawing. The fact that the joint signatures on this superb copperplate do not appear in alphabetical order signifies a somewhat greater share of Legros in this effort (possibly owing to Dulos's failing health, who died in April of that year).[39] A few other names crop up besides Dulos and **(p.148)** Legros in the administrative records of the Académie des Sciences, but it was Dulos who had the lion's share of its illustration work between 1852 and 1874.[40]

Like Dulos, Legros also had links to architecture: both were always listed in the professional directory under the subcategory of ‘graveur en architecture’, among only some 20 other names. For comparison, the category ‘graveurs sur métaux’ lists about 500 names and ‘graveurs sur acier et en taille-douce’ has 145. Thus in the 1880s, Legros was responsible for engraving various other spectrum maps, including the second part of Cornu’s near-ultraviolet spectrum which appeared in 1880 and those that Henri Becquerel obtained in the infrared by means of phosphorescence.[41] Engravers like Dulos, Legros, and Pérot had carved out a very specialized niche in the huge printing market: Pérot, for instance, was listed under three separate categories in the 1875 *Didot-Bottin:* ‘sur acier et en taille-douce’, ‘sur bois’, and ‘en architecture’, and generally described his expertise as “pour les sciences, les arts et l’industrie”. But because of the technical and scientific nature of most of their illustrations, neither Legros nor Pérot are listed in any of the many dictionaries and reference works on nineteenth-century lithographers. So it was considerably more difficult to identify them at all.

In Britain, the printing agency West Newman & Co. made most of the engravings for the London *Philosophical Transactions of the Royal Society* during the 1880s, succeeding the companies of W.H. Wesley and W. West & Co. lith., who had performed this task in the preceding decade. The central figure in both organizations was William Henry Wesley (1841–1922), one of London’s best-known scientific engravers. Wesley, who was also scientific bookseller, publisher, and sales agent for the Smithsonian Institution, the United States Government Departments, and various scientists, who distributed their privately produced atlases via his publishing house, advanced to the position of Assistant Secretary of the Royal Astronomical Society and held this position from 1875 until his death in 1922.[42] Between approximately 1800 and 1864, the same prestigious commission had been firmly in the hands the Basire family, for four generations.[43]

Competition among printers was fierce and the choice bewildering. The various editions of the *Berliner Adressbuch* are a good indicator of the makeup of the market in Germany. Its 1836 edition, the first to include professional categories in addition to the alphabetical address listings, names about 70 independent engravers and 38 independent lithographers, **(p.149)** in addition to half as many lithographic and copperplate printing agencies (cf. Table 5.1). The number of listed artisans and presses increased during the following decades, with the peak for copperplate experts around 1860, and for lithographers, between 1875 and 1890 (depending on whether one focuses on the agencies or independent professionals). The nascent field of photography was another factor in the market of illustration reproduction. Photographers first appeared in the Berlin directory during the early 1850s, and their numbers rose quickly, overtaking engravers around 1865.

Tab. 5.1 Statistics on Berlin lithographers, copper engravers, and photographers according to the Berliner Adressbuch, 1836–1905. The dash signifies the absence of that category in the relevant year.

	1836	’40	’46	’50	’55	’60	’65	’70	’75	’80	’85	’90	’95	1900	’05
copper plate press owners	31	42	44	45	54	60	53	45	-	40	16	20	-	17	21
copper engravers & etchers	73	82	98	83	83	82	73	66	41	32	36	28	18	26	13
lithographic agencies & inst.	18	24	46	71	91	141	192	238	204	254	293	359	357	206	185
lithographers	38	64	101	116	118	-	-	123	201	123	102	77	98	61	58
photographic ateliers	-	-	-	-	-	-	-	-	180	197	175	221	258	280	345

	1836	’40	’46	’50	’55	’60	’65	’70	’75	’80	’85	’90	’95	1900	’05
photographers	-	-	-	-	38	96	227	229	-	-	-	-	-	-	-
photomechanical printers	-	-	-	-	-	-	-	-	-	-	19	18	21	18	41

The distribution is similar but the totals are considerably higher in France. Parisian ‘graveurs’ fill 20 columns of the *Didot-Bottin* of 1860, each containing about 50 entries, and the 1888 edition carries 28 columns of about 40 listings each. Both these Parisian directories also identify roughly 100 lithographers in 8 1/2 columns and fill 11 1/3 with photographers, respectively. From a handbook on Victorian book illustration, we may infer that in London alone there were 367 registered printers in 1852; 1086 in 1876; and 1511 in 1900.[44] The following table (5.2) indicates that the number of Londoner lithographers rose sharply in the early 1860s and reached a plateau of some 400 in the mid-1870s. Thereafter it continued to inch upwards to its peak level of 474 in 1893, followed by a gradual decline due to the entry of techniques of photomechanical reproduction. The jump in the number of persons working in the printing trade between 1862 and 1876 is mainly explained by the lithographer figures during this period. Based on British census statistics and studies by social historians we know that about half of the artists, dealers, and engravers lived in that English metropolis in the early nineteenth century. In 1871, no less than 46% of all printers registered in the census for England and Wales were resident in London; by 1891, their percentage had fallen to 40%, but because of the general expansion their total number (including letter press printing, of course), had risen from 23 000 to 40 000 during these twenty years. In the heavily centralized countries of France and Austria, this proportion may be even higher. Germany and the US probably had somewhat less dramatic concentrations.[45] Nonetheless, in his comparative survey of photolithographic establishments in **(p.150)** Central Europe, Lieutenant James Waterhouse (1842–1922) reported: “there are several exceedingly clever photo-lithographers in Berlin and I found more established there than in any other city I visited.”[46]

Tab. 5.2 Statistical survey of various printers and engravers in London between 1852 and 1900 (the figure in parentheses actually relates to 1872). From Wakeman [1973] p. 15.

	1852	1862	1876	1880	1885	1889	1893	1896	1900
copperplate printers	55	64	126	90	83	75	73	68	66
lithographers	123	156	398	425	420	449	474	453	429
photolithographers		(5)	14	22	29	35		33	29
collotype printers							5	9	14
Photoengravers			1	8	13	36	67	89	94
Photozincographers			1					1	4
Totals	178	225	540	545	545	595	619	656	636

Despite their considerable numbers, practicing lithographers—in contrast to woodcut and copperplate engravers of the eighteenth century—did not enjoy the privileges of a guilded craft.[47] This explains the so much lower average wage of lithographers against that of their guild-protected competition. But between 1786 and 1855 even engravers (as opposed to etchers and artists) were not admitted into the Royal Academy of Arts. They were perceived as “mere copyists, lacking originality and thus excluded from the highest honors”.[48] To counter this common misconception of lithography, manuals like Charles Hullmandel’s went out of their way to emphasize the necessity for a good aesthetic sense and artistic skill in the manufacture of a print:

> a lithographic printer […] may be compared to an artist who is giving the last finishing touch to an Indian ink or sepia drawing; like the painter, the printer must study the effect of his drawings, and distribute his ink accordingly. If the light and delicate parts have taken too much ink, he must barely touch them with his roller, while the darker parts must be passed over several times.[49]

When Kirchhoff submitted his map to the Prussian Academy of Sciences in 1861, there was, nominally speaking, quite an ample choice of lithographers and engravers. In practice, **(p.151)** though, many lithographers concentrated on their own specialties. Nor did it escape the notice of their clients that lithographers “vary greatly in their capabilities”, and the best among them were in as high demand as any top-class engraver.[50] The lithographer chosen for the first imprint of Kirchhoff’s maps of 1861/1862, C. Laue, first appears in the *Berliner Adressbuch* for 1866 at the address Alte Jakobsstrasse no. 1. Between 1871 and 1885, he resided at Oranienstrasse no. 145 in Berlin (in the municipal district of Kreuzberg), around 1890 on the nearby Brandenburgerstr. at no. 25, and around 1895 at Prinzenstr. no. 23, a parallel street leading up to Moritzplatz.[51]

When looking for an engraver for his map of the solar spectrum in 1881, the observer at the Potsdam Astrophysical Observatory, Gustav Müller did not pick at random either. He chose Wilhelm Friedrich August Grohmann (1835–1918), who was already quite well known as a scientific illustrator for the Imperial Office of Public Health (kaiserliches Gesundheitsamt) in Berlin, for instance. In the early 1860s, Grohmann had lived at Se-bastianstr. no. 13—not far from C. Laue's first address. In 1865, he moved to Dragonerstr. no. 43, three blocks north of Alexanderplatz, in 1872 further north to Wortherstr. 8, and in 1884 to Linienstr. 110 where he remained until his name vanished from the directory a year after his death in 1918.[52] The relatively prominent medical illustrator Albert Schütze resided at Zimmerstr. no. 21, and is listed in the Berlin directory with the gloss "lithographisch-naturhistorisches Atelier" but later seems to have cooperated with a larger (chromo)lithographic institute.[53] Shortly before his death, he had advanced to co-ownership of a publishing house that specialized in printing and distributing brochures, located at Jostystr. 10. His private address was Breslauer Str. 33 in an artisanal neighborhood of central Berlin.[54] With one exception, the professional directory lists third-floor apartments for Laue and Grohmann—obviously not the *bel étage.* In the proverbial dinginess of Berlin tenament housing, the lighting was generally better on the upper floors.[55] Both competed for commissions as independent professionals against the many agencies, or Lithographische Anstalten. By 1872, in Berlin alone, there were 200 independent lithographers listed, along with 192 lithographic printing agencies and five shops specializing in **(p.152)** lithographic prints.[56] Contemporary statistics for 1875 give us a better picture of the percentages of large and small enterprises in the relatively new trade of photography, and the more traditional businesses of engravers, draughtsmen, and sculptors: As Table 5.3 shows, a total of 372 people working in photographic establishments was still a minority against the grand total of 2214 staff members in "artisanal enterprises for commercial purposes". Not more than approximately 7 % of the commercial establishments in either sector had more than five employees. Only 30 photographers, and about 123 other artisans were female; thus women comprised roughly 8 % and 5.5 % of these two fields, respectively, with an even lower representation at the managerial level.[57] By 1895 the total number of photographic establishments in the German *Reich* has risen to 3086 small firms (one or two persons), 1316 medium size, and 87 large establishments (with 11 to 100 employees).[58]

Tab. 5.3 Statistics on photographic agencies and the workshops of sculptors, engravers, and draughtsmen in Berlin. Managerial staff, employees and, finally, amanuenses, apprentices, and laborers, are categorized by gender, with their respective totals. The reference date is 1 December 1875. From Veröffentlichungen des Statistischen Bureaus der Stadt Berlin 1876, vol. LXXI, pp. 105–8. For similar statistics on Munich, also referring to the date of the business census of 1 December 1875, see Ranke [1977], p. 110.

Type of enterprise	Staff size	No. of enterprises	Managers		Employees		Other		Total	
			m	f	m	f	m	f	m	f
photographic agencies	≥5	7	11	0	11	0	60	15	82	15
	<5	141	153	4	-	-	107	11	260	15
artisal workshops	≥5	47	50	1	21	1	598	51	669	53
	<5	747	745	27	-	-	707	13	1452	40

Thanks to Prussian pedantry, we can check the social setting of all these professionals by consulting the street index in the Berlin *Adressbuch*, which lists house-by-house the businesses on all the major streets of Berlin. Thence we learn, for example, that all three of our print experts lived in the midst of other artisans: C. Laue's neighbors included a carpenter, a hatter, a physician, a salesman, an insurance agent, two pensioners, and the owner of a dyeworks. A. Schötze lived nextdoor to a book dealer, four salesmen, a plumber, a turner, a shoemaker, a bookkeeper, and an actress. W. Grohmann initially shared the same building with a carpenter, a shoemaker, a tailor, a former wheelwright, an ex-captain, a policeman, a salesman, a cathedral chorister, another retiree, and a widow. Between 1872 and 1883 he resided near two tailors, a metal turner, a milkman, a butcher, a nuncio, and a designer, moving upwards socially when he entered a neighborhood of real estate agents, managers, owners of grain and wine businesses, and schoolmasters in 1884.[59]

(p.153) Grohmann's case is particularly interesting because it was possible to find out a bit more about his professional career. This son of a university employee had received his training as an engraver and draughtsman at the Royal Academy of Arts in Berlin; he entered the Academy's preparatory classes *(Vorschule)* in 1850 and graduated in 1856. In later years, he regularly provided engravings for its annual exhibitions.[60] Both in engraving and etching, he seems to have favored the roulette technique. In 1882/83 he prepared a large number of color drawings for the first publication of the public health office in Berlin, at the instigation of its director, the Privy Councillor and pioneer bacteriologist Robert Koch (1843–1910).[61] When the position of head librarian at the Berlin Royal Academy of Arts became vacant in 1883, the historical painter and director of this institution, Anton Alexander von Werner (1843–1915), arranged to have his close friend Grohmann fill the position, at first as an interim solution but later with a fixed appointment. Thus, in 1883 Grohmann returned to his alma mater of thirty years.[62] Considering that he did not have any professional training in library science, his service as honorary librarian for the Association of Berlin Artists probably helped further his candidacy at the Kunstakademie.[63] A year after this promotion, the directory listing of our engraver, known in particular for his works using the roulette technique and for medical book illustration, indicated the new address. Linienstr. no. 110 (third floor) and the modified professional designation: "Kupferst[echer] u. Zeichner, Bibliothekar der kgl. Akad. d. Könste', which is the way it remained until 1918. According to a short obituary by the art historian Willy Kurth (1881–1963), who gave a vivid description of this odd character, Grohmann, a widower since 1886 (he had married Luise Hary from Stettin), bore a striking resemblance to types featured in paintings by Johann Peter Hasenclever (1810–1853):

> With Wilhelm Grohmann, whom many of his friends accompanied to his final resting place this Wednesday, traditional Berlin has lost one of its last originals. Born in Berlin in 1835, he became a copper engraver during the grand decades when reproduction engravings were still so celebrated, without it carrying him along to its heights. Only as librarian of the Academic institution [was he] able to shine as the marvelous original with whom younger generations might get a taste of post-revolutionary Berlin. He managed his office with all the virtues only he who considers a library a fine collection to be admired, not read, can cherish. He would call out scoffingly to the younger scholars: “Do you really want to read that book, well then, take it, there are pictures **(p.154)** in it too”. This banter may well have hit the mark. He had no need for reading. Two generations he had seen go by, a friend of Menzel and of Skarbina. And when dictionaries […] failed; one could rest assured of obtaining information from him about any Berlin artist—but it was a hard climb to his apartment.[64]

In acknowledgment of his “many years of loyal service” in managing the library, Grohmann was awarded the Royal Crown Medal 4th class in 1902, and the Royal Prussian Red Eagle Medal 4th class in 1909, both Prussian decorations usually awarded to civil servants and military men.[65] Grohmann’s career exemplifies the considerable social advancement open to print experts within their own educational institutions or through connections made during this formative period of their life. The engraver Pierre Dulos in Paris exhibits similar career traits, and the previously mentioned Aimé Henry was likewise promoted to a position as librarian, in his case at the German Academy of Scientists Leopoldina.[66]

It is remarkable that Kirchhoff submitted his spectral map to the Berlin Academy and not to the local Academy in Heidelberg, even though his Württemberg colleagues certainly would have done anything to accommodate their local hero. Was he merely attempting to express his thanks in this way for having been elected corresponding member of the Prussian Academy of Sciences in June 1861?[67] Or was he making use of this opportunity to gain access to the superior lithographers at the Prussian capital and to pass the considerable engraving and printing expenses on to the generously funded Academy? (Cf. here § 5.4 and the quote about Berlin lithographers on p. 150.) And why was a different printing agency, the Lith. Anstalt F[erdinand]. Barm in Berlin, chosen for the first reprinting of Kirchhoff’s map in book form?[68] The paper and print quality[69] clearly indicate that the remake is far inferior to the original—C. Laue’s work marks one of the high points in lithographic printing of nineteenth-century spectrum maps. Were independent lithographers unable to cope with the higher runs needed for commercial impressions?

In any event, the attractive pull of large urban centers was by no means less powerful than it is now. His Heidelberg colleague and collaborator Robert W. Bunsen chose lithographers far away from that southern German university town, namely, the Lithographische Anstalt of E.A. Funke in Leipzig and the Topographisch-literarisch-artistische Anstalt of L.C. Zamarski & C. Dittmarsch in Vienna,[70] respectively, for the engraving of his famous **(p.155)** maps of terrestrial spectra, which soon became icons of spectroanalysis.[71] Similarly, spec-troscopists at the Observatoire de Nice chose the established publishing house Gauthier-Villars which openly advertised its close connection to the École Polytechnique and the Bureau des Longitudes, two world-renowned institutions of precision measurement.[72] After some unsuccessful trials with photographic techniques, they turned to the lithographer C. Legros, who had done a beautiful job with maps of the ultraviolet region of the solar spectrum for Cornu in 1874 and 1880.[73] A Swedish instance of the attraction of big cities is Ångström's and Thalén's choice of Stockholm over Uppsala for the printing of their maps; their case is discussed in § 5.3. But beforehand, I would like to discuss the changes in the trade elicited by the rise of photomechanical printing techniques in the 1870s.

5.2 Photomechanical printing techniques

The aspiration to circumvent lithographic draughtsmen, engravers, or other fallible intermediaries between the observer's original representational device and the final print harks back to the very beginnings of photography (see here § 6.1). Yet the earliest photographs were not suitable for journal and book illustrations with higher runs. As Table 5.4 shows, between 1852 and the 1880s, some 10 different techniques were developed, a few of which managed to enter the rapidly expanding market, while others never quite made it past the experimental stage.[74] In the following, I comment particularly on the techniques that were used in the reproduction of photographic spectra, in the order of their chronological introduction into the production process.[75] Thereby I consciously bracket out the photographic processes used in generating the pictures in the first place, which is legitimate, I think, because the focus here is on printing technologies in their economic context. The interesting and complex science behind photographic techniques as such, and their impact on the research in spectroscopy, is postponed to the next chapter.

(p.156)

Tab. 5.4 Survey of photomechanical printing techniques in the order of their invention (for refs. see note 75).

Trade name	Inventor	Year	Essentials of the procedure
photoglyphic print	Talbot	1852	Light-sensitive bichromated gelatine first exposed through silk screen, then to sunlight through photographic positive
photogalvanography (heliotypography)	Pretsch	1854	Bichromated gelatine relief coated with graphite and then electrotyped to create copper-plated block
photolithography	Poitevin	1855	Mixture of gelatine, albumen, gum arabic, and potassium bichromate is transformed by light into a relief, then inked, and this image is transferred onto stone
photozincography	H. James	1855	Mixture of gelatine and bichromate of potash is exposed to light through photograph, the inked relief soaked in warm water, and then transferred onto zinc plate
photoglyphic engraving	Talbot	1858	Etched copperplate coated with gelatino-bichromate relief and melted resin dusting
carbon print	Pouncy	1858	Carbon-based asphaltum ink hardens on paper upon exposure; turpentine removes soft residue
autotype	-	1860s	Nongeneric term used by the Autotype Co. to signify both collotype and Albertype in the 1870s
collotype (photogelatine process)	Poitevin Window	1859/1869	Tanning of photosensitive surface hardened by exposure through negative which then absorbs greasy ink in proportion to exposure

Trade name	Inventor	Year	Essentials of the procedure
carbon transfer print	Swan	1864	Sandwiching of two layers (collodion and bichromated gelatine) stripped from its glass support after exposure; relief image allows continuous-tone development in copperplate press
Woodburytype	Woodbury	1866	Gelatine relief is cast in soft lead then colored with pigmented gelatine ink
Albertype	Albert	1869	Collotype replacing lithographic stone with glass plate coated with bichromated gelatine film
heliotype	Edwards	1871	Albertype with detachable thin gelatine film to substitute thick glass plate
platinotype	Willis	1873	Handprinted image is formed from photosensitive metal grain within the paper fiber
photogravure (heliogravure)	Klič	1879	Application of aquatint base to photoglyphic engraving for costly high-quality intaglio engravings
halftone	Klič *et al.*	1890s	Photogravure using halftone screen

These photomechanical processes may be categorized in different ways. One way is to sort them according to the traditional taxonomy of prints: relief, intaglio, planographic, and serigraphic. Thus all varieties of photoengraving are examples of the relief process, since the prints are taken off raised surfaces on a metal plate after the blank areas have been etched away. Photogravure techniques, on the other hand, are intaglio because the image is printed from the recesses etched into the metal plate. Photolithography along with its many variants of autotype and collotype are planographic techniques, because the printing face is chemically treated to gain lithographic qualities. Finally, the photographic stencil technique is serigraphic because it forces pigments through a stencil or screen.

(p.157) Another classification is by the various chemical processes involved. The first might be called the **bichromated gelatine group,** since the photogalvanograph, collotype, photogravure, Woodburytype, and carbon transfer print all rely on the action of light hardening a film of gelatine containing bichromate of potash as first used in Talbot's photoglyphic print. A warm-water bath then exposes a relief that is transformed into the printing block for printing continuous tones in various ways. The more prominent techniques forming separate groups of their own are the original carbon print and the platinotype print. Another categorization might be based on what role light exposure plays in the printing, whether it is applied for each individual copy or whether exposure to light is needed only once to create the printing matrix from which a large number of imprints can be run off by mechanical means. Strictly speaking, only the last category falls under the definition of *photomechanical* printing, as opposed to a *photomanual* one (such as the carbon print or the photolithograph).[76] Moreover, several of the earlier techniques may have been **polyau-tographic** in allowing multiple reproductions of the originals. But for most of the above-mentioned techniques, apart from the autotype class and photogravure, the technically feasible runs before the printing block begins to disintegrate from repeated subjection to pressure and friction remained disappointingly low. Consequently the originator of the carbon transfer print, for instance, never considered his technique a rival to the economically viable "printing press processes" but only an alternative to the usual photographic "silver printing" processes, which yield soft, halftone prints not subject to the fading suffered by the silver-based photographic print. Likewise the term 'autotype', initially proposed by the art critic Tom Taylor to designate all types of "reproduction of the artist's work in monochrome without the action of another hand or eye", should be reserved for photographic pictures individually formed on a gelatine film that has been acted upon by light.[77]

The Scot Mungo Ponton (1801–1880) noticed a discoloring of bichromated paper as early as 1839 but it was only a dozen years later, in 1852, that Talbot discovered the photosensitivity of a mixture of potassium bichromate and gelatine and was able to devise a workable technique with it, the **photoglyphic print.**[78] Talbot placed a transparent photographic positive onto a polished metallic surface coated with a layer of bichromated gelatine and exposed it to sunlight, causing the gelatine to harden in direct proportion to the incident light. Thus the image was reproduced in inverse proportion to the transparency of the photograph, which effectively served as a negative. The unexposed soft gelatine parts, protected by the darker areas of the image, could be washed away to yield a relief. This was then used as an ‘etching resist’, shielding the metallic plate against the corrosive action of the acid in direct proportion to its thickness. The result was that the darker areas of the photograph had thinner layers of gelatine which allowed the acid to attack the metal more **(p.158)** aggressively. For large areas of darker shades, though, the printer’s ink needed a textured foundation to prevent smudging. To achieve this Talbot hit upon the idea of first exposing the bichromated gelatine surface to light through a dense mesh of muslin or silk. So Talbot’s **photoglyphic printing** already contained the key elements of many of its later modifications, borrowing the basic idea of the cross-hatch in traditional copperplate engraving and foreshadowing the later use of the halftone screen. Then this surface was exposed through the photograph. **Photolithography,** for example, emerged from Alphonse-Louis Poitevin’s (1819–1882) discovery in 1855 that mixtures of gelatine, albumen, gum arabic, and potassium bichromate retain their ability to absorb greasy printer’s ink even after exposure to light while remaining repellent to water-based solutions. Bichromated potash is the key chemical ingredient for the formation of the relief by exposure to light, which is then used for transferring an ink image onto a lithographic stone.[79] Because these stones were quite cumbersome, especially in cartographic applications, lighter and cheaper surfaces like specially prepared zinc plates were also used, but the resulting prints never produced quite as delicate or sharp clean lines as lithographs off stone.[80]

Another variant, called **collotype,** can also be traced back to Poitevin, although this process became practical only toward the end of the following decade. The bichromated gelatine and albumen-gum mixtures shared the property of absorbing greasy lithographic ink in an amount proportional to exposure to light while repelling the ink on unexposed areas. This made it possible to print from the gelatine coating directly. But Poitevin himself and a few other printers encountered problems with the fragility of the thin gelatine film. It could tolerate only very low runs before disintegrating or coming off the printer’s block. Furthermore, the manual production of collotype prints was slow before rotary lithographic processes were adopted in the 1870s. A modified form called **Albertype** was then developed by the Munich court photographer Joseph Albert (1825–1886) and patented in November 1868.[81]

Bavarian patents were valid for only two years in a row, requiring regular applications for extension. Because Albert missed a deadline, his German patent ceased in November 1874. Edward Bierstadt's New York-based Photo-Plate Printing Company initially was the sole proprietor of the American patent, but in 1872 it was bought by the Albertype Printing Company in Boston.[82] By 1875 it had been acquired by the Forbes Lithograph Company **(p.159)** in the same town, which retained the trademark Albertype until the turn of the century, although closely related printing techniques were also practiced under different trade names (such as artotype, autotype, heliotype, indotint, or phototype) by other companies.[83]

Fig. 5.2 Photograph of the interior of Joseph Albert's Munich Printing House (Lichtdruck-Anstalt), Atelier Briennerstr. 38, circa 1869/70, showing various ink rollers on lithographic stones ready for printing on the rolling press in the center. To the left directly against the wall we see the stands for the thick glass plates needed for Albertype prints, and a storage area for more ink rollers and various photographic chemicals, some of which have to be stored in the light-proof cupboard in the back. Notice how well the workshop is illuminated by the huge windows opening northwards. Albertype reproduction. From Stein 11877] pl. II.

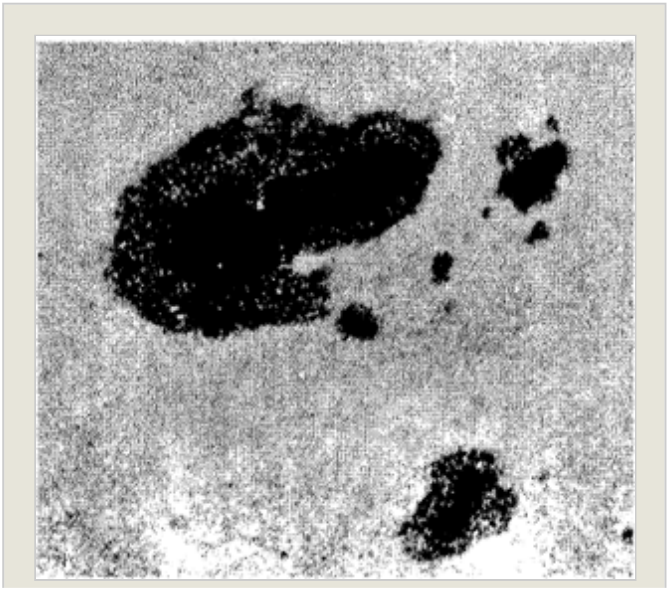
Instead of working with a thin gelatine relief on a metal surface, Albert used a thick glass plate coated with two layers of bichromated gelatine, the first of which had been pre-exposed, to ensure adhesion. After exposing such a plate to light from behind through a negative, and subsequent rinsing in cold water in order to wash out any superfluous chro-mate salts, the glass plate with its firmly affixed gelatine layer could then be used as a printing block, replacing the normal lithographic stone. The fully exposed parts of the layer, corresponding to the darkest shadows in the original, were totally water repellent and would thus take most of the greasy lithographic ink: those areas not hit by light during the exposure, i.e., the darkest ones on the negative, would absorb more water and thus repel **(p.160)** the ink. The intermediary exposed parts absorbed the ink in direct proportion to the degree of exposure, so Albert was able to obtain high-quality prints with subtle halftones and without any grain. And—unlike photographs on a silver basis—they did not fade over time. As a contemporary printer assessed in 1872: “Some of the results produced by Herr Albert are most beautifully soft and delicate, but the whole are wanting in strength and robustness, and the process seems unsuited for the production of lines or subjects where firmness and strength are required.”[84]

Because the glass plates tended to fracture during the Albertype process, the London printer Ernest Edwards (1837–1903) developed a variant called **heliotype.** In this process the gelatine's pores are closed by means of a chrome alum mixture, which transforms it into a "tough, tawny, insoluble substance, like leather or parchment, capable of standing an apparently unlimited amount of rough usage" without thereby losing its photosensitivity, provided that bichromate of potash is admixed. A thin film of this 'waterproofed' gelatine was produced by pouring it over a carefully leveled waxed surface, which allowed easy removal once the film had dried. Formerly, it had been difficult to close the gap between the gelatine-coated glass plate and the negative completely. These films "of the thickness of stout paper", on the other hand, adhered perfectly to photographic negatives and could thus be exposed to the light without any loss of definition. In the next step, the exposed film was brought into contact with a metal plate (usually zinc or pewter) while immersed in water; the remaining water pockets between the film and the metal were squeezed out by mechanical pressure and the superfluous bichromate was washed off in warm water. Now the plate with its attached relief film was ready for the press which, according to Edwards, could produce runs of up to 1000 or even 1500 copies "without the least loss of quality".[85] As the heliotype process yielded a daily rate of 100–500 impressions per printer, it was a competitive alternative to lithography, particularly for low runs. One could save on the costs of a lithographic draughtsman, although it would "probably not be so cheap for large numbers". The comparatively simple sequence of mechanical manipulations needed to produce the printing relief prompted Edwards's praise as "of course, infinitely cheaper than any photographic or carbon process, or any other photomechanical process."[86] Towards the end of the century, before the advent of the halftone process and offset lithography, the various versions of collotype prints were most widely used for the reproduction of photographs.[87]

Another branch in photomechanical printing utilized the electrolytic process to galvanize the relief surface. The relief is composed of chromated glue or gelatine chromate and is formed by the methods already discussed. The idea of first treating the relief surface with tannin or another astringent to cause a corrugation or crinkling of the ink-carrying surface before fixing it with a galvanic deposit—which at the time was already a common procedure in the electrotyping of hand-drawn engravings—was first employed by the Viennese **(p.161)** printer Paul Pretsch (1808–1873) for the reproduction of photographs.[88] He had left a lifetime position at the Viennese Imperial and Government Printing Office in 1854 to work independently in England on developing his ideas. There he patented the process called **photogalvanography** in the same year and founded his own company a year later. Despite bad luck, economically speaking, which led to the bankruptcy of the Photo-Galvanographic Company and to the loss of his patents, his 'photo-electrotypes' held their place especially for 'line matter' and in map production, which is of central interest to us.[89] Pretsch's case is noteworthy because he established contacts with one of the leading scientific photographers of the time, Warren De la Rue (1815–1889). In 1862 De la Rue published a brief note on 'heliotypography' in the *Monthly Notices*, which he illustrated with a plate reproducing his photograph from 1861 of two groups of sunspots, printed—as the caption informs us:[90]

> "at the ordinary typographical press from an electro-copper block, obtained from the original negative by means of light and electro-metallurgy. Absolutely untouched by the Graver".

A slightly enlarged detail from this plate in Fig. 5.3 shows that the reproduction does set off the dark umbra in the center from the less dark penumbra, and the much brighter solar surface around the spots. However, it also shows superimposed structures related not to the photographed object but to the reproduction technique itself. De la Rue commented:



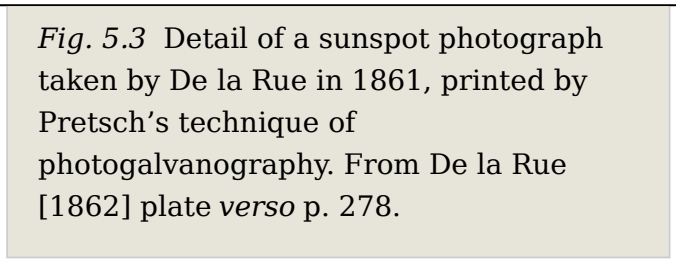


Fig. 5.3 Detail of a sunspot photograph taken by De la Rue in 1861, printed by Pretsch's technique of photogalvanography. From De la Rue [1862] plate *verso* p. 278.

> On observing the impression at a little distance from the eye, a sort of mottling will be perceived on the bright parts of the picture; this is a true representation of the sun's surface; on the other hand, an examination of the picture by means of a magnifier will show a vermicelli sort of granulation, which does not belong to the sun, but results from the process and arises from the change which takes place in the gelatine film passing as it were from the gelatinous or dynamic condition to the cristalline or static condition of matter.[91]

(p.162) De la Rue tried to downplay this shortfall in the new printing technique's rendition of the photograph, by pointing out that "the grain may be made coarser or finer and need in no way interfere with a picture more than the lines of a steel plate or the grain of a lithographic stone interferes with pictures engraved on the first or drawn on the second".[92] But this plate was quite certainly the best that could be achieved by Pretsch's photogalvanog-raphy at the time. Two years later, another photomechanically reproduced plate appeared in the *Monthly Notices*, showing the lunar surface. Again printed by Pretsch, this time it was done by a slightly modified technique known as **photoengraving.** Whereas photogal-vanography creates a *relief* image from which the print is made, here, as in typography, an *intaglio* process is obtained by printing "from the *recesses*, as in ordinary copper-plate printing (*taille-douce*)."[93] The minute mottling of the surface did not disappear, however, and new drawbacks emerged, such as a nearly total loss of halftones. Finally, this plate exhibited many areas (e.g., along the Moon's rim, but also in the dark background) where an engraver had obviously manually retouched the printing block. As another practitioner wrote in 1872, "it was found, in practice, that so much work was necessary to prepare the electrotype-plate for printing, that it became almost equivalent to an entirely new engraving."[94]

Pretsch's version of photoengraving as well as Fox Talbot's description of **photo-glyphic engraving** from 1858 are early examples of efforts to find printing processes "wedding engraving to photography".[95] Talbot etched a copper plate coated with the usual solution of gelatine and bichromate, treated chemically to bring out the relief. It was then dusted with a thin layer of resinous powder and heated to distribute it evenly over the gelatine surface (somewhat analogous to the aquatint grounding in lithography). This is followed by an application of the etching liquid, such as iron chloride, which attacks the metal plate in proportion to the thickness of the complex coating.[96]

Talbot's technique was particularly suitable for representations of landscapes and architectural motifs, owing to its soft gradations of shade. However, it only gained popularity with the improvements introduced by the Czech Karl Klič (1841–1926), occasionally spellt Klietsch), which made it more reliable and efficient and better suited for extended inked areas. Klič's method of **photogravure** consisted in applying an aquatint ground of powdered resin to a copper plate coated with photographically prepared bichromated gelatine. Microscopically examined, the etched plate thus exhibited an irregular surface of tiny spots whose physical depth correlated with the degree of darkness in the original. The image was then developed in warm water to set the relief, and finally the surface was etched with iron chloride solutions of varying concentrations, so that the various halftones of the original were translated into layers of different depth in the printing block.[97] The resulting rich **(p.163)** halftones soon won it praise as "the most beautiful of all photomechanical processes", but until the 1890s photogravure was also the most expensive, since the production of "one photogravure plate cost as much as the printing of a whole edition of the same picture by one of the other reproduction processes."[98] The competitiveness of this reproduction technique improved when, around 1890, Klič introduced the rapid method of rotogravure printing from cylinders and also implemented cross-line screens similar to those now still in use for the production of halftone prints.[99]

In the improved **halftone engraving** process,[100] a finely ruled cross-line halftone screen is interposed between the photographed object and the camera. The dots into which each picture is decomposed falls below the threshold of vision at normal distances and can be seen only by very close or microscopic inspection of the print. Consequently, this technique has been hailed as "the most valuable" of all photomechanical reproduction techniques dispensing with the traditional engraving 'syntax' (such as cross-hatching, stippling, etc.).[101] But even at this sophisticated level of photomechanical reproduction, towards the close of the nineteenth century the constraints on photoengraving had by no means completely disappeared. According to a letter by George Ellery Hale, editor of the *Astwphysical Journal*, not just any photograph submitted by authors for publication conjointly with their papers could be printed: "The photo-engravers always ask us to send highly finished prints, as in this case there is practically specular reflection of the light from the surface of the print, while in the case of dull surfaces the light is uniformly diffused and part of it enters the copying camera. If you can send hereafter "squeegeed" prints, I shall be glad to use them whenever possible."[102]

5.3 Transfer of skills from topographic to spectrographic maps

Ångström and Thalén in Uppsala chose the lithographers Schlachter & Seedorff in Stockholm for several of their spectral maps between 1865 and 1875. The famous Ångström map of 1868, however, bears the insigne: “Gen.stab.Lith.Inr.” This indicates that it was engraved at the ‘Generalstabens litografiska inrattning’ in Stockholm, the topographic mapmakers for the Swedish military. This institution had its origin in the litografiska tryckeri, the lithographic printing agency founded in 1827 by G.L. Dreyer. After 1833, it was upgraded with Swedish state funds and in 1834 was converted into the state-controlled Litografiska tryck-eriet vid Generaladjutantens för armén, and renamed in 1837 Generalstabens litografiska **(p.164)** inrättning. When in 1874 all official mapping activities in Sweden were reorganized under the guidance of the General Staff Topographical Division with its headquarters in the capital Stockholm, the Generalstabens litografiska anstalt became Sweden’s main lithographic printing house.[103] So Ångström was able to tap into the resources of the military, whose specialists had developed lithographic skills for ‘mapping’ in a much more literal sense than our spectral plates. These draughtsmen came from the Topographical Corps that had been set up in Sweden in 1831 as a specialized unit within the Corps of Engineers formed in 1811.[104] In the 1860s this transfer of resources to civilians did not present the problem it would have four decades earlier when the military kept all the processes used in engraving and printing its 1 : 100 000 topographic map series strictly secret.[105] Whereas this particular Swedish map series was still printed from engraved copper plates, the British Military Depot of the Quarter-Master General’s Office were already emersed in the rival technology of lithographic printing: between 1808 and 1825, the number of copies of maps, schedules, circulars, and miscellaneous forms printed lithographically by a single draughtsman, four printers, and one laborer, came to nearly 170 000.[106] I don't know of any historical study on the training of these cartographers, draughtsmen, engravers, and printers, but a glimpse at the curricula of contemporary training schools and academies for the graphic arts confirms my thesis that these skills came in a package that made transferral from cartography to spectroscopy conspicuously easy. Wilhelm Grohmann, for instance, whom we have met above as one of the Berlin specialists for spectrum maps, had been trained at the Berlin Royal Academy of Arts and Mechanical Sciences. Its curriculum included sketching, reproduction of oils by drawing and painting, geometry and perspectival drawing, sculpting of statues from Antiquity, and most significantly, projection drawing and copperplate engraving of maps.[107] The skills of drawing and engraving learnt at these institutions with such exercises as topographic maps and various artisanal motifs were easily applied to the new topic of spectra.

(p.165) In a later period, the astrophysicist J.N. Lockyer asked his friends at the Chatham School of Military Engineering,[108] where Captain W. de W. Abney had been teaching since 1869 and was Assistant Director of Science from 1877–1899, to help him with photographic enlargement of his spectrum photographs and reproduction of the finished maps. These friends in turn had good connections to the headquarters of the Ordnance Survey, originally established in the Tower of London but relocated to Southampton since the great fire of 1842.[109] The local experts of the Corps of Royal Engineers were well-versed in photography, engraving, and in particular in zincography and electrotype processes regularly used in the production of topographic maps.[110] They were also particularly well equipped with special apparatus normally used for distortion-free enlargement and reproduction of topographic maps. Thus another link between mapping the spectrum and cartography is established. In 1880 Corporals Murray and Ewing at the School of Military Engineering in Chatham[111] did most of the photographic enlargements and the final photographic reduction of Lockyer's hand-drawn map, to a scale appropriate for replication in the *Philosophical Transactions of the Royal Society*, in which plates only very rarely exceeded the format of two quarto pages.

The following Fig. 5.4 shows a cartographic camera that could be moved along rails on its massive steel support to adjust the distance between the photographic plate at the left end of the camera and the original map to the right on the easel. Usually installed indoors to shield the camera against the weather, daylight was guided onto the map from above, in some cases also from below with the aid of additional mirrors.[112]

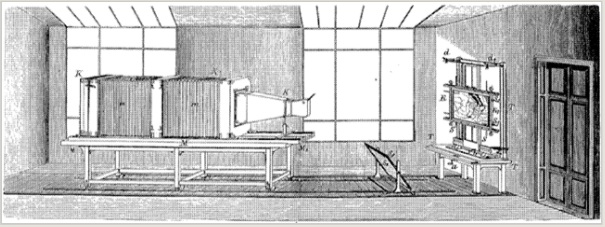


Fig. 5.4 Cartographic camera in use at the Vienna Military-Geographic Institute. From Volkmer [1885] fig. 1.

(p.166) With the aid of such cartographic cameras, a master copy of the map in question, very often a lithographed map, was duplicated much faster than was possible by traditional methods. It had the additional advantage that enlargements of critical sections or selections of certain relevant parts of a bigger map could also be done with the same apparatus and the same master copy after only a few minutes of refocusing. A new enlarged lithograph would have taken weeks or months to prepare, depending on the size and quality needed. As historians of cartography have pointed out, "the first applications of repro-cameras to map reproduction was the production of photographs of maps and *not* the production of photographically obtained master plates or stones from which to print them."[113] But the next transition towards photolithographic reproduction of maps in large numbers was already underway, pioneered by the Austro-Hungarian ordnance survey map comprising 715 plates printed as heliogravures.[114]

This instance of Lockyer's map being reproduced at such an establishment shows that the 'spectrum mappers' simply tapped into existing resources and skills, and adapted them accordingly. The earliest link between spectroscopists and cartographers that I am aware of is the friendship between Fraunhofer and Pater Udalricus Riesch, who had been a map-maker at the Benediktbeuern monastery in southern Germany and later became Fraunhofer's co-worker at the Optical Institute.[115] We know of various other scientists working in spectroscopy who had a strong interest in cartography, mineralogy, and geology, and actually took part in geological excursions,[116] but hitherto no connection has been made between these side activities and their spectroscopic work—or their visual style of thinking.

Among my spectroscopists, Karl Hofmann personifies the strongest link to the geosciences and the centuries-old tradition of mapping terrain. As a student Hofmann assisted Kirchhoff in plotting the map of the solar spectrum. A son of a mine owner, Hofmann had focused his studies on the geosciences from the very beginning, not on physics or chemistry. After his Ph.D. in Heidelberg, Hofmann accepted a professorship for mineralogy and geognosy at the Ofner Polytechnic in 1864. Five years later he was hired as second geologist at the newly founded Royal Hungarian Geological Institution, advancing to chief geologist in 1872, which position he retained until his death in 1891.[117] Hofmann was responsible for the geological mapping of various regions in Greater Hungary and published prolifically during the 1870s and 1880s. Many of his publications include folio-size plates—several of them even chromolithographs—with topographic maps, profiles, or drawings of mineralogical or paleological specimens. In a way, Hofmann's trajectory thus illustrates the feedback **(p.167)** to other sciences of the visual culture of spectroscopy, in which he was trained.[118]

Another compulsive map maker bridging the gap between geography and astronomy was the Victorian astronomer and science popularizer Richard Proctor. Proctor has recently been described as “the most widely read astronomical author in the English-speaking world” in his time. His popular books, bearing titles like *Other Worlds than Ours* (1870), included maps of various astronomical objects. The surface of Mars was one, based on earlier drawings by the astronomer William Dawes (1799–1868). But Proctor’s rendition went into much greater detail, identifying continents—labeled, incidentally, with the names of famous astronomers, not statesmen—and applying the familiar representational modes from geographic maps of the Earth, that is, drawn both in the stereographic manner and in Mercator’s projection. Proctor argued that his designation of various Martian regions as land, water, or ice was supported by Huggins’s recent examinations of the spectrum of Mars. Huggins had shown that the Martian atmosphere contained gases and vapors similar to those present on Earth.[119] This visual rhetoric was bolstered by a three-dimensional model. The London instrument maker John Browning, whom we had met earlier as the supplier of the finest spectroscopes in Britain during the 1860s, built a globe of the red planet that emulated a terrestrial globe. When it was exhibited at a meeting of the Royal Astronomical Society in 1868, small numbers of them were sold, along with many more, comparatively cheap stereoscopic photographs. The results of stellar spectroscopy thus began to leave their imprint on public perception.[120]

The business relationship between the Astronomer Royal for Scotland, Charles Piazzi Smyth, and the printing house W. & A.K. Johnston in Edinburgh constitutes one more example of strong ties between spectroscopy and the geosciences. This printing establishment, founded in 1826, not only prepared Smyth's many lithographic plates of solar and gaseous spectra for the Edinburgh *Philosophical Transactions*, but also drew up most of the official atlases of the Great Kingdom, such as the National Atlases of 1843, Humboldt's Physical Atlas of 1848, the Royal Atlas of 48 maps sized at 19.25 × 24 inch in 1861, and its sequel the Handy Royal Atlas. All these maps were destined for the American edition of the *Encyclopœdia Britannica* in 1898, and there were many more. In fact, soon after the company's establishment in 1826, geographic map production had become the "main concern" of Alexander Keith Johnston (1804–1871) who personally engraved most of the 45 maps of the National Atlas of 1843. Eventually he was elevated to the status of "Geographer at Edinburgh in Ordinary to Her Majesty", and the firm was appointed "Geographers to the Queen". His brother William Johnston (1802–1888) was appointed "Engraver and Copperplate Printer to the Queen" in 1837.[121] In quantitative terms, therefore, the occasional spectroscopic map printed for the Edinburgh *Philosophical Transactions* was only a marginal affair for this printing house. It is inconceivable that they would not, as a matter **(p.168)** of course, transfer the techniques used in their routine printing of geographical maps to this other task as well. The same is true of Stanford's Geographical Establishment, which were also responsible for lithographing Capron's map of the rainband (cf. here p. 107).

From a practical point of view such a transfer was straightforward, since both topographic maps and spectrum maps consisted to a large extent of 'line matter'. The machine depicted in Fig. 5.5 had been designed for the ruling of parallel and equidistant lines onto a lithographic stone,[122] but it could just as well have been used for spectroscopic line patterns. Their interstices could be precisely mapped onto the stone through adjustment of the micrometric screw (on the right side of the figure), which sets the position of the ruling head over the lithographic stone.

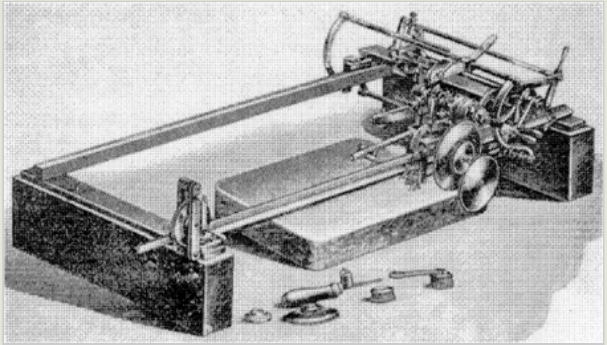


Fig. 5.5 Ruling machine for precision drawing of parallel line patterns, as used in cartography. From a contemporary advertisement.

Another way to transfer a final drawing to a plate of the same size was to affix the drawing firmly onto the copper plate and then pierce markings through the paper for each line. We have descriptions of this procedure for some of the older geographic maps, and at least one such perforated manuscript seems to have survived,[123] but I have never seen a similarly perforated spectrum drawing.

At least two of the engravers whose names are familiar from our discussion of the printing of spectrum maps, namely P.E.S. Dulos and J. Basire, made such maps literally alongside their geographic and topographic projects.[124] The Parisian engraver Dulos will exemplify this link in more detail. Aside from his mappings of the French waterways, irrigation systems, and hydraulic plants for the Ministère des Travaux Publics, Dulos also had running contracts with the Commission des Ports de France concerning copperplate engravings of topographic maps for the *Atlas des Ports de France*; with the French Ministry of War for topographic maps of the French Départements; and with a London-based **(p.169)** Company concerning the preparation of plates for bond securities by the Ottoman Railway.[125] The final maps were published in the large folio-size (A2) atlases for the Ministry of Public Works: *Atlas statistique des cours d'eau, usines et irrigations*, printed in Paris by the Imprimerie Nationale in 1878; and *Atlas des Ports de France* printed by the Parisian Imprimerie de Sarazin, between 1873–1897.[126] Presumably it was in acknowledgment of his involvement in the production of topographic maps, which certainly were of prime importance to the French military, that Dulos received the distinction of ‘Chevalier de la Légion d’Honneur’ on 30 June 1867.[127] Dulos’s relationship with the French Ministry of War and the harbor commission for topographic work is as good an instance as it can get for my general argument of a close link between cartography and spectroscopy, as far as the production of spectroscopic atlases is concerned. This transfer was facilitated by the fact that when signing contracts, many of these engravers, lithographers, and print experts did not confine themselves strictly to their specialties. The Johnston brothers in Edinburgh had their supporting leg firmly planted on topographic map making, others like Aimé Henry in Bonn lent on natural history, while others like Dulos readily changed their sujets with their clients. Such flexibility provided an inventory of patterns commonly found in fields as diverse as architecture, perspectival drawing, artisanry, commercial advertisement, cartography, etc., making a transfer of representational techniques—along with their visual analogies (cf. here § 10.6)—from one domain to another considerably easier.

5.4 The economy of the printing trade

Historians of cartography have occasionally unearthed documents allowing inferences about the wages and average productivity of engravers and printers of cartographic maps between the seventeenth and the nineteenth centuries.[128] A first rule of thumb is that anyone commissioning a larger topographic map, usually the sovereign, had to expect to pay at least half as much again of what had already been spent on the surveying in order to have it printed. Aside from intentional secrecy surrounding many older maps, this financial aspect was one of the main reasons why so many maps were never printed. Given the case that a copperplate engraving was what was wanted, one had to be prepared to pay compensation **(p.170)** four times the average income of an employee in the book trade. This wage was unusually high for most other artisans and a lot of time was needed for such a map as well. Usually a small group of engravers worked on one or more plates simultaneously: one specialized in the captions and lettering, others concentrated on topographic features, relief, or outlines, yet others on ornamentation, etc. The level of productivity depended, of course, on the complexity of each map, with averages between 15 and 150 cm^2 per day. A map of a densely populated city, for instance, has a complex relief requiring many more hachures than a marine or desert region. Even under extreme time pressure (such as in times of war) a more complex large map could scarcely be engraved and printed in less than two weeks, with several months being a more likely average.[129] The relation between the price of a map and an engraver's fee likewise fluctuated between 1 : 60 and 1 : 435, with more expensive maps needing higher print runs of 500 or more just to cover the engraving costs. From a bill by an academy geographer for a map made in 1793 we can infer the relative expenses incurred by the production of such a map around the end of the eighteenth century.

Tab. 5.5 The various expenses connected with the production of a geographic map in 1793. The expenses are given in Thaler (Th) and Groschen (Gr). For comparison: the annual income of a Prussian professor was between 1000 and 1500 Thaler, and approximately 200 Thaler for a skilled map engraver. From Jäger [1980] p. 125.

	type of work	expense	%
1	drawing	153 Th	11 %
2	engraving	690 Th	49 %
3	paper	114 Th	8 %
4	printing 1500 copies of 6 sheets @ 35 × 25 cm	56 Th 6 Gr	4 %
5	flattening (7 Gr @ 100 sheets)	26 Th 6 Gr	2 %

	type of work	expense	**%**
6	hand coloring (1500 sheets 4 Gr.)	250 Th	18 %
7	shipping and storage	125 Th	9 %

Table 5.5 shows that the actual copper engraving constituted nearly 50% of the total production costs. Lower print runs added to the percentage taken by the paper. The three plates accompanying Fraunhofer's famous paper from 1815 on the determination of refractive indices are an example. The optician forwarded the following bill to the Academy:[130]

Paper for 412 copies of copper prints and 824 copies of plain prints, as per invoice	50 fl 17 kr
printer's wage for 412 copies of copper prints, as per invoice	12 fl 28 kr
printer's wage for 824 copies of plain prints, as per invoice	22 fl 39 kr
Indian-ink wash [*Tuschen*] of 412 copies copper prints, as per invoice	26 fl 47 kr
	112 fl 4kr

(p.171) This bill did not include charges for the actual engraving of the copper plates, because Fraunhofer had done that himself. With such high engraving and hand-painting costs, it is no wonder that new techniques were sought. As discussed above, lithography was the first real alternative to copper etching and engraving. Apart from the greater range of drawing techniques available to lithography, it also enjoyed some commercial advantages:

- It took far less time to prepare the engraving (just one or two days for a normal lithograph in contrast to five or six days for a copper engraving).[131]
- Printing was about three times faster (owing to the time-consuming removal of surplus ink after each copper-engraved impression).[132]
- The stone could withstand considerably higher runs than a copper plate. It had an average maximum of about 1000 copies,[133] whereas "a copperplate with a moderately fine ground will furnish 150 good impressions, and may be made to give 500, by alternately touching up and printing by fifties."[134] Higher runs could be achieved by hardening the plate electrochemically by means of a galvanic process, but this was at the expense of the finer details on the plate.[135]

• The average wage of a lithographer was c. one fourth less than that of an engraver.[136]

Because of the substantial reduction in working time and hence wages, lithography could also be used for printing specialized material for which there was only low demand. For instance, in the 1850s a large-scale Irish topographic survey of many thousand sheets, for which only a few takers could be expected, could be printed in lithographed form. According to contemporary calculations, the sale of only 30 copies already covered the production costs. An engraved map would certainly not have been able to make itself profitable.[137]

For the early nineteenth century we have reliable information about engraving costs within the American, German, and British contexts. To start with the United States: At the beginning of the nineteenth century a copper plate cost $5.66 each, the engraving work anywhere from $50 to $80, depending on the engraver's reputation, and hand-coloring would add another 25 cents per printed sheet. Nevertheless, 542 copper plates were included in the first American edition of the *Encyclopœdia Britannica*, printed in Philadelphia between 1790 and 1797.[138] The substantial risk involved in such a great investment may well be **(p.172)** reasonable for a general reference work, but it was out of the question for more specialized publications, which were consequently less generously illustrated.

One might expect that the introduction of steel plates as a substitute for copper would cause the plate prices to fall, but this is not so. In the mid-nineteenth century, steel of sufficient purity and homogeneity to be suitable for polishing and engraving was quite difficult to manufacture so that, unlike today, steel plates were actually more expensive. We have comparative costs of both types in 1861 in Scotland (cf. Table 5.6): Steel plates were about four to five times as expensive as copper plates.[139] They were thus only feasible for very high printing runs that a copper plate would not have managed without a substantial loss in quality. Hence the cost of reengraving or restoring the copper plate would be saved.

Tab. 5.6 Cost comparison (in pounds sterling, shillings, and pence) for copper and steel plates of various sizes (in inches), based on Scottish values in 1861.

Quantity and type	Size	Cost
1 doz. copper plates	5×4	13s
1 doz. copper plates	4×3	8s
2 doz. steel plates	5×4	£3
repolishing 3 copper plates	4×5	1s, 8d

Quantity and type	Size	Cost
repolishing 1 steel plate	4×5	1s, 3d

Lithographic stones, on the other hand, were cost effective from the very outset because they just had to be broken into manageable slabs at the quarry, transported to the printing center, and then polished on site. Their considerable thickness of over an inch meant that they could be reused many times over before becoming too worn to withstand the high pressures in the press.[140] In the *New American Cyclopedia* of 1875, the cost of lithographic plates is estimated to be less than 1/3 of that of copperplate engraving, and it is claimed that from one stone 10 000–12 000 impressions may be taken without loss in quality. Further down in the same article the average run estimates are specified in more detail:

> the number of perfect copies obtainable from crayon drawings upon stone is from 500 to 1,500. Fine ink drawings furnish about 6,000, and those in coarse lines have afforded as many as 80,000 without deterioration. Transfers from steel and copper plates and engraved stone to plane stone yield from 1,000 to 5,000 prints, varying with the quality of the drawing.[141]

An exchange of letters between a British engraver and an astronomer concerning the production of plates taken during a solar eclipse expedition reveals that around 1870 the manufacture of 1000 prints from a steel-engraved plate cost about £46: between £25 and 30 for the engraving, compared with £7 for a lithographed plate, and £10 for the actual printing run of 1000 copies. This is compared to about 30 shillings for a small wood engraving that could be inserted directly as an in-text illustration.[142] Anthony Dyson provides **(p.173)** the most detailed documentation of the various expenses involved in nineteenth-century engraving and printing. He based his fascinating account, *Pictures to Print*, on the surviving ledgers, delivery books, day-books, wage books, and correspondence of the London printing houses McQueens and Dixon & Ross, copper and steel-plate printers since 1833.[143] Charles Booth’s study *Life and Labour of the People in London* provides supplementary data particularly on wages, based on the census of 1891. His statistics indicate a broad income range between roughly 20 shillings a week (only 4 % of adult men earned incomes lower than that) and 45s (with 18 % even higher), with the highest percentage of printers (27 %) in the bracket between 35 and 40s a week. Unfortunately, his statistics are averages for printers of widely different specialties and qualifications, but those working on spectrum representations were most likely in the two or three uppermost wage categories. This would correspond to social living conditions with typically 1 person per room (or less), an average of more than 4 rooms per family, 4 or more persons to a servant, and preferential living areas spread throughout the outskirts of London, South-East London, with Walworth being the favored district.[144]

As already discussed in considerable detail in § 5.2, the rise of photomechanical printing techniques, in particular various types of collotypes, from about 1870 on, fundamentally changed not only the aesthetics, but also the economy of the printing trade. Focusing on the latter, Helena E. Wright has stated that “in the 1870s and 1880s, before the development of rotary gravure printing and the halftone screen, collotype provided the fastest and cheapest continuous-tone reproductions for small editions. […] Photogravure plates, although equal to collotype in image quality, cost more to produce and did not become competitive economically until the edition size reached several thousand”.[145] This was, of course, hardly the case for representations of spectra. Most of this efficiency stemmed from the fact that collotype plates could be produced in an hour or so and still be far better at rendering halftones than, say, wood engravings which took hours if not days to carve, while copper and steel engravings took even longer with the associated higher compensation costs in addition. The one serious disadvantage that each plate could produce only a limited number of impressions, between 1500 and 2000, could be circumvented by printing from secondary negatives which also made it feasible to work with duplicate plates at the same time to speed up the printing of higher runs.[146]

I discovered reliable figures for American production costs of photographic plates from the early 1870s into the late 1880s. In 1873 the New York printer Edward Bierstadt agreed a price of 5 cents per 9.5 × 12-inch sheet at an estimated run of 5000 copies.[147] Over the next fifteen years, the price seems not to have changed very much. When in 1888 Edward Charles Pickering ordered from the Artotype Printing Company in New York 1000 copies of a plate in the quarto format of 10 × 12 inches for the second report of the Draper memorial, he had to pay $48 for this photomechanical reproduction of one photograph **(p. 174)** (that is, nearly 5 cents a copy), even though the glass plate with the stellar spectra had been prepared at the Observatory “ready for reproduction on paper by some of the modern processes of photographic printing”.[148] Prices of the same order of magnitude are also charged by Frederick Gutekunst in an advertisement from the year 1881.[149]

These economic factors, along with the constraints of the minimum quality required to fulfill the purpose of a particular illustration, heavily influenced or ultimately determined the choice between lithography and one of the many rival printing techniques. I know of only one area in which statistics have been compiled on the relative preferences among the various techniques, and that is Geoffrey Wakeman's illustration count from 1200 art books at the Bodleian Library for the years 1850–1900.[150] Accordingly, woodcut and wood engraving ranked number one until c. 1880 with nearly 30 % in the decade 1850–1860, decreasing to roughly 25 % in the period 1871–1880; but throughout these years it was followed by lithography as a close second. This reproduction technique occupied c. 25 % in the 1850s and c. 15 % in the 1870s, rising to a maximum of 25 % in the period 1881–1890 only to fall back to less than 10 % in the 1890s. Because of substantially higher costs, chromolithography always took a minor place among reproductions, covering not more than roughly 10 % of the total production in the 1850s, and then steadily declining to roughly 3 % in the 1880s.

According to the historian Ian Mumford, "a great deal of work remains to be done on the trade directories of the period to establish who were the lithographers and lithographic printers, as a basis for searching 'author' or other 'name' catalogues in map collections to see if they were responsible for any maps at all. Lithographers considered as printers do not always get mentioned in map catalogues, even if their name appears somewhere on the map."[151] I could not agree more: for the purpose of research on visual representations in the history of science we need a systematic prosopographic study of the print experts engaged in the production of maps, atlases, and other types of illustrations appearing in the contemporary scientific literature.

Although I was able to trace a few of the lithographers, in general we lack information about their vita and backgrounds, and in a more general sense about the social history of their trade in the nineteenth century. Astonishingly many of these specialists for scientific illustrations have virtually no traceable biographical information whatsoever. It only reflects the sad current state of research into these matters, but also the surprising neglect by archivists and scientific institutions throughout the ages to preserve the memory of a social group that contributed significantly to the fame and the persuasive power of their institutions' proceedings. The Académie des Sciences in Paris is but one example. As already mentioned previously, their archive has kept virtually nothing on their lithographers C. Legros and Dulos, whose masterful maps of solar and terrestrial spectra are repeatedly **(p.175)** admired in this monograph. So I had to rummage through the records of the Paris City Archives and other holdings far off the beaten track of historians of science.

Concerning the issue of distribution of these works, we also lack studies paralleling the marvelous research by Robert Darnton on the dissemination of Diderot's *Encyclopédie* in the eighteenth century.[152] From a variety of accidental mentionings in the private correspondence and laboratory notebooks scrutinized for my purposes, I can reconstruct a few print runs of some major journals: Towards the beginning of the nineteenth century, the proceedings of the Bavarian Academy of Sciences were also only printed in a relatively low run of 412 copies.[153] In the mid-1860s, the *Philosophical Transactions of the Royal Society of London* issued 1000 copies;[154] by 1873 the *American Journal of Science and Arts* was printed in 1650 copies, the *London, Edinburgh and Dublin Philosophical Magazine* ran 1000 copies, a minor journal such as the *Memorie della Societá Spettroscopisti italiani* had a run as low as 300 copies. In contrast to these impressions averaging 1000 copies for a typical well-known scientific journal, Lockyer's weekly semi-popular journal *Nature* was distributed in 7000 copies. This high profile had its price, though: unlike the other periodicals, *Nature* was issued without any plates, limiting illustrations to relatively coarse woodcuts or wood engravings integrated into the text. Some of Lockyer's own publications in *Nature* demonstrate his ability to stretch this constraint to its limits.[155] But for most other authors this simply meant sending in only short notices to that journal, and publishing the more extensive reports with illustrations elsewhere.

What can be said about the receiving end, especially with regard to the more specialized publications of high-quality maps and atlases? As we shall see in the following chapter, I was lucky enough to find among Rowland's papers a list of advance-order customers for the first edition of his photographic map of the normal solar spectrum (cf. here p. 234). It is to this application of photographic reproduction that we now turn.

Notes:

(1) A term (homomorphic and in contrast to the term 'artist') coined by William Whewell in 1833 to describe those present at that year's meeting of the British Association for the Advancement of Science: see, e.g., Bynum *et al*. (ed.) [1984] p. 381.

(2) Kirchhoff [1861/62*f*] p. 1; cf. also footnote 33 on p. 86 for other examples.

(3) According to the *Matrikel der Universität Heidelberg. Teil 6: von 1846 bis 1870*, edited by Paul Hintzelmann, Heidelberg: Winter, 1907, at that time the only immatriculated student of that surname and first initial was a Karl Hofmann, who enrolled himself there on 29 October 1860 to study the natural sciences. He was born in Ruszkberg (then in Hungary, now called Ruszka-Montana in Rumania); his father was a mine owner in Paulis, Hungary, and a Catholic by faith (p. 392). According to his file at Heidelberg University (UAH, H-IV-102/61), Hofmann had attended lectures by Bunsen and Kirchhoff on chemistry and physics, by the mineralogist Johann Reinhard Blum (1802–83), and by Heinrich Georg Bronn in geology. His dissertation was accepted on 28 January 1863 after oral examinations, but without submission of any written Ph.D. thesis. In the curriculum vitae Hofmann submitted to the University of Heidelberg, he specifies that he had worked in Bunsen's chemical laboratory for two terms, but his joint work with Kirchhoff is not mentioned. The obituary of Hofmann by his brother-in-law Böckh [1892] p. 4 mentions this privilege of working in Kirchhoff's private laboratory. On Hofmann's prior education and later activities as a geologist see also pp. 430 and 166.

(4) See Ångström and Thalén [1865/66]: Thalén's collaboration is mentioned in the foreword to Ångström [1868]. Thalén took up studies in Uppsala in 1849, becoming amanuensis, then adjunct for physics and mechanics in 1860, professor of mechanics in 1873, and succeeding Ångström as professor of physics at Uppsala University after the latter's death in 1874; see Hasselberg [19O6], Beckman and Ohlin [1965] pp. 22f. (with a photograph of their spectrometer manufactured by Schmidt & Hacnsch in Berlin), Widmalm [1993] pp- 39, 46ff., and Beckman [1997] pp. 18, 38-40).

(5) See Shapin [1989] and [1994] chap. 8.

(6) Sec Ångström [1868*a*] atlas vol. One of the few commentators to acknowledge Thalén's involved participation in the production of this map was A. Herschel [1869] p. 157.

(7) The most famous exception is, of course, Josef Fraunhofer (cf. footnote 43 on p. 34), another is S.P. Langley, who (according to Jones [1965] p. 106) had studied architecture and hence was considerably experienced in draughtsmanship before entering astrophysics; cf., here § 10.2, pp. 429ff.

(8) Such a terminological distinction between lithographers as printers and lithographic draughtsmen—although useful in principle—was rarely made in contemporary discourse.

(9) See here footnote 2 on p. 111. On the occasionally difficult negotiations between scientists and their draughtsmen on contract terms acceptable to both parties, cf. also Blum [1993] pp. 3, 279, 287. and Pang [1994/95] p. 255. 258, and 271, whence I borrow this reference.

(10) Pang [1994/95] p- 258. Ranyard's correspondence concerning the production of vol. xli of the Royal Astronomical Society's *Memoirs* is a telling source for reconstructing this process.

(11) See, for instance, Smyth [1843/46*a*] p. 71: "Astronomical Drawing has been so little followed up and […] will fall entirely within the province of amateurs", M. Huggins [1882], and Hill [1915] on the "essentials of illustration […] for the use of scientists".

(12) G. Fritsch in his article on anthropology in Wolf-Czapek [1911] part IV, p. 19 (quoted by Krauss [1978] p. 298); cf. also Jussim [1974] chap. 8, pp. 237f., 254.

(13) For the above quote, see Schaaf [l980/81*b*] pp. 32ff., 48. We know of similar examples from eighteenth-century expeditions. On contemporary discussions about the virtues and pitfalls of photography, see here § 6.8, and on C.P. Smyth see here pp. 314f., 425f.

(14) For examples from Philadelphia, where, by 1850, circa 95 % of all employees in the printing trade were working for firms with six of more employees, nearly half of these in firms with more than 50 employees, see Blum [1993] p. 122. Statistics reflecting a faster growth in the number of agencies over proprietorships in Berlin are given here in Tables 5.1 (on p. 149) and 5.3 (on p. 152).

(15) See Courboin [1914], esp. pp. 156f. on the election of an engraver and the issuance of a 'brevet de Graveur du Roi' very similar in style to the 'Brevet d'Academicien', or pp. 158ff. on their pensions, lodgings, and titles.

(16) See, e.g., Fox [1973] and further references there.

(17) See. e.g., the protocols of the 'Commission Administrative 1829–1877' (AASP) for December 1872 and February 1873 on Dulos; 2 October 1881 on M Pierre, graveur; and 7 July 1884 on M Debray. graveur—all relating to payments for engravings and prints. Brian and Demeulenaere (ed.) [1996] discuss the various types of holdings in Parisian archives (particularly the AASP).

(18) Examples are Boetticher [1891–1901], Bryan [1849], Heller [1850], [1885], Ottley [1831], Singer [1922].

(19) See the records of the 'Commission administrative 1829–1877' (AASP), entries of 30 December 1872 and 24 February 1873, where Dulos is granted a sum of 551 francs for a plate supplementing a paper by Mr Becquerel. Cf. e.g., Barre [1862], [1864] for reports "drawn up […] in the name of the Committee for the Applied Fine Arts in Industry on the processes of relief and line engraving by Mr Dulos, engraver of the Academy of Sciences". On the case of Dulos, cf. also K. and A. Hentschel [2001].

(20) See the *Didot-Bottin. Annuaire-Almanach du commerce et de l'industrie, un Almanach des 500,000 adresses.* Paris, Didot-Frères, Fils et Cie, vol. 63 (1860), p. 753, vol. 65 (1862), pp. 243, 836, and vol. 73 (1870).

(21) See *Fichier des marriages Parisiennes 1795–1862* (AdP) and the liste électorate dressée en 1871 (AdP, D1M2 art. 175).

(22) See the Parisian ‘déclarations des mutations par décès’, première partie, no. 6 (1878), dated 2 June 1879 (AdP, D Q7, art. (1582).

(23) See the lists of ‘entrées et sorties’, and Pascal’s grade sheet at the Archives Départementales de Maine-et-Loire (cote 1 ETP 630 and 1 ETP 697, my copy by courtesy of Mme Brigitte Pipon), where the old school files of the École des Arts et Métiers in Angers have been transferred.

(24) On the proceedings after his death, see also the records of the ‘Commission administrative 1829–1877’ (AASP), entry of 27 April 1874, which deals with matters relating to “la Situation de l'Académie, vis-à-vis des héritiers de M Dulos, son graveur”, and designates an estate lawyer, “M Lesage, avoué, de prendre […] toutes les mesures usitees au pareil cas.” Unfortunately, I could find no more traces of Dulos in the files at the AASP.

(25) See, e.g., Dulos’s plates for Diacon [1865], Salet [1873], or Cornu [1874/80*a*]. Particularly outstanding are his 129 in-text figures and three tipped-in plates (two of them in color) for Secchi [1870*a*], and a set of 14 color plates for the atlas accompanying M.E. Chevreul’s *Résumé d'une histoire de la matiére depuis les philosophes Grecs*, published by Firmin Didot in 1878 as vol. 39 of the Paris Academy’s *Memoires*. Samples of Dulos’s technique of ‘capilligraphie’ (see main text below for details of the ‘procédé Dulos’) are printed in vol. XI of the 63rd annee of the *Bulletin de la Société d’ Encouragement pour l’ Industrie Nationale* in 1864.

(26) See the *Annuaire Statistique de la France* **1** (1878), pp. 384–5, 388 and Chevalier [1950] p. 99, who also quotes figures from the *Journal de la Société statistique de Paris*, July (1884). p. 281.

(27) On the salary of A. Legros (cf. here footnote 36), see Bénézit (ed.) [1976]. vol. 6. p. 546.

(28) According to Pierre Larousse, *Grand Dictionnaire universel du XIXe siécle*, reprinted by Slatkine, Geneva. 1982, vol. XI, p. 129, “métal de Darcet” is a fusible alloy of bismuth, tin, and lead.

(29) On the preceding, see Barre [1864] pp. 6–7 or the reprint of this description in Motteroz [1871] pp. 38–40, Monet [1888] pp. 203–6, and Adeline [1893] pp. 142ff.

(30) According to Motteroz [1871] p. 42: “many times I gave a plating to proofs taken from certain relief engravings by Mr Dulos, and once they had thus obtained the distinctive mark of the line engraving, I showed them to specialists in the field, who more often than not were deceived by them”.

(31) See Kirchhoff [1861/62*g*] (1863), pl. **I–III** and (1864) pl. III. The text was translated by the French spectroscopist L. Grandeau.

(32) See, e.g., Perrot [1865] p. 315, Adeline [1893] p. 148: “the Dulos process is […] one that justifies and explains the term ‘chemical engraving’ most completely”.

(33) On this title see footnote 127 on p. 169 below. Dulos’s employment for the Ministére de la Guerre is evidenced by the inventory of his unfinished engravings (referenced in footnote 125 on p. 169 below). On p. 9, it itemizes 21 ‘planches des cartes de départements’.

(34) *Ibid.*, pp. 9–10. The full price of 700 francs is of the same order of magnitude as the amount paid for a plate in one of Becquerel’.s *Mémoires* for the Académie des Sciences: see footnote 19 above, as well as ‘Commission administrative 1829–1877’ (AASP), entry for the meeting on 3 October 1881.

(35) Pérot was identifiable only by his address: Rue de Nesle, no. 10, as listed in the *Didot-Bottins* for the late 1870s and early 1880s. The city cadastre files (at ArP) for this house number in 1876 then provided his given names and described the apartment in which he lived between 1873 and 1883 (3rd étage of a four-story building, seven windows plus an atelier with three windows towards the rear facing north, and a total annual rent of 800 francs). The profession under which he was entered, along with three of his five successor tenants by 1903, was: metal engraver of city matters (‘graveur sur métaux objets dit de ville”). Other tenants included a beer saleswoman, a café owner, a florist, an independent accountant, a bookseller, and a painter. Pérot also contributed pl. 46 to the 60 (A2-size) plates accompanying Ferdinand de Dartein’s *Etude sur l'architecture lombarde*, Dunod, Paris, 1870. On his production of topographic maps, see also p. 169 below.

(36) It is not clear whether this lithographer is related to the famous art engraver Alphonse Legros (1837–1911), born in Dijon, who migrated to England and became professor in South Kensington; the available biographical literature on the latter does not indicate any links. From the unpublished *Dictionnaire Biographique*, a draft manuscript compiled by Jules Jouvin, we learn that in 1879 “Legros d'Amisy” hit upon the idea of transferring copperplate proofs to stone and also first applied the lithographic reproduction process to ceramics. (I am grateful to the archivist at the Bibliothéque des arts graphiques in Paris, where the book manuscript is preserved, for pointing out this source.)

(37) See the two pages of ‘notes relatives á l'élève Legros’, provided by courtesy of Monique Turover, Centre de documentation of the Ecole Nationale d'Arts et Métiers, Aix-en-Provence. Dulos received his training in a similar technical school in Landes.

(38) According to the *Bulletin Mensuelle de la Société des Anciens Élèves des Ecoles des Arts et Metiers*, annee 1875, 2ème série, p. CXXXIV, Monsieur C. Legros, of the above profession lived on rue de Crémieux à la Guillotière near Lyon.

(39) See Cornu [1874/80*a*] pl. I and here Fig. 4.13. This plate is signed ‘A. Cornu del.’ on the lower left-hand corner, and ‘Legros et Dulos, sc.’ on the lower right. In the main text Cornu mentions a regrettable delay in the completion of the engraving for his memoir due to circumstances beyond his control—Dulos’s declining health may well have necessitated this unusual exchange of engravers.

(40) For a more detailed account of Dulos’s life, social setting and work, see K. and A. Hentschel [2001].

(41) See Cornu [1874/806] pl. II, H. Becquerel [1883e] and the plates for Thollon [1890], commented upon here in more detail on pp. 135ff.

(42) On Wesley see, e.g., Knobel [1922], Turner [1923], and Pang [1994/95] pp. 259ff. Becker [2000] pp. 227–9 discusses Wesley’s lithographs of the solar corona as observed during a solar eclipse. See also McClean *et al.* [1908] pp. 9–12 and pl. 11, as well as here pp. 238 and 241 on Wesley as sales agent for Higgs’s 1894 photographic atlas.

(43) Since three of the four engravers in this family were christened James, it is not easy to assign “with assurance to each member of the family his proper share in labour or reputation”, as Wedmore [1885] puts it in their collective entry in the *Dictionary of National Biography*. However, mere chronology identifies James Basire (1796–1869) as the one to have engraved the maps by J. Herschel [1840*c*], J.W. Draper [1843c], and Brewster and Gladstone [1860]. The sketch for Wollaston [1802], however, may have been engraved by James Basire (1769–1822) or his father (1730–1802), who was appointed engraver to the Royal Society in 1770. For a full listing of plates of the latter in the *Philosophical Transactions* between 1772–1778, comprising astronomical, physical, technological, mathematical, biological, geological, and geographic motifs, see Doxey [1968].

(44) See Wakeman [1973] p. 15. For comparison purposes: the 1862 Parisian *Didot-Bottin* has the following sub-categories for engravers: “graveurs sur bois, sur metaux, en architecture, sur cristaux et verres, en écriture, en ge'ographie et topographic héraldiques, pour impressions, en lettres. en médailles, de musique, pour fleuristes. paniconographes, sur pierres lithographes”. It lists in addition “lithographes, imprimeurs lithographes, en taille-douce, en couleur”, and “photographies (artistes)”. A table listing the various statistics on independent print professionals in Paris between 1764 and 1915 is provided in K. and A. Hentschel [2001]. For the figures on printing agencies, see the table in Hentschel [200l*b*].

(45) Fox [1976] covers the situation in London between 1830 and 1850: on the 1871, 1881 and 1891 census data see Booth [1895] p. 185–90, according to whom “except bookbinding no other important trade is so distinctly metropolitan in its character” than printing. On Austria see, e.g., Schwarz [1988]. The main centers for printing in the US were New York City, Philadelphia, and Boston; see, e.g., Blum [1993].

(46) Waterhouse [1870*c*] p. 83. While working for the Royal Cartographic Service in Calcutta, Waterhouse advanced to the level of major general. Returned to London, he became the president of the Royal Photographic Society: cf. Eder [1945] pp. 464f.

(47) See Twyman [1970] p. 3. Much of the impetus in the lithography movement came from the rhetoric of free access for ‘everyman’ to the technique, as reflected in treatises like *Every Man His Own Printer; or Lithography Made Easy*, Waterlow and Sons, London, 1859. However, as Twyman also argues (on p. 65), “the artist did not immediately realize this freedom. He was bewildered by the apparent lack of discipline and so, in the first place, borrowed his syntax from a wide variety of processes.”

(48) On the engraver’s “battle for recognition”, see Anon. [1884*b*], Fox [1976] pp. 4ff. and Dyson [1984] pp. 57ff. Fox (pp. 11ff.) also discusses early efforts to form union-like associations, as later described in Booth [1895] pp. 211–25, Möller [1917], Leese [1929], Munson [1963], Strauss [1967], and Mayer [1971]; Dyson (chap. 3) and Dörflinger [1983] address earnings by engravers. Cf. also Hadon [1883] pp. 718f. for one of the many unsuccessful pleas for change, in begging a distinction between a translator-engraver and an interpretative one.

(49) Hullmandel [1824*c*] p. 71; cf. also Dyson [1984] pp. 46ff. on similar enhancement techniques in engraving.

(50) Quoted from Hill [1915] p. 19; cf. also Dyson [1984] p. 13. Nickelsen [2000] pp. 67–78 documents the careful choice of draughtsmen and engravers by the Prussian Academy of Sciences in the 18th century.

(51) Brandenburgerstrasse was renamed Lobeckstrasse in 1929; Alte Jakobsstrasse is two blocks East of Spittelmarkt. Two other lithographers with the same family name, G. and E. Laué. were listed under addresses close-by at Lindenstr. 115, and Prinzenstr. 101. Later, one even shared the same building at Oranienstr. 145. In the 1900 directory, the Prinzenstrasse address was specifically advertised as a “lithographic atelier for scientific work”. This clutch of Laues exemplifies the still strong familial ties within the printing trade.

(52) lndependent sources confirm that Grohmann died in that year. This indicates that entries in the Berlin professional directory were updated promptly, hence we may approximate the date of C. Laue’s death at about 1895. Dragonerstr. was renamed Max-Beer-Str. in 1902.

(53) See the *Allgemeiner Wohnungsanzeiger nebst Adreß- und Geschàftshandbuch för Berlin, dessert Umgebun-gen und Charlottenburg* **12** (1867) part I, p. 567, part II, p. 219, part III, p. 281. The *Mittheilungen aus dem kaiserlichen Gesundheitsamte* **2** (1884), for instance, contain 13 plates printed at “Alb. Schötze Chromolith. Inst. Berlin”, ten of which had been drawn in color by W. Grohmann. We have encountered Schötze on p. 124.

(54) See *Berliner Adressbuch* (1907), part I, p. 2255; his neighbors included a silversmith, a master butcher, a book binder, a mason, a locksmith; a manufacturer of driving belts, a cigar maker, and a retired policeman. Schötze’s fellow proprietor of the publishing house was a businessman, Emil Leipold, who lived at Straßurger Str. no. 2.

(55) ln his obituary Kurth [1918] describes Grohmann’s home as a dark apartment: “He lived in a dusky room in old Berlin, on Linienstrasse.”

(56) According to the *Berliner Adressbuch* **4** (1872), part IV, pp. 85f. For comparison against other branches: 8 shops specialized in maps, 19 in photographs; there were 55 copper engravers and 174 photographic ateliers.

(57) These findings for Berlin may be compared with Ranke’s [1977] p. 110, based on the business censuses *(Gewerbezàhlungen)* in Munich for the years 1875 and 1895. According to Ranke, the number of female photographers in Munich rose from 32 to 121, comprising always around one fifth of the respective employee totals of 161 and 554. The number of photographic establishments in the Southern capital rose from 50 large and five small undertakings in 1875 to 101 large establishments by 1895, to be set against 1330 registered artisanal enterprises.

(58) Hoerner [1989] pp. 36f., who also describes typical working conditions of professional photographers.

(59) *Berliner Adressbuch* (1872) part II, pp. 251, 65, and (1867) part II, pp. 190, 219, and (1885). A similar picture emerges from an analysis of London engravers' living quarters in Fox [1976], and Dyson [1984] pp. xxiii ff. The previously cited case study on a Parisian engraver also contains details about his urban neighborhoods and his social milieu; see K. and A. Hentschel [2001].

(60) See Thieme and Becker (ed.) [1907ff.] vol. 15 (1922) p. 77, according to whom the alumnus was a regular participant of the Academy's exhibitions between 1870 to 1890. Boetticher [1891/1901] vol. I. no. 1, p. 413 specifies the four engravings on natural motifs exhibited there annually between 1886 and 1890.

(61) See pl. *8–9 of Arbeiten aus dem kaiserlichen Gesundheitsamte* **1** (1886), and pl. I—X in *Mitteilnngen* 2 (1884).

(62) See Dobbert and Grohmann [1893] p. XII, Anon. [1898], Kurth [1918]: protocol of Senat meeting of 11 July 1883 (SAdK, file PrAdK no. 247, sheet no. 199) on the interim appointment, and Senat meeting of 27 April 1887 (PrAdK no. 248) on the fixed appointment; and his personal file (PrAdK I/I6I fol. 15). Unfortunately, neither the archivist of the Berlin Academy of Arts, Mrs Gudrun Schneider, who was so kind as to provide me with copies of the above unpublished documents, nor the archivist of the Hochschule der Könste Berlin. Dr Dietmar Schenk. could find any records from his period of training. Nevertheless we can get a good idea of what was offered to aspiring draughtsmen and engravers from the memoirs of von Werner [1994] pp. 39–52. who also studied at the Berlin Academy of Arts shortly after Grohmann, from 1859 to 1862. and even met him at the affiliated athletic club; cf. also Wefeld [1988] pp. 29. 54–7.

(63) According to Anon. [1898] p. 247, Grohmann was a member of the Verein Berliner Könstler as well as of the Berlinische Könstlerverein and the Deutsche Kunstgenossenschaft.

(64) Kurtz [1918] col. 356.

(65) On these awards of the 'kgl. Kronenorden' and 'kgl. Roter Adlerorden 4. Klasse', see Geheimes Staatsarchiv Preußischer Kulturbesitz (I HA Rep. 90 Staatsministerium, jöngere Registratur, no. 2124 (D)). As Dr Marcus from that archive has pointed out to me, however, on 18 January 1909 over 1000 others received the same distinction: Grohmann was no. 23 of a list comprising roughly 100 names, submitted by the Prussian Ministry of Education.

(66) For detailed documentation of Dulos's case, see here pp. 143ff. On Henry see here pp. 127f.

(67) Cf. Ernst Kummer's 'Wahlvorschlag för Gustav Robert Kirchhoff', dated 24 June 1861, in Kirsten and Körber (ed.) [1975] pp. 75–6. The nomination emphasizes his contributions to mathematical physics and mentions only in passing his contributions to 'Optics' since 1859.

(68) See Kirchhoff [1861/62*c,d*]. The subsequent reprints were done by the well-known publishing house Ferd[inand]. Dömmler in Berlin, then owned by Dr phil. Julius Harrwitz and J. Goßmann, and located at Wil-helmstr. 86 just south of the city center. Ferdinand Barth's lithographic printing agency was located at Branden-burgstr. 44 on the ground floor. Barth is entered in the *Berliner Adressbuch* of 1872, part I, p. 29, as "Steindruck-ereibesitzer und akademischer Könstler."

(69) The 1866 reprint has messy blotches of printer's ink and appears to have been printed altogether too heavily.

(70) The latter was established in 1856. Around 1868 its main office was located at Schauflergasse no. 6 in the center of Vienna, whereas the bookprinting, lithographic, and xylographic printing was done at Windmöhlenweg in the Viennese district no. VI; cf. the half-page advertisement inserted into *Adolph Lehmann's allgemeiner Wohnungs-Anzeiger för Wien* **7** (1868) p. vii for a detailed listing of their specialities and printing equipment. One of its proprietors, (K)Carl Dittmarsch (1819–1893), had started out as a writer. Opening a printing house in Triest in 1849, he later moved to Vienna, living at Am Graben, no. 1 in 1868. Between 1879 and 1890, he was the main editor of the *Österreichisch-ungarische Buchdruckerzeitung.* Ludwig Johann Karl Zamarski (1824–?) was a book-dealer's apprentice in Tarnow, Lemberg, Vienna, and Leipzig. In 1854 he bought the printing house of Sollinger in Vienna and modernized its operations to incorporate such graphic techniques as lithography, chromolithography, and galvanography.

(71) As already mentioned (on pp. 47f), Kirchhoff and Bunsen's map was repeatedly reprinted elsewhere.

(72) See the title page of Thollon [1890], where Gauthier-Villars is described as the "Imprimeurs-Libraires de l'École polytechnique, du bureau des longitudes". According to employees of its successor company in 1997, the business papers of this important publishing house unfortunately have not been kept.

(73) See Thollon [1890] text vol., p. A17: "As for the reproduction, I tried out some photographic processes that did not yield any good results. Happily, Mr Legros, the eminent craftsman, who has already provided so much evidence of his skill, kindly agreed to assume this task." Cf. above p. 133 on Cornu's map.

(74) Dyson [1984] p. 32 also reminds us that the introduction of photomechanical techniques was by no means a “clear-cut infiltration” but often led to interesting cross-fertilizations, providing the engraver with intriguing and novel tools.

(75) For surveys of photomechanical printing techniques and their history see, e.g., Levy [1915], Eder [1922], [1945] chaps. 79–81, 88–93, H. and A. Gernsheim [1955] chap. 23, Ostroff [1969], Jussim [1974] chap. 8, Crawford [1979] pp. 235–89, Naef [1980] pp. 38ff., Hammond [1989]. Specific references are provided along with a discussion of the individual techniques.

(76) On this distinction, see in particular Edwards [1872] p. 1, Hammond (1989) pp. 172f. Lietze [1888] P. 1 calls all processes in which semitransparent objects like photographic negatives, leaves, drawings, etc., are copied on the same scale as the original ‘heliography or solar printing’.

(77) This is the way it is defined, for instance, by Edwards [1876] p. l; cf. also Hammond [1989] p. 172.

(78) See Ponton [1839] and Talbot [1853]. Cf. in particular Ostroff [1969M pp. 102ff., and Abney *et al.* [1896] p. 254. Eder [1891] p. 151, [1945] pp. 553 and 793, repeatedly defended Talbot’s claim against those who attributed this discovery to Ponton, such as, e.g., Edwards [1887] pp. 367, 369 or Schiendl [1891] pp. 78, 89. Talbot’s earlier work on photogenic drawing and calotypes is discussed here on pp. 181 ff. See also the account by C.H. Talbot, Talbot’s son, about his photoglyphic print for Tissandier [1878] app. A, pp. 368ff., where Talbot’s two relevant patents registered in 1852 and 1858 are also quoted.

(79) On photolithography, which seems to have been comparatively unimportant in the printing of spectra, see, e.g., Osborne [1862], Waterhouse [1870*c*], who gives a comparative survey of photolithographic establishments in Europe, Poitevin [1862/83*b*] pp. 94ff., Lietze [1888] pp. 106, 112ff., with excerpts of Poitevin’s English patent of 1855, and Eder [1945] chap. 91.

(80) On the use of photozincography particularly for topographic map-printing see, e.g., James [1860], [1862], Osborne [1862], Crookes [1865] p. 4 and pl. 1, Fortier [1876] pp. 22ff., 65ff., Waterhouse [1877/78*b*] pp. 2ff. and chap. 5, [1890], in particular on the various photographic procedures and on the preparation of the drawings; Sampson [1957], and Wakeman [1970] chap. 4.

(81) In German-speaking countries it is also called *Albertotypie* or *Lichtdruck*, while in English-speaking countries often the less specific term ‘collotype’ was used to denote Albert’s variant of it. About this method see, e.g., Scamoni [1872] pp. 28–31, Towler [1872], Anon. [1870–73], Stein [1877] pp. 126–9; Poitevin [1862/83*b*] p. 264 (which is a reprint of his priority claim in November 1869); Eder [1945] chap. 92, Mayer (ed.) [1965], Ranke [1977] p. 97f., Krauss [1978] pp. 296–8, and H.E. Wright [1988]. On Albert see Ranke [1977] pp. 7–68.

(82) According to Ranke [1977] p. 97, Anon. [1870–73] p. 159; see also H. Draper [1873*b*] p. 401, Taft [1938] pp. 431ff., 513, footnote 455, Blum [1993] pp. 194, 274–6, and here p. 219 for Bierstadt’s print of H. Draper’s spectrum photograph.

(83) See Wright [1988] an unpaginated brochure with a portrait of Joseph Albert as frontispiece. Cf. Waterhouse [1877/78*a*] p. 38 and Engen [1979] p. 228 on the London-based Autotype Co., the British patent owner of Joseph Wilson Swan’s double transfer system of the carbon print process since 1869. For a comparison of Albert’s French patent (1869) and Poitevin’s British patent of 1856 see Simpson [1869].

(84) Edwards [1872] p. 3. However, according to Anon. [1870–73], up to 4000 impressions could be obtained from a single plate, at least 1000 of them “good impressions”. The last figure is also quoted as the maximum number of prints by Simpson [1869] p. 106; according to Ripley and Dana [1875] p. 572 one operator could produce about 200 prints a day.

(85) Edwards [1872] p. 3; on heliotype cf. also Edwards [1876] with 28 illustrations, Tissandier [1878] pp. 385f., Jussim [1974] pp. 52–6, Wright [1988].

(86) Edwards [1872] p. 4.

(87) See Hill [1915] p. 23.

(88) On photogalvanography see, e.g., Pretsch [1856], [1859], Hunt [1856], Smyth [1861] pp. 87f., Crookes [1865] p. 3, Stein [1877] pp. 130ff., Edwards [1887] p. 400, Eder [1922] chaps. 29–30, [1945] chap. 88, H. and A. Gernsheim LI955] pp. 359–61.

(89) See, in particular, Eder [1945] pp. 583f., and Glotz [1922] on work at the Viennese Government Printing Office and at the Military Geographic Institute, respectively.

(90) De la Rue [1862] pl. *verso* p. 278; on the issue of intervention by the engraver, see also the quote under footnote 94 below as well as here p. 218.

(91) De la Rue [1862] p. 279.

(92) *Ibid.*

(93) De La Rue [1865] p. 171; emphasis original.

(94) Edwards [1872] p. 2; cf. also De la Rue [1862] p. 279 where he admits that despite runs of many thousand prints from these plates, it was “however necessary from time to time to clear the block, which is liable to become clogged on account of the want of depth in the light parts.”

(95) This expression is used by Crookes [1865] p. 5.

(96) See Talbot [1858], as well as Eder [1945] pp. 593–5, Buckland [1980] pp. 112f.

(97) On photogravure, sometimes also called photo-aquatint or heliogravure, see, e.g., K. Albert [1927], Eder [1922] chap. 4, [1945] pp. 596ff., Jussim [1974] pp. 56f., Naef [1980] pp. 40ff., and Hammond [1989] p. 177 esp. on the similarities to mezzotints.

(98) Ivins [1953*a*] p. 180.

(99) On later modifications of the photoengraving process, which included, for instance steel-facing of the plates to draw from a single plate up to 20 000 impressions see, e.g., Edwards [1887] pp. 401–3, 430–2, Nemethy [1891], and Jenkins [1902]. On the halftone process see, e.g. Hill [1915] pp. 37ff., Eder [1945] pp. 601ff., 621ff.; pp. 626ff. on its invention and pp. 632ff. on the introduction of cross-line screens on glass by Frederic Eugene Ives in the US.

(100) See, e.g., Jenkins [1902] for an early manual that already contains an appendix on three-color halftone work.

(101) See, e.g., Ivins [1953*a*] pp. 51–70 on cross-hatching as the ‘net of rationality’, representing a projection of the Cartesian grid onto nature, and *idem*, pp. 113 and 128 on halftone engraving and photography as a ‘pictorial statement without syntax’; for a critique of this interpretation see Jussim [1974] p. 11.

(102) Hale to C.E. Pickering, 15 March 1898 (HUA, UAV 630.17.7. box 2). A ‘squeegee’ is an instrument used in heliotype print to squeeze out the water between the gelatine film and the metal support before printing, consisting of a blade of india-rubber set into a strip of wood (cf., e.g., Edwards [1872] p. 3).

(103) See the dictionary *Svensk Uppslagsbok* **11** (1950) p. 463, and **29** pp. 630ff., Bratt [1958] pp. 71–80, and Goss [1993] pp. 22If.

(104) On the preceding organization as well as on its precursor in the Fortifikationens-Corps which merged with the Field Survey Corps in 1809, see Goos [1993] p. 221.

(105) According to Goss [1993] p. 221, before the 1820s, the maps were not printed at all but kept in manuscript as secret documents.

(106) See Twyman [1970] pp. 33f., and Mumford [1972] p. 31 who asserts that in this early period “the principal output of the original Senefelder press was the printing of maps and forms for the military and not for sale”.

(107) See von Werner [1984] chap. 2 and Wefeld [1988] p. 29; even though these two texts refer to the years 1860–62 and 1806, it does not seem that the curriculum changed substantially within this time span. For a similar curriculum at the Berlin Akademische Zeichenschule and the Berlin Royal Academy of the Vocational Trades (Gewerbeakademie) see Wefeld [1988], pp. 57, 102.

(108) Founded in 1812 under the name Royal Engineer Establishment, it added to its curriculum practical architecture in 1826, surveying in 1833, and chemistry, photography, electricity, and telegraphy in 1865: see Porter [1889] vol. 2, pp. 169–254 in particular pp. 172, 176f., 183ff., and vol. 3(1915), p. 234.

(109) On the history of the Ordnance Survey, founded in 1791: Seymour [1980], Owen and Pilbeam [1992].

(110) See, e.g., Porter [1889] vol. 2, pp. 243ff. according to whom around 1885 a total of 3240 persons, both military and civilian, but excluding temporary hires, were employed for this purpose, and 453 000 maps was supplied to the Boundary Commission by 1885; on the applications of zincography to map printing, see here p. 158.

(111) GH. Murray was superintendent of the photographic department of the Surrey Photographic Company—presumably this is the same person mentioned in the introduction to Capron [1877] p. 1.

(112) See, e.g., Versteeg [1879] or Woodward (ed.) [1975] p. 141 for a photograph of the cartographic camera in use at the Military Topographic Surveys of the Netherlands about 1880.

(113) C. Koeman in Woodward (ed.) [1975] pp. 140, 145.

(114) According to Petermann [1878] p. 205, the working time needed for a plate was reduced from as much as five years in copper engraving to four weeks for a heliogravure; cf. also Volkmer [1885], Glotz [1922], Versteeg [1879], and the interesting comparative report on cartographic applications of photography in Europe and India by Waterhouse [1870*a*].

(115) Cf. Jackson [2000] p. 78; cf. *idem* pp. 49ff., 235 on Fraunhofer's connections to the ordnance surveyor Johann von Soldner.

(116) J.B. Listing, for instance, together with Sartorius von Waltershausen took part in a three-year excursion to Italy and Sicily to study Mount Etna and to perform geomagnetic measurements for Gauss's Atlas; Bunsen, who had also studied mineralogy, traveled to Iceland to study minerals and geysers; John Herschel took part in many sessions and discussions of the Royal Geological Society.

(117) See Hofmann's obituaries by Böckh [1892] and Roth von Telegd [1892]. For the documentation concerning Hofmann's Ph.D., see here footnote 3 on p. 140.

(118) On the emergence of a visual language for geological phenomena, and its further development in the nineteenth century, see Rudwick [1976].

(119) See Proctor's [1870] chapter on 'Mars, the Miniature of our Earth'; cf. also Huggins [1867] and Lightman [2000] pp. 661–71.

(120) See Lightman [2000] p. 667 and references given there. On Browning see here p. 92.

(121) The foregoing information according to Rigg [1892] and Johnston [c. 1926]. On the House of Bartholomew, a local competitor, and on the school of map engraving in Edinburgh, for which it was famed from the eighteenth century, see Bartholomew [1998].

(122) For more about these 'ruling machines' see, e.g., Nicholson [1795], Heath [1838], Anon. [1841], Warner [1843], Hunt [1848*b*] and Swan [1853].

(123) See Stone [1993] p. 3, who also provides an interesting comparison of the map content and accuracy between engravings and preparatory drawings.

(124) On Dulos see here pp. 143ff., on Basire see Doxey [1968].

(125) On the foregoing, see the assessment of the copperplates and plates, articles 5, 6. 8, and 13 (ANP, Minutes des études notaires: notaire Denis-Edmond Pourcelt, étude LX, liasse 932).

(126) From the waterway atlas, two plates displaying the regions of Ariége and Haute-Garonne are dated 1878 and signed by E. Hellé (in the sizes of A2 and Al, at BNT, LF 262-67). Concerning the latter atlas, Dulos had a running contract totaling 15 000 francs with Dartein (cf. here p. 147). A complete set of these maps can he examined in the Bibliothéque Nationale de France. Dépt. des cartes et plans, rue de Richelieu (BNC, GeDD 23. nos. 1–166). Another nearly complete set (nos. 1–78 and 80–166) is a part of the Pusey Library map collection at Harvard University (map LC G 1841.P55 F73 1871 Pf). Cf. also the *Catalogue des notices, cartes et plans composant l' atlas des Ports de France, idem,* 1891ff., based on engravings made between 1869 and 1906. The 22 maps completed by Dulos, dating between 1872 and posthumously to 1881, are (BNC, GeDD 23) nos. 2–11, 16. 18, 20–1, 23, 28, 63, 111–12: the larger scale coastline maps were generally unsigned or attributed to E[ugeène]. Hellé (e.g., nos. 1, 15, and 31)—the same Hellé, who also took over Dulos's atelier at Rue de Seine no. 34 three years after his death, but resided at Rue Royer-Collard, no. 4. The 'inventaire aprés décès' compiled after Dulos's death lists a debt to Mr Sarazin, printer, of 1099.80 francs, very likely for the printing of some of these maps.

(127) A file on his nomination exists (ANP. Léonore, L0841004), but unlike most cases this dossier only consists of one document (dated 1872) retrospectively confirming the conferral of the title to Dulos, and thus does not indicate why he got it or who had nominated him.

(128) On the following sec Jàger [1980] and Dörflinger [1983].

(129) Dörflinger [1985] p. 219 quotes the extremes of five weeks fora smaller map of Vienna, and ten months for complex maps of Styria and Illyria, and daily averages of 50 and 15 cm^2, respectively. Jàger [1980] p. 126 refers to the example of Napoleon's army occupying Danzig in 1807: Despite Napoleon's order to produce a city map within three days for the exorbitant sum of 1500 francs, the three copper engravers only completed their task after 16 days of uninterrupted labor.

(130) The prices are quoted in Bavarian guilders (abbreviated fl) and kreutzers, at 1 fl = 60 kr. See the draft of Fraunhofer's letter dated 28 December 1817 (SPK, Fraunhofer papers, folder 3,3).

(131) See, e.g., De Serres [1809*b*] p. 127: "A drawing that a copper engraver could not transfer onto a copper plate even in five or six days can now be applied to the stone in one or two days."

(132) *Ibid.*: "and in the same time that a copper engraver makes 600 to 700 prints, 2000 copies are produced with the chemical press"; cf. also Hill [1915].

(133) De Serres [1809*b*] pp. 127f. writes somewhat overenthusiastically: “A copper plate bearly tolerates 1000 prints, the stone easily affords many thousands, of which the last is just as fine as the first.”

(134) See Smyth [1843/46*e*] p. 78. According to Koschatzky [1975] pp. 101, 130f., a typical copper engraving can issue 300–400 prints, maximally about 1000, while etchings are limited to no more than 100 or 200 copies before the print quality begins to deteriorate rapidly.

(135) For more about the actual printing process as well as the average runs off a single stone see, e.g., Twyman [1970] chap. 6, esp. p. 81; cf. also Pang [1994/95] p. 266 about James Tennant’s caution that a lithographic stone “will not give 1000 copies without sensible deterioration”. See here § 4.2.

(136) This refers to the 1820s according to Twyman [1970] p. 113. Pang [1994/95] p. 265 reports steel engraving was still three times as expensive as lithography in the early 1870s. The introduction of lithography about 1865 had the “result of greatly cheapening the cost of production of maps”: Johnston [1926] p. 10.

(137) See Mumford [1972] p. 32.

(138) Blum [1993]p. 38.

(139) See Ostroff [196%] p. 112 (based on a bill to Fox Talbot, issued by David & John Greig, Edinburgh).

(140) A complete price list from 1830 for all available stone formats is reprinted in Winkler [1975] p. 433.

(141) Ripley and Dana [1875] p. 571. According to Winkler [1975] pp. 425f., the lithographic print runs in the earliest period (1796–1821) were more limited for lack of experience or from the use of inappropriate tools.

(142) See the correspondence between A.C. Ranyard, Daniel J. Pound and G.B. Airy from December 1872, Royal Greenwich Observatory Archive, as quoted in Pang [1994/95] pp. 266, 274. For roughly contemporary consumer prices and middle-class standards of living, see May [1987] pp. 201ff.

(143) See Dyson [1984], particularly app. I, pp. 173ff. with annotated transcripts of documents between 1833 and 1887.

(144) See Booth [1895] vol. 6, pp. 225–9.

(145) Wright [1988] (unpaginated).

(146) *Ibid.* One example of such a procedure is given here on p. 227.

(147) See Henry Draper’s notebook no. 11 (further specified in footnote 164, p. 213), p. 48, as well as here § 6.7. On Bierstadt’s printing house and the Albertype technique used, see here footnote 166, p. 213.

(148) See E.C. Pickering to E. Bierstadt, 6 and 16 March 1888 (HUA, UAV 680.14, box A7, nos. 709, 729); cf. also Pickering’s correspondence with Lithotype Printing in Gardner, Massachusetts, of 11 and 25 March and 24 April 1900 about the third installment.

(149) See the table reprinted in Wright [1988] (unpaginated) with prices ranging between $35 for a print 4 × 6 inches, $60 for 9 × 11 inches, and $200 for 16 × 20 inches.

(150) On the following, see Wakeman [1973], pp. 161–3.

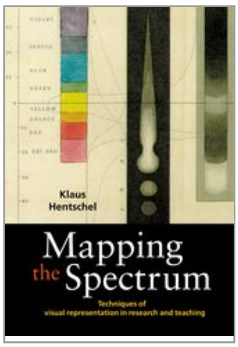
(151) Mumford [1972] p. 31.

(152) See Darnton [1979].

(153) See the bill forwarded by Fraunhofer to the Königlich-Bayerische Akademie der Wissenschaften for the printing of the plates for his 1815 paper in the Academy’s *Denkschriften* (SPK, Fraunhofer papers, folder 3,3), draft of Fraunhofer’s letter dated 28 December 1817. The bill is translated above on p. 170.

(154) See the letter by Plöcker to Stockes, undated [late 1864] (RS, 2379), mentioning a cost estimate for 1025 copies, 25 of which were most likely author’s private offprints. On the following see here p. 217 for references relating to Henry Draper’s correspondence in 1872/73.

(155) See, e.g., Lockyer [1872/73].



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
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Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

The Rise of Photography

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DOI:10.1093/acprof:oso/9780198509530.003.0006

Abstract and Keywords

This chapter relates the emergence of early photographic techniques, such as the Daguerreotype and calotype, with spectrum research, most notably through Fox Talbot and John Herschel. Early photographs of the solar spectrum and of stellar spectra are scrutinized. The beginnings of colour photography and scientific applications since 1860 are also retraced. Draper's diffraction spectrum photograph and its Albertype reproduction in 1873 is dealt with in depth as well as various photographic maps of the normal solar spectrum from 1885-1900. The virtues and pitfalls of spectrum photography are presented.

Keywords: Fox Talbot, John Herschel, Albertype, photography, Daguerreotype, calotype

> to do it beautifully is an art to be learned, & many and curious minutiæ will have to be discovered and reduced into practice before either of us can arrive at that perfection which I am confident the thing is capable of. (J. Herschel to Talbot, February 1839, original emphasis)

The advent of photographic recording marks a pivotal point in the history of representation. Technical constraints, however, obfuscate the actual entry of photography into the different scientific disciplines and this temporal ambiguity has repercussions on the cross-disciplinary claims about the transition from a ‘truth-to-nature’ to a ‘mechanical’ mode of representation. This chapter opens with a brief historical survey of the most important early photographic techniques. In § 6.3, I turn to the interpretative issue of how these “photogenic drawings” were understood by their makers, that is, how the images were seen in relation to the depicted objects. Following this introductory overview, I step back in time to the year 1839 and trace photography's tortuous path into spectroscopy (§ 6.4), the early efforts at color rendition (§ 6.5), and further improvements in scientific photography after the mid-1860s (§ 6.6). In § 6.7 the earliest successful photomechanical reproduction of a spectrum photograph is discussed in greater detail. Since its invention, photography's relative merits over traditional printing techniques, such as lithography, were a recurrent point of contention. The growing importance of photomechanical reproduction in spectroscopy fueled new controversies between advocates of the new technique and defenders of the more traditional means of representing spectra, to which I turn in § 6.8. The chapter closes with what might be conceived as the final victory of photographic techniques in our context, namely the emergence of photographic maps of the full solar spectrum towards the end of the nineteenth century (§ 6.9).

6.1 Early techniques

The early history of photography is an often retold story.[1] So I may confine myself here to a brief outline of the four main periods: daguerreotype and calotype (1839–1850s), wet collodion-plate photography (1855–1870), gelatine dry-plate photography (1871–1906), with its use of dyes for green since 1873 and orthochrome for blue and green since 1882, and panchromatic film (since 1906).

(p.177)

Tab.6.1 Main photographic processes between 1839 and 1879 (exposures times are estimates for brightly illuminated objects).For further literature cf. crawford[1979] or Mike Ware's alternative photography homepage.

Year	Inventor	Designation	Light-sensitive surface	Exposure
1822	Niépce	niépceotype, heliography	Asphaltum-coated glass plate	6 hours
1834–39	Talbot	photogenic drawing	Silver nitrate solution spread on salt-saturated paper	3–15 min
1839	Daguerre	daguerreotype	Silver iodide on silvered copper	5–30 min
1839	M. Ponton	bichromate salt	Paper soaked in bichromate of potash solution	?
1840	J. Herschel	thermograph	Smoked paper soaked in alcohol solution	c.10 min
1841	Talbot	calotype	Iodized paper permeated with solution of gallic acid, silver nitrate, and acetic acid	1–3 min
1842	J. Herschel	chrysotype also known as chripotype	Paper permeated with solution of ferric ammonium citrate, wash with gold or nitrate of silver solution	several min.

Year	Inventor	Designation	Light-sensitive surface	Exposure
1842	J. Herschel	cyanotype “blue-print”	Paper coated with above and potassium ferricyanide	15–30 min.
1847 onwards	Niépce de Saint-Victor	albumen process	Mixture of egg-white and iodide of potassium on glass	5–15 min
1850 onwards	Blanquart-Évrard	albumen paper print	Modification of albumen process suitable for paper prints	-
1851	F.S. Archer	wet collodion	Collodion and chemical mixture on glass	10 sec/1 min
1853	Talbot	photoglyphy (bichromated gelatine)	Copper plate coated with potassium bichromate, exposed under negative, later etching of the plate with acid	several min.
1854	Spiller and Crookes	moist collodion	Mixture of wet collodion, silver, and zinc or magnesium nitrate (plates kept moist for a week)	10 sec/1 min

Year	Inventor	Designation	Light-sensitive surface	Exposure
1854	Gaudin, Taupenot	dry collodion	Collodion plate coated with albumen, sensitized in silver-nitrate bath, acidified, and developed with pyrogallic acid and silver	1–5 min
1862	C. Russell	dry collodion, tannin process	Dry plates with silver bromide and chloride, tannin treatment, alkaline developer	c. 1 min
1864	Bolton and Sayce	collodion emulsion dry plates	Collodio-bromide of silver emulsion dispensing with sensitizing nitrate of silver bath	15–30 sec
1871	Maddox	dry gelatine emulsion	Gelatino-bromide of silver emulsion on glass	initially 30 sec
1871 onwards	H. Cooper, Wortley *et al.*	collodiobromide process	Collodio-bromide emulsion with slight excess of silver nitrate, pyrogallic acid as developer	varying

Year	Inventor	Designation	Light-sensitive surface	Exposure
1874	Abney	albumen beer process	Very porous collodion on glass, sensitized with silver nitrate and layer of albumen-beer mixture	several min.
1879	Monckhoven *et al.*	improved gelatine emulsions	Silver nitrate added to gelatinous solution of ammonium bromide	≤ 1 sec

(p.178) Some older histories of photography erroneously assert that the ancient Egyptians and the alchemists had observed silver salts darkening under the action of light.[2] It is certain, though, that Georgius Fabricius (1516–1571) experimented with various compounds of silver, including the semi-opaque mineral horn silver *(luna corned)*, which occurs as an ore in the silver mines of Germany and is also easily prepared artificially by adding common salt to a solution of silver nitrate ($AgNO_3$ in modern nomenclature).[3] In the eighteenth century naturalists like the professor of anatomy at the University of Altdorf, Johann Heinrich Schulze[4] (1687–1744), and the Swedish apothecary Carl Wilhelm Scheele[5] (1742–1786) expanded our knowledge about this reaction. Schulze would amuse himself and his friends by copying letters onto the surface of a mixture of calcium carbonate and silver nitrate inside a sealed bottle through exposure to light. He conceived this entertainment as 'natural magic'.[6] Fifty years later Scheele analyzed the chemical reaction and established that photo-reduction of silver chloride to metallic silver was caused by the blue rather than the green or red components of solar light.[7] In 1782 the botanist Jean Senebier (1742–1809) quantified the chemical action of different parts of the spectrum by measuring the time needed to blacken a silver-coated surface: while violet light needed no more than 15 seconds, purple light required 23, blue light 29, and green light 37 seconds; yellow light took 5 1/2 minutes, orange light 12, and red rays 20 minutes.[8] Shortly after 1800, Humphry Davy (1778–1829), the newly elected director of the chemical laboratory at the Royal Institution in London, and his friend Thomas Wedgwood (1771–1805), also experimented with silver salts. They succeeded in obtaining a temporary image of a painting on a white leather surface coated with silver nitrate. But their efforts to fix their 'shadowgrams' of leaves and other flat objects, so as to prevent further light exposure from destroying the imprints, utterly failed.[9] This problem of **fixing the image** after exposure was not solved until the 1820s. At that time the amateur lithographer Josph Nicéphore Niépce (1765–1833) in Chalon-sur-Saône, France, tried out a substance often used as a varnish for lithographic stones. He coated a glass plate with a thin layer of asphaltum, then placed a drawing on top **(p.179)** and exposed it to intense sunlight. After several hours, an imprint of the drawing became visible on the asphaltum surface because the sunlight selectively bleached and hardened the parts not shielded by the traces on the page. The unexposed areas remained soft and soluble and with care could be washed away with a mixture of lavendar and petroleum. Niépce thus obtained a permanently fixed positive image in a process that he dubbed **heliography.**[10]

Although he even succeeded in 1822 in fixing a camera image of his house onto an asphaltum plate positioned in the focal plane, his experiments with heliographic etching on metals in the following years did not make much progress: the images remained diffuse and coarse-grained and could not nearly compete with drawings or conventional prints. Niépce died shortly after signing an agreement with the graphic artist and panorama painter Louis Jacques Mande Daguerre (1789–1851), who had recently experimented with related techniques. In a letter written shortly after his first meeting with Daguerre in Paris in the middle of August 1827, Niépce reported that Daguerre explicitly referred to the solar spectrum as an ideal test for the sensitivity of his various plates. But as the following quote suggests, instead of decomposing the light prismatically, he had simply used colored glass filters. Daguerre thus proceeded similarly to the botanist Senebier in his explorations of the ‘spectral’ sensitivity of plant leaves. And like many of his predecessors, he was confused by the experimental results, which revealed insufficient separation by these absorptive media of Newton's seven primary colors, as well as opposite chemical actions at the red and violet ends of the spectrum:[11]

> M. Daguerre has succeeded in fixing on his chemical substance some of the prismatic colours; he has already fixed four and is working to fix the three others, in order to have the seven colours of the spectrum. But the difficulties which he encounters constantly grow in proportion to the modifications which this same substance has to undergo in order to retain several colours at the same time; what frustrates and completely baffles him is the fact that from these various combinations entirely opposite effects result. For instance, a blue glass which throws on the said substance a darker tone, produces a tint lighter than that on the part submitted to direct [sun]light. On the other hand, this retention of the elementary colours is limited to fugitive tints so feeble that one cannot perceive them at all in full daylight: they are only visible in the dark, and for this reason: the substance in question is of the nature of Bologna stone and Pyrophore.[12]

The inherent problems with asphaltum led Daguerre to try many other substances, including phosphorus and ‘pyrophore’ (potassium sulphide) until he finally hit upon iodized silver. Plates silvered with that compound were developed with mercury vapor (1835) and a salt **(p.180)** solution served as the fixing agent (1837).[13] When their scheme to sell their new discovery by subscription in 1838 fell through, Daguerre and Niépce's son Isidore decided to offer it to the government. The response by the official whom they had approached, Dominique François Jean Arago (1786–1853), was enthusiastic. The report by this director of the Paris Observatory and secretary of the Paris Academy was made public in January 1839. After the negotiations about a state pension for Daguerre came to a close, Arago was able to announce the hitherto secret process at a meeting specially arranged for the purpose at the French Academy of Sciences on 19 August 1839.[14]

The **daguerreotype process**[15] “burst upon the public like meteors” and “startled the public mind by [its] novelty and grandeur”.[16] A silvered copper plate was sensitized to light by means of iodine vapor. It was placed in a vapor-filled box at room temperature for 5–30 minutes; when the surface had become golden yellow (observed by red-lantern light in the dark room), the plate was slipped into a light-proof envelope for subsequent insertion in the camera. Exposure in the camera lasted between 5 and 30 minutes, depending on how well the object was illuminated, but direct sunlight was absolutely indispensable.[17] In June 1841, Antoine Claudet (1797–1867), a Frenchman living in London, realized that the sensitivity of the iodine film could be augmented by passing it over the mouth of a bottle containing chlorine, iodine, or bromine: the exposure time was thus shortened to a few seconds.[18] After exposure, the latent image was ‘brought out’ by subjecting it face downwards to mercury fumes heated to 75°C. The photosensitive salts were reduced to a silver amalgam wherever the plate had been exposed to light. The remainder were washed off in a bath of hyposulphite of soda[19] followed by a rinse in distilled water, after which the plate was dried and finished. The combination of stronger scattering by the silver-mercury amalgam and reflection off the silver surface created an image of fairly high resolution with a metallic sheen. The quite long exposure times required by this technique made it especially well-suited for stationary subjects like still-lifes and architectural motifs. Live portraiture, on the other hand, was a trying affair. Improved Voigtländer cameras with Petz-val lenses and advances in photochemistry in 1841, however, unleashed a veritable craze for daguerreotype ‘likenesses’, as they were called, to set them apart from conventional **(p.181)** painted or drawn ‘portraits’. As a result, roof-top studios, shops selling cameras, equipment, and sensitizing chemicals cropped up everywhere, and photographic societies and exhibitions featuring the new form of representation were organized in all the major cities, in particular in France and America where no patents protected Daguerre's invention.[20] The main disadvantages of daguerreotype were that it could only provide originals that

were not easily duplicated. Additionally, each daguerreotype plate was quite heavy, and the equipment was bulky as well.[21] Other problems with the new technique, namely, the susceptibility of the silver plates because the mercury adhered so lightly to the surface, as well as the tendency of the image to oxidize after a while, remained. When Hippolyte Louis Fizeau (1819–1896) toned the image with chloride of gold after fixing, the additional layer not only protected the image from abrasion but also increased the contrast and effectively prevented its oxidation.[22] Not long afterwards, the druggist and self-taught photochemist Robert Hunt[23] (1807–1887) and the Resident Chemist of the Polytechnic Institution on Regent Street, London, John Thomas Cooper (1790–1854) managed to make a daguerreotype on sensitized paper carefully selected for its homogeneity and smoothness.[24] Nevertheless, the main disadvantages remained and both factors prevented daguerreotypes from being included in books and impeded the expansion of this technique into domains of printing and illustration beyond architecture and portrait photography.[25]

In Scotland another technique was flourishing, developed independently by the English chemist, physicist, inventor, and archeologist William Henry Fox Talbot (1800–1877). Tal-bot had started out with the same aim as Daguerre of finding a new way to fix the contours of landscapes and other interesting objects on a plane surface.[26] Talbot, however, tried from the outset to sensitize paper as opposed to a metallic or glass backing. In an extended series of experiments initiated in early 1834 he first tried a solution of silver nitrate, then silver **(p. 182)** chloride. Finally, that spring he found that an “imperfect chloride” or “subchloride” of silver was more sensitive to light.[27] But he got no further than a few contact prints of flat objects such as leaves, laid on a sensitized sheet of paper and covered with a sheet of glass before exposure to intense sunlight. He did not follow this up because he had difficulty protecting these **photogenic drawings,** as he called them, against further exposure. They were also limited in size because of the paper's tendency to be “acted on irregularly”. However, the announcement of Daguerre's invention in January 1839 reminded Talbot of his earlier experiments on ‘sciagraphy’, as he also called his method—the art of depicting objects by means of their shadows. Even though a priority dispute with Daguerre was ultimately not resolved in his favor,[28] this incident at least put him back on track in the ‘black art’,[29] which he had temporarily abandoned in 1835. His perfected method of photogenic drawing entailed the following: fine writing paper was first dipped in a weak solution of common salt, then dried, impregnated on one side only with a dilute solution of nitrate of silver, and then dried again at the fire (the last two steps only by candlelight). After the thus sensitized paper had been exposed for several minutes, the image was fixed in a dilute bath of iodide of potassium, which transformed the unreduced silver salts into silver iodide. Talbot deemed the result “absolutely unalterable by sunshine.”[30] One month later, after informing Talbot privately in February 1839, John Frederick William Herschel[31] (1792–1871) publicly announced in the *Proceedings of the Royal Society* his suggestion of using hyposulphite of soda as an alternative fixing chemical,[32] which greatly improved the process and eventually became the norm in Talbot's own photographic work as well.[33]

In September 1840, Talbot arrived at another method, this time making negatives, which he decided to christen **calotype** (from the Greek *kalos*, meaning beautiful). In this process, **(p.183)** fine writing paper of exceptionally high wet strength[34] was soaked in a sodium chloride solution, and then painted with an “exciting fluid”, essentially a solution of gallic acid and silver nitrate, just before exposure. The dried paper was exposed for approximately 1–3 minutes,[35] then developed with a more dilute form of Talbot's sensitizing fluid. The image was then fixed in a potassium or sodium halide solution (later replaced with hyposulphite of soda), and finally dipped in a bath and allowed to dry.[36] The process differed from Talbot's earlier technique of photogenic drawing insofar as the image on the sensitized paper remained “latent” or “sleeping” (as Talbot put it) during the initial exposure to light, only becoming visible after subsequent coating with a dilute solution of gallic acid and silver nitrate. This had the advantage that the light did not have to reduce the silver salts fully in the exposed areas of the image but just transform them enough to make them sensitive to the developing agent. As a consequence, the exposure times were drastically reduced from a matter of hours to a minute or less.[37]

Neither Talbot's calotypes—sometimes also referred to as talbotypes—nor his photogenic drawings constitute what we would call a positive image, but contact prints depicting the objects by means of their silhouettes.[38] This is one reason why some of the earliest commentators vehemently attacked Talbot's method.[39] ‘Positives’ could, however, be printed from these ‘negatives’ using a contact print procedure in which the negative was put on top of another sensitized sheet and exposed to intense sunlight, repeating the same developing and fixing procedure as for the positive print. A terminological remark: The terms ‘positive’ and ‘negative’ as well as the term ‘photography’ were first used in 1839 by John Herschel, who preferred the latter over Talbot's more cumbersome description ‘photogenic’.[40] However, **(p.184)** it was not before the 1850s that the word ‘photography’ came into more general use.

Calotype had many advantages: more than one positive print could be made from each exposure, they were easier to send, and cheaper and easier to use, the final image was not reversed, and the tones were warmer and richer in contrast. A disadvantage was that paper usually could not retain as much detail as a polished metallic surface. It was often uneven as well and had a tendency to fade with time. Talbot's patent restrictions in France, America, and England (but not Scotland) presented the main obstacle to widespread use of this first negative-to-positive technique, however. Thus daguerreotype soon dominated internationally, with calotype remaining the hobby-horse of a few enthusiasts.[41]

The situation only changed in the early 1850s, when a new process called **wet collodion** or ‘wet plate’ photography conquered the world. Invented by the sculptor and photographer Frederick Scott Archer (1813–1857) in 1851, it was essentially an improved version of the calotype but using a glass plate coated with collodion, which was a mixture of nitrated cotton (gun cotton), dissolved in ether and alcohol, and potassium iodide. The iodide-rich acetate film was sensitized (in the dark) by a 2–3 minute soaking in a silver-nitrate solution. After draining, it was ready for exposure, which lasted typically between 10 sec and 2 min. A developing solution of pyrogallic acid was then poured over the plate until the image looked fully developed, rinsed in water, fixed in hyposulphite of soda, rinsed off, dried, and varnished. From this negative a positive contact print was made either on paper or on glass coated with albumen (raw eggwhite) mixed with common salt and sensitized with silver nitrate.[42] Spectrum photography used either glass plates or photographic paper, whereas stellar photography usually preferred albumenized glass plates, which guaranteed greater mechanical stability for later micrometric measurement.[43] The glass plate could be used for projection onto a bigger screen using a ‘magic lantern’, or for examination under the microscope and translation into wavelength measurements using a micrometer. Though glass-plate photographs were usually preferred because of their better image definition, improvements in albumenized paper ultimately afforded good-quality images less prone to fading than Talbot's salt paper.[44]

The main strengths of wet plates were a high definition of the photographic negatives, a potentially unlimited number of permanent positives, and a fairly reasonable price per paper print, at about 1/10 of the cost of a daguerreotype. The handling involved was awkward, though, because the plates had to be coated, exposed, and processed, all within minutes. **(p.185)** Otherwise the excess silver nitrate in the acetate film would crystallize and the emulsion would become strangely mottled. Many faint objects could not be photographed at all because the exposure time depended on the evaporation rate of the wet emulsion. For experimental work with spark spectra conducted in a confined space, another problem presented itself: the chemically aggressive ozone generated by the electric discharge rapidly covered the wet collodion with a thick deposit of silver.[45] Considerable skill was needed just for pouring the viscous collodion evenly over the glass surface, and most of the tedious preparatory steps for the photographic plates had to be done in the darkroom. That necessitated improvisations on the field with tents or other portable equipment. By the mid-1850s it was established that, when treated with silver and zinc- or magnesium nitrate, the wet emulsion's duration of sensitivity was considerably extended, by up to a week.[46] But the other inconveniences proved intractable.[47] Even when **dry collodion** plates became commercially available a decade later, they did not gain much popularity because they were only a fourth as sensitive as wet plates, which meant four times as long exposure times, suitable only for inert subjects.

In the third phase of development, after 1871, these serious drawbacks were finally overcome with the development of **gelatine-based dry plates.** This technology originated from “somewhat careless experiments tried at first on an exceedingly dull afternoon” by an English physician, Richard Leach Maddox (1816–1902).[48] Maddox tested other materials to replace commonly used collodion to carry the silver halides. This idea had occurred to others too but gelatine (as used in jellies) had not yet been tried as a substitute. He found a way to prepare a milky emulsion of slightly acidic gelatine, to which first a soluble bromide and then silver nitrate was added. While still warm, this emulsion was coated directly on one side of a carefully cleaned and polished glass plate. As the gelatine emulsion was drying, the chemicals did not crystallize out as in collodion. The plates had a “thin, opalescent appearance, and the deposit of bromide seemed to be very evenly spread.”[49] Development of the plates was achieved as before in a series of baths in solutions of pyrogallic acid and water, and the fixing was done with a solution of hyposulphite of soda. The resulting prints were “very delicate in detail, of a colour varying between a bistre and olive tint, and after washing dried with a brilliant surface.”[50]

(p.186) The necessary exposure times still remained between 30 and 90 seconds, so Maddox's plates were slower than contemporary collodion plates. Further optimization of the chemical ingredients and their concentrations, however, as well as the discovery that the sensitivity of the plates could be greatly enhanced by prolonged heating (called ‘ripening’) during preparation, reduced the necessary exposure times to under a second. By 1880 commercial gelatino-bromide dry plates were more sensitive still, by about a factor 20 as compared with their collodion-based forerunners, and tripods could be dispensed with for normal applications. Underexposed negatives could be enhanced subsequently by chemically enlarging the individual silver agglomerates suspended in the silver-bromide emulsion.[51]

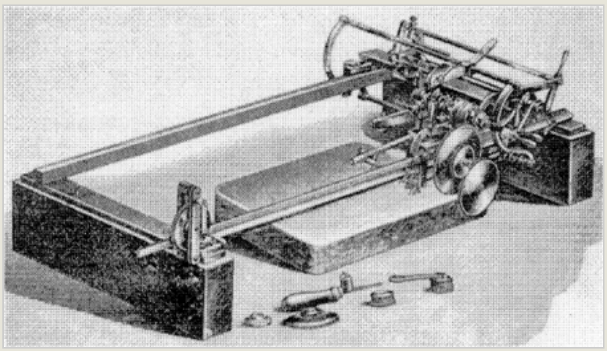


Fig. 6.1 Microphotograph of a silver-bromide emulsion enlarged by a factor of 900. *Left:* A normal Perutz plate, developed with Rodinal. *Right:* Enlarged grain with a metallic core and (yellow-brown) envelope after uranium nitrate enhancement. From Kaiserling [1898] pp. 32, 188.

By 1880, the production of gelatino-bromide dry plates was no longer in the hands of the photographer, who would do little more than emerse his plates in a bath containing a sensitizer solution (in cases where such special sensitivity was needed) shortly before exposure. True, photographic experts and scientists requiring plates sensitive to very special frequency ranges might still go through this ‘bath’ procedure, but the vast majority of customers preferred ready-made plates with the sensitizer forming a part of the emulsion.[52] A specialized industry in photographic supplies catered to the demands of the rapidly growing market. The Liverpool Dry Plate Company was one notable supplier as well as the firms Kennett and Wratten & Wainwright, Ltd.[53] The photographic gelatine was made from calf **(p.187)** skin (generally facial clippings and ears because these parts had little value as leather). The clippings were washed and treated with lime to remove the fat and hair. The lime was later removed with a weak acid followed by a rinse in water. The resulting mass was cooked in a steam kettle until the gelatine could be extracted, concentrated if necessary and allowed to set into blocks of jelly, which were cut into thin slices and stretched out on a net to dry.[54] The industrially manufactured plates were much improved in quality over the custom-made kinds in terms of emulsion homogeneity and reliability of sensitivity. By the mid-1870s paper coated with a gelatine emulsion was available for sale for making enlargements from smaller negatives using a gas-lit enlarger. Formerly, albumen-paper enlargers needed strong sunlight and outdoor mirror installations.[55] Easy-to-use handheld cameras with magazines of several plates, and later cellulose-based transparent roll film eventually made photography accessible to amateurs.[56] George Eastman of Rochester, New York and other entrepreneurs in the late 1880s thus transformed photography into today's mass technology, epitomized by Eastman's slogan “You press the button, we do the rest”.[57]

6.2 The dry-plate spectrum

The late 1870s were a time of change not only in commercial photography. As soon as these new plates arrived in the laboratory, scientific practice was likewise drastically altered. Substitution of ‘wet’ collodion for ‘dry’ gelatino-bromide plates very much depended on the specific application, the time constraints,[58] the wavelength range under study, and the regional availability of the various commercial plates. In Potsdam the astronomer Hermann Carl Vogel still preferred wet plates for the task of mapping the solar spectrum even as late as 1879. His reason was the very limited sensitivity of the dry plates available to him, which essentially confined him to the spectral range between 4270–4340 Å. Exposures of the spectrum near G were clear, but those above and below it were hardly visible on the plate. Alternatively, upon longer exposure, the other parts of the spectrum came out clearly, but then the region around G was totally overexposed, and consequently, solarized.[59] In the early stages of their photographic explorations of the solar spectrum, Vogel and his assistant Wilhelm Oswald Lohse (1845–1915), a trained chemist, even mistakenly interpreted **(p. 188)** similar inversion effects beyond the line A as indicative of unwanted reflection of light from other spectral regions within the 60° crown-glass prism. The unfamiliar appearance of spectral lines in the infrared regions led them to dismiss their records as artefacts of the instrument and prematurely conclude that, contrary to contemporary claims, photography was not suitable for recording any infrared spectra at all.[60]

Just a few dozen kilometers away, however, another spectroscopist of almost the same name made a quite different assessment. Hermann Wilhelm Vogel[61] (1834–1898) at the newly founded Charlottenburg Polytechnic[62] adopted the new commercial dry plates early in 1879 for his examination of spectra of various gases generated in a Geissler tube.[63] Wet plates had dried out too fast for the long exposure times (which could easily fill several hours) needed for these very faint spectra. Aside from this, wet plates were particularly insensitive in the more refrangible ends of the ultraviolet, that is, precisely in the region that depended on photography as the only available detector for the spectrum lines. Finally, as mentioned above, the ozone produced by the electric discharge generating the spark or light arc spectra acted chemically on the wet collodion plates, causing them to become coated with a thick deposit of silver after the developing solution had been applied.[64] With the new gelatine-based dry plates H.W. Vogel found the sensitivity increased overall by a factor of 15. As a result, he was able to photograph very faint spectral structures that had never before been recordable photographically, and some had never yet been observed visually either. For instance, Vogel found several new lines in spectra generated in a Geissler tube containing very pure hydrogen. Thus the hydrogen series, which until then was thought to consist of only four lines, could be extended into the far violet and ultraviolet.[65] Meanwhile, in England, the gentleman scientist William Huggins had also discovered the usefulness of dry gelatine plates for the purposes of spectroscopy—in his case stellar spectroscopy—which likewise dealt with very faint luminous objects whose spectra had to be recorded for hours at a time before they could be examined under a microscope. Initially **(p.189)**

> I used wet collodion, but I soon found how great would be the advantages of using dry plates. Dry plates are not only more convenient for astronomical work, being always ready for use, but they possess the great superiority of not being liable to stain from draining and partial drying of the plates during the long exposures which are necessary even with the most sensitive plates. I then tried various forms of collodion emulsion, but finally gave up in favour of gelatine plates, which can be made more sensitive.[66]

Because Huggins was using quartz, he advanced further into the ultraviolet than H.W. Vo-gel had with his flint-glass prism spectrograph. Huggins's spectra of certain white stars then showed striking coincidences with four of the newly discovered lines in H.W. Vogel's hydrogen emission gas spectra from the laboratory. It became exceedingly plausible that Huggins's stellar spectrum lines were attributable to hydrogen in the stellar atmospheres. Moreover, the very regular distribution of these lines, with the interval between any two adjacent lines differing in size by a constant amount, provided a decisive clue for the contemporary search for patterns in spectral line series (to which we shall return on pp. 295ff.). The use of gelatine dry plates in spectroscopy thus led to progress on more than one front.

6.3 The photographer's self-image

From today's point of view, the earliest photographs by Niépce, Daguerre, and the other pioneers are scarcely naturalistic renderings of the objects originally observed through the camera view-finder. But how were these early photographs ‘seen’, that is to say, ‘interpreted’ by their makers? Did they comprehend their products as truthful depictions of reality or only as short-hand memory aids, black-and-white guides for subsequent artistic translation by means of engraving? And what kind of arguments did the proponents of the new technology use against its conventional competitors? To answer these questions we must return to the *annus mirabilis* of photography: 1839, before taking note of conceptual changes in the following decades.

After some experimentation with silver-salt mixtures which ended in a reduction of the exposure time to ten minutes for a landscape, “though faint” yet suitable to “serve as a traveller's sketch”, John Herschel felt the time had come to declare in a letter to Fox Talbot: “that the process of photography is now placed within the reach of every body -is quicker than copperplate engraving (i.e. than the more elaborate sorts) -is susceptible of quite as great delicacy as the most finished copper plate work —and is quite available for *self-registry of all sorts*.”[67] This verbalizes the already intense competition between photography and other available printing techniques. One of the most popular applications of early photography was reproduction of engravings and lithographs, both as negatives and as positives—as if the new technology had first and foremost to demonstrate its ability to reproduce what the senior mechanical arts already mastered. As with lithography, the radically new features it offered were appreciated only later. Talbot's assertion expressed early on, in 1839, is a case in point: “There is not the smallest doubt that the finest engravings can be imitated […] I am so confident about the success of copying engravings judging by those which I have already made, that I should like very much to prepare a fine collection **(p.190)** of them, to be shown at the Scientific Meeting at Birmingham or sooner.”[68] John Herschel was similarly fascinated with the idea of applying photography to “the art of Copying Engravings, lithographs, mezzotints, or original drawings of every description” and assessed his trials positively in a note in March 1839 about applications of the art of photography to the purposes of pictorial representation by pointing precisely to its ability to reiterate faithfully all the intricate details of the original plates: “Many of these [sample photographs] are copies from very elaborate and highly finished ornamental steel-plate engravings and when examined with a powerful magnifier, will be found to render every stroke and dot with a fidelity quite equal to that of a printed impression.”[69] As the historian of photography Graham Smith remarks, these intricate patterns “would have challenged the most patient and skillful draftsman,”[70] and it is certainly possible that these motifs were chosen for precisely that reason. I suspect, though, that they also appealed to Talbot's aesthetic sense, especially when you consider that he had embarked on his gentle excursions into science in the field of botany.[71] It would not be long before the “multitude of minute details” that Talbot documented in leaves, ferns, flowers, and haystacks reappeared in the graphic representations of spectra, which were no less intricate in structure and design.

The parallel with lithography continues, for during its introductory period, it too was praised for its ability to imitate copperplate engravings. Photographers too extolled the new autonomy won from the dictate of mindless draughtsmen, employing the rhetoric of ‘self-recording’ features of the new technology. Upon becoming aware of Daguerre's achievement in early 1839, Talbot decided to exhibit ninety-three of his ‘photogenic drawings’ from years past at the Royal Institution, essentially contact prints on paper of flat objects including plant leaves, copperplate engravings, and other intricate patterns. Both the term ‘photogenic drawing’ and the somewhat unusual activity of ‘exhibiting’ the results of research gain meaning when we place them within the contemporary context of recording and printing techniques which all derived from the arts.

In a letter to John Herschel, Talbot spoke of his early photogenic drawings as “the possibility of fixing upon paper the image formed by a Camera Obscura, or rather, I should say, causing it *to fix itself*”.[72] For instance, an image of Lacock Abbey taken in May 1839 was labeled “self-represented in the Camera Obscura” by Talbot. According to his conceptualization, the house “had painted its own portrait”, so to speak.[73] The option of applying photography to tiny filigree objects such as flies' wings was appreciated, “to let Nature substitute her own inimitable pencil, for the imperfect, tedious, and almost hopeless attempt **(p. 191)** of copying a subject so intricate.”[74] When in the years 1844–46 he later published a selection of his calotypes under the title *The Pencil of Nature*, Talbot found it necessary to assure the public that the illustrations were indeed photographs. In some copies he inserted a “Notice to the Reader” which reaffirmed: “the plates of the present work are impressed by the agency of the light alone, without any aid whatever from the artist's pencil. They are the sun-pictures themselves, and not, as some persons have imagined, engravings in imitation.”[75] The six fascicles included various motifs, each with a commentary of at least a page. A haystack was chosen, for instance, to demonstrate that “the photographic art will enable us to introduce into our pictures a multitude of minute details which add to the truth and reality of the representation, but which no artist would take the trouble to copy faithfully from nature.”[76] *Nomen est omen: The Pencil of Nature* was a program: it suggested that no longer was any more-or-less skilled human draughtsman at work, but Nature herself, using the inscription device conveniently provided by camera and photographic plate. Talbot failed to mention, however, that in order to meet the demand for the calotype prints (1440 alone for the first installment printed between June and November 1844), he had established a separate factory in Reading, the first mass-production facility for photographs, where many by no means unskilled hands aided in the delivery of nature's inspirations.[77]

In a similar vein, Arago described Daguerre's method in terms of a self-recording mechanism, rigorously mapping colored objects in black and white:

> everything that the image contains is reproduced, down to the minutest detail, with incredible accuracy and sharpness. […] *light itself reproduces* the shapes and proportions of the external objects with almost mathematical precision; the photometric relations between the various white, black, and gray parts are exactly retained; but the half-tones represent red, yellow, green, etc., for the method creates drawings, not color paintings.[78]

When summarizing the recent progress in photography for *The Edinburgh Review* in 1843, Sir David Brewster used the metaphor of a mirror to describe the "incalculable advantages" of photography over the arts of painting and sculpture. And he left no doubt that in his opinion it was superior to the "travelling artists" with their "hurried sketches" and their "false and ridiculous illustrations, which are equal mockeries of nature and art":

> when the photographer has prepared his truthful tablet, and 'held his mirror up to nature', she is taken captive in all her sublimity and beauty; and faithful images of her grandest, her loveliest, and her minutest features, are transferred to her most distant worshippers, and become the objects of a new and pleasing idolatry.[79]

(p.192) The rhetoric of photography as a faithful, precise, and complete rendering of objects was by no means confined to these scientific circles. Even the Art Union applauded some of Talbot's calotypes as "truly wonderful representations […], a transfer to paper of the masses and tracery of light and shade by a means utterly inimitable by the ordinary resources of Art […] there is nothing inharmonious in nature, therefore the closest imitation of nature is the nearest approach to the beautiful".[80] This technique was praised in a similar spirit by the publisher of another book containing photographic illustrations, which appeared at the end of the 1850s, with the words: "[photography] sees anything, omits nothing, is never negligent, does not tire […] the sun dictates".[81]

But not everyone was swept up by this enthusiasm. Lithographic draftsmen, printers, and artists alike felt threatened by this new rival, and they had legitimate doubts about whether photography really was all it was trumped up to be. Assuming a more tempered tone, Hunt's subsequent article assigned a much more subservient role to photography of providing a kind of “skeleton map” to the artist “which saves him some rough work, and sets him free to supply the deficiencies in truth, in life, and in spirit. […] there is no reason to fear that either [talbotype or daguerreotype] will supersede the labors of the artist; in spite of all the chemical and optical aid we can afford him, the Sun will continue to be a very bad painter, too literal in his details, and at the same time too false in his proportions. But solar pictures offer valuable materials on which the artist can work.”[82] This moderation was the more opportune since Talbot's pictures of the Sun were not only far less brilliant and clear than daguerreotypes but they also faded rapidly: today, hardly more than a ghostly greenish shadow remains of the first calotypes that were mounted into the June 1846 issue of *The Art Union.*

This did not put an end to the debate about photography versus conventional art forms, however. On the contrary, it intensified with each new improvement in photographic technique. An essay on the relation between photography and painting written by the art historian and critic Philip Gilbert Hamerton (1834–1894) in 1860 shows how tense these ‘relations’ still were 15 years after Talbot's pioneering publications. By pointing to the serious problems contemporary photography encountered in representing immense variations in light intensity, rapidly moving objects, and sudden changes in light conditions, besides rendering the subconscious human focusing of foreground and background alike, etc., he attempted to debunk systematically the many myths that photographers had been spreading about their trade. For this critic, “painting is a great intellectual art; an art of compensation, and compromise, and contrast; an art capable of moderation, and subject to mastery. […] photography is not a fine art, but an art science; narrow in range, emphatic in assertion, telling one truth for ten falsehoods, but telling always distinctly the one truth that it is able to perceive.”[83] The same literalness, directness, and lack of moderation which Talbot and other photographic pioneers had presented as a virtue was here turned into a deplorable **(p.193)** deficiency stripping photography of its aspired status as a ‘fine art’ and degrading it to a “useful and curious invention”, to a mere craft.[84] Time and again, this qualification made by advocates of the traditional arts of genius (in the emphatic sense) in the sphere of the liberal and fine arts *(artes)* against the—at best—‘ingenious’ mechanical and chemical manipulations involved in photography *(technes)*, was disputed by some of the more aggressive spokesmen of the new field.

6.4 Early photographs of the solar spectrum, 1839–1846

The possibility of applying Daguerre's method of fixing “images that form on the focal plane of a camera obscura”, in order to check whether the optically manifest black lines in the solar spectrum were also “effets photogéniques”, had already been raised by Arago in his official report to the Paris Academy.[85] Just a few weeks later, Arago's colleague Jean Baptiste Biot presented a follow-up report on his efforts to use this new technique as a tool for scientific studies of optical problems, not as the object of study itself, as had been the case with other publications on daguerreotype up till then. Indeed, daguerreotype was well-suited for the study of solar radiation. Unlike the human retina, which is just sensitive to radiation within the visible range, surfaces sensitized with Daguerre's silver salts proved to be sensitive to actinic and caloric rays (or, as we would say today, the ultraviolet and infrared spectrum) which had both been discovered shortly after 1800. Biot claimed that sensitized paper first dipped in a solution of hydrochloric acid, then sensitized with silver nitrate, was at least as sensitive to heat radiation as Melloni's thermopile, which had been used up to that time for detection of radiation beyond the visible red end of the spectrum.[86] Biot and his assistant systematically tested the effect of sunlight on silver salts, collecting it with the aid of a heliostat, guiding it through various color filters, and projecting it onto sensitized paper in an otherwise sealed container. By changing the light absorbers, the degree of polarization, and the exposure times, they established, for instance, that a blue filter caused the most serious weakening of the resulting image, which suggested that the blue part of the spectrum was instrumental in forming the photographic image.

In close parallel to developments in flame analysis, where color filters were used in the earliest exploratory experiments, the next step was decomposing the light prismatically and examining the sensitivity of the photographically sensitized surface to various parts of the spectrum. Biot did not do this himself. In the following years he was assisted by “an aid, as intelligent as he is zealous”. Edmond Becquerel (1820–1891), the son of one of Biot's colleagues in the Paris Academy,[87] took up this photochemical analysis of prismatically decomposed light from the Sun as well as from various artificial sources.

Becquerel's initial idea was to cover chemically sensitized paper with glass of various colors in order to see how their different absorptions influenced the chemical reactions. He noticed that after a few minutes exposure to the Sun through red and yellow glass, no action **(p.194)** was observable on the surface, while it was soon blackened through blue glass. When he first exposed the surface to violet rays for a very short time, and then placed the paper under red glass, the chemical action continued nearly as intensively as it did under blue glass. In 1839 Edmond Becquerel reached the conclusion that radiation from these light sources contained at least two different classes of rays: (1) “rayons excitateurs” which were able to initiate chemical action in sensitized surfaces such as paper soaked with silver bromide; and (2) “rayons continuateurs”, which only became chemically active once these surfaces had been exposed to the first class of rays. The first class seemed to be confined to the spectral region between blue and violet and beyond. The second class was active between red and blue. This dual divisioning also held for surfaces sensitized with chloride or iodide of silver; further corroboration derived from the ease in screening out either one of the two classes by means of color filters.[88] The mysterious strengthening of latent pictures by extended exposure to longwave radiation was also confirmed in later studies, long after Becquerel's dichotomy of rays had broken down. It is now known as the **Becquerel effect.**[89]

Three years later, Edmond Becquerel had advanced to the position of assistant at the Paris Muséum d'histoire naturelle, where his father had been occupying the chair for physics since 1837. In June 1842, Becquerel junior utilized both processes by Daguerre and Talbot for the first permanent recordings of a chemical spectrum extending substantially beyond the violet end of the optical spectrum.[90] By varying the exposure time between two minutes (the minimum time needed for a trace of the spectrum to appear on the plates) and an hour, Becquerel soon revealed that the extension of the chemical spectrum beyond the violet depended upon how long it was exposed. Along the same vein, Becquerel investigated the sensitivity to the chemical spectrum of specific preparations and chemical compositions of the sensitive layer on a photographic plate (see Fig. 6.2). He experimented with Daguerre's standard recipe of silver iodide as well as with silver chloride and bromide, and gold halides. To this list he added several phosphorescent substances that also formed an image of the incident radiation (see here § 2.8 on phosphorogenic spectra). Furthermore, he worked with several kinds of filters that altered the extension and intensity of the registered spectra as well as the location of their respective maxima.

By careful adjustment of the exposure time of his daguerreotypes, Becquerel was the first to show that the Fraunhofer lines were zones of chemical inactivity within the spectrum. Because of the absence of radiation at any of these dark lines, the photographic paper simply was not darkened along their traces. Although the relatively low dispersion of his prism (generating a visible spectrum of only about 15 cm total breadth on the photographic plate) allowed registration of only the strongest lines, their positions coincided exactly with those of the Fraunhofer lines (e.g., F and H) in the optical spectrum. However, a virtually “infinite number” of finer lines could be recorded by augmenting the total length of the **(p.195)** spectrum or parts of it up to a factor of ten with the aid of lenses, and by optimizing the aperture of the shutter.[91] This coincidence of dark lines in overlapping spectral regions in the optical, phosphorogenic, and chemical spectra (cf. Fig. 2.30) convinced Becquerel of the essential identity of the three kinds.[92] Thus he felt justified in plotting the newly discovered dark rays beyond the violet end of the spectrum as a natural extension of the Fraunhofer spectrum, with a continuation of Fraunhofer's labels from H to Z.

Fig. 6.2 Edmond Becquerel's extended spectrum including many newly discovered dark lines beyond the violet end of the visible spectrum. Copper engraving by Dulos. From E. Becquerel [1842*a*] plate, fig. 2 (note: the symbolic labels are not identical to the ones later adopted; cf. also Fig. 6.4).

It is true that by 1843 Becquerel was still talking about ‘rayons excitateurs’ and ‘continua-teurs’,[93] but he understood this distinction—just like the standard ones between chemical, calorific, and optical rays—merely as convenient terminological demarcations of different classes of phenomena without any ontological or epistemological implications. In that year he explicitly argued against any premature postulation of different entities.[94] Becquerel then attributed the differences in the chemical, phosphorescent, and optical effects of solar radiation to the different media used for detection and recording, and no longer saw them as indicating any fundamental differences in the efficacious entities:

> among this mass of remarkable phenomena which the action of solar rays engenders, the various observable effects thus originate merely from the differences existing between sensitive materials and not from an alteration of the producing agent. All the facts known thus far depend on this observational approach. These differences between impressionable bodies are such that on the retina, the optical sensation is of but short duration; on a sensitive chemical material, the solar rays destroy the equilibrium of the particles in such a way as to effect a new molecular arrangement and on a phosphorescent substance the rays disturb the equilibrium of the molecules only momentarily.[95]

(p.196) Thus the chemical differences counted less for Becquerel than a homogeneity among chemical, phosphorescent, optical, and calorific rays with respect to reflection, refraction, polarization, and interference. The presence of all these properties was essential for unification under Fresnel's mathematical wave theory of light.[96]

As we shall see in a moment, the special target of Becquerel's critique of premature generalizations in interpreting these photochemical findings was the American chemist and physiologist John William Draper[97] (1811–1882), professor of chemistry and natural philosophy at the University of the City of New York since 1839. Draper was one of the pioneers of photography on the American continent. He was among the earliest to set up a photographic studio on the roof of his house on 4th Street, right across from the campus.[98] Draper was possibly the very first photographer to adopt daguerreotype successfully at the early date of 1839 for portrait photography. Hitherto it had mostly been used for landscapes and buildings. And he was quite certainly the first scientist to succeed in photographing the Moon, in 1840.[99] To reduce the exposure times to the required minute or less for live portraiture,[100] Draper improved the camera design as well as his technique of illuminating objects and persons. But above all he optimized the sensitivity of the silver-halide photographic plates. In mid-1842 he experimented with different fixing methods. At that time, and hence nearly concomitantly with—and quite certainly independently of—Edmond Becquerel, Draper also succeeded in recording a daguerreotype of the solar spectrum (or as he preferred to call it, a “tithonographic representation”). Soon thereafter he produced daguerreotypes of flame spectra, and by 1845, Draper was the first experimenter to have recorded a diffraction grating spectrum.[101] Because spectra generated by reflective interference of a metal grating were much weaker than prismatic spectra, he had to expose it twice as long as before (30 min). Regrettably, in 1865 most of Draper's photographs were destroyed in a fire. At least one of Draper's earliest daguerreotypes of the solar spectrum **(p. 197)** has survived, however. It is one dated 27 July 1842 that he had sent to Sir John Herschel in England[102] (cf. Fig. 6.3).

(p.198) This photograph shows that, unlike Becquerel, Draper did not succeed in recording any trace of the Fraunhofer lines in the yellow, orange, and green parts of the spectrum. He explained to John Herschel in September 1842:

> You will see, Sir, that the darkening action ends at the termination of the blue ray, and then after a fringe of certain width & of a white colour is passed, a powerful protective action takes place, wholly arresting the action of diffused daylight. This goes down beyond the extreme red, and if you look very narrowly, there is within this protected space a faint white ray that in certain lights exhibits a play of colours. […] At the other end, beyond the rays you have termed lavender, the same kind of negative action reappears,— it is therefore entirely independent of refrangibility. This upper negative ray I cannot obtain in New York, though operating under circumstances [temporally?] similar.[103]

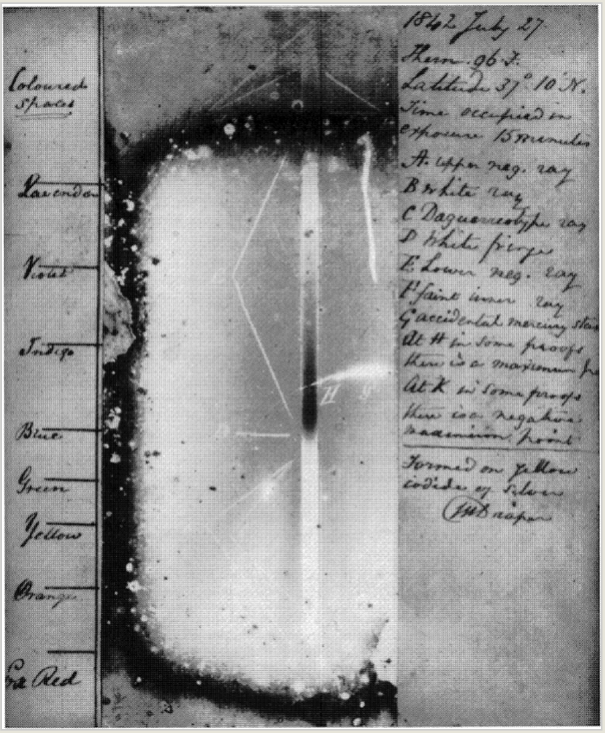


Fig. 6.3 J.W. Draper's daguerreotype of the solar spectrum, with his handwritten commentary on the right margin. 27 July 1842. The original, sized 9 × 7.5 cm. is now a part of the Herschel collection of the National Museum of Photography, Film, and Television, Bradford.

As did other pioneers of spectrum photography, Becquerel and J.W. Draper compared their photographs against Fraunhofer's map of the solar spectrum. A clear coincidence of the strongest among Fraunhofer's dark lines revealed that daguerreotypes recovered parts of the spectrum not visible to the eye. It was also apparent that the chemical action of the spectrum on a photographic plate was *minimal* precisely in those areas of the spectrum where the eye gauged a *maximum* intensity. Further experimentation eventually led Draper to find, independently of Becquerel, distinct spectrum lines beyond the violet and red ends of the spectrum. These he labeled *α, β*, and *γ*, because they appeared before Fraunhofer's line A.[104] Draper drew a conclusion about these findings that was at odds with Edmond Becquerel's (see above) and John Herschel's. The latter tended to regard such a variation in the effects that the spectrum had on different media and different chemicals as “a different form of expression, and so to speak a different language [of a single entity], each having its own peculiar idiom.”[105] The dazzling effect of the spectrum on the eye and its aggressiveness on the silver salts seemed to Draper evidence of two completely separate physical entities: an optical spectrum and a chemical one, which he drew side by side (see here Fig. 6.4).[106] Draper suggested calling the latter “Tithonic rays”, to distinguish it more clearly. Other names were also proposed, such as ‘helioplaston’, ‘actinicity’, ‘metamorphia’, or *ενειγεια*. But none were accepted by the scientific community, which continued to refer to the ‘chemical spectrum’.[107]

(p.199)

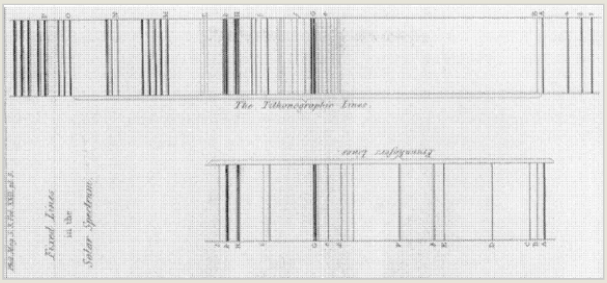


Fig. 6.4 J.W. Draper's dual representation of the optical and the tithonic solar spectrum, 1843. Note the features *α, β,* and *γ* beyond the red end of the spectrum, and the line groups M, N, O, and P beyond the violet, which are quite distinct from the way they are drawn in Becquerel's graph of 1842 (Fig. 6.2). Engraving by J. Basire. From J.W. Draper [1843*c*] pl. **III.**

John Herschel had pointed out in 1839 that diffraction gratings would be better suited for “minute examination of the chemical actions of all the parts of a pure spectrum”, because prisms absorbed part of the light. The weak spectra produced by gratings presented a serious drawback, however. Nor were these instruments easy to obtain: Draper eventually convinced the highly skilled mechanician Joseph Saxton at The US Mint in Philadelphia to make one for him. Initially using this glass grating (sized 5/8 of an inch by 1 inch) in transmission, Draper was able to take the photograph, later obtaining even better results after coating the ruled surface with a tin amalgam.[108]

The following will focus on the photographic exploration of what we would nowadays call the near-ultraviolet section of the solar spectrum. The experimental strategy chosen by the early ‘photologists’, as John Herschel referred to this handful of fellow photochemical researchers, was **variation.** They explored the sensitivity of as many different substances, in as many combinations and concentrations as possible, to the different types of radiation. Obviously thermometers and thermo-multipliers were more sensitive to heat radiation than to visible light. Light-sensitive chemicals, on the other hand, reacted most strongly with the chemical spectrum in the indigo—violet region of the spectrum and beyond. But most substances exhibited characteristic gaps in sensitivity in the yellow-green region of refran-gibility. Photographic plates and paper differed considerably in sensitivity to different parts of the spectrum, depending on the precise chemical constitution of their sensitized surfaces, and to some degree also on their concentration.[109] As if this wasn't complicated enough, the sensitivity also seemed to depend on the precise physical conditions experienced prior to exposure. For instance, Herschel discovered that his plates became more sensitive if previously **(p.200)** subjected to heat. This effect was later routinely used to optimize the sensitivity of photographic plates.[110] The options were virtually endless, ranging from silver halides, gold, platinum, and mercury compounds, to organic sensitizers, such as various dyes and even bacteria. Exploration of this experimental space was—and still is—an immensely complex affair. Since an all-inclusive overview is beyond the scope of this book, I would just like to point out the exploratory character of this early work, which was devoid of any theoretical guidelines or understanding of the complex chemical processes involved.[111]

(p.201) Fig. 6.5, taken from Robert Hunt's 1844 survey of experiments, summarizes the main research strands pursued at the time. The relative sensitivities of 29 chemicals to different parts of the spectrum are indicated by the lengths and positions of the enumerated vertical lines. The respective maxima of sensitivity are indicated by the intersecting dotted line.

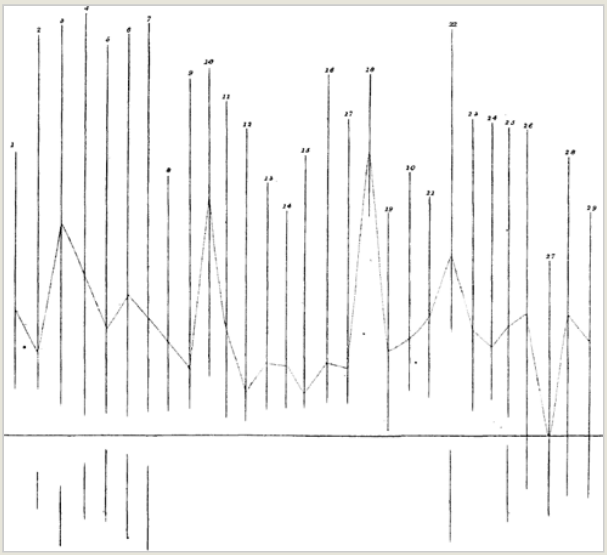


Fig. 6.5 Hunt's survey of contemporary photochemical experiments, 1844. The numbers 1–13 stand for “salts of silver”, with 1: nitrate, 2: chloride, 3: iodide, 4: iodide and ferrocyanide, 5: darkened silver and iodide, 6: daguerreotype plate, 7: bromide, 8: fluoride, 9: phosphate, 10: tartrate, 11: benzoate, 12: formobenzoate, 13: benzoate hyd benzule. Nos. 14–18 represent “salts of gold”, with 14: chloride, 15: protocyanide of potassium, 16: protocyanide of potassium and formobenzoate, 17: the same and ammonia, 18: percyanide of gold and ammonia; 19: platinum chloride, 20: mercury carbonate, 21: ferrocyanide of potassium, 22: the same and perchlorate of iron, 23: chromate of copper, 24: bichromate of potash. Nos. 25–29 reflect various “vegetable compounds”, 25: gum guaiacum 26: corchorus japonica, 27: ten week stocks, 28: wallflowers, and 29: green of leaves (chlorophyll). From Hunt [1844*b*] tipped-in oversized plate.

Organic extracts and vegetable dyes were also tested, such as the brilliant orange *pa-paver orientale, chryseis californica*, and *bulbine bisulcata*, the bright yellow *cheiranthus cheiri* (wallflower), the dark brown *ferranea undulata*, the violet *viola odorata*, or the intensely blue *viola tricolor* (commonly known as heartsease).[112] John Herschel's first experiments in early 1839 included tests of the effect of exposure to a spectrum, on such organic substances, most prominently on gum guaiacum, a resin from the West-Indian gua-iacum tree. The sensitivity of pulverized gum guaiacum to light was already known to the eighteenth-century Bremen pharmacist A. Hagemann, who noticed a blue coloration on its surface after a few weeks of exposure to light in a sealed glass vessel; the powder underneath kept its natural color. He interpreted this finding on the basis of the phlogiston theory, assuming that the gum guaiacum extracts the phlogiston from the light and turns blue, but loses this color as soon as it is in contact with the “fiery air’ which withdraws the combustible parts from the gum.[113] When Herschel took up these experiments on the effect of rays in “discharging vegetable colours”, the age of phlogiston had, of course, irretrievably passed. To him what was most important was finding out which rays were most “efficacious” in such discoloration. Overcast skies initially inhibited the spectral work, but more complete reports about the results of his experiments with extracts from these exotic flowers appeared in the following years.[114] The various “vegetable juices” exhibited dramatically different responses to light exposure lasting between one hour and two months. The following features were listed by Herschel as being “almost universal” to all the observations:

1. If exposure to the spectrum had any impact at all, it essentially annihilated the surface color by bleaching, although in some cases a residual color differing from the initial one remained.[115]
2. The action seemed confined to the visible part of the spectrum. In particular the calorific rays seemed not to have any impact at all and the actinic rays apparently were “for the most part ineffective” as well.[116]

(p.202)

3. Color complementarity seemed to be of special importance. Yellow-orange vegetable colors, for instance, tended to be destroyed predominantly by the blue rays, “blues by the red, orange and yellow rays; purples and pinks by yellow and green rays”, etc[117]

The inquiries into the action of solar rays on vegetable juices by Mary Fairfax Somerville (1780–1872) is another example of research along these lines. Already known as a scientific expositor,[118] she originally chose her research topic within photochemistry at John Herschel's suggestion.[119] In these analyses, thick white paper moistened with the liquids to be examined was exposed to the solar spectrum. She recorded the transformations on the paper surface and found a “peculiarly strong influence of the rays of mean refrangibility in darkening vegetable juices”, quite in contrast to the silver salts whose maximum sensitivity occurred in the part of the spectrum beyond the violet. She also noticed a “very frequent recurrence of two insulated dark spots” (see here Fig. 6.6 lower end), which reminded her of the isolated spots α to ε observed in J. Herschel's thermograph in the same spectral region (see Fig. 2.28).

Since these distinct spots concurred so often with the parts of the paper darkened by the yellow-green rays of the spectrum, she inferred “a similarity, possibly identity, in the nature of the agent producing these phenomena”.[120] Hers is a strange visual representation **(p.203)** of the spectrum, quite different from the many other forms discussed in this monograph.

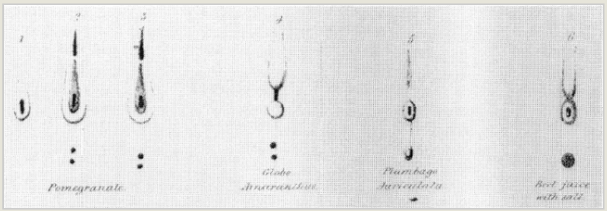


Fig. 6.6 Visual representation of the action of the solar spectrum on paper moistened with vegetable dyes. Lithograph by J. Basire. From Somerville [1846] pl. Ill, first row.

These experiments were neither a mere curiosity for eccentric gentleman scientists nor were they an odd side-product of skewed activities by a new breed of self-educated female investigators.[121] They were typical of the type of research practiced at the time. John Herschel, who presented Somerville's paper to the Royal Society in 1845, had worked on the effect of the solar spectrum on vegetable dyes, following a similar pattern; and further parallels may be seen with Robert Hunt's and John William Draper's research on plant physiology in general.[122] This research strand dates back to the botanist Jean Senebier (1742–1809), whose *Mémoires physico-chymiques* of 1782 must be regarded as fundamental of what the historian of optics Alan Shapiro has aptly called the ‘chemistry of light’.[123] It reflects a chemist's or pharmacist's perspective on optical problems. Forgotten in the physics literature of the 1820s, it remained alive in a small interdisciplinary research tradition to which disparate individuals like the chemist Michel E. Chevreul, the exploratory photographer Robert Hunt, the botanist Charles G.B. Daubeny, and others in the old school of natural history contributed.[124] It would be worthwhile to examine the full extent to which photochemical investigation was connected with research in botany, plant physiology, and chemistry during this period. We, however, must continue on with the work on color photography, which was not far removed from the above-mentioned systematic analyses of photochemically sensitive substances.

6.5 Early work in color

The above list of responses by organic dyes evidences the optimism of early “photologists' not only about improving photochemical sensitivity, in general, but also about developing color photography—or as Herschel explained: “in short that the spectrum photographs its own colours.”[125] John Herschel's recording of a solar spectrum in 1839, generated with a high-quality Fraunhofer crown-glass prism and imprinted on silver-chloride-coated paper in “sombre, but unequivocal tints, imitating those of the spectrum itself” proved not to be preservable unless it was shielded from further exposure to light.[126] Nonetheless, his variants of Talbot's calotype process, known as chrysotype and cyanotype, which had emerged **(p.204)** from his photochemical study of the action of the solar spectrum on vegetable colors, intensified the resulting images.[127] These temporary photographs did allow him to explore the action of spectral colors on specific chemical preparations of the photographic paper. He determined, for instance, the variation in length of the photographically recorded spectrum: for silver-nitrate paper it was 1.57 times as long as the visual spectrum, for almost colorless silver-chloride paper 1.8 times as long, and for pale yellow silver-bromide paper even 2.16 fold.[128] Herschel was also the first to note the following strange effect: He projected the image of a spectrum onto silver-chloride paper which was simultaneously exposed to diffuse daylight. The latter discolored the paper by forming print-out silver, but this discoloration was annihilated just where the red part of the spectrum had fallen. Instead of the latent silver image, a “full and fiery red” could be seen for a short while. This meant that red light had an inverse action to violet light, bleaching rather than darkening silver-chloride paper. He then checked the combined action of red and violet radiation on photographic paper with a special combination of prisms and lenses, which confirmed the strange destructive action induced by the red rays, now known as the **Herschel effect.**[129]

Other experimenters did succeed in producing a stable photographic image in color that corresponded at least partially to the continuous range of spectral colors. One prominent example is the solar spectrum recorded by Hunt on paper first dipped into nitrate of silver, and then into sodium fluoride, obtaining thus a thin coating of silver fluoride. The result was a spectrum photograph “not in shadows merely, but in colours, which have the peculiar appearance of the down upon the nectarine”. As Fig. 6.7 illustrates, the green part of the spectrum was represented nearly in “its true colour”, while the yellow rays remained “without action”, and the red region was mapped into a sequence of rose hues followed by white with a shade of green and a black band, which reminded the American amateur photographer of “the effect produced by the interference of coloured media on some photographic drawings”.[130]

Hunt too had “no means of fixing the colours which the Spectrum impresses.”[131] But he didn't give up. Between 1840 and 1843, he experimented with many other chemical preparations for sensitive paper, including washes of ferro-cyanate of potash, bichromate **(p.205)** of potash, or muriate of barytes,[132] all

combined with nitrate of silver which, after exposure to diffuse light under different glass filters, “became red under the red glass, a dirty yellow under the yellow glass, a dark green under the green, and a light olive under the blue”.[133] He, and John Herschel too, with whom he frequently exchanged letters during this period, also experimentally substituted the silver with other metals, such as mercury, copper, gold, or platinum.[134] Edmond Becquerel likewise jumped onto the bandwagon, en route since Herschel's well-known experiments of 1839, and made a series of color photographs of the solar spectrum in the mid-1840s. Unlike his predecessors, Becquerel took special care to produce a very uniform and smooth coating of chloride of silver. He repeatedly immersed the polished silver plate in chlorine water until the silver assumed a rose tint, or dipped it into a solution of cupric or ferric chloride. The best results, however, were obtained by an electrochemical method: the silver plate and a platinum plate were emersed in a solution of hydrochloric acid and the silver plate was connected to the positive pole, and the platinum one to the negative pole of a voltaic battery. The electrically induced decomposition of the hydrochloric acid released chlorine molecules which were electrically attracted to the silver plate. Combining with it chemically, a surface of silver chloride of great purity was formed. Careful observation of this electrolytic process under dim light revealed changes **(p.206)** in the surface color of the silver plate from gray to yellow to violet to blue as its coating thickened. Continuing the action, these colors reappeared in the same sequence. The best photographic results and the greatest sensitivity were obtained if the silver plate was taken out of the electrolytic bath once it had acquired a violet tint for the second time. It was then washed, dried, and carefully heated until it exhibited a pink hue. Another improvement in the results was gained by exposing this plate to diffuse light for a short time and then projecting the solar spectrum onto the intricately sensitized plate for just a few minutes: “again it takes on a bluish tint, distinctly registered within prismatic blue, discolors slowly toward yellow, and turns into pink within red.”[135] One of the best specimens of Becquerel's color photographs of the spectrum is actually preserved inside an ornamental box in the archives of the Conservatoire national des arts et métiers in Paris.[136] The gap in the yellow region of the spectrum, which mysteriously left no imprint on the usual silver salts, was soon closed by Abel Niépce de Saint-Victor, a nephew of the inventor of the asphalt process, who generated what he called “images héliographiques colorées par la lumiére”. According to him, intense yellows could be obtained by chlorides of uranium, sodium, or potassium, and by hypochloride of soda, and the color orange by calcium chloride, green by boric acid, nickel chloride, and copper salts, etc.[137] However, neither Becquerel, Niépce de Saint-Victor, nor A. Poitevin, J. Trail Taylor, William de W. Abney, and other experimenters who picked up this thread in the 1860s and 1870s, found a working method for fixing the resulting ‘heliochrome’ images, which had to be kept shut away in light-proof drawers to preserve the spectral images.[138]

The problem was that no one could point to any theoretically successful avenue towards obtaining permanent color photographs. All they could do was experimentally probe the immense range of possibilities in chemical and physical preparations of silver salts. As William Jerome Harrison (1845–1909) put it in 1887, himself a dedicated photographer and one of the first historians of photography, after nearly 40 years of such exploratory work, with no sign of a tractable way,

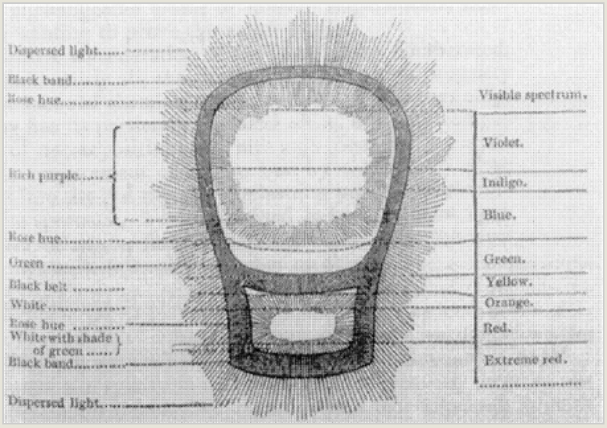


Fig. 6.7 Hunt's color photograph from 1840 of the solar spectrum. Reproduced as a wood engraving with explanatory text. From Hunt [1840*b*] p. 273.

> There is probably only one thing which it is safe to predict about the problem of obtaining permanent photographs which shall represent objects in their natural colors, and that is that the discovery, if it is ever made, will not be the result of an accident. The question must be studied and the conditions mastered before the attempt can be made with even the least chance of success.[139]

E. Becquerel and Abney did offer ad hoc hypotheses on different molecular reconfigurations of the silver salts to explain their results but these were just vague post-facto rationalizations without any predictive force.[140] It is only with hindsight that we know why **(p.207)** the early daguerreotype silver images exhibit their tints while the later developer-paper images, such as calotypes, generally appear neutral. Colloidally suspended silver particles in the plate emulsion, formed by the reduction of the silver salts and subsequent development in mercury vapor, are extremely small, in the nanometer range, in fact, and hence are smaller than the wavelength of visible light. In the latter case, the silver filaments produced by the developer process are much larger.[141]

The solution seemed to be so near at hand, yet the problem of color photography was far larger than many of the early photochemists had anticipated. Allow me to interrupt for the remainder of this section the chronological line we have been following, to list the most important stepping stones in this quest:[142]

• In a lecture demonstration in 1861 James Clark Maxwell (1837–1879) showed that a color image could be generated by first taking three lantern slides of the same object through a red, a green, and a blue filter, and then projecting the superimposed image onto a screen. In order to obtain the right mixture of primary colors on the screen, each slide had to be illuminated with white light that was filtered by the same color filter (then typically fluids) originally used for taking the negative.
• By 1869, Louis Ducos du Hauron (1837–1920), and independently of him Charles Cros (1842–1888) also succeeded in transforming this idea into a practicable technique of three-color photography. The **'héliochromie'** of Ducos du Hauron produced three negatives exposed through the back of the sensitive layer in a camera, that is, with the blue, green, and orange filter layer towards the lens. After development and a reversal process, monochrome complementary red, yellow, and blue pigment prints were made, either by chromolithography, Woodburytype, or another toning process. When superimposed, these transparent positives yielded a polychrome image.[143] Both inventors also developed special cameras to obtain the three monochromatic negatives.
• In 1891 Gabriel Lippmann (1845–1921) presented a report on his **'photochromie'** to the Paris Academy of Sciences. In this method the colors are generated by interference of standing waves within the very fine-grained sensitized layer of the film. In this case, albumen containing 0.5–0.6 % potassium bromide is sensitized in a silver bath, then washed off with a cyanine solution to make its spectral sensitivity as uniform as possible, and dried. The back of the color-sensitive film is then coated with totally reflective mercury, so that the light rays entering from the front are reflected back again into the emulsion. For each color, constructive and destructive interference will occur at different levels of the sensitive layer, depending on the wavelength of each color. But only the zones of constructive interference at regularly spaced intervals will react chemically. This 'interference photograph' is then developed and viewed in light reflected at the same angle as during the recording. The same standing waves pass through the plate at the spots where each color had originally hit the sensitized emulsion. The others are impeded and absorbed. In this way, Lippman succeeded in recording solar and electric arc **(p.208)** spectra in brilliant colors from the blue to the red.[144] The extremely low light-sensitivity of his albumen plates compelled Lippmann to confine his subject matter to the most luminous spectra, and the practical difficulties of this photographic technique were so inhibiting that it never was widely used.

• In 1893, the Irish physicist and photographer John Joly (1857–1933) obtained a patent for what he termed color screens. The idea behind this procedure had already been published by Ducos de Hauron in 1868, but Joly's achievement lay in making it practicable. Rather than obtaining three separately colored negatives, he exposed a panchromatic emulsion through a fine three-color line screen, consisting of a regular sequence of parallel red, green, and blue lines (each of Joly's lines being 0.12 mm wide). The negative thus obtained was illuminated with white light from behind and viewed through such a color screen: where blue had hit the panchromatic emulsion, blue light would then be transmitted to the viewer while impeding red and green, and correspondingly so for the other colors.

The disadvantage of Joly's screen plates was that the filter pattern of finely ruled lines in colored ink produced a noticeably coarse grain in the photograph. A finer grain was obtained with the Autochrome plates of the Lumiére Company available in France from 1904 on, which replaced the ruled lines with dyed grains of rice starch scattered over the whole plate surface. However, all these systems needed careful handling, both during exposure and during subsequent projection and their use was consequently limited to a few expert commercial photographers. Color photography as we know it today only became possible once black-and-white photography could register the whole spectral range and dye research had produced sensitizers that did not bleed into adjacent layers, enabling one negative to carry three layers of differently sensitized emulsion. Two distinguished musicians earning their bread in the Kodak Research Laboratories since 1930, Leopold D. Mannes (1899–1964) and Leo Godowski (1900–1983),[145] hit upon the right combination of sensitizers, couplers, and developers, and made color pictures feasible by means of multiple coatings. Modern color film like Kodachrome or Agfacolor, both placed on the market in the mid-1930s, are based on three separate layers of emulsion, each selectively sensitive to blue, green, or red light. Thus was Maxwell's vision realized of composing a color picture by a superpositioning of monochromatic images in the three primary colors.[146] But this side remark has taken us far ahead of the roughly chronological path and we must pick up the narrative about black-and-white photography where we left off.

6.6 Scientific applications since 1860

In his experiments with the sparks of various metals taken in air, W. A. Miller recorded their spectra, after absorption in other media, on a film of plain iodized collodion followed by a nitrate of silver bath, occasionally also using a bromo-iodized collodion with pyrogallic acid as developer. At the time, no technique was yet known with which he could have published these photographic results directly. So he had to resort to other techniques of **(p.209)** graphical reproduction for the plates accompanying his paper in the *Philosophical Transactions.* The engraver J. Basire took great pains to reproduce faithfully the overall appearance of Miller's plates. The dominance of black with only intermittent, somewhat diffuse bright lines led to his choice of mezzotint engraving. Figure 6.8 shows what an appropriate choice this was: even the effects of overexposure in the few bright patches of light, and the overall diffuseness, caused by a general lack of focus of Miller's camera in the ultraviolet, are well captured. The most notable deficiency is the coarse appearance of the gray areas, which are much coarser in grain than the original photograph.[147]

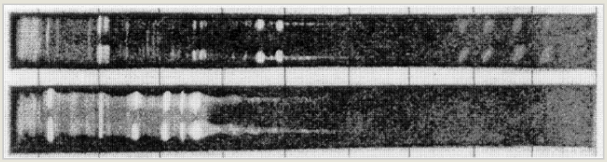


Fig. 6.8 Ultraviolet spark spectra of zinc and magnesium recorded photographically by W.A. Miller in 1862. Mezzotint engraving by J. Basire. From Miller [1862*e*] pl. XXXIX.

But this figure also shows that in the early 1860s spectrum photography in this region was still hopelessly inferior with respect to precision, definition, and focus, to the traditional techniques of engraving or lithography for illustrating such results as obtained by Mascart or Cornu.[148] The 78.7 cm-long photograph of the solar spectrum taken by the wealthy New York amateur astronomer and photographer Lewis Morris Rutherfurd[149] (1816–1892) was the first of its kind able to compete with existing drawings and published lithographic maps (see Fig. 6.9 for a sample segment). In 1864, Rutherfurd presented one copy of his set of photographs to the newly founded National Academy of Sciences as well as to a few other pertinent institutions.[150] At the meeting of the Literary and Philosophical Society of Manchester in January 1865, a pupil of Bunsen's, Henry Enfield Roscoe, proclaimed Rutherfurd's map “a most valuable confirmation of the accuracy of Kirchhoff's map. Each line in these maps can be easily and distinctly traced in the photograph, while many bands **(p.210)** drawn as single ones by Kirchhoff are seen in the magnified photograph to consist of bundles of fine lines.”[151] Despite having at his disposal a grating of his own design, Rutherfurd used a high-resolution prism spectroscope to make these photographs. This instrument incorporated three to six 60° bisulphide of carbon prisms that were automatically adjustable to the angle of least deviation. The numerical values attached to his map were consequently not wavelengths but Kirchhoff's prismatic scale. Kirchhoff's and Hofmann's map covered almost the entire visible spectrum (the region A-G) apart from the extreme violet. Rutherfurd, on the other hand, had to confine his map's range to between the line b in the green and the line H in the violet, because the wet collodion plates available to him were not sensitive in the red and yellow regions.

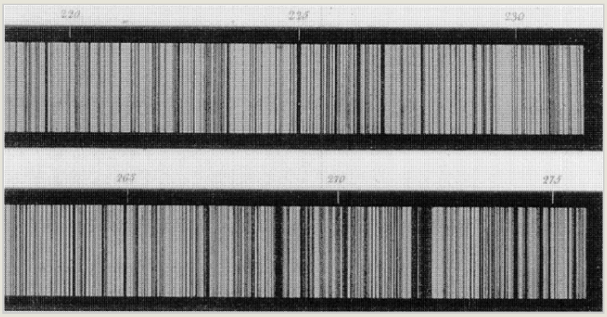


Fig. 6.9 Segment of Rutherfurd's photograph of the solar spectrum, c. 1864. Lithographic reproduction by A. Schütze. From Secchi [1870*c*] pl. VI.

The obvious disadvantage of Rutherfurd's photographic map was that for several years it was accessible only to a few lucky individuals or institutions who, like Roscoe in Manchester or the Royal Astronomical Society in London, had obtained photographic prints from Rutherfurd personally. No technique had yet been devised that would have allowed a replication of this map as it was. Consequently, whereas Rutherfurd's stereoscopic photographs of the Moon's surface, for instance, were widely appreciated at the time and frequently reprinted even much later in popular books on astronomy and photographic handbooks,[152] a decade had to pass before his efforts in spectrum photography were carried forward. For the German translation of Secchi's standard work on spectroscopy, which appeared in 1872, the editor decided to make Rutherfurd's map generally available in a lithographed rendidon **(p.211)** of the photograph, measuring 210 cm in length.[153] One year later, the New York book dealer A. Mason started distributing an enlarged set, measuring a total of 3.5 m.[154]

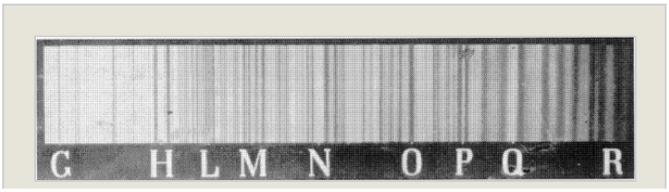
Photography could not compete with visual observations in registering spectra, nor could it even approach the performance of lithography in duplication. In fact, wet collodion photography was in many respects not suited to the needs of experimenters, who were busy enough as it was with conducting their experiments without having to fuss with the finicky plate preparations necessary immediately before exposure. Also, many spectra were simply not ‘photogenic’. Stellar spectra, for instance, or the spectra generated in very fine Geissler tubes were too faint for the available exposure times, which revolved around the rate of evaporation of the wet organic emulsion. As a result, many spectroscopists avoided photography altogether. One research branch had no choice, however: no other detector was available that produced a permanent record of the ultraviolet region. But even there, photography posed a host of serious problems. Unequal sensitivity of the wet collodion in the spectral range under examination, for example, forced experimenters to do a piecemeal analysis of small intervals at a time, which subsequently had to be assembled as an artificial composite before an integral ‘view’ of the spectrum was possible.[155] The collodion coating also tended to shrink, during evaporation, depending on its precise chemical consistency and various environmental factors.[156] When emulsions sensitive to different regions were combined on a single plate, there was always the danger of overexposure in the more sensitive parts of the photograph. Strange effects were the result, like solarization, which is a transformation of the centers of very bright areas on the photograph into dark spots.[157] For strong spectrum lines this could cause confusing reversals. An overexposed line (i.e., a broad dark stripe on the negative) that turned into a bright line center with dark fringes was hard to distinguish from ‘real’ line reversals that occur under special physical conditions.[158]

Thus around 1860 wet-plate photography could not be used without recourse to the traditional representational modes of drawing and lithographic printing. The following excerpt from a physics textbook (the 1862 edition) by the Freiburg professor of physics, Johann Heinrich Jacob Müller[159] (1809–1875) illustrates this:

(p.212)

> Since, based on the above remarks, it is impossible to produce a directly photographed spectrum, displaying all bands from G to R equally distinctly, I have produced with utmost accuracy an ink-wash drawing of the spectrum, copying it line by line on a large scale; and PI. IV is therefore a reduced photographic copy of it. That is why in spectrum photograph PI. IV, all the dark lines from G to R appear sharply as well, whereas in the directly photographed spectrum, only the bands between G and H distinguish themselves upon brief exposure to light; as the exposure time was progressively extended, however, the various sections emerged, between H and M, or between M and O, O and Q, or finally, between Q and R.[160]

His representation of the broad range in the solar spectrum between G and R is thus by no means based on a single exposure, but on a whole series of photographs of shorter spectral ranges, taken at increasing exposure times. The best segments were then selected and carefully assembled in their proper places in the full spectrum.



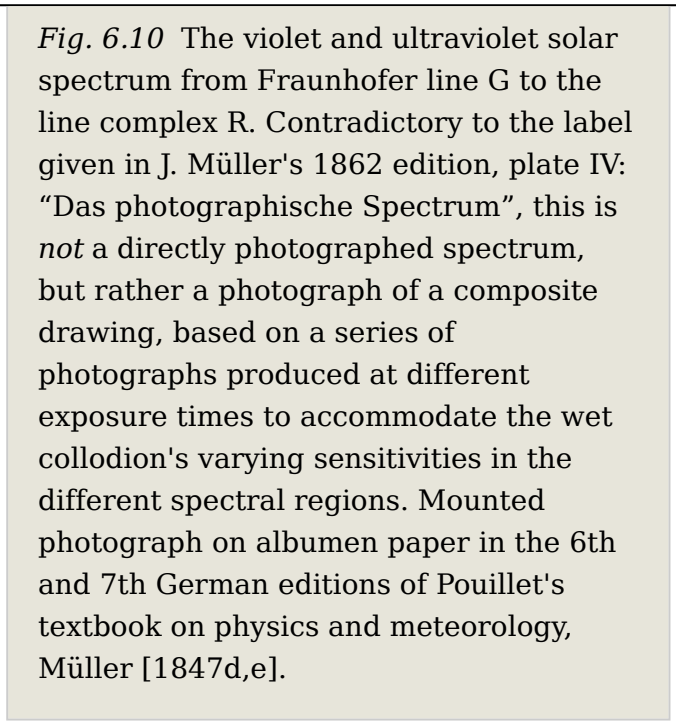


Fig. 6.10 The violet and ultraviolet solar spectrum from Fraunhofer line G to the line complex R. Contradictory to the label given in J. Müller's 1862 edition, plate IV: “Das photographische Spectrum”, this is *not* a directly photographed spectrum, but rather a photograph of a composite drawing, based on a series of photographs produced at different exposure times to accommodate the wet collodion's varying sensitivities in the different spectral regions. Mounted photograph on albumen paper in the 6th and 7th German editions of Pouillet's textbook on physics and meteorology, Müller [1847d,e].

We thus find the same kind of “symbiotic relationship” between direct observation, photographs taken with different exposure settings, and drawings, as has been found in other scientific applications in the early 1860s.[161] In the context of spectroscopic research in this period, photography was undoubtedly a useful detector for invisible radiation; but in the later stages of the research practice and subsequent replication in publications, it was little more than an auxiliary tool. Only with the invention of dry-plate photography, particularly the gelatinous silver-bromide dry emulsion in 1871 and the first modern negative emulsion for chemical development in 1874,[162] do we find more than scattered attempts at producing **(p.213)** photographic maps of the spectrum or parts thereof. Unlike collodion wet plates with their silver-nitrate base, silver-bromide gelatines did not crystallize as they dried and, as a result, they could be prepared well in advance of exposure. They became commercially available and could be stored by the user. Being sensitive enough to allow exposure times of less than one second, they eliminated the need for tripods and for the first time made feasible photography of rapidly moving objects, high-speed processes, and the faint lines in stellar spectra. Consequently from the mid-1880s on, advances in dry-plate technology, which became increasingly prevalent in industry, went hand-in-hand with an expansion of photography into major areas of solar and stellar spectroscopy.[163]

6.7 Henry Draper's diffraction spectrum photograph and Albertype in 1873

As we have already seen in § 5.2, pictorial representations used in publications were revolutionized when photographs could be transferred directly into print, thus removing intermediary translation into a lithograph or engraving. Let us look at one example in more detail. A scientific notebook, covering the period June 1872 to April 1876,[164] records the development of wet-collodion spectrum photographs taken by Henry Draper[165] (1837–1882) and their subsequent reproduction as Albertype in 1873 by the New York printer Edward Bier-stadt[166] (1824–1906). It consequently affords a particularly well documented case. These some 400 pages cover every stage in Draper's experiments with spectrum photography between mid-1872 and late December 1873, when Draper finally sent out Bierstadt's Albertype prints. They also contain many fragile collodion photographs, which had been stripped off their glass backings, as well as various print samples from Bierstadt. Altogether, these materials document closely the development of the final Albertype print, including the intricate negotiations between photographer and printer about what was feasible and what still needed improvement.

(p.214) We meet Henry Draper in his private observatory in Hastings-on-Hudson, in the summer of 1872, experimenting with various types of spectroscopes for recording solar and stellar spectra. The first instrument, of Draper's own construction, incorporated five prisms arranged as in Hofmann's direct-vision spectroscope and fed by a condensing mirror. It generated a spectrum 1/32 inches wide and about 1/2 an inch long.[167] Because visual observation of the indigo-violet region of the spectrum yielded no useful results, Draper turned to wet bromo-iodized collodion photography, which was most sensitive to that range. From previous experiments in photomicrography, he also had experience in intensifying negatives by applying a solution of chloride of palladium or other chemicals to the collodion before it had dried.[168] As he noted in July 1872: “in the photographed spectrum a cumulative effect can be reached + atmospheric tremor will count for nothing because it is not magnified. In addition the upper [blue-violet] parts of the spectrum contain the most characteristic lines.”[169] Dissatisfied with the considerable loss in light intensity, Draper soon abandoned this setup for his stellar applications and reverted to an arrangement with a quartz prism positioned in the light path just at the focal plane of a small mirror, which threw the image onto the photographic plate. With this setup Draper obtained the spectrum of Vega “at once”, discerning at least three groups of spectrum lines, “the lowest I think somewhere about G, though I have not used a reference spectrum yet to be certain.”[170] He also built himself an automatic prism chain spectroscope with six heavy glass prisms, “combining the ideas of Browning and Clark” with his own design improvements.[171] The quality of this instrument was tested by checking the resolution of the Na_D lines and the b group against Kirchhoff's atlas. In October 1872, Draper described his agenda, which combined chemical spectrum analysis with solar, terrestrial, and stellar spectroscopy:

> my intention is to get the spectra of all the metals that I can procure in a pure state together with the gases and non-metallic elements as far as possible. Then I mean to compare these with the violet, ultra-violet end of the spectrum of the sun (from ([I] to P) and ascertain the substances represented by the great groups M, N, O, P. Subsequently I hope to extend comparison of the spectra of the fixed stars, for I have already photographed the spectrum of Vega.[172]

Among the problems still to be solved, he listed “how to get a more intense deflagrating spark and more dispersion of magnifying of the spectrum”.[173] One way to achieve the latter **(p.215)** was to switch to diffraction spectra because they could be photographed in higher orders where the distances between the lines get progressively larger. This was on the condition that the light source was intense enough, as was the case with a spark and the Sun. To this end he obtained several Rutherfurd gratings[174] which he carefully compared, particularly for uniformity in the ruling.[175] After ranking his gratings and picking out the best one,[176] he took his first diffraction spectrum photograph of the most refrangible end of the solar spectrum (cf. Fig. 6.11).

(p.216) The minute imprint on a very thin and transparent collodion surface was just the very start of long labors by this spectroscopist in diffraction-spectrum photography. The fragile film first had to be carefully removed from its glass backing with the aid of gelatine and glycerine and placed under a microscope. The spectrum was observed visually under sixfold magnification and then drawn by hand.[177] This latter stage still very much resembles the common procedure for direct mapping of eye observations of spectra, so perhaps the new advance lay in the temporal integration on the photosensitive surface. The chemical action of very faint lines not visible to the naked eye was thereby able to become concentrated during the 10 to 30 minutes of exposure.

Fig. 6.11 Above: Henry Draper's wet collodion photograph of the violet and near-ultraviolet segment of a solar diffraction spectrum, from the line H_1 to the line group O, dated by him, 27 October 1872. The exposed part is about 2 cm long. The photograph was stripped from its glass support and glued into his notebook. *Below:* Draper's pencil drawing, based on a 30-fold microscopic magnification of a six-fold enlarged negative. Both from Draper's notebook XI, p. 21 verso; courtesy of Deborah Warner. NMAH.

The next months were spent on improving the quality of his diffraction photographs. In recording the third order, Draper managed to extend the length of the spectra significantly, first to 2 inches, then to 7.5 inches from G to about O. Further photographic enlargement brought them to a total length of about 12 inches. By photographing different regions of the spectrum with exposure times ranging between 10 and 15 minutes (in the ultraviolet region around O) and 2 and 2 1/2 minutes (near G), Draper circumvented the problem of varying photosensitivity in his silver-bromide and iodide collodion surface. The choice of a very narrow slit width of 1/100 of an inch (0.00023 m), carefully adjusted to be perfectly parallel to the lines of the ruled grating, improved the definition of the lines further.[178] Another problem he attacked at that time involved the drying stains on his long narrow plates “arising,” as he explained, “from the fact that the superfluous nitrate of silver while draining to the lower edge leaves irregular lines of concentrated fluid near that edge.”[179] But in January 1873 Draper felt confident enough to contact his friend Bierstadt about having these diffraction spectrum photographs reproduced by the Albertype process (see here p. 158). As it turned out, the negatives were “not intense enough so that the effect is not

as good as I had hoped—still they are almost good enough for my purpose."[180] But from earlier research, Draper already knew how to intensify his photographs by applying a solution of protochloride of palladium to the still wet collodion image.[181] Upon Bierstadt's requesting even more intensity and contrast, Draper used pyro followed by bichloride of mercury in the developing, "till they were black + finally Schlippe's salt which they say is sulphanti-monate of potash". The results were indeed markedly improved, as the samples appended to his notebook confirm.[182] In late February 1873, after also solving the problem of how to integrate a numerical scale of precisely the right extension into his picture, Draper felt ready for publication. "There is little left to be desired after this one for the purpose of publication; **(p.217)** the Albertype has done wonders."[183] Despite this successful trial, several proof versions were rejected by Draper for one reason or another, and more than once he had to furnish Bierstadt with a negative showing better contrast.[184] Furthermore, the variation in spectral sensitivity of the collodion required a difference in exposure times by a factor of ten between the region near G and near O. It is only in the more technical article, though, written for the journal of the Italian association of spectroscopists—the audience most likely to attempt replication of his photograph—that Draper admitted using diaphragms "to reduce this excess of action."[185] Nor was the actual printing process for such high runs by any means standardized enough to guarantee uniform results. The fragile collodion negatives transferred onto thick glass plates for use in the printing press in place of a lithographic stone rarely withstood the printing for long before deteriorating. Consequently, Draper had to supply Bierstadt repeatedly with fresh negatives made from the same master and had to control the quality of each newly printed set.[186] Eventually 1650 copies were made for the *American Journal of Science and Arts,*[187] where Draper's spectrum photograph was first published in December 1873. Another 1000 copies were sent to the *Philosophical Magazine*, 300 to the *Memorie delta Societá Spettroscopisti italiani*, and finally no less than 7000 for a republication in Lockyer's weekly journal *Nature.*[188] As a courtesy to the New York printer, for whom this was a unique chance to advertise in one of the major scientific journals, a footnote was added emphasizing the feasibility of such high runs in the Albertype process: "From the original negative of the spectrum 12 000 copies have up to the present been printed, and it is not in the slightest degree injured as yet".[189] But this printing process using more than one working photograph yields a variation in quality. The plate in *Silliman_s Journal* or in the *Philosophical Magazine*, for instance, is much fainter, with far less contrast, than the plate in the copy *of Nature* at Harvard's Widener Library. Nonetheless, the editor of the *Philosophical Magazine*, where the plate appeared in the December 1873 issue, thanked Draper for having provided the journal with "the impressions of the beautiful photograph" which was as close to the original photograph as possible with contemporary means.[190] Later reprints in Secci's *Soleil* and in the *Report of*

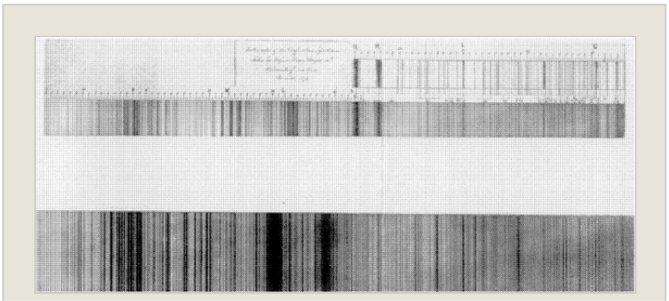
the British Association were made on the basis of steel-plate printing and lithography.[191]

(p.218) In this first article ever to be illustrated with a photomechanically reproduced spectrum, Henry Draper argued along three lines for the superiority of photographic recording in conjunction with photomechanical reproduction by the Albertype process. First of all, this representation was based on a recording technique that allowed extension of the spectrum into regions beyond the visual range. Secondly, the published segment contained more recorded lines than comparable hand-drawn maps, such as Ångström's, even in the optical range. And thirdly, it qualitatively improved representational accuracy of features like line strength, width, and satellites.

> The value of such a map depends on the fact that it not only represents parts of the spectrum which are with difficulty perceived by the eye […], but also that even in the visible regions there is obtained a far more correct delineation in those portions which can be photographed. In the finest maps drawn by hand […], the relative intensity and shading of the lines can be but partially represented by the artist, and a most laborious and painstaking series of observations and calculations on the part of the physicist is necessary to secure approximately correct positions of the multitude of Fraunhofer lines. Between wave-lengths 3925 and 4205, Ångström shows 118 lines, while my original negative has at least 293. […] The eye is not able to see all the fine lines, or even if it does, the observer cannot map them with precision, nor in their relative strength and breadth. For example, in Ångström's justly celebrated chart […], in the construction of which the greatest pains were taken by him, many regions are defective to a certain extent. The region from 4101 to 4118 is without lines, yet the photograph shows in the enlarged copy seventeen that can easily be counted, and the original negative shows more yet. […] As an illustration of the difficulty of depicting the relative intensity of lines, we may examine 3998, which in Ångström's chart is shown of equal intensity with 4004, while in reality it is much fainter, and instead of being simple, is triple, as is well seen in the enlarged spectrum.[192]

This enlarged section of his photograph (cf. Fig. 6.12 below) had been carefully chosen. The unenlarged upper half of his illustration (Fig. 6.12 above) reveals that this was the most problematic segment of Ångström's map (at the extreme violet end of the visible spectrum). Here Ångström's optics selectively absorbed all but the strongest lines.

Draper was well aware that if he had picked other regions (such as around the scale values 41.4 or 42.5 (i.e., 4140 and 4250 Å, respectively), the comparison would have been far less advantageous for his photograph.[193] Overall, Draper's rhetoric contrasts man-made representations with natural imprints, and suggests that the latter was created essentially without human intervention: “The spectrum is absolutely untouched. *It represents therefore the work of the sun itself*, and is not a drawing either made or corrected by hand.”[194] A more blatant call for ‘mechanical objectivity’ could not be made. Instead of a ‘mere’ representation of line 3998, “in reality,” as Draper states, “it is much fainter,” as if the photograph **(p.219)** were a faithful one-to-one mapping of reality in a surrogate black-and-white world. When Cornu's contemporary engraving was compared with Rowland's photographic map thirteen years later, the way that the spectrum line profiles were represented and even their absolute positionings did not agree. Improved apparatus and enlarged scale revealed systematic differences even between the photographs by Draper and by Rowland. Draper's wavelength values were too large for lines of short wavelength as well as for lines at the other end of the spectrum. But these discrepancies were always lower than 0.6 Å and averaged to a mean difference of only 0.12 Å. A similar comparison with Cornu's engraved map yielded a considerably larger average deviation of 0.25 Å. This was turned into one more victory for the “accuracy attainable from a record obtained automatically by photography”.[195] The contemporary reception of Draper's photograph and its reproduction was enthusiastic. Anders Jonas Ångström, probably the greatest living authority on these matters, called Draper's plate “extraordinarily beautiful and the most perfect I have ever seen”, and John Browning, the London instrument maker, wrote Draper: “I am glad you have stated so clearly that the plate is a perfectly untouched photograph, for I have not been able to get my friends to believe this in many instances.”[196]



6.8 The virtues and pitfalls of spectrum photography

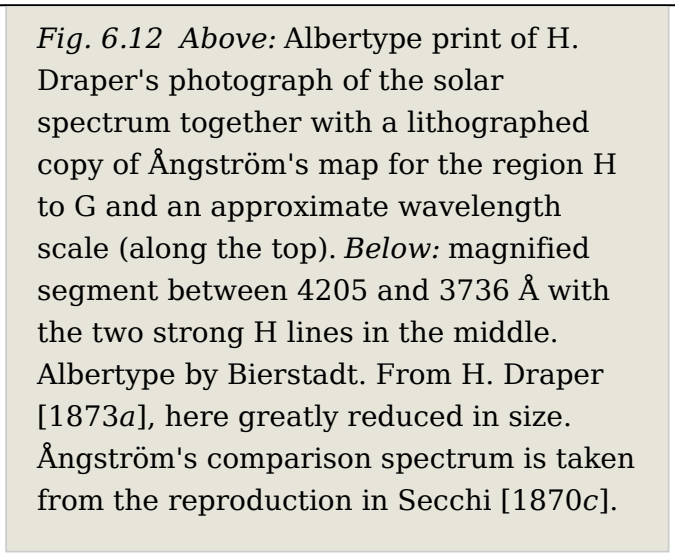


Fig. 6.12 Above: Albertype print of H. Draper's photograph of the solar spectrum together with a lithographed copy of Ångström's map for the region H to G and an approximate wavelength scale (along the top). *Below:* magnified segment between 4205 and 3736 Å with the two strong H lines in the middle. Albertype by Bierstadt. From H. Draper [1873*a*], here greatly reduced in size. Ångström's comparison spectrum is taken from the reproduction in Secchi [1870*c*].

In the many heated debates over the pros and cons of early spectrum photography during the transitional period between 1870 and roughly 1885, Henry Draper was, of course, **(p.220)** not exceptional in using such rhetoric to commend photography, by virtue of its automatic character, as a reliable recording device. John Rand Capron (1829–1888), a fellow of the Royal Astronomical Society and best known for his work on the spectra of aurorae, was another of its advocates. In the introduction to his 136 photographs of metal and gas spectra, printed by the Autotype Company in 1877, he reminded his readers: “Absolute truth is everything in spectroscopic work, and the very best draftsmen working with the most perfect micrometer cannot, even at the expense of a vast amount of labour, equal in accuracy a good photograph of a set of spectral lines.”[197] And to one of his correspondents he proudly reported: “Printing them goes all quite well”, implying that unlike the conventional mapping procedures of lithography or engraving, photomechanical reproduction as autotype was mere child's play.[198] His plates included many minor defects, ranging from a lack of focus to scratches and uneven exposure. But that apparently did not disturb Capron too much. Perhaps he considered these little flaws a hallmark of authentic, candid reproduction of the original record.[199]

But for all this praise of photographs as the ‘pencil of nature’ or as the ‘chemical retina’, we must not forget how manipulable the final outcome in fact was, even after the exposure has been taken. One of the greatest photochemists of the day went so far as to condemn “the many untruths of photography”. These included inadequate rendering of different light intensities, solarization and halation, and foremost the widely differing sensitivities to different colors of the spectrum.[200] The only way to deal with these imperfections was to **retouch** them after exposure. In the early stages of photography such tinkering was frequently done without much comment. But later handbooks, written for the rapidly growing audience of professional photographers, often did go into great detail about the various techniques of influencing the contrast—such as weakening with Farmer's reducer (potassium ferricyanide) or ammonium persulphate, or enhancing with mercury or uranium compounds[201]—and the even broader range of possibilities for retouching. As illustrated in Fig. 6.13, the retoucher can make unwanted objects disappear, reinforce contour lines, sharpen objects outside the focal plane, modify the surface texture, and strengthen (or weaken) the overall contrast. Some retouching compensated for the unequal color sensitivity of the photographic plate (the yellow–orange region was a longstanding problem). But the majority of these corrections substantially modified the otherwise true-to-life recording. In handbooks written for the scientific practitioner, in particular, we find justifications for this indispensable step in the manufacture of an image, in an effort to thwart calls to abandon such manipulations for the sake of preserving the work of ‘Nature's pencil unretouched’ (see above).

(p.221)

> There has been much preaching about the inappropriateness of retouching exposures of research objects. This is as correct as it is false. If by it is meant that all plate faults, ugly backgrounds and other unsightly marks caused by imperfect exposure technique should be retained, then it is exaggerated. Whoever does not have a sufficient command of the simple method under consideration here, should obviously keep his hands off plates that are supposed to serve as pieces of evidence; and it is precisely this impotence of their's which has no doubt prompted some to censure retouche unconditionally. This author also holds the view that it is better to take really impeccable exposures than to present artifices of retouche; but wherever it is possible without damaging the objectivity of the presented object, retouching is entirely justified.[202]

In other words, the unskilled should not venture to retouch such a plate. The scientist, however, allegedly knows whether or not this intervention would taint the ‘objectivity’ of the photographic documentation. In this way, subjective judgment sneaked in through the back door of perfectionism, disguised by the sober arguments of improvement, correction, and enhancement of certain features. Because this ‘doctoring’ of illustrations was by no means as uncontroversial and occasionally even led to quite extreme distortions, the pros and cons of retouching were hotly disputed between the 1860s and the 1890s.[203] Hence *in praxi* it is by no means true that photography eliminated the tradition of the ideal, metaphysical image, to replace it with fully mechanized, automated registration. Much trimming and, indeed, highly subjective manipulation of the outcome was common in photography, and more so in photoengraving. On the user's end, too, as much skill as connoisseurship was needed in order to avoid a false ‘reading’ of such prints and mistaking photographic grain for ‘real’ structure in the depicted object. Photography was no less a craft than its forerunners.

Photographic retouche was inextricably linked to rapid developments in photomechanical technique during the 1870s (see § 5.2). Even after 1900, retouching of photographs before and after printing was so much in demand that larger printing houses even maintained an assembly line of retouchers—somewhat reminiscent of the armies of copying scribes before the emergence of book printing.[204] Much of this retouching had ‘beautifying’ as its purpose. Portraits called for highlighting of the eyes, lowering or lifting of eyebrows, removal of double chins, unwanted hair, sagging neck muscles, and so on. In the context of spectroscopy of the late nineteenth century many blemishes also remained that needed covering up before going to press.

(p.222)

(p.223) For instance, the contemporary praise for Capron's wet collodion photographs of arc and spark from 1877 notwithstanding,[205] closer examination reveals some **inherent shortcomings of early spectrum photographs** (see Fig. 6.14):

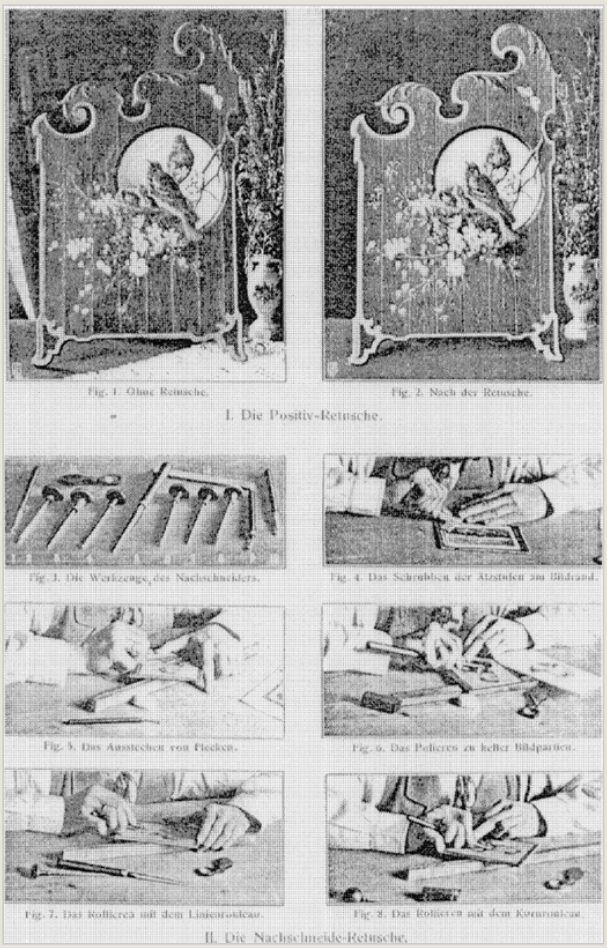


Fig. 6.13 Photographic retouching procedures: Nos. 1 and 2 are a positive before (left) and after (right) retouching. No. 3 displays some of the retoucher's instruments; nos. 4–8 demonstrate such procedures as polishing, spot removal, line and grain rouleau. From Emmerich [1910] pl. 8.

- The overall range of the spectra (from about b to H, that is, 5300 to 3990 Å) was considerably more limited than contemporary lithographs (such as, e.g., Lecoq de Boisbaudran's of 1874 which ranged from 7900 to 3900 Å).
- The background intensity and overall sensitivity of the plate varied noticeably, because the contemporary emulsions were much less sensitive at the red extreme of the spectrum than at the violet. The result is underexposure on the left side and overexposure on the right side of the photographs of the antimony arc spectrum.
- Sometimes the overall exposure was quite uneven (e.g., the middle section of the antimony spark spectrum).
- Spark spectra in particular were often strangely diffuse or out of focus (see nos. 1 and 3 of Fig. 6.14), owing to the comparatively long exposure times.[206]
- Accidental defects in the photographic plates, such as scratches, were retained in the reproduction (see, e.g., the two middle spectra of Fig. 6.14).

• With no scale provided, photographs offered little more than a rough impression.
• A further loss of detail resulted from the transition from photograph to Albertype copy.[207]

While Capron downplayed these difficulties in his discussion of the individual plates, Henry Draper could not suppress the occasional complaint about the quality of the reprints of his own photographs, thus admitting the existence of technical limitations in the published representation:

> The reader of course understands that a paper print of a collodion picture is never as good as the original; the coarseness of grain in the paper, want of contact in transferring, etc. effect such a result. Moreover, the Albertype process depends on a certain fine granulation which is given to the bichromated gelatine, and this forbids the use of a magnifier upon these paper proofs.[208]

Moreover, he revealed that in photographing the whole spectrum, he had to cover parts of the sensitive plate temporarily with diaphragms, for removal during exposure, in order to compensate the sensitivities of his emulsion to the different spectral components. Finally, contrary to Draper's apparent hopes in 1873, the advent of photography did not put an end to the discussions about adequate representation of the relative line strengths. An **(p.224)** example from the next decade shows that Joseph Norman Lockyer, one of the leading spectroscopists, was still not perfectly happy with the way in which certain lines came out in his photograph. He chose to provide instead a conventional representation based on a drawing alongside an enlarged photograph (reproduced as a heliotype):

> In the annexed plate I have not only given the map, as reduced from the photograph in the manner described, but introduced a permanent enlargement of one of the photographs. It has not been possible to represent the intensities absolutely, on account of the varying tones of the absorption-lines themselves. The untouched photograph will allow of the detection of any errors of this nature.[209]

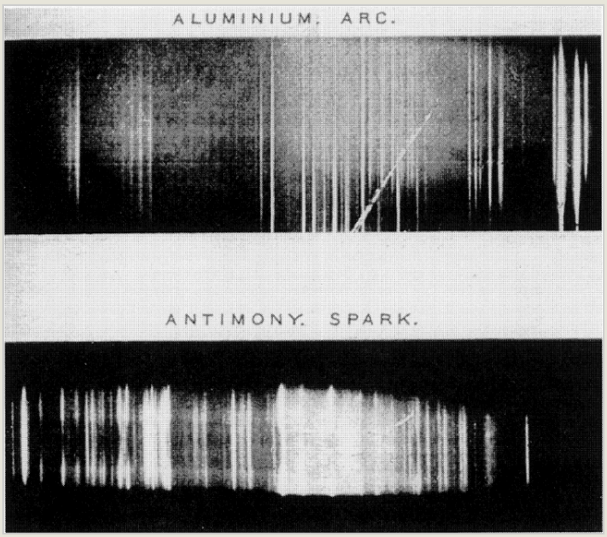
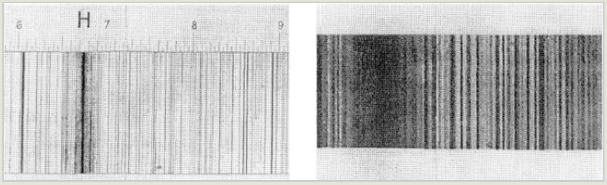


Fig. 6.14 Sample plate from Capron's 1877 atlas of arc and spark spectra, illustrating many problems encountered in spectrum photography of the 1870s (cf. main text for details). From Capron [1877] pl. 2.

Lockyer's construction of the map was quite complicated and illustrates the degree to which photographic and traditional techniques of representation were intermingled during this period. He had at his disposal photographs of the diffraction spectrum, taken with a Rutherfurd grating, as well as of the prismatic spectrum of the same region. The first group of **(p. 225)** photos showed the spectral lines on an absolute wavelength scale but could only be used to gauge the positions for the “chief lines.” It was too weak for the others. Lockyer consequently also had to refer to the prismatic photos.[210] On a piece of cardboard he carefully drew a ‘trial map,’ on a scale four times finer than Ångström's map of 1866. He entered the main lines taken from the diffraction spectrum photograph, and then the other lines interpolated between these markers. This sketch was enlarged photographically 3 × and compared directly with the enlarged diffraction spectrum photographs.[211] After the positions of the marker lines had thus been checked, further details and line intensities were added to the large ink drawing, which was then reduced photographically for publication.[212]



The traditional spectrum map did have significant advantages over a photograph, as we can see by comparing the photographic enlargement of a small spectral segment against the ink drawing in Fig. 6.15. The ink drawing is far superior, both with respect to line definition and recognizability of certain line groupings. Moreover, certain sections, such as around the very intense H and K lines, are inevitably hopelessly overexposed. This could be circumvented by selective underexposure, but where strong and weak lines were right next to each other the problem remained of adequately rendering the relative intensities (cf. here § 7.4.3, p. 273 on photometry).

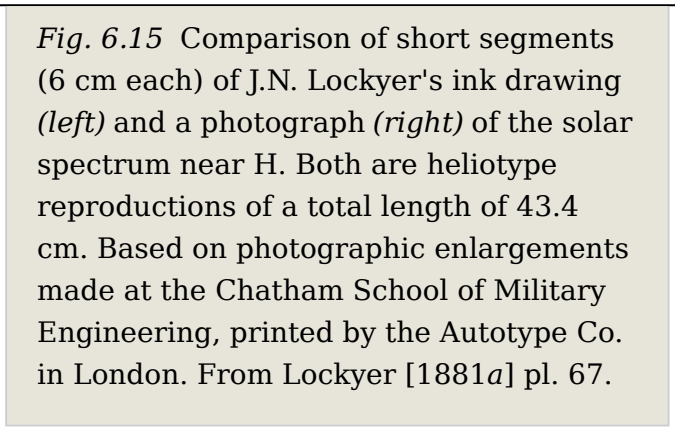


Fig. 6.15 Comparison of short segments (6 cm each) of J.N. Lockyer's ink drawing *(left)* and a photograph *(right)* of the solar spectrum near H. Both are heliotype reproductions of a total length of 43.4 cm. Based on photographic enlargements made at the Chatham School of Military Engineering, printed by the Autotype Co. in London. From Lockyer [1881*a*] pl. 67.

Thus in the 1880s visual observations were used in conjunction with photography. Often it was simply not meaningful to ask which of the two modes of representation yielded better results because they supplemented each other.[213] The choice of one, or both in combination, depended very much on the spectral range under study and on the specific research goals being pursued. From contemporary practice it is evident that photographs were superior in resolution for the spectral range from F into the blue, violet and, obviously, into **(p.226)** the ultraviolet range, whereas visual observations were usually preferred for the D–F region. H.C. Vogel was one observer to compare the results of the two recording techniques in 1879, varying additionally the exposure times so as to register not only very weak lines that were not observable visually but also details around strong lines, for which short exposure times were required.

> Photography has recently made major advances in the closer study of the solar spectrum, in the indigo and violet, the more refrangible parts from the Sun's surface. The photographs by Rutherfurd, Draper, *et al.* yield astonishing detail, but unfortunately till now we lack a careful comparison of these photographs with the work of Kirch-hoff and Ångström. One had been content with noting the generally very satisfactory agreement.[214]

In summarizing his detailed tabular comparison of his own wavelength determinations with those by Ångström from twelve years before, which yielded average discrepancies of no more than ±0.2 Å, Vogel concluded by also placing photography and eye observations on a par, excepting the violet and ultraviolet regions of the spectrum:

> The photographs offer a few more weak lines that could not be observed directly, but in return, direct measurement has successfully ascertained separations between very closely lying lines, which on the photographic exposure are fused into a single line.
>
> In general, though, the differences are very inconsequential. With regard to the agreement between the measurements, let it be mentioned that Ångström's observations in the relevant region of the spectrum have, in comparison with other regions, a lower degree of accuracy, and even some of the brighter lines that had to be used as a basis for the conversion into wavelengths are quite uncertain.[215]

A preference for one representational method over the other and its relation to the research goals being pursued may also be illustrated with a statement made by John Trowbridge and Wallace Clement Sabine from the Jefferson Physical Laboratory at Harvard University in 1887 in the context of precision wavelength measurements in the ultraviolet region. Although they clearly acknowledged the merits of photography for efficient registration of a great number of spectral lines and therefore preferred it for the purposes of qualitative work, “in the absolute measurements of the wave-length of light, the spectrometer method with eye observations and with a micrometer is unquestionably more accurate than any photographic method.”[216] In the same year, however, Trowbridge openly admitted to using Rowland's photographic map extensively as opposed to, say, Vogel's lithographed maps, which are based on such visual observations:

> The photographic map of the solar spectrum of Professor Rowland has made easy what would otherwise have been an undertaking of extreme labor and difficulty. The best of engraved maps of the violet region of the spectrum to beyond F are comparatively worthless. Even on the elaborate map of Vogel, the result of years of labor, it is difficult certainly to recognize other than the more prominent lines, and you never feel quite sure of your positions; but we turn to the map of Rowland with the certainty of finding every line in its true order and magnitude.[217]

(p.227) Admittedly, in this case, such ease of recognition arose partly from the fact that Trowbridge and his collaborators were using a big Rowland concave grating in a Rowland mounting, while Vogel had worked with a Rutherfurd four-prism chain. But in other passages they also challenged Ångström's and Thalén's normal map and Thalén's work on metallic spectra as “occasionally wrong by as much as two wave-lengths.”[218] Arguments about increased precision from the new type of spectro*graph* thus were being jumbled together with arguments about a greater naturalness of these automatic representations when compared with the ultimate product of the visual spectro*scope*, the lithographic map.

Exaggerated expositions of the strengths of photography over lithography certainly have to be seen in the light of the early euphoria about this relatively new recording technique; they are nevertheless characteristic of the type of arguments put forward by enthusiastic advocates like Henry Draper and Joseph Lockyer in the 1870s and 1880s.[219] They might also be explained by widespread frustration among spectroscopists at seeing many a cherished detail in their meticulous drawings either vanish or suffer severely upon ‘translation’ into the syntax of the conventional print media. Until the mid-1870s, the only alternative was mounting the original photographic prints in the publication. One example relevant to our context is Piazzi Smyth's account of his experiments in Tenerife. As he himself reported elsewhere, it was a very difficult business to get the some 40 000 pictures printed from secondary negatives, so as to keep his original glass negatives safely away from the destructive vice of the press frame.[220] Because each photographic print had to be trimmed before being pasted into the volumes—a task “necessitating workshops that resembled assembly lines with the labor supplied by women and children"—thus requiring two completely different production stages, this mode of illustration was clearly too expensive to be done more than occasionally.[221] With the arrival of Albertype (in German: ‘Lichtdruck-Verfahren’), a cheaper alternative came on the market in the late 1870s, but the specialists’ were not easily pleased. Hermann Wilhelm Vogel, one of the leading experts on color-sensitive emulsions and scientific photography, included two Albertype prints in his textbook of 1877 on practical spectral analysis (*Practische Spectralanalyse irdischer Stoffe*), namely, slightly reduced copies of Lecoq de Boisbaudran's molecular spectra (originally drawn in 1874). But his remarks about the plates indicate a mild dissatisfaction with the printing process:

> The spectral plates supplemented to our work, reproduced by means of the new and interesting Albertype technique and photographically true as regards contours […], did not all come out equally well at printing. […]. Thus in the dark versions of plate I spectrum 1, the bands to the left of 70 are too intense with respect to the α band; **(p.228)** furthermore in spectrum 2 the 4 bands between ι and κ have merged together into a single one, likewise β and γ and α, δ, and ε.[222]

Continuing in the same vein for another half page, he closed with the following somewhat resigned note: “Whoever knows from personal experience the great difficulties in *faithful* representation of spectral effects by means of the graphic arts will not fail to acknowledge what has been achieved despite the present discrepancies.”[223] The same symbiosis between photography and eye observations is reiterated in the 1880s between Albertype and lithography in research publications. Even scientists who relied heavily on photography in their research often had to resort to lithography for subsequent publication of their findings.

One interesting illustration of the state of the art of both techniques is Eugen Lommel's ‘phosphoro-photographs’ in the infrared part of the spectrum (cf. Fig. 6.16). In his original publications, which appeared in the proceedings of the Munich Academy of Sciences in 1888 and 1890, his photographs were reproduced directly as ‘phototypes’ (i.e., a variant of the Albertype process). Yet a reprint of this paper in the *Annalen der Physik* of 1890 presented only lithographs. In the original publication, Lommel had proudly announced his Albertype reproductions of the photographs as “the first […] in which the habitus of the ultrared spectrum is published, without any interference by the sketcher's hand—as it were, by nature's own imprint [*Naturselbstdruck*].”[224] It goes without saying, the punctilious lithographic “imitation of these phototypes” introduced by the editor of the *Annalen* had none of that natural aura.[225]

(p.229) When we compare the two kinds of reproduction, the lithograph obviously contains a far greater amount of information on the fine structure and intensity of line groups A and Z, for instance. The ‘phototype’ made by the Albertype Company Bruckmann looks very diffuse overall, and the area labeled Z is just a big black blur with the individual lines hardly discernible. By contrast, the lithographic print clearly distinguishes 16 separate fine lines between 7630 and 7690 Å, and several groups of lines of differing intensity around the strong lines Z and X_1. The latter label does not even appear in the photomechanical print, presumably because that line was barely visible, if at all, on the reproduction, although it may well have been distinct enough on the photographic original. In the original publication, Lommel conceded in passing that “these [photomechanical] reproductions are inferior in sharpness to the original plates and do not render, or only unclearly so, some of these extant, very fine lines”.[226]

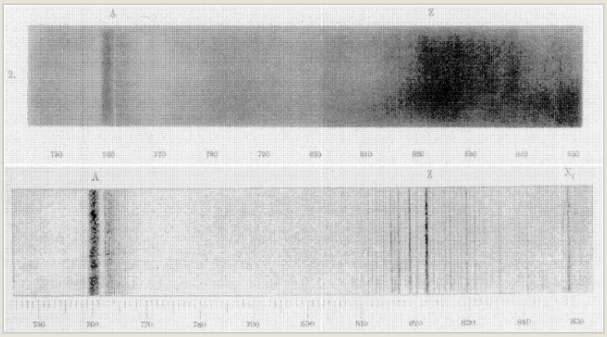


Fig. 6.16 A photomechanical print (*above*) compared against a lithograph based on a redrawing of the same photograph (*below*). From Lommel [1888/90*b*] pl. I, fig. 2, and [1888/90*c*], pl. VI, fig. 4.

In summary, considering the many inherent weaknesses in early spectrum photographs, both the practices of “retouching” positives and “correcting” negatives (as demonstrated in Fig. 6.13) remained important preliminary stages to the actual printing, even once photographic and photolithographic techniques had been perfected in the late nineteenth century. All in all, the quality of spectrum photographs around 1880 was still decidedly inferior to lithographic drawings. As we shall see in the next section, by the middle of that decade this had changed, and so had the practice of mapping spectra.

6.9 Photographic maps of the normal solar spectrum 1885–1900: Rowland, McClean, Higgs

No single publication in the spectroscopic literature did more to promote the use and acceptance of photography in this field than Henry A. Rowland's photographic maps, which appeared in two installments in 1886 and 1888. These maps were actually a side-product of Rowland's ambitious inventory of c. 20 000 Fraunhofer lines in the solar spectrum, for which he had used his newly developed concave gratings. With these gratings the whole spectrum, from the line F to the extreme violet, could be conveniently recorded in a matter of minutes (the red region required longer exposure times).[227] The spectrum was split into several strips 20 inches in length on a single plate. Because of the superposition of several orders of the spectrum, Rowland registered different ranges of the spectrum at once on a single photograph. This allowed additional internal consistency controls because the different lines λ_1 and λ_2 of orders n_1 and n_2 were coincident on his photographs if and only if $\lambda_1 \cdot n_1 = \lambda_2 \cdot n_2$. Since this coincidence method, as it was called, required photographic registration of the full spectrum using a broad range of exposure times and emulsion sensitivities, it was only natural for Rowland to consider publication of the best of these photographs, the more so since his instrument was at the cutting edge of the then attainable precision in grating technology.

Rowland issued a first series of maps in the form of six plates, each containing two or three spectrum strips. Since these plates had a length of nearly 90 cm, he decided to have **(p.230)** them printed on heavy albumen paper mounted on sturdy canvas of the same size, so that the whole set of plates could be rolled into a scroll. The frequency range of this set was roughly 5790 to 3200 Å, and the dispersion varied between 4.7 Å per cm (above 5200 Å) and 2.3 Å per cm (between 3700 and 4130 Å). A wavelength scale was added above each photograph so that the wavelength of each line could easily be read off.[228] Rowland was quite sure that "the photograph of the spectrum can have none of the local irregularities of wave length which occur in all engraved maps and which […] often so distorts a group of lines as, in conjunction with the imperfect intensities, to render them almost unrecognizable".[229] However, the quality of his photographs of the normal solar spectrum still varied very much and depended greatly on the color range. The results were good in the green-to-violet range, but fairly poor towards the yellow–red end of the spectrum, with considerable uncertainties towards the near-ultraviolet end as well. This variable quality is evident even in the following promotional text for Rowland's first series, which is also interesting for what features its draughtsman found to be particularly noteworthy:

> The definition of the spectrum is more than equal in every part, down at least to wave length 5325, to any map so far published. The 1474 line is widely double as also b3 and b4, while E is given so nearly double as to be recognized as such by all persons familiar with spectrum observation. Above the green the superiority increases very quickly so that at H we have 120 lines between H and K while the original negatives show 150 lines. The photographs show more at this point than the excellent map of Lockyer of this region. Above H to wave lengths 3200 the number of lines in excess of all published maps is so great as to make all comparison useless. However, above H the determination of the wave length is more uncertain than in the visible part and must remain so until a special investigation can be made.[230]

The high demand led to a second series entitled *Photographic Map of the Normal Solar Spectrum*, issued in 1888. It consisted of ten plates with two spectral strips, each 91 cm in length, and with a dispersion of 3 Å per cm (cf. detail in Fig. 6.17). It was announced as a “new and greatly improved edition” of the first maps, based on several much better and larger concave gratings with 20 000 lines to the inch, all ruled with Rowland's second dividing engine.[231] Comparison of both series readily confirms this improvement.[232] Its wavelength range overall was extended to cover the full optical spectrum plus the near-ultraviolet region between 6950 and 2900 Å. These photographs of the second series convey very well the subtle differences in line intensity, and the great variety of line widths and line profiles (ranging from very sharp to diffuse). The definition is much finer throughout, **(p.231)** the background fairly uniform, nearly perfectly free of scratches, spots and other inhomogeneities in the emulsion and, in general, sufficiently bright to provide maximum contrast for the dark lines, although the shading still varies considerably with color region: compare the bright region 4500–4700 Å with the messy regions around 6700 or 3100 Å. Towards the violet end of the spectrum, in particular, the line widths vary even along their vertical extension, which indicates an unequal illumination of the grating. Below the Na_D line, Rowland used cyanine plates and chlorophyll plates to correct the effects of overexposure and lack of definition in the first series for the yellow–red region. Generally, the prints are not black but have a slight brownish tint, which contrasts well against the yellowish hue of the paper.

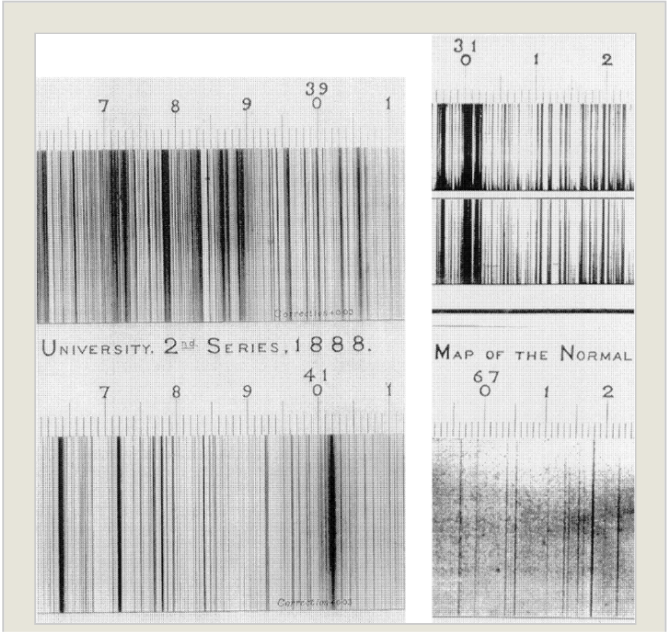


Fig. 6.17 Detail of spectral regions around 3900, 4100, 3100, and 6700 Å. The spectrum range around 3100 Å was reprodueced twice, with photographs of different exposure times. From the second series of Rowland's *Photographic Map of the Normal Solar Spectrum* [1888].

(p.232) Systematic optimization of the photographic work contributed considerably to the improvement in quality. Although the advertisement for the second series proudly proclaims: “Professor Rowland has devoted years to the making of dry plates, simple and orthochromatic, and is thus better prepared than before for the work of making the map”, documents among the Rowland papers prove that most of the research and development in this area were actually fruits of his assistant Lewis E. Jewell's labors.[233] Just as for the actual ruling of the gratings and the necessary laboratory routine for his complete inventory of the solar spectrum, Rowland likewise delegated to his laboratory specialists the quite elaborate and at times rather monotonous task of optimizing the photographic emulsions and developers.[234] For instance, as we know from Jewell's photographic notes published a few years after the “extensive series of experiments” which culminated in the *Photographic Map*, it was Jewell who found a good technique for preventing halation. This disturbing diffuse brightening of parts of the photographic plate caused by reflection on the reverse side of the glass plate could be prevented by coating the plate backs with water-color lampblack before exposure and removing this coating before development. More importantly, he adopted a specific formula for a standard hydrochinone developer that could be easily adapted to the exposure level by means of prescribed changes in the added amounts of potassium bromide.[235] The second series was also more advanced with respect to the separations of the different color regions. Because there was a great amount of overlapping of adjacent orders of the spectrum, which in the case of a concave grating are all simultaneously in focus, it became a much more urgent problem than for other types of diffraction gratings to cut off parts of the spectrum not wanted for a given exposure. In 1889 a list was published of principal absorbents (cf. Table 6.2) used in Baltimore to filter small segments of the spectrum.

The last problem that Rowland identified had to do with the enlargement off the negatives. He had already mastered the problem of plate fragility. The negatives of the first series, “which were originally none too good, soon became broken or defaced, so that many of the prints, especially the later ones, were not satisfactory.” To remedy this they were backed with thick French plate glass, but no matter how the contrast and overall intensity of the print was chosen, some information was inevitably lost during magnification.[236]

> As to the definition, much is lost in the enlargement, not so much from want of definition in the enlarging lens, […] as from the radical defect of photographic processes; for when one brings out the fine doubles in which the streak of light in the centre is very faint, he loses many of the fainter lines. The original negatives show E, and even finer lines […] but there is little hope of showing this on the map. The atmospheric **(p.233)** line just outside of one of the D lines also nearly merges into it, although in the original negative it is widely sundered from it.

Tab. 6.2 List of absorbents used by Rowland to filter parts of the spectrum for photography (left) and the respective wavelength range (λ) of sensitivity that filtered through (right, in Å). From Ames [1889a] p. 73.

Absorbent	λ range
Greenish plate glass	3300–8000
Salicylic acid in alcohol, saturated, in quartz cell	3500–8000
Aesculin, 1 gr. in 1 oz. water, with one drop of ammonia	4100–8000
Potassium ferrocyanide	4400–8000
Primrose or aniline yellow	5000–8000
Fluorescine or chloride of gold	5200–8000
Chrome alum	3200–3700
Chrome alum and	4600–5200
Malachite green	4600–5200
Bitter-almond green	4600–5200
Brilliant green	4600–5200
Cobalt chloride	3400–4500
Gentian violet, strong	3600–4600
Potassium permanganate	5800–8000
Gentian violet and Potassium permanganate	6000–8000 & 3900–4600

Rowland even quarreled with his assistant about the faintest lines just barely visible on the negatives. Having measured most of the spectrograms for the accompanying table of standard wavelengths, Jewell, who had much sharper eyesight, wanted to include them, against Rowland's judgment. Jewell reported that Rowland in fact “disbelieved in the existence of many of them. Upon these points we were not in agreement at all, and as a result a sort of compromise was arrived at.”[237] Notwithstanding these minor problems with the ‘photographic process’, Rowland generally recommended his map not only because of the “immense improvement” over the first series, but also because of its considerable superiority over other available maps of the solar spectrum, in particular over lithographed maps. This is where the rhetoric of automatic recording returns. Just as Henry Draper and William Fox Talbot before him, Rowland also played the trump card of ‘Nature's own imprint.’ Ignoring the many levels of interference and manipulation we have just been discussing (absorbents, sensitizers, changes in contrast during enlargement, retouching, etc.), Rowland considered his photographic map free of all-too-human distortions and errors: “The photograph is the work of the sunlight itself and the user of this map has the solar spectrum itself before him, and not a distorted drawing full of errors of wave length and of intensity. The superiority is so great that there is no possibility for comparison.”[238] His photographic map was much more than the conventional definition of a map would imply. **(p.234)** being “a visual concept, a constructed or projected image, referring to and bearing information about something outside itself”. His map was not merely a somewhat arbitrary image, a convention-laden two-dimensional black-and-white depiction—to him (as to many of its users as well) it became the object *per se.* Since, surely no other contemporary instrument would show more, Rowland's map transmuted into the solar spectrum itself—object and sign had become blurred. The conscious modesty that foregoing map-makers had about the limitations of their representations had dissipated, overshadowed by the presumptuous self-confidence of a turn-of-the-century experimental physicist, who believed he had, in many respects, achieved the ultimate in technological progress.

Rowland's photographic map is a quite interesting case also from the commercial point of view. Not published in a journal for distribution to a list of regular subscribers (as was the case, e.g., with Cornu's map), nor disseminated by a company specializing in accessories for scientific instruments (like Bunsen's poster map), it was issued by The Johns Hopkins University. Rowland's team initially distributed it directly and later it was obtainable through Johns Hopkins's Publication Agency, which had the exclusive rights. Copies of the second set could be ordered for $18.[239] From a still extant list[240] we learn that the first customers included the well-known astrophysicists S.P. Langley and C.A. Young. The experimentalists specializing in optics or spectroscopy C.S. Hastings in New Haven, Louis Bell at The Johns Hopkins, and Mace de Lepinay in Marseilles also placed orders. Some book dealers (such as A. Hermann who bought as many as 20 copies for distribution in the Paris area), major research institutions (e.g., MIT, the Harvard College Observatory, and the US Military Academy), ordinary colleges and high schools (for example, the Principal High School in Washington, DC), and even scientists whose main interests lay in quite different fields (such as George Francis FitzGerald at Trinity College, Dublin) were also among the purchasers. It was not easy even for Rowland's fellow countryman Edward C. Pickering from the Harvard College Observatory to obtain a copy of the photographic map. Upon seeing the announcement in *The Johns Hopkins University Circulars*, he wrote to the Publication Agency, eagerly ordering “any of the plates as soon as they are ready for distribution […] and also all extra plates of the B and D lines, the carbon bands, and any others which may be included in the series.” In February 1889 he finally received the set of plates of the normal solar spectrum, but still none of the announced supplements with the enlarged band spectra.[241]

One of the leading experts in *visual* spectroscopy also started to map the solar spectrum *photographically*, independently of Rowland in Baltimore. A long series of exploratory **(p.235)** experiments[242] convinced Charles Piazzi Smyth, Astronomer Royal for Scotland, of photography's superiority over the human eye in that region of the spectrum “where the mysterious spectrum violet begins to mix up with the blue, in forming the luminous back-ground or ‘continuous’ part of the spectrum,—the dark lines beyond that point, or in the further more violet-ward plates, began to grow fainter, broader, mistier, and at last became quite incapable of focussing to any sharpness.”[243] Photography not only circumvented these problems of visual spectrometry in the violet, it allowed the mapping of that region of the ultraviolet where “the very last remaining traces of anything recognizable in any way as part of the Solar Spectrum went under.”[244] A preliminary progress report delivered at the 1890 meeting of the British Association for the Advancement of Science in Leeds led to the establishment of a committee consisting of Arthur Schuster, George Liveing, James Dewar, and himself as secretary. It approved a modest grant for Piazzi Smyth to continue his otherwise privately financed researches, which enabled him to purchase an extra-large Barlow photo-achromatic lens.[245] Like Rowland, Piazzi Smyth too worked with color filters to absorb unwanted orders of diffraction, but his retirement home obviously could not accommodate a large Rowland concave grating. That is why he continued to use the plane Rowland grating with 14 400 lines to the inch, which had been in his possession since 1883.[246] The thus obtained photographic plates measuring 3.25 × 6.75″ were enlarged with the assistance of a local joiner identified as Mr S.H. Fry. They used a copying and enlarging photographic camera, about 16 feet long, and capable of linear magnification by a factor of 10–30.[247] During the second half of 1891, Piazzi Smyth experimented with increasing **(p.236)** the focal magnification by a factor of 2.3 by means of the aforementioned Barlow concave lens. In February of the following year a new Rowland grating finally arrived with 20 000 lines to the inch. Needless to say, he found it a considerable improvement over his previous ones, and it allowed him to supplement his map with photographs extending down to 3550 Å.[248] As a safeguard against unwanted distortions, induced by the photographic enlargement process, Piazzi Smyth meticulously compared the distances between the spectrum lines micrometrically. Readings were taken every tenth of an inch or so for the whole length of the sheet and each separate sheet enlargement was measured as well, to check for any alteration in the camera focus or for warping of the page.[249]

To forestall any residual distrust in the reliability of his photographs, he rephotographed the same spectral region under slightly different weather, temperature, and light conditions, at intervals between 3 hours and 5 days. Additionally, he varied the exposure times and the photographic material, using such plates, paper, and developers as were becoming increasingly available on the expanding market for photographic supplies.[250] Hence “after abundant inter-comparisons,” he found

> most cumulatively, that such high confidence may be placed in sufficiently large photographs for everything which is really wanted in modern spectroscopic enquiry,—that in spite of proverbial spits, blemishes, and those accidents innumerable which photography is born heir to, and besides the probability of wholesale darkenings or palings on any and even every sheet of paper, on account of the far too easy errors to commit, of either over or under exposure, or over or under development,—two photographs however murky-faced, are vastly safer than three, five or more hand drawings. And never have I met with such a difference between any two of these photographs as to require a third to settle the point, as to the existence, or character, or place of a true spectral line, and not an accidental mark.[251]

Piazzi Smyth thus conceived his map of the visible and near-ultraviolet regions of the solar spectrum as a twin set. Each segment (of about 55 Å per plate) was to be reproduced photomechanically, from “two separate and independently taken pure and untouched photographic representations”, on the argument that such a procedure would convert a “single photograph, whose *sole* testimony is next to naught,—into a store-house of many proofs of exactitude; and investing every earnest and studious beholder with a sort of judicial **(p.237)** authority within himself, to pronounce on the truth and trustworthiness of the representation.”[252] Printing them adjacent to each other on facing pages would facilitate for each user the inspection and comparison of critical features on each photograph. Of course, this plan also doubled the number of printed plates and as early as August 1890 we find Piazzi Smyth optimizing the page layout, presuming a page format 11.2 × 8.9 inch suitable for the *Transactions* of the Royal Society of Edinburgh.[253] Unfortunately, its Council was not too pleased with the prospect of funding such an elaborate and costly endeavor. In correspondence with its General Secretary Peter Guthrie Tait (1831–1901), Piazzi Smyth tried to convince the Council to accept his paper including the proposed plates as a supplement to his 1884 Winchester solar spectrum map. Aside from putting the general point of “latter day improvement of our knowledge as to essential Solar physics” by photography, the Royal Astronomer for Scotland argued that the reproduction of photographic plates

> require not the manual dexterity of the lithographer, the wood-cutter, or the copperplate-engraver, but the more absolute trustworthiness of some automatic reproduction by some natural process […] now brought to such a high state of both excellence and cheapness in America as to threaten to turn the tables on wood-cutters, lithographers, and copper plate press-men, with most effective pictures, of any size, printed in the ordinary type press, and on ordinary type paper coincidently with the type of the letter press required to accompany.[254]

Whatever may have been the real reasons for the rejection of Piazzi Smyth's paper by the Royal Society of Edinburgh, he ultimately lost the race against his American rival, whose " 'most exact photographs'—truly described as 'of undreamed of excellence of definition' " he unhesitatingly applauded.[255] However, the first series of Rowland's map only incorporated parts of the optical spectrum (from 3200 to 5800 Å). When it reached England around 1887, two researchers in particular felt compelled to fill in this gap and started working on a photographic map of the remaining portions of the solar spectrum. One was the amateur astronomer Frank McClean (1837–1904), a wealthy engineer with an academic training at Westminster College, Glasgow, and Trinity College, Cambridge. In 1870 he had retired in order to concentrate on his scientific and artistic interests, and maintained a private observatory and laboratory at Tunbridge Wells. But unlike many gentleman scientists, he engaged no laboratory assistant.[256] In December 1888, McClean presented to the Royal Astronomical **(p.238)** Society a portfolio of photographs, enlarged 8 1/2 times, of the solar spectrum from D to A in seven sections, corresponding in representational mode and approximate dispersion to Ångström's normal solar map.[257] Whereas Ångström's instrument was the Nobert grating, McClean's was a Rutherfurd grating with 17 296 lines to the inch and with a ruled surface of about 1.74 square inch. His "Photographs of the Red End of the Solar Spectrum" covered that half of the Sun's visible spectrum not included in Rowland's photographic map. McClean's photographs also included "subsidiary" photos displaying "in the same sections, both the red spectrum of the second order as before, and also the overlapping, green to violet, spectrum of the third order."[258] The purpose of these double spectra was to aid the spectroscopist in testing the red part of the spectrum with third-order spectra, for lack of overlappings in the same order. Commendable as was this extension of Rowland's photographic map into the yellow–red region of the spectrum (λ 5800 to 7700 Å), it had the serious problem of not being enlarged enough photographically. One copy of this set of portfolio enlargements was deposited in the library of the Royal Astronomical Society. So it was accessible to the London-based scientific community and, to some extent, to visitors from other parts of Great Britain; but it was not easily available to researchers elsewhere. The only part of this series of photographs 'published,' in the proper sense of the word, was a small segment of the spectrum around the line A at 7600 Å. Technically speaking, though, this plate

was not a photograph but a lithographed sketch by the assistant secretary of the Society and highly skilled lithographer W.H. Wesley—“taken from the photograph”.[259] Wesley did a superb job in bringing out the beautifully striated structure of this line group and the nearly plastic appearance of some of the split lines. Yet this mixture of techniques clearly did not meet the purpose, which was to complete the map *photographically*. This omission became moot with the appearance of Rowland's second series in 1889, which included the red extreme of the spectrum. In spring of that year, McClean once again presented a set of spectrum photographs before the Royal Astronomical Society, this time “parallel photographs” of the solar spectrum, iron, iridium, and titanium, produced in the same manner.[260] His next two spectrographic publications adopted the contemporary photomechanical reproduction technique, however, even though this amounted to surrendering his do-it-yourself principle which he had rigorously followed up to that point.[261] In late 1890 he published “comparative photographic spectra of the high sun and low sun from H to A showing the atmospheric absorption bands” (in a sense, the photographic analogue of Thollon's contemporary lithographic comparative map), and in November 1891 he completed comparative photographic spectra of the Sun and fifteen metals for the wavelength **(p.239)** region 3800 to 5750 Å.[262] The latter map, compiled with the aid of a plane Rowland grating acquired in 1890, was especially useful because it was the first of the rare metals palladium, rhodium, and ruthenium. In both cases, McClean's collotype prints were reproduced, from mounted photographs, by the Direct Photo-Engraving Company in London. As McClean himself disappointedly remarked, this technique of reproduction had the unavoidable side effect that “the white lines unfortunately become a little coarser in the process”.[263]

The second British observer interested in completing the available photographic atlases of the solar spectrum compiled before the turn of the century was George Higgs[264] (1841–1914). A fellow of the Royal Astronomical Society, member of the Liverpool Astronomical Society, founding Council member of the Liverpool Physical Society, and owner of a private observatory in Tuebrook, Liverpool, this dedicated hobby scientist earned his living as a watchmaker and jeweller. He had been working since the mid-1880s on the problem of photographing the solar spectrum, with the purpose of satisfying the needs of both the spectrometrologist and the amateur seeking a convenient photographic guide through the solar spectrum. The demand for a normal photographic map was strong among his fellow countrymen, since Rowland's photographic maps had been distributed on a first-come-first-served basis and were quickly sold out after the second series in 1888 was issued. Higgs also intended to improve upon some of the features of Rowland's maps, which lacked information about the changes spectra exhibit under different atmospheric conditions, such as are presented in Thollon's engraved map from 1890 (cf. here p. 102). The many versions of his photographic records of the solar spectrum document some of the steps in this endeavor. Initially, his “photographic studies of the solar spectrum” ranged only from 4400 to 3860 Å, including the regions around G, h, and H,[265] but within a year he succeeded in extending the color range to include the highly sensitive blue–indigo region. Encouraged by “several leading men of science on both sides of the Atlantic”, Higgs managed by 1889 to cover the entire region between the yellow D lines and H (with the exception of a small portion near F). But Higgs's improved photographic emulsions were at least as important. Experimenting with various sensitizer dyes for the most problematic red region he finally settled on using bisulphite compounds of alizarine blue and coerulin, with which he obtained plates possessing “all the detail and definition usually so characteristic of the violet end. Numerous lines are sharply depicted which were previously not known to exist. λ8400 has been reached, giving almost equal detail.”[266] For the green, yellow, and orange regions **(p.240)** Higgs used dry plates stained with erythrosine and cyanine, which greatly augmented their color sensitivities in this spectral range, and “enabled him to photograph all the lines which can be seen with the eye, a result which had not been before obtained.”[267] After carefully comparing Rowland's photographic map and the earlier photographic map by Rutherfurd against Higgs's enlarged prints, which Higgs had made publicly available at the library of the Royal Astronomical Society, one contemporary expressed his admiration as follows:

> The most striking feature of these enlargements, at first sight, is the extreme clearness with which every line stands out on the bright background, nothing hazy or obscure, the whole a perfect marvel of distinctness and sharpness of definition. All must admire the fine solar spectrum […] by Professor L.M. Rutherfurd; and yet viewing this grand work, and then turning to the enlargements of Mr. Higgs, is like looking at the delicate outlines of a fine public edifice first through a November fog, and then in the brilliant sunshine of a clear spring morning.[268]

A year earlier, Perry had compared Higgs's four photographic studies of 1888 with the first installment of Rowland's map of 1886. Although he confessed at the outset that “in the visible portion of the spectrum I know as yet of no photographic map that is comparable with the excellent results of Professor Rowland”, the near-ultraviolet region between the lines H and K was an altogether different matter. Higgs's atlas might have represented this region on a scale smaller by a factor 3 than Rowland's, nevertheless Perry found that “the faintest lines of Rowland were nearly all more distinct in the smaller photographs, and that several lines of Higgs were altogether wanting in Rowland.”[269]

Higgs achieved this “marvel of distinctness” in his enlargements with a trick that helped him eliminate the granular structure of the silver in the original negatives. During exposure of the print, he purportedly moved the photographic plate parallel to the spectral lines, or else inserted a cylindrical lens in front of the enlarging lens. The effect of either method was to stretch out the lines and smooth out the grain in the background, in a manner not unlike modern picture-enhancement techniques.[270] Furthermore, Higgs took “extreme care in making his adjustments”, and in choosing auxiliary equipment; he had made the very finely machined steel-jawed slit himself especially for his spectroscope.[271] As soon as he obtained a small Rowland grating, Higgs repeated his earlier work, replacing the prism-spectrometer with a concave grating in a mounting differing from Rowland's in that it positioned the grating opposite the slit along the diameter of a large circle, and the photographic plate was moved along this circle in a tangential fashion to observe the different spectral orders.[272]

(p.241)

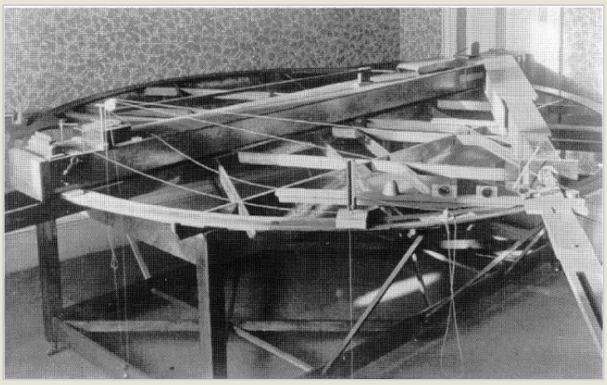


Fig. 6.18 Higgs's mounting for a concave grating: The light enters from the right into the slit, is guided towards the grating in the back (not visible), and from there onto the photographic plate in the box at the tar left. Moving the slit along the big semicircle by means of an intricate pulley system causes different orders of the spectrum to fall onto the photographic plate. The path of the light, fully enclosed in card boxes, shields the plate from stray light. As the wallpaper in the back reveals, the whole apparatus was installed in Higgs's private home. From Higgs [1894] pl. 90.

This small grating with a radius of curvature of 10 feet 2 inches, yielded about half the dispersion of Rowland's big 21.5-foot concave gratings. With it Higgs plotted a normal map essentially covering the entire visible spectrum in consecutive wavelength parts along with the near infrared and ultraviolet (8346 to 2988 Å). Higgs's atlas covered a wavelength range in some respects similar to Rowland's map, but his sensitized dry plates allowed him to forge further ahead into the infrared than Rowland, whose map stopped short of 7000 Å. The atlas was distributed by the printing agency of William Wesley & Sons and was available in three different scales of enlargement,[273] the largest of which consisted of more than one hundred segments of 30.5 cm each.[274] Although even Higgs's greatest enlargement, at a dispersion of approximately 7 Å per cm, did not approach Rowland's **(p.242)** dispersion of c. 2.5 Å/cm, he had other features to offer. First of all, the photographs he had taken “were decidedly sharper and showed more lines than those of Prof. Rowland.”[275] Rowland had omitted spectra of lower orders, thus making comparisons and orientation much harder for inexperienced users of his map, so Higgs often combined photographs with comparison spectra of superposed orders “to establish the relation between the wavelengths of any two or more parts of the spectrum”[276] (cf. Fig. 6.19). He also made a point of reproducing segments with strong atmospheric lines under “every possible condition of solar altitude, temperature, and humidity.”[277] Thus Higgs's photographs fulfilled a very similar function, with respect to Rowland's photographic map, as Thollon's map of 1890 (cf. footnote 91 on p. 135) with respect to the earlier lithographic maps: it provided explicit comparisons of the Sun under different seeing conditions, absent in the earlier standards.

Even though Higgs's personal papers have not survived, some of his letters have been preserved among the papers of other astrophysicists, demonstrating that his work was known and quite highly regarded by the experts, even if sometimes only as a serious competitor. In a note to a close friend, the ultraviolet spectrographer Victor Schumann remarked:

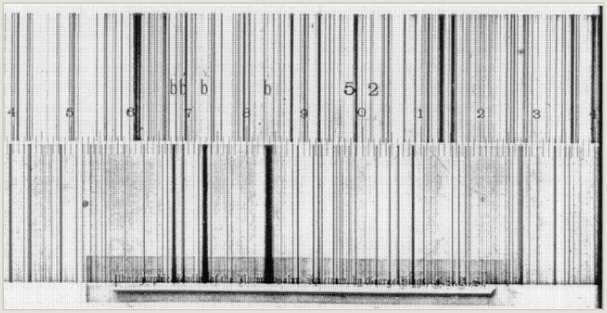


Fig. 6.19 Higgs's photograph of the b group in the upper half of the figure, together with a superimposed scale (52 = 5200 Å). The upper half was photographed in the spectrum of the third order; the lower half is the fourth order spectrum (with wavelengths λ exactly three quarters of those in the upper half), including, for instance, the cyanogen band at 3888 Å (i.e., between 51.72 and 51.78 on the upper scale). From Higgs [1894], also reproduced in Watts [1904] p. 62.

(p.243)

> as to the definition of the spectra, with Mr George Higgs of Liverpool I [have] gained a serious, indeed, a dangerous rival. Dangerous because Higgs likewise builds his own instruments and—this is the critical thing—has become aware of the great effect that the slit-edge design has on the definition of the line images. Like me, Higgs uses true cutting edges for his luminous slit. He also seems to prepare his own light-sensitive plates. In short, Higgs is beginning to become quite terrifying to me.[278]

Oliver Lodge, department head at Liverpool University, was a close friend of Higgs and later used Higgs's instrumentation for his experiments on the Zeeman effect. Plans by Samuel Pierpont Langley in Washington to collaborate with Higgs in infrared spectroscopy in the late 1890s fell through, partly because Higgs did not have the time to spare.[279] In 1902 George Ellery Hale from the Mount Wilson Observatory even tried to secure a grant of $1000 from the Carnegie Institution to support Higgs's research. Despite favorable endorsement by the Advisory Committee on Astronomy, the Board of Trustees argued that “the needs of research in the United States would absorb all the funds now available”.[280] However, Higgs's overall productivity in working on the solar spectrum was quite limited: the charting of these photographic maps was but a side activity for him, so that new orders often were put off until he found the time.[281]

Despite the useful features of Higgs's photographic atlas for identification of atmospheric absorption lines and its convenient 12-inch format, against Rowland's monumental 3-foot-long sheets, it was the latter that quickly became the standard map of the solar spectrum. Despite the many corrections and revisions since 1900 to Rowland's accompanying wavelength tables, I do not think that spectrometrologists and solar astrophysicists regularly referred to any photographic atlas other than Rowland's, at least until the publication of the Utrecht photometric atlas in 1940 (which is discussed in § 7.4 on photometry), and possibly even afterwards.[282] As late as 1936 it still read in one of the leading astronomical periodicals: “It is well known that the high quality of Rowland's solar spectrum plates has never been surpassed or even reached afterwards, and that they show faint lines and details not seen on other plates”.[283] Indeed, from the late 1880s on, access to a Rowland photographic map was as critical in spectroscopic research as possessing a Rowland concavegrating **(p.244)** (see above p. 56). The photographic map of the solar spectrum was mainly used for comparison purposes even when terrestrial spectra were being examined. According to a more detailed description of its actual use in spectrometric work: “With the aid of the new Map of the Solar Spectrum published by Professor Rowland, it is very easy to determine the wave-length of metallic lines in the visible spectra of metals; for it is merely necessary to photograph a portion of the solar spectrum upon the same plate as that which receives the spectra of the metals under consideration, and then to refer to the published map.”[284]

Just as in the case of the gratings, the price of the map was not at issue, since it was sold practically at production cost (c. $12 for the first series and $20 for the second).[285] What mattered was obtaining one before the stock ran out. As mentioned earlier, the first series of photographic maps issued in 1886 was depleted so quickly that a second series had to be issued just two years later. When in late 1890 the Bonn physicist Heinrich Hertz asked the spectroscopist Heinrich Kayser (who was still in Hannover at the time) to lend him his Rowland map, the latter replied:

> I am sending you the first edition of Rowland's atlas; this one is admittedly *much* worse than the second edition, which I also have; but we cannot well do without that one for a fortnight or longer since we are continually comparing the elements with the Sun. I also think, for your purposes this atlas will be entirely sufficient.[286]

For specialists in spectroscopy, Rowland's map had evidently become indispensable even for short periods of time. They were carefully hoarded, never loaned out to anyone, and even found mention in wills.[287] In his letter to Hertz, Kayser elaborated on how he had used the first series of Rowland's map soon after its appearance in 1886. He had just started a big research project to redetermine all of the approximately 4000 iron spectrum lines, which were best suited as wavelength standards because they are evenly distributed over the whole spectrum.[288] “You shall see that very many lines are marked: these are all iron lines, which will surely be of interest to you and your students; it shows how, notably in the ultraviolet, the solar spectrum is almost exclusively an iron spectrum.”[289] Eventually, Kayser's and Runge's research, published between 1888 and 1893, provided another convenient set of wavelength standards. Although their plates could not compete with the quality of Rowland's solar map, they were popular as well, particularly for purposes of emission spectroscopy and chemical analysis, and their atlas of the line-rich iron spectrum remained **(p.245)** in use until it was superseded by better photographs published in Vienna and Marseilles in the early twentieth century.[290]

Normal spectra of several other metals, including zinc and magnesium, in the electric arc were published by Henry Crew (1859–1953) from Northwestern University in Evanston, Illinois.[291] Crew and his co-workers used a big Rowland concave grating, but to improve the contrast they developed a method by which both poles of the arc and the photographic plate were moved synchronously, in order to avoid the continuous spectrum generated by heated-up poles.[292] Like Rowland's map, these photographic maps of normal metallic spectra were distributed by the local Business Agent of Crew's home institution, at $3 per set. Only a few copies of these silver prints on lithium paper mounted on white cardboard 2.5 × 12″ have survived.[293] As the small excerpt from one of these photographs of the zinc arc near 2800 Å (in Fig. 6.20) shows, the middle of the spectrum was far less sharp than the iron comparison spectrum at the bottom, which served as the real wavelength standard for the user of the map, while the numerical scale at the top gave an approximate indication of the wavelength range. The idea behind the photographic map was thus to scale an unidentified spectrum by juxtaposition with a much more familiar comparison spectrum.

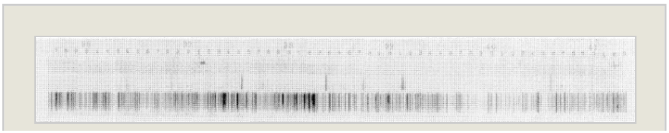


Fig. 6.20 Detail from Henry Crew's photographic atlas of the zinc spectrum, recorded in 1895. From Crew [1896], greatly reduced in size from one of the original photographic prints on ‘lithium paper’, each eleven inches in length and mounted on white cardboard.

Maps like Rowland's two series of the normal solar spectrum, along with their counterparts in Crew's maps of various metallic arc and spark spectra, or Kayser and Runge's, Eder and Valenta's, and Buisson and Fabry's charts of the spectra of various other elements mark the climax in the rise of *photographic* maps of the solar spectrum against their *lithographic* forerunners. Compared with other areas of map production, as studied by Daston and Galison, this transition occurred surprisingly late. The explanation lies in the necessity to overcome enormous technical difficulties (cf. § 6.8) before a print based on a spectrum photograph could fully compete with, say, a carefully prepared lithographic map by **(p.246)** Ångström, Cornu, or Thollon.[294] Rowland's maps continued to be used during the first three decades of the twentieth century, and even much later for purposes of general instruction and practical training. However, the advent of photoelectric methods of registration, which convey far more information on specific line profiles and to which we shall return in § 7.4, started to replace these photographic atlases in spectroscopic and astrophysical research in the 1930s.[295]

Notes:

(1) See, e.g., Eder (ed.) [1913] for an anthology of primary texts up to the late eighteenth century; Eder [1945] for the best technical history to that date, Gernsheim [1982], Pollack [1969], Langford [1980] pp. 7–61, Newhall [1982], Darius [1984] (cf. also footnote 163, p. 213, on scientific photography in particular).

(2) The origin of this myth seems to be Arago’s report of July 1839 on the daguerreotype process. It was then adopted by Tissandier [1878] pp. 5–10, Harrison [1887] pp. 8ff., and first corrected by Waterhouse [1903] pp. 160ff.

(3) See Fabricius's *De rebus metallicis* (1556). On these earliest historical roots of photochemistry see Hunt [1850], Eder [1881], (ed.) [1913], [1917] pp. 33–5, [1945] chaps. I—III, and H. and A. Gernsheim [1955] pp. 20ff.

(4) Schulze taught at the teacher’s seminar in Halle from 1708, becoming professor of medicine at the University of Altdorf in 1720. In 1729 he also started teaching Greek and Arabic languages there and three years later was appointed professor of rhetorics and the classics—this change of focus was quite typical among university teachers of early modern times. For further literature see Eder (ed.) [1913], [1917], and *Poggendorff's Handwörterbuch*, vols. II (1863) and VIIa suppl. (1962), pp. 610–11.

(5) On Scheele’s life and work see, e.g., Zekert [1936], [1963], Cassebaum [1982], Girnus (ed.) [1987], and Smeaton [1986].

(6) See Schulze [1727], Schiendl [1891] pp. 9–10, Litchfield [1903] pp. 217ff., and Eder [1917], [1945] chaps. 9–10, who even calls Schulze the ‘inventor of the first photographic procedure’.

(7) See Scheele [1777], esp. § 60ff., and in particular § 66 on heavier blackening of silver salts in the violet region of the spectrum. Cf. also Hunt [1844*b*] pp. 9, 279, Harrison [1887] pp. 8f, Waterhouse [1903] pp. 165ff.

(8) See Senebier [1782] vol. 3, pp. 192–210, esp. pp. 199f. on the time spans. Cf. also Eder [1881] pp. 62ff., [1945] chaps. 11–12, and Kottler [1973] for the context of Senebier's research on plant physiology.

(9) See Wedgwood [1802], cf. Bérard [1812/17] pp. 38f., and Harrison [1887] pp. 14f., Litchfield [1903] pp. 17–23, 185–205, 246ff., Waterhouse [1903] pp. 175ff., Eder [1945] chap. XV, Schaaf [1990] pp. 12f., [1992] pp. 25f.

(10) On Niépce’s heliography, in French *héliogravure* (not to be contused with the process of photogravure, sometimes called heliogravure, nor with general solar photography, also denoted that way by De la Rue [1861] p. 95), see, e.g., Eder [1945] chaps. XIX-XX, Schaaf [1990] pp. 13f.

(11) On Senebier's research, see here p. 178 as well as Kottler [1973]. The opposing qualities of the ends of the spectrum were also noted later by E. Becquerel [1839*c*] pp. 702f, who distinguished two classes of solar lines: “raies excitateurs” (blue to beyond violet) and “raies continuateurs” (red to blue): see here p. 194.

(12) Nicéphore Niépce to Isodore Niépce, mid-August 1827, published in Fouqué [1867] pp. 140–4, quoted from the English translation in H. and A. Gernsheim [1956] p. 56. Cf. also Arago [1839*c*] p. 243 for quotes from Daguerre's notebook of the 1820s, and here p. 70 on contemporary research on phosphorescent detection of near-ultraviolet rays. Bologna stone is the naturally occurring mineral CaS which exhibits phosphorescence, as first observed by the Italian alchemist Vincencio Casciarolo from Bologna (hence the term) at the beginning of the seventeenth century.

(13) On the prehistory of the daguerreotype see, e.g., Daguerre [1839] pp. 12ff., 37ff., Harrison [1887] chap. 3, Eder [1945] chaps. XX-XXIV. On Daguerre’s life and work as a graphic artist, painter of dioramas and photographer, see H. and A. Gemsheim [1956], esp. the appendices, pp. 182ff., and chap. Ill, pp. 68f. on a possible link to Berzelius's *Treatise on Chemistry* which appealed in French translation in 1829.

(14) See Arago [1839*a*,*b*], Biot [1839*b*, and Daguerre [1839]. Robinson [1839*b*] p. 155 immediately praised the “perfection and fidelity of the pictures”; Brewster [1843*a*] pp. 320ff. contrasted the French government’s response to the disinterest by the English authorities. Cf. Eder [1945] chaps. XXV–XXIX; Taft [1938] pp. 5–8, H. and A. Gernsheim [1956] on the historical context and the reception of daguerreotypes.

(15) Technical descriptions are, e.g., Daguerre [1839] pp. 17–19, 57–70, Fyfe [1839], Robinson [1839], Anon. [1840], Hunt [1852] chaps. 12–14, 18; Hopkins [1889] pp. 337–46, Waterhouse [1899], Langford [1980] pp. 10f.

(16) Brewster [1847*c*] p. 465 in a review of some early popularizations.

(17) Arago [1839*a*] p. 5 estimates that “in summertime and at high noon, eight to ten minutes suffice”, but we also have eyewitness accounts of roof-top portrait exposures taking up to 30 minutes—in direct sunlight!

(18) See, e.g., Lerebours [1846] pp. 20ff., 112ff.; H. and A. Gernsheim [1956] pp. 117ff., Brewster [1843*a*] p. 319.

(19) This chemical is sodium thiosulphate pentahydrate ($Na_2S_2U_3 \cdot -5H_2O$). The ambiguity of its name is discussed, e.g., by Brothers [1892*a*] p. 283. Hyposulfites were first prepared by Chaussier in 1799, but Schützen-berger's isolation of a new ‘hyposulphorous acid’ in 1869 required that the previously existing ‘hyposulfphites’ be renamed ‘thiosulphates’. Nowadays, the fixer is still widely known as ‘hypo’, and the salt as sodium hyposulphite.

(20) On the ‘daguerreotypomania’ that soon broke out see. e.g. Braive [1966]. Taft [1938] chaps. III–V, Eder [1945] chaps. XXXII–XXXV, H. and A. Gcrnsheim [1955] chap. 6: [1956] chaps. 4–7. On the incompatibility of daguerreotype and book printing see, e.g. Blum [1993] p. 267. Photographic lenses gradually improved during the nineteenth century: see Ray [1990] and H. and A. Gernsheim [1956] pp. 108f’. 129. 168f.

(21) Cf., e.g. Hunt [1840*a*] p. 325 quoting Arago [1839*b*]: “It had unquestionably been preferable, for the convenience of the travellers, and also on the score of economy, could paper have been here employed.” Cf. also Hunt [1852] chaps. 19–20, Ostroff [1969*a*] pp. 72–7, and H. and A. Gernsheim [1956] p. 107 on early efforts to convert these daguerreotypes into engraved plates.

(22) See Fizeau [1840]; cf. also H. and A. Gernsheim [1956] pp. 108. 118.

(23) From 1840 on Hunt was secretary of the Royal Cornwall Polytechnic Society, and between 1845 and 1883 keeper at the Mining Record Office; sec Lang [1892], Pearson [1976], and the introduction to Hunt [1841*b*].

(24) See Hunt [1840]. [1841] part I, and pp. 73ft”. [1852] chap. 13, and chap. 3 for the selection criteria and testing procedures of paper for photographic purposes. Cf. also the introduction by J.Y. Tong (1973) to the reprint Hunt [1841*b*], esp. pp. xiii-xvi on Hunt’s direct-positive paper and Cooper’s photogenic paper (for negatives).

(25) According to H. and A. Gérnsheim [1956] p. 153, the portrait photographer Richard Beard (1802–1885) suggested in 1841 substituting the term ‘photograph’ for ‘daguerreotype’, because he found it “a name better suited to the principles of English nomenclature than that of daguerreotype, which, although a favourite word on the continent, is by no means suited to our views, as it has no reverence whatever to the principles of the subject”.

(26) See Talbot [1839*c*] pp. 205f. On his role in the early history of photography see. e.g. Talbot in Tissandier [1878] app. A. as well as Hunt [1852] chap. 9, Jammes [1972], [1973], Hannavy [1976]. Arnold [1977]. Buckland [1980], Beaumont Newhall in Talbot [1844–46*b*] pp. iii-iv, 5f’.: G. Smith (ed.) [1990] pp. 15ff., the introduction in Schaaf (ed.) [1996]. Schaaf [1992] pp. 35f. describes Talbot's “fruitless attempts” in October 1833 to take sketches of Lake Como with a camera lucida or a camera obscura. The Scottish context and other local experimenters are also addressed by Graham [1874]. Morrison-Low [1988]. Schaaf [1989], [1992] pp. 28f.

(27) According to Tong in Hunt [1841*b*] p. xxix. Not knowing the chemical nature of the darkened material, Lassaigne [1839] p. 547, called the silver chloride darkened by exposure to sunlight ‘sous-chlorure d'argent’, which was translated into English as sub-chloride of silver.

(28) The priority dispute between Talbot and Daguerre is discussed in Talbot [1839*a*], Arago [1839*b*] pp. 170ff., [1839*b*] and Petzholdt [1839]; cf. also Talbot in Tissandier [1878] pp. 345f., H. and A. Gernsheim [1956] pp. 139ff.

(29) Yet another metaphor for photographic experiments used, for instance, in David Brewster's letter to Talbot, 12 February 1839, as summarized in Schaaf [1994] p. 18.

(30) Talbot [1839*a*] p. 125, [1839*c*] pp. 209ff.; cf. also Buckland [1980] pp. 37–14, Schaaf [1992] pp. 37ff. and the technical chronology in Ware [1994] pp. 39f.

(31) On the life and work of John Herschel, son of William Herschel see, e.g., [Herschel] [1861], Anon. [1872], Pritchard [1872], Dodge [1873], Clerke [1891], Buttmann [1965], Schultze [1965], Millman [1980] part II, Schweber (ed.) [1981], Schaaf [1992] chaps. 1 and 4, and King-Hele (ed.) [1992]. On his philosophy of science, see J. Herschel [1831] and the commentary in Cannon [1961] and Agassi [1969].

(32) See footnote 19 on p. 180 about this chemical for removal of unreduced silver halides. See J. Herschel's letter to Talbot, 12 February 1839, published in Gernsheim [1959] p. 136, J. Herschel [1839] p. 132, as well as f 1840*c*] § I, pp. 4ff., § 13ff. Herschel had explored the chemical properties of hyposulphurous acid to dissolve the chloride and other combinations of silver already in 1819 (see J. Herschel [1819], [1820], Hunt [1852] chap. 6, Buttmann [1965] pp. 156ff., Jammes [1973] p. 10 on ‘hypo’). See also Gernsheim [1959] and Schaaf [1980], [1992], on the interaction between John Herschel and Fox Talbot based on their correspondence, diaries and notebooks, in particular Schaaf [1980] pp. 194ff., [1992] on the issue of Herschel's “secret of fixing”, and Schaaf [1980] p. 191, [1992] pp. 26ff. and (ed.) [1996] p. xxiii on the terminology of ‘fixing’ and ‘washing out’.

(33) According to Ware [1994] pp. 20f., 31f., 39, Talbot “displayed an abiding reluctance to employ thiosulphate fixer”, but switched over to it in 1843.

(34) Talbot obtained this smooth and homogeneous paper from Whatman's Turkey Mill, founded in Maidstone, Kent, by James Whatman upon his return from a trip to study the production methods of Dutch paper makers: see Talbot [1841*c*] pp. 1055ff., Furlonge [1856], Hammond [1989] p. 163, and Ware [1994] P. 29.

(35) According to Brewster [1843*a*] p. 325, 2–3 minutes exposure time were needed “when the sun is not strong”, while 10–50 sec sufficed “in the light of a summer sun”.

(36) On the preceding see, e.g., Talbot [1841*b*] pp. 312ff., [1841*d*] pp. 89f., [1841*a*] pp. 139ff. The series of letters in which Talbot reports to Biot on improvements in paper sensitivity that reduced the exposure time to only eight seconds, are found in [1841*c*] p. 183. On the crucial importance of gallic acid as a developer in the calotype process and on the contemporary work by J.B. Reade and G.P.A. Petzholdt, see Wood [1979].

(37) The progress Talbot made in his photographic experimentation between 6 February 1839 and April 1843 is documented in his notebooks P and Q, recently published and annotated in Schaaf (ed.) [1996]. Cf. also his account for Tissandier [1878] app. A, esp. pp. 358ff. on the reduction of exposure times for calotypes as compared with photogenic drawings by a factor of 100.

(38) See the abstract of Herschel’s paper dated 5 March 1839, published in Schaaf [1979*a*] “the author employs the terms ‘positive’ and ‘negative’ to express, respectively, pictures in which the lights and shades are the same as in nature, or as in the original model, and in which they are the opposite; that is light representing shade, and shade, light”; cf. also Talbot [1844–16] pl. XX, the adjacent comment, J. Herschel [1840*c*] p. 3, and the letters by John Herschel and David Brewster to Talbot. 16 March and 14 October 1841, respectively, as summarized in Schaaf (ed.) [1994] pp. 31, 34.

(39) See, e.g., Petzholdt [1839] who contrasted a good method of photography (Daguerre’s) with a purportedly bad one (Talbot’s), as the latter yielded only “*distorted images*, in that there, everything relates contrary to nature”.

(40) See J. Herschel's correspondence with Talbot (Science Museum London), in particular the letter dated 28 February 1839, published in full in I.M. and A. Barclay [1937], as well as J. Herschel's 1839 Royal Society paper (first published in full by Schaaf [1979*a*]), esp. pp. 54, 57: “the very remarkable applications of the Chemical rays of Solar light to the representation of natural objects or works of art by a species of painting or drawing (to which it appears to me that the term adopted in the title of this note [photography] may on the whole be most appropriately applied)”; cf. also Schaaf [1980] p. 191, [1992] pp. 54, 62, and Buttmann [1965] pp. 160ff. Cf. here footnote 25 on p. 181.

(41) This comparison between calotype and daguerreotype is made particularly in Brewster [1843*a*] p. 333, and Langford [1980] pp. 18–20. The introduction of calotype into the US is recounted by Smith [1982]; Scotland is covered by Smith [1989], (ed.) [1990] pp. 27ff. For Talbot's patent lawsuits, see Wood [1975]; cf. also Jussim [1974] pp. 50f. which discusses the similarity between Talbot's early calotypes and mezzotints.

(42) See Archer [1851]. More detailed and illustrated descriptions of the preparation and development of a wet collodion photograph are given in H.W. Vogel [1874*a*] pp. 220f., Stein [1877] pp. 101ff., Liesegang [1864*b*] part II, Langford [1980] pp. 26–34, and De la Rue [1859] pp. 133–8, who was also one of the first to use this process for astronomical purposes.

(43) See, e.g., Rutherfurd [1872] vs. Paschen [1870/72] on the issue of the collodion film’s robustness.

(44) The price of photographic paper fell so steeply that the average cost of photographic prints dropped from 5–6 francs per print (at a rate of 3–4 positives per day per photographer) to only 5–15 centimes per print in 1851 (with up to 300 prints per day per photographer), see Blanquart-Évrard [1850], [1851], Legray [1851].

(45) On this problem with wet collodion plates see, e.g. Hartley [1881] p. 102. who was the first spectroscopist to switch to gelatine dry plates in 1877: see Hartley [1882*a*,*b*]. Hartley and Huntington [1879]. Hartley and Adeney [1884] p. 63.

(46) See Gaudin [1853*a*], Girod [1853], Spiller and Crookes [1854], Taupenot [1854].

(47) See, e.g., Ackland [1859] for a contemporary list of chronic problems with early dry processes, including frequent blistering, opaque lines in the excited collodion flim, brain-like markings, reticulations, water marks, fogging, want of intensity, insensitivity, stripping off of the film, and pinholes in the highlights.

(48) See for the following Maddox [1871] as well as Robiquet and Duboscq] 1856], Harrison [1887] pp. 58ff. and 130ff. (quoting from a letter dated 19 August 1887 by Maddox himself on his discovery), Abney [1885] pp. 828f., Taft [1938] pp. 365ff., Jenkins [1975] pp. 68ff.; cf. also Stein [1877] pp. 107–9 on comparable contemporary processes by others.

(49) Maddox [1871] p. 422.

(50) *ibid*. For a detailed description of the practical procedures for preparation, development, and fixing of dry plates see Monckhoven [1879], Hartley [1881] pp. 104ff., Hopkins [1889] pp. 319–26. Liesegang [1864*b*] part III. Roebuck [1928] pp. 10ff. On the contemporary knowledge about pyrogallic acid see the entry in Ure (cd.) [1868] vol. 2, pp. 518–20.

(51) One recipe involving uranium nitrate is given in Kaiserling [1898] PP- 187ff. For a technical description of the manufacture of photographic emulsions—more an art than a science—see Davis and Walters [1922] pp. 3f., Mees [1947] p. 471, or [1961] chap. 12.

(52) Flemming (ed.) [1965] p. 38 makes this distinction between ‘bath plates’ *(Badeplatten)* and ready-made plates, pointing out the slightly lower sensitivity of the latter.

(53) On the increasing commercialization and differentiation of the photographic supply industry after Charles Bennett's discovery of ripening in 1878, and on Wratten & Wainwright in particular, see Mees [1961], pp. 12f., 35ff. McGucken [1969] p. 118 mentions the Beechy standard dry plates as another option besides those produced by the two companies mentioned above, who both produced gelatine pellicle plates.

(54) See Mees [1942] and [1961] chap. 10, who also reports on Sheppard's discovery of mustard oil as the sensi-tizer active in the acidic liquors used to wash out the lime.

(55) See Langford [1980] p. 50.

(56) This is particularly true of the US where the Eastman Dry Plate Company, founded in 1880, introduced its Kodak camera that generated 100 pictures on a paper roll film in 1888, and 35 mm celluloid roll films in 1899. Cf. Taft [1938] chap. 18, H. and A. Gernsheim [1955] chap. 23 about the initially sluggish adoption of the dry plate, and *idem.*, p. 378 as well as Jenkins [1975] pp. 96ff., 145ff., 177ff., Mees [1961] pp. 15f., 141ff. Welling [1978] pp. 297ff., Langford [1980] chap. 4, about the rise of the Eastman (Kodak) Company, and Eder [1945] p. 492 or Schütt [1974] for the patent suit with Goodwin concerning the invention of the nitro-cellulose based roll film.

(57) See, e.g., Jenkins [1975] pp. 113ff., Langford [1980] pp. 50ff. on this process of industrialization and marketing. Alt [1987] discusses the internationalization of the photographic and photochemical market; sec also here pp. 260ff. on photochemical research at the Kodak Research Laboratories.

(58) In 1885 the professional photographers von Angerer or Luckhardt in Vienna still preferred wet plates because, although faster during exposure, dry plates took much more time in the later stages of developing, fixing, and washing. So effectively ‘rapid’ dry plates actually slowed them down: see H.W. Vogel [1885*b*] pp. 134, 1491f.

(59) See H.C. Vogel [1879*a*] p. 163. On solarization see footnote 157 here on p. 211.

(60) On H.C. Vogel see here p. 82. On Lohse see Kempf [1915], Stempell [1940] Brandt [1998] pp. 160ff., and here p. 429. H.C. Vogel and Lohse [1876] included their photographs of the red region; H.W. Vogel [1877*c*] reinterpreted their findings as inverse photographic action. See also J.W. Draper [1874*b*], [1877*a*], Abney [1876], and Waterhouse [1875] for other early infrared photographs.

(61) Born in Dobrilugk (Lower Lusatia), H.W. Vogel—no relation to H.C. Vogel—studied at the Schools of Commerce in Frankfurt/Oder and in Berlin, where he became assistant to the mineralogists Rammelsberg, Dove, and Rose in 1858. In 1863 he earned his Ph.D. at Göttingen University in absentia on the basis of a thesis about the theory of photography (H.W. Vogel [1863]). In the same year he received a call to the Royal School of Commerce (Gewerbeakademie) in Berlin, the precursor to the Polytechnic in Charlottenburg, where he taught photography, spectroscopy, and photochemistry, and opened a photographic laboratory. In 1863 he founded the Photographi-scher Verein zu Berlin, from 1864 on edited the journal *Photographische Mitteilungen*, and in 1878 was the co-founder of the Deutsche Chemische Gesellschaft. On H.W. Vogel see, e.g., Kaiserling [1899], Landolt [1899], Stenger [1934], Röll [1939], Eder [1945] pp. 462ff, and Herneck [1984], H.W. Vogel's discovery of sensitizing dyes is discussed here on pp. 248f.

(62) H.W. Vogel's photochemical laboratory with 24 rooms for photochemical and spectroscopic research and teaching had cost 1 143 000 marks to build. On the architectural planning of the lab and scientific instrumentation see, e.g., H.W. Vogel [1885*c*] pp. 177ff.

(63) According to Röll [1939] p. 79, Vogel's switch over to gelatine dry plates had been triggered by Bennett's discovery in 1878 that their spectral sensitivity could be improved by a prior heat treatment.

(64) See H.W. Vogel [1879*a*] p. 116, Hartley and Huntington [1879] p. 260, and McGucken [1969] p. 118.

(65) See H.W. Vogel [1879*b*] and [1880*a*]; the hydrogen had been prepared electrolytically by Vogel's Charlottenburg colleague Carl Adolf Paalzow (1823–1908).

(66) Huggins [1880*a*] p. 673. On Huggins see here pp. 344ff.

(67) J. Herschel to W.H.F. Talbot, 27 April 1839 (Science Museum London), original emphasis, quoted in Schaaf [1979*a*] p. 54, [1980] p. 201: facsimile in Schaaf (ed.) [1994], p. 6.

(68) W.H.F. Talbot to J. Herschel, 11 February 1839, quoted in Schaaf [1980] p. 192; cf. also Talbot [1839*c*] pp. 207ff., “the invention may be employed with great facility for obtaining copies of drawings or engravings, or facsimiles of MSS”.

(69) Herschel [1839] as published in Schaaf [1979*a*] p. 58. Although this note was communicated to the Royal Society in London on 14 March 1839, it was not published in full until 1979 since Herschel withdrew it from publication for reasons discussed by Schaaf.

(70) See Smith (ed.) [1990] p. 20.

(71) See Talbot’s *The Flora and Fauna of Harrow*, published in 1812; cf. Smith (ed.) [1990] p. 20. John Herschel had a similar interest in this field: see, e.g., Schaaf [1992] pp. 12f., 42–4, 69, 74, 100.

(72) W.H.F. Talbot to J. Herschel, 25 January 1839, original emphasis, quoted in Schaaf [1980] p. 185.

(73) Both quotes from Smith (ed.) [1990] p. 19; cf., *idem*, p. 22, Talbot [1844–16] p. 2 about his insistence that his photographs were taken “without any aid whatever from the artist's pencil”, being “impressed by Nature's hand”.

(74) Talbot [1839*c*] p. 203; cf. also Hunt [1846] p. 155: “taken from the actual objects they represent, they were, strictly, copies from *em nature*”.

(75) According to Newhall's introduction to Talbot [1844–46*b*]. p. vii; cf. *idem.*, and Krauss [1978] p. 292 about a comparable French edition of *Excursions Daguerriennes* in which the photographs had been skillfully ‘translated’ into aquatint engravings “incised by hand from tracings of Daguerreotypes”.

(76) See Talbot [1844–46] pl. X and adjacent commentary.

(77) On the Talbotype Manufacturing Establishment in Reading operating between 1844 and 1847 see, e.g., Snow and Thomas [1966], Jammes [1971*a*] pp. 11–12, 162–4, 170–3, Buckland [1980] pp. 77ff, Naef [1980] pp. 12f., and *idem*, p. 14 on difficulties in the production of part 2.

(78) Arago [1839*a*] p. 5 (7 January 1839), emphasis mine.

(79) Brewster [1843*a*] p. 329. Similar rhetoric is found in Brewster [1847*a*] pp. 466f., where he speaks of the photographer as representing nature “as she is—neither pruned by his taste, nor decked by his imagination”.

(80) [Talbot] [1846] p. 143. On the early reception of calotypes, which reinforced the rhetoric of ‘faithful representation’, see also Naef [1980] p. 15, Schaaf [1992] pp. 144f.

(81) Prospectus on Théophile Gautier: *Tresors d'art de la Russie ancienne et moderns*, 1859, as quoted in Gold-schmidt[1980]p. 4

(82) Hunt [1846] p. 195; cf. [1848*a*] p. 136 middle column. The first talbotype is inserted in Talbot [1846] verso p. 143.

(83) Hamerton [1888] p. 59, who dates this essay back to 1860.

(84) *Ibid.*, p. 64: photography is “of the greatest value for the record of plain facts about persons and places, but it is not a fine art at all, and can never be made one”. Cf. also Nickel [1989] pp. 1f., 9f.

(85) See Arago [1839*a*] p. 4 and Daguerre [1839] P. 25 footnote.

(86) Biot [1839*b*] pp. 259f. On Melloni and the thermopile see above pp. 72f. Cf. also Hunt [1840*b*], [1841] part 1, [1852] chap. 13 on the application of daguerreotype to paper prints.

(87) Biot [1839*b*] p. 260; cf. *ibid.*, p. 265: “the same young and intelligent aid still assisted me.” Edmond, son of Antoine César Becquerel, was then 19 years old.

(88) See E. Becquerel [1839*c*] pp. 702f. The relative strengths of the two classes of radiation was determined thermoelectrically with Melloni's thermopile: see Becquerel [1839*a*] as well as the controversy between Becquerel [1839*b*] and Biot [1839*b*] on the linearity of this instrument's response relative to the incident radiation. Boberlin [1993] p. 23 also alludes to E. Becquerel's reception.

(89) See, e.g., von Angerer [1931*c*] pp. 216f.; cf. also here p. 204 about the opposite ‘Herschel effect’.

(90) See Becquerel [1842]; Lockyer [1874*e*] p. 109 gives the date 13 June 1842 for Becquerel's first photograph, “what I may venture to call a stupendous feat”. On A. and E. Becquerel's scientific research see also Violle [1892], H. Becquerel [1892].

(91) On the foregoing see E. Becquerel [1842*b*] pp. 542f. 549, 554f., [1843] p. 265.

(92) See, e.g., E. Becquerel [1843] p. 312: “Wherever the luminous spectrum is broken by black bands or lines, the chemical spectra too are broken.”

(93) See, e.g. E. Becquerel [1843] p. 264 and his table on p. 277, and [1842*b*] p. 542. Cf. also [1876], [1877], and H.W. Vogel [1874*a*] pp. 248f. for the full revocation of the distinction thirty years later.

(94) See Becquerel [1843] p. 257: “in this area of physics, as in any other, hypotheses must rest on well established fact alone, and it is for lack of following this directive that some physicists […] have advanced some mere conjectures, which will fall on their own as soon as the reactions operating under the influence of light are examined and studied with care.”

(95) E. Becquerel [1843] pp. 321f.

(96) See, e.g. E. Becquerel [1842*b*] pp. 554ff. for his explicit endorsement of Fresnel's theory.

(97) The son of a British methodist priest studied at the University College, London (esp. with Edward Turner) and then migrated to Virginia in 1832. From 1833 on, he attended classes in physics, chemistry, and medicine (esp. with Robert Hare and J.K. Mitchell) at the University of Pennsylvania. On Draper see, e.g., Anon. [1882], Hammond [1882], Barker [1886], Wain-Morgan Draper [1892] pp. 225–8, E.H. [1930], Fleming [1950], [1971], and Trombino [1980]. Becquerel [1843] pp. 258f., 266, 312 identifies him as the culpable party in this regard.

(98) On the early period of daguerreotype in the USA see, e.g., Taft [1938], esp. pp. 14ff., Newhall [1968], esp. pp. 23f., Pollack [1969] chap. 5, esp. pp. 70–1 on J.W. Draper, Welling [1978] pp. 7–65 (esp. p. 11 with a photo of what is now called New York University).

(99) The model for Draper's portrait photograph was his sister Dorothy Catherine; the exposure time was 65 seconds. This daguerreotype is preserved among the papers of John Herschel to whom he had proudly sent it in 28 July 1840 (RS, HS 6.501), reprinted in Taft [1938] pp. 22 and 29. See also Herschel's reply to Draper of 6 August (LOC, J.W. Draper papers, box 4), in which he averred, it was the “most satisfactory portrait which I have yet seen, so extended and considering the shortness of the sitting does equal credits to the brilliancy of your transatlantic sunshine and to your own perfect mastery of the details of that most surprising process.” The Moon photograph is reproduced in Trombino [1980] p. 568 and Darius [1984] p. 16.

(100) See J.W. Draper [1840], where he mentions the then necessary five to seven minutes under good light conditions and his introduction of blue screens to shield his poor sitters somewhat from the glaring heat. Cf. also Taft [1938] p. 23 for a tabular survey of typical contemporary exposure times taking the weather and the time of day into account.

(101) See Draper [1843*c*], [1844*b*] p. iv, and [1845] on ‘interference spectra’. Cf. also Harvey [1957] pp. 352f., Darius [1984] p. 20.

(102) See J.W. Draper to J.F.W. Herschel, 26 September 1842 (RS, HS 6.502) with the handwritten remark by Herschel: “arr[ive]d Dec. 5/ 1842”. According to this cover letter, the daguerreotype was made in Virginia on yellow iodide of silver according to Daguerre's original recipe. His efforts to produce a similarly distinct spectrum in New York had failed, presumably because of much higher atmospheric absorption there.

(103) *Ibid.*, original emphasis.

(104) See, e.g., J.W. Draper [1843*c*] p. 363 and pl. III, [1844*b*] pl. III, fig. 103.

(105) See J. Herschel to J.W. Draper, 5 December 1842 (LOC, John William Draper papers, correspondence, box 4), and the draft among the J.F.W. Herschel papers (RS, HS 25.6.16). Herschel also argued there that upon removing from the silver-salt paper any “excess of iodide of silver, the action under the influence of iodide is positive throughout”.

(106) See, e.g., J.W. Draper [1843*c*] pl. III, [1844*a*] frontispiece, and pl. III, or [1874*b*] p. 243. The published papers, of course, contain drawings made exclusively on the basis of these daguerreotypes. J.W. Draper's interpretation is analyzed in Hentschel [2001*a*].

(107) See Draper [1842], [1843*c*-*d*], [1844*b*] chap. 7, and app., chaps. XII and XVIII; J. Herschel [1843*b*] pp. 13 If., Hunt [1844*b*], H. Draper [1875] p. 290. Terminological issues are also discussed in the letters by J. Herschel to Draper, 5 December 1842 (RS, HS 25(6). 16), pp. 3–4, where Herschel argues that “the time is hardly yet come for the final imposition of names”, and by R. Hunt to J. Herschel, 8 December 1842 (RS, HS 10.95), where he strongly criticizes Draper's view as “singularly loose” and “to me most unsatisfactory”; see also Hunt's letters of 22 March and 12 December 1843, 26 January 1844 (RS, HS 10.108, 10.105, 10.106) for alternative designations.

(108) See J. Herschel [1843*b*] p. 132, Barker [1886] pp. 367f., J.W. Draper [1843*c*], and in particular J.W. Draper [1844*a*] frontispiece for Draper's comparison of prismatic and diffraction spectra. On Saxton see Frazier [1979].

(109) See, for instance, John Herschel's draft postscript to his letter to J.W. Draper (RS, HS 25(6).16), p. 4, where he sketched the vast differences in the spectra recorded on paper covered with nitrate of silver, depending on whether there was much, little, or no excess of nitrate present in the paper.

(110) See, e.g., J. Herschel [1840*c*] § 114 and two earlier drafts of this paragraph about heat augmenting the sensitivity, quoted in Schultze [1965] p. 61, and R. Hunt to J. Herschel, 8 Dec. 1842 (RS, HS 10.95), pp. 3f.

(111) On the gradual understanding of the photochemistry behind silver-based processes, see Hunt [1852], Maskelyne *et al.* [1859], Hardwich [1855], Monckhoven [1863], Jamin [1867], H.W. Vogel [1863], [1885] chap. XI, Schultz-Sellack [1871], Eder [1886], Meldola [1889] lect. II, and Sheppard and Mees [1907] part II. ‘Bacterial photographs’ of the solar and electric spectra are discussed in Ward [1894].

(112) Herschel had collected some of these plants while at the Cape of Good Hope in South Africa: see, e.g. Herschel [1843*a*] pp. 109, 113, § 190, 197; cf. also Evans *et al*, (ed.) [1988].

(113) See Hagemann [1782]; Eder [1945] p. 102 and Buttmann [1970] describe these experiments in more detail.

(114) See J. Herschel [1840*c*] pp. 33ff., [1843*a*] pp. 17ff., 107ff., 170ft., and 246ft. Some samples of this early research into ‘vegetable photographs’ (mostly based on the juice of viola tricolor and crimson poppy) are preserved in the Museum of the History of Science at Oxford. See the brief description in Sehultze [1965] p. 66.

(115) See Herschel [1843*a*] [p. 14: “the action is *positive*, that is to say, light destroys colour, either totally, or leaving a residual tint, on which it has no further or a very much slower action.”

(116) See. e.g., J.F.W. Herschel to J.D. Forbes, 10 August 1840 (RS, HS 22.62): “The rays most efficacious arc neither the chemical (commonly so called) nor the calorific—but the luminous, i.e. the range of action lies within the illuminated spectrum. The same rays however are not efficacious equally on all colours.” Cf. also Hunt [1844*b*] pp. 190ff., J. Herschel's letters to Hunt, 10 February and 31 May 1841 (RS, HS 22.79 and 22.87). as well as to W.H.F. Talbot, 6 April and 14 May 1841, the latter two summarized in Schaaf (ed.) [1994] p. 32.

(117) *Ibid.* Cf. also the postscript to J. Herschel's letter to R. Hunt, May 1842 (RS, HS 22-117), p. 2.

(118) On Mary Somerville's role in the cultivation and popularization of science see, e.g., Clerke [1898], Cannon [1961] pp. 231f., Patterson [1974], [1975], [1983], Weitzenhoffer [1987], and Brück [1996]. Her photochemical research has yet to be studied thoroughly.

(119) See, e.g., her letter to him of 12 November 1843 (RS, HS 16.347): “It is so impossible to obtain any continued account of the progress of the Daguerotype [*sic*] from the beginning up to the present time that I have been tempted to encroach upon your occupation by asking you kindly to let me know if there is any work you would recommend on the subject.”

(120) All foregoing quotes from Somerville [1846] p. 117; cf. also Hunt [1844*b*] pp. 201ff. According to J. Herschel's letter to Somerville dated 2 November 1845 (RS, HS 22.254), this paper was submitted “in the form of ‘an extract of a letter’ to myself to the Royal Society. You may be very sure that I would not do this if I thought that the experiments were not intrinsically quite deserving to be recorded in the pages of the Phil. Trans. and if I were not sure that they will lead to a vast field of curious and beautiful research”.

(121) contextual description of Victorian science in the 1820s and 1830s is provided by Patterson [1983] chaps. 4–5. Cf. also Lightman (ed.) [1997].

(122) See Herschel [1843*a*], and Draper [1844/45]; cf. also Fleming [1950] pp. 15f., and the excerpts from John Herschel's correspondence with Mary Somerville in Martha Somerville (ed.) [1876] pp. 265ff., 278ft’.

(123) See Senebier [1782], esp. vol. 2, pp. 55ff., Kottler [1973], and Shapiro [1993] pp. 253ff.

(124) See Hunt [1844*b*] pp. 192ff. for a good overview of the contemporary literature, and pp. 375–85 about one possible practical application in the design of the green house with a roof of tinted glass for the Royal Botanic Gardens at Kew.

(125) See J. Herschel's diary entry of 7 July 1839 (RS, reel 28, box 2, 00127). Cf. for instance, Arago in Daguerre [1839] p. 28, Hunt [1840*b*] p. 267 on “coloured photographs within the range of probabilities”, [1841] pp. 82f.: “few speculations are more replete with interest”, [1844*b*] p. 337: “advancing rapidly to the desired end”; J. Herschel [1840*c*] p. 18 on “the possible future production of naturally coloured photographic images”. Talbot [1839*c*] p. 203, on the other hand, was “not very sanguine respecting the possibility of this”. The tirst historical surveys of this early research in color photography are given by Hunt [1852] chap. 16 and Taylor [1865].

(126) J. Herschel to W.H.F. Talbot, 7 July and 28 August 1839, and 30 August 1840 (RS, HS 25.5.14, 25.5.16, and 17.302). He enclosed with these letters a sample of spectra thus obtained, which were only to be observed briefly by candlelight, because “a few minutes exposure [to full daylight] would obliterate all its peculiar character”. Cf. also J. Herschel [1840*c*] pp. 18f. for a tabular summary of the various colors obtained.

(127) See, e.g., Herschel [1840*c*] pp. 18ff. on his colored photographs of the solar spectrum, which he started to make in July 1839; and J. Herschel [1843*a*] pp. 177 and 246, § 213, 217, and 219ff. as well as his letters to Talbot, 7 July 1839 and 21 April 1842 as summarized in Schaaf [1992] pp. 82f., 100f., Schaaf (ed.) [1994] p. 25: “the tint produced on the sensitive paper is actually a coloured picture of the spectrum”, p. 26, as well as p. 43 for a letter from 25 March 1843 about chrysotype and cyanotype, and Schaaf [1992] p. 131 on Anna Atkins's book on British algae illustrated with cyanotypes.

(128) See again J. Herschel [1840*c*] pp. 22ff. on this “opposition of qualities”. Herschel's photochemical experiments are also discussed in Eder [1945] pp. 263f., and Buttmann [1966] chap. 6.

(129) See J. Herschel [1840*c*]; cf. also Buttmann [1966] pp. 170f., von Angerer [1953] pp. 217f. Hillson [1931*c*] reviews the literature and gives the modern explanation for the effect: ionization of the silver-halide molecule, caused by absorption of a light quantum of just the right energy to lift an electron into the conduction band.

(130) On the foregoing see Hunt [1840*b*] p. 274, [1841*b*] pp. 82–3. Cf. J. Herschel's table of the color imprints on paper in his calotype recording of the solar spectrum, in Herschel [1840*c*] p. 18 and fig. 80 in Schaaf [1992] p. 125 reproducing John Herschel's sheets of experimental photographs of the spectrum taken in 1841–42 including three exposures on silver-treated paper (also used by Hunt—cf. Fig. 6.5, nos. 1–5).

(131) R. Hunt to J.F.W. Herschel, 19 April 1840 (RS, HS 22.49). According to this same letter, the “only sure fixing substance” used by Hunt at that time was hyposulphite of soda.

(132) In today's nomenclature, these substances are called potassium hexacyanoferrate (II), more commonly known as potassium ferrocyanide ($K_4Fe(CN)_6$,), potassium dichromatc ($K_2CT_2O_7$), and barium chloride ($BaCl_2$), respectively, according to the chemical index compiled by James Yingpch Tong in his edition of Hunt [1841*b*].

(133) Hunt [1844*a*] p. 277, and (*b*) p. 338. Hunt's experiments with muriate of barytes date back as early as December 1839, those with bichromate of potassium to January 1841, and those with ferro-cyanate of potash to December 1842: see, e.g., his letters to J.F.W. Herschel, 14 December 1839, 17 January 1841, and 24 December 1842 (RS, HS 22.32, 10.89, and 10.97).

(134) See, e.g., RS, Hunt to J. Herschel, 23 March 1843 (RS. HS 10.99). A total of 64 letters from the Hunt–Herschcl correspondence between 1839 and 1849 are among the archival holdings of the Royal Society, London: see the catalogue and finding aid compiled by Kesaris (ed.) [1990] pp. 113f.

(135) E. Becquerel [1848*b*] p. 452; cf. also *ibid*., pp. 448ff. on the electrolytic preparation.

(136) Bellone and Fellot [1981] pp. 38f. includes a color reproduction of the spectrum photograph and its box labeled “image photographique du spectre solaire obtenue directement avec ses couleurs par M. Edmond Becquerel (1848)”.

(137) See Niépce de Saint-Victor [1851]; cf. also Hunt [1844*b*] pp. 341f.

(138) See Niépce de Saint-Victor [1851] p. 380: “I have not succeeded in fixing the colors to this day; they disappear very promptly, even in diffuse light; nothing can retain them.” See also Poitevin [1865], Taylor [1865], Abney [1879], Lea [1887]; cf. Harrison [1887] pp. 120ff. for further references to the later research.

(139) Harrison [1887] p. 117. Cf. the biographical sketch there.

(140) See E. Becquerel [1848*b*] p. 457, and Abney [1878*b*] p. 350, quoted here on p. 255.

(141) Ware [1994] pp. 17, 71–5 explains the excitation by light of so-called plasmons, i.e., collective electron oscillations in the conduction band, and provides on p. 71 a table with the colors transmitted and scattered by particles of diameters between 10 and 130 nm.

(142) See. e.g., H.W. Vogel [1873*a*],[1874], Abney [1885] pp. 836ff., Klein [1910]; cf. Eder [1945] chaps. XCIV–XCV, H. and A. Gernsheim [1955] chap. 23, Mees [1961] chap. 17, Welling [1978] pp. 232ff., Langford [1980] pp. 64ff., and Bellone and Fellot [1981] chaps. 6–12.

(143) See, e.g., Ducos de Hauron [1878], where he and his brother Alcide already make use of the orthochromatic collodion process; cf. Eder [1945] pp. 642ff., Mees [1961] pp. 205ff., and Isler-de Jongh [1982].

(144) For a color reproduction of Lippmann’s photochrome of the solar spectrum, see Bellone and Fellot [1981] pp. 92ff. Thomas (ed.) [1997] p. 74 reproduces a few arc spectra recorded by Hermann Krone (1827–1916) using the Lippmann process. Cf. Berget [1891], Lippmann [1893], Vogel [1893], Zenker [1893], Eder [1945] pp. 668f.

(145) On their backgrounds and transition to freelance, then fully-paid researchers in the Kodak Laboratory see Hodges [1987].

(146) See, e.g., Hodges [1987], or Mees [1961] pp. 216ff., esp. p. 224 on color couplers, which compensate for the fact that the blue–green dyes, for instance, absorb not just red, but also green, and even some blue.

(147) See Miller [1862*c*] pl. XXXIX–XL. Cf. also Hartley [1881] pp. 94f., who had the opportunity to compare them with Miller's original photographs and testified to their “being faithful representations, but the character of the metallic lines is wanting in delicacy of detail and sharpness.” Hartley divulged the reasons for this failure: a too wide slit, and a lack of focus in the ultraviolet. The latter was actually a systemic defect of all early ultraviolet photographs, which he remedied with his invention of the tilted plane spectrograph: see here p. 325. On W.A. Miller's earlier efforts at spectrum representations, going back to 1845, see here pp. 42ff.

(148) Aside from Hartley [1881], Henry Draper [1873*d*] p. 224 also found fault with Miller's results: “for some reason, probably insufficient intensity of the condensed induction spark, his pictures do not bring out the peculiarities of the various metals in the striking manner that is both necessary and attainable”.

(149) On Rutherfurd see esp. Rowland [1883*d*], Warner [1971], Devons [1976]. The National Museum for American History of the Smithsonian Institution in Washington, DC, possesses an even larger wall-hanging poster of Rutherfurd's solar spectrum; cf. footnote 154 below.

(150) See Devons [1976] p. 1736 on the original size of the photograph. Rutherfurd [1865*a*,*b*] describes his multi-prism spectrometer with an estimated resolution of 30 000.

(151) Roscoe [1865*b*] p. 69, and analogously Schellen in Secchi [1870*c*] pp. 232f. Rutherfurd [1865*c*] treats astronomical photography in general (including photographs of the Sun, the Moon, and stars); [1872] covers his later work in collodion photography. See also Warner [1971].

(152) See, for instance, Stein [1877] frontispiece; cf. also J.W. Draper [1862] p. 438, Gill [1887] pp. 268f.

(153) See Schellen's German edition of Secchi [1870*c*] pl. VI and pp. 231–3.

(154) One set with a spectrum breadth of 11.5 cm, mounted in a wooden frame, has been preserved in the instrument collection in Washington (NMAH, no. CAI 333.934). It was owned by the Department of Physics at Princeton University until 1973. I am grateful to Deborah Warner for showing me this map in April 1997.

(155) One nice example given in Pang [1994/95] pp. 262ff. is W.H. Wesley's composite drawing of the corona based on several photographs by De la Rue, in McClean *et al.* [1908] pl. 11. Other examples of composite images in scientific illustration are mentioned in Daston and Galison [1992] pp. 101–3.

(156) According to Paschen [1870] col. 189ff., the shrinkage was strongest for albumenate collodion, while non-albumenates shrank more inhomogeneously; the maximum effect was about 1/500 of the initial size of the negative. Around 1920, these experiments were taken up by Frank Elmore Ross at Kodak.

(157) See, e.g., H.W. Vogel [1863] pp. 545ff., von Angerer [1931*c*] pp. 34f.

(158) See, e.g., Lockyer [1874*e*], [1878*c*], [1879*a*]. Cf. also Wood [1903] for examples and a distinction of at least four different types of photographic reversals in spectrum photographs.

(159) This son of a court painter had studied at the Universities of Bonn (with Plücker) and Giessen (with Liebig, Buff, and Umpfenbach), receiving his Ph.D. in 1833 for a thesis on the optics of crystals. He was then a teacher at a *Realschule* in Giessen 1837–44, becoming professor of physics and technology at Freiburg University and editor of the German translation of Pouillet's textbook on physics and meteorology. See Warburg [1877], Kangro [1970] p. 9, [1974], as well as here p. 428.

(160) J. Müller [1847*d*] vol. 1, p. 661. Cf. Twyman [1951] pp. 24ff., according to whom Müller's (and Esselbach's) line O is Stokes's p, whereas Müller's P, Q, and R do not appear in Stokes's drawing. Earlier in 1856, Müller had collaborated with the chemist Clemens Heinrich Lambert von Babo (1818–1899) and the Freiburg court photographer Theodor Hase to obtain photographs between Fraunhofer's line F and N.

(161) See, in particular, Rothermel [1993] and Pang [1994/95] p. 263 on Warren de la Rue's observations by the naked eye and photographs during the 1860 eclipse, and the subsequent printing stages of the plates taken during this event.

(162) See, e.g., Maddox [1871], Abney [1874], [1885] pp. 828ff., [1878*h*] chap. XVII, or [1871*g*] chap, xxvi for descriptions of procedures of the dry-plate process.

(163) Overviews on the history of scientific photography with special attention to astronomical applications include, in particular, De la Rue [1859], [1861], Paschen [1870], [1872], Wortley [1874], Tissandier [1878] chap. VII. Janssen [1883], Common [1886], Gill [1887], Gill *et al.* [1888], Huggins [1891*b*] pp. 96ff., Norman [1938]. Hoffleit [1950], Baker and Smyth [1955]. See also Vaucouleurs [1961] pp. 39ff. on ‘The rise of astronomical photography from 1879 to 1887’; Warner [1967], and Dreyer (ed.) [1923] pp. 76, 112f., 144, 156, 197f., 213–15; cf. here footnote 1 on p. 176 on the general history of photography, and Pang [1997*a*] on the technical difficulties posed by photoengraving in stellar photography.

(164) This relic was fortunately bought by the National Museum of American History in 1985 (cat. no. 85.359.1). Although the notebook carries the number XI and obviously continues foregoing notebooks, it seems to be the only one to have survived. Charles Augustus Young must have had access to others, however, when he wrote his introduction to the posthumous publication of H. Draper's ‘Researches upon the photography of planetary and stellar spectra’ in 1884; see, in particular, pp. 237f. there for quotes from Draper's notebook records dated 29 May 1872 (probably notebook no. X), and from the years 1876–1879 (presumably notebook no. XII). I am indebted to Deborah Warner (at the NMAH) for having made me aware of the existence of this treasure and allowing me to examine it.

(165) For survey of Henry Draper's contributions to scientific photography and spectroscopy see, e.g. Anon. [1883], [H. Draper] [1884], Barker [1882], [1885], [1895], W.H.M.C. [1883], R.S.D. [1930], Whitney [1971]. His father John William Draper is the subject of footnote 97 on p. 196 here.

(166) Bierstadt acquired the licensing rights for Albertype in the United States in 1870 and, together with his brother, the landscape painter Albert Bierstadt (1830–1902), established the Photo-Plate Printing Company (later renamed Artotype Printing Company) in New York City at about the same time. See H.E. Wright [1988] and Welling [1976] p. 85.

(167) See Draper's notebook no. XI (NMAH)—in the following called notebook XI —p. 6 and the scheme on p. 6 verso. Contemporary direct-vision spectroscopes are examined by Janssen [1863*a*], Schellen [1870/72*d*] pp. 115–20, Hofmann [1874], and Warner [1993] p. 40. The instrumentation in Draper's observatory is described in Warner [1968] pp. 57f. and Plotkin [1972] pp. 26f., 36–53 (cf. also here footnote 242, p. 350).

(168) See H. Draper [1859], [1875] pp. 289f., and Plotkin [1972] pp. 11f.

(169) Notebook XI, p. 7, cf. also p. 8 verso for a collodion photograph of the solar spectrum, 10 min exposure time, exposed part less than 1 cm long, and p. 9 verso with photographs of the spectrum of Vega showing 4 lines. The NMAH also possesses various glass plates with, often undated, stellar photographs taken by H. Draper in this early period.

(170) *Ibid.* p. 9. Draper outlined his contemporary experimentation with various silvered glass reflectors in [H. Draper] [1884] pp. 231–6.

(171) As Draper proudly noted, notebook XI, p. 11, he thus spent only $54 instead of the roughly $300 that a Browning spectroscope would have cost. Cf. also the sales catalogues: Browning [1874], [1878], and Warner [1968] about the instruments that Draper purchased from Alvan Clark & Sons.

(172) Notebook XI, p. 16.

(173) *Ibid.*

(174) Initially, Draper obtained two gratings from a Mr Wakely with 4320 and 12 960 lines to the inch, the third (with 6480 lines to the inch) was given to him directly after a visit at Rutherfurd's laboratory “looking at ruled gratings + the ruling machine”, *ibid.*, pp. 19f.

(175) Draper described the procedures in painstaking detail, *ibid.*, pp. 20–2: essentially, he removed the telescopic eye-piece of his spectroscope and looked at slight changes in the appearance of the grating surface as various orders of the solar spectrum passed by—although the naked eye obviously cannot resolve 6000 lines/inch, it is nevertheless able to discern slight deviations in uniformity and periodic errors.

(176) According to Hartley [1880] p. 300 it had 6481 lines to the inch and a ruled surface of 1.08 × 0.64”, and was “unquestionably more perfect than any similar grating made by Nobert and others.”

(177) According to notebook XI, p. 21, it took Draper one evening at the microscope to draw the map in Fig. 6.11.

(178) On these stepwise improvements see *ibid.*, pp. 22–38 as well as the various sample collodion photographs glued onto the versos of pp. 25, 26, 33, 36; cf. also H. Draper [1873*b*] p. 404.

(179) Notebook XI, p. 36.

(180) *Ibid.*, p. 39.

(181) His discovery of palladious chloride as an intensifier was made while researching his Ph.D. thesis. See H. Draper [1859] as well as Barker [1883] p. 90. Cf. H. Draper [1875] p. 289: “This instantly produces an inky blackness in the dark parts, and affects in like manner the shades in the order of their gradation. It imparts no stain or impurity to the proof.”

(182) On the contemporary techniques of darkening silver-based wet collodion see, e.g., Eder [1945] pp. 363f., in particular p. 364 on the effect of Schlippe's salt (sodium sulphantimonate) to darken the negative to a “nice reddish brown”. The above procedures were partly based on Draper's own experiments, partly on closely guarded recipes obtained from Bierstadt: see notebook XI, pp. 30 verso, 42, 43 verso.

(183) Notebook XI, p. 44, entry of 23 February 1873.

(184) See *ibid.*, p. 51 of 21 April, p. 54 of 19 May, and p. 65 of 15 June 1873.

(185) H. Draper [1874*a*] p. 6.

(186) Notebook XI, 21 November 1873 (pagination discontinued): “I had to go downtown a good deal […] partly from the necessity of surveying Bierstadt in the printing of my pictures” […] But the process is very tedious and the plates seldom stand much printing”.

(187) These print runs reveal interesting figures for the relative distributions of various scientific journals in the mid-1870s. See *ibid.*, p. 48 of 27 March 1873, and 21 November 1873. According to the entry on 25 December 1873. Draper started mailing the offprints from *Silliman‘s Journal* on 20 December 1873, c. 100 of them to Europe.

(188) The latter reprint appeared in the issue of 22 January 1874 (vol. 9, pp. 224–6) with a plate printed in the same scale, but on larger-size quarto paper.

(189) *Ibid.*, p. 226. The 2000 copies not accounted for by the above list of reprints must have gone to the *Annalen der Physik* where a German translation with an original plate appeared in 1874 and to the *Comptes Rendus de l’Acude'mie des Sciences* in Paris, where a French translation appeared dated 9 March of the same year: H. Draper [1873*c*], [1874*b*]. On Bierstadt's pricing of 5 cents per copy see here p. 173.

(190) See H. Draper [1873*a*] p. 417; the plate labeled Phil. Mag. S. *4, Vol. 46, Pl. IV* was inserted after p. 416.

(191) See the German edition of Secchi [1870*c*], and Hartley [1880] pp. 299f. as well as the adjacent lithographic plate made by Spottiswoodc & Co. London. When Draper thought he had discovered oxygen in the Sun in 1877, however, his relevant publications were again illustrated with an Albertype of his spectrum photograph printed by Bierstadt from Draper's "original negative": see H. Draper [1877/78], in particular the plate in the French translation verso p. 613—with an English caption.

(192) H. Draper [1873*b*] pp. 402, 408. A similar comparison is made with the map in Mascart [1864*b*] of the near-ultraviolet region. For other examples of quantitative line-counts as an argument for photography, see here footnote 61 on p. 39.

(193) See in this regard notebook XI, pp. 29 and 49.

(194) *Ibid.*, my emphasis. On 'mechanical objectivity' in the sense of Daston and Galison [1992], see here § 10.8.

(195) E.C. Pickering [1886] p. 226, comparing the near ultraviolet of the maps by Cornu [1874/80] and H. Draper [1873] with the first edition of Rowland's photographic map [1886*c*] which is commented on further here on pp. 230f.

(196) See A.J. Ångström to H. Draper, 21 February 1874, and J. Browning to H. Draper, 7 January 1874 (LOC, H. Draper papers).

(197) Capron [1877] p. 16; cf. Anon. [1889] on Capron's biography and here p. 104 for his work on the rainband.

(198) J.R. Capron to C.P. Smyth, 20 March 1877 (ROE, 13.58, folder C). On the London-based Autotype Co. see here p. 159, footnote 83.

(199) See here Fig. 6.14, p. 224 for an example. Cf. also Hentze [2000] pp. 319f. and Schlich [2000] p. 49 for a similar argument by Robert Koch. The very presence of disturbing streaks and spots on his photographs of bacteria vouched for their "purely objective character".

(200) See H.W. Vogel [1894] vol. 2, p. 467, and [1884*b*] p. 45. Cf. also the plate after p. 58 there comparing a vividly colorful original with a conventional and an orthochromatic photograph. On solarization and halation, see here pp. 211 and 248, respectively.

(201) See, e.g., Kaiserling [1898] pp. 191ff.; von Angerer [1931*c*] pp. 179–88 offers a charming apology for addressing the "higher art of retouching", even though it was "legitimately strictly taboo".

(202) Kaiserling [1898] p. 191.

(203) A good example is Nicolaus Rüdingcr's anatomical atlas with Albertype reproductions of ‘original photographs’ that turned out to be heavily manipulated; see Hentze [2000] p. 310. Similar problems with photoengravings in astrophotography are discussed by Pang [1997*a*] pp. 196ff.

(204) See, for instance, the illustrations in Gandy [1940] p. 10, and Woodward (ed.) [1975], as well as, e.g., the manuals on *Retouching and Finishing for Photographers* by J. Spencer Adamson, London, Pitman (1st edn 1925, 3rd edn 1935), or *Negative and Print Retouching for Amateur and Professional* by Anne J. Anthony, Director of the Hollywood School of Photography, New York: Greenberg, 1950, which focuses on portrait photography. The working conditions and average salaries of retouchers (often female, with relatively low monthly wages between 30 and 70 Mark per month around 1894) are described in Hocrner [1989] pp. 46–54.

(205) See, e.g., Smyth [1879*b*] p. 236: “37 remarkable plates”. Compare, however, an unpublished remark in his notebook (ROE, 18.114), p. 176 about Rand Capron's spectra: “some of them by intensified spark, with broad slit and poor definition and some by arc-light with narrow slit and often excellent definition, but both of them are greatly confused and concealed by air-lines.”

(206) This particular defect was somewhat diminished with the development around 1910 of emulsions requiring shorter exposure times of about a minute, as the figures given in Gissing [1910] indicate. But the above-mentioned weaknesses remained nonetheless.

(207) See, e.g., the complaints by H.W. Vogel [1877*a*–*b*]. Christie [1878] p. 473 carefully examined some of Henry Draper's ‘evidence’ for the existence of bright lines in the solar spectrum and attributed them to insufficient spectral resolution.

(208) H. Draper [1873*b*] p. 408.

(209) Lockyer [1881*a*] p. 572.

(210) See Lockyer [1881*a*] p. 568: “though there was no difficulty in recognizing the chief lines in both, still in the diffraction photograph the smaller details were in many places quite different, and in many others very difficult to harmonise, the intensities of the lines having been greatly changed.”

(211) See *ibid*. on Lockyer's method of simultaneously viewing both images through a small sighting aperture of 3 mm diameter at various distances until both segments matched.

(212) There is a link to military cartography at this stage of photographic enlargment and reduction, see here p. 165.

(213) A similar thesis is put forward by Blum [1993] pp. 254, 278, with respect to zoological illustrations.

(214) H.C. Vogel [1879] p. 136. For details about the wet collodion exposures with times between 15 and 40 minutes, see also pp. 161ff. there. Rutherfurd's photographs are discussed above on p. 211.

(215) H.C. Vogel [1879] p. 211.

(216) Trowbridge and Sabine [1887] p. 291.

(217) Trowbridge and Hutchins [1887*a*] p. 4.

(218) *Ibid.*, p. 7: they obviously mean two wavelength units, i.e., 2 Å. The Rowland mounting is described in Rowland [1883*a*], Glazebrook [1883*e*] p. 207, and Waterhouse [1889*b*) pp. 284–6.

(219) See, e.g., Lockyer [1874*e*,*f*], [1875*a*] p. 153.

(220) See Smyth [1858a–c] and [1861]. This expedition and the resulting book are also mentioned in Schaaf [1980/81]. See particularly p. 301 on the production of the 40 000 albumen prints in series of 2000 prints per glass negative (enhanced secondary negatives to act, likewise, as replaceable surrogates).

(221) It was usually reserved for frontispieces—see, for instance. Stein [1877] pl. V. Cf. the surveys of photographically illustrated books by Krauss [1978] and Naef [1980], esp. p. 10 for the quote; it is estimated there that 3–4000 books were illustrated in this manner prior to c. 1880.

(222) H.W. Vogel [1877*a*] p. 382; similar reservations are also expressed in H.W. Vogel [1879*a*] pp. 117f.

(223) See H.W. Vogel [1877*a*] p. 382.

(224) Lommel [1888/90*a*] p. 403.

(225) See Lommel [1888/90*c*] p. 686: “as faithful lithographic redrawings as possible”.

(226) Lommel [l888/90*c*] p. 689. This statement is equally true of reproductions in the dissertation by Lommel's doctoral student Ludwig Fomm [1890] pl. I—IV.

(227) See. e.g., Rowland [1883*a*], Ames [1889*a*], Glazebrook [1883*e*] pp. 203ff, and Preston [1890*a*] pp. 194ff. for the theory underlying this instrument. Hentschel [1993*b*], [1998*a*] chaps. 2–3 cover the research practice with this device: cf. also here pp. 56f. for further commentary and references on concave gratings.

(228) According to a separate undated two-page advertisement sheet, preserved among the Rowland papers (JHUA, ms 6, ser. 4, box 35), at the time Rowland estimated that the error due to accidental displacement of the scale “at no parts exceeds 1/50,000 of the whole”. Rowland [1887*b*] p. 183 claims a probable error of relative determinations of 1/500 000 and “at least ten times the accuracy of any other determination”. Cf., e.g., Huggins [1891*a*] p. 71 and Hentschel [1993*b*] pp. 270ff. for evidence that this precision was drastically overestimated.

(229) Rowland's advertisement, *ibid.*

(230) *Ibid.*; slightly abbreviated versions of this text also appeared in scientific journals like *The Observatory* **9** (1886) p. 203. Cf. also E.C. Pickering [1886] and here p. 219 for a comparison of the ultraviolet part of Rowland's map with those by H. Draper [1873] and Cornu [1874/80].

(231) Rowland [1888]. See, e.g., Rowland [1889*i*] pp. 240–1.

(232) Archives with both series among their holdings include JHUA and NMAH.

(233) See the documentation in Hentschel [1993*b*] as well as, e.g., R.W. Wood to G.R. Harrison, January 1949 (MITA, Mc60, box 2, folder Wood): “Jewell had been Rowland's assistant since 1887 (about), partly concerned with the operation of the [rulingl machine, I think, but chiefly with the photography of the solar spectrum and measurements of λs”. Cf. also Meggers to Jewell, 8 January 1919 (AIP, Meggers papers, box 1, in carbon copy): “I understand that you did the major portion of the work in preparing Rowland's Table”.

(234) See the laboratory notebooks among the Rowland papers (JHUA, ins 6, ser. 4, box 25), which document the work of his assistant Jewell; his notes on emulsion tests for the recording of spectra have been preserved (see the notebook entries of 19 December 1889, 24 and 26 April [no year], 9 January 1883).

(235) See Jewell [1900*b*] pp. 241 f. for the details about his developer, which was later widely used by other spectroscopists (such as, e.g., Uhler and Wood [1907] p. 6). Hydro-kinone (as it was also spelled) as a substitute for the ordinary alkaline developers was first suggested in Abney [1880*b*].

(236) Quotes from the advertisement for the second series, Rowland [1889*i*].

(237) See Jewell [1905] p. 28. Cf. Babcock and Moore [1947] pp. 2f., who later confirmed all but 70 of these faint lines in the range 6600–7330 Å covered in Rowland's atlas and tables which listed altogether c. 20 000 lines.

(238) Rowland [1889*i*] p. 80.

(239) See *ibid.*, p. 240. Cf. also the handwritten draft letter by C. Piazzi Smyth to Rowland, 17 February 1886 (ROE, 15.72, folder R,S); Smyth had placed a double subscription of Rowland's map (“one of two things in this life I have been in daily anxiety [about] ever since … 1882”) with Nicholas Murray at the Johns Hopkins University's Publication Agency.

(240) This list of purchasers (JHUA, Rowland papers, ms. 6, ser. 2, box 15) is also drawn up in the handwriting of his assistant Lewis E. Jewell.

(241) See Pickering to N. Murray Esq., the publication agent of The Johns Hopkins Univ., Baltimore, 21 July 1888 (HUA, UAV 630.14, box A8, no. 183) and 19 February 1889 (no. 493), in which a bill for $18 for the first set is mentioned, with a 10 % reduction for subscribers of the old 1886 edition. See Rowland [1889*i*] p. 240, as well as p. 241 there and Rowland [1889*e*] about the two separate plates of the B and D lines, each 3 × 2 feet in size, suitable for framing; and Pickering to Gibbs, 12 July 1886 (box A6, no. 459).

(242) Piazzi Smyth was an avid travel photographer, fully appreciating this convenient means of documenting such exotic places as Egypt, Tenerife, etc.: cf. Schaaf [1980/81]. His photographic experimentation extended back into the 1870s but was systematized only after his retirement in August 1888 and his subsequent move to Ripon, South England, prompted by the better observing conditions there.

(243) Charles Piazzi Smyth: ‘On two series of enlarged photographs; one in the visible, the other in the invisible of the violet of the solar spectrum; being an appendix to the R.S.E.’s whole visual solar spectrum of 1884.’ 17 pp. handwritten ms. (RSE materials on loan at ROE, inside the album case with solar spectra) sent to the Royal Society of Edinburgh, 9 May 1891; quote from p. 2.

(244) *Ibid.* Cf. also Smyth [1892] p. 573 for a comparison of “eye and hand registration” of lines in the violet with photographic records of the same region: “what photography depicts in such cases is what the human eye ought to see, and would see were it divinely perfect simply as an eye.”

(245) See, e.g., Smyth [1890], and Liveing *et al.* [1891/92] which provide further technical details about the magnification and focusing, which proved to be the main hurdle. The British Association's Report for 1890 lists a grant of £50, but none for 1891 and 1892. According to H.A. and M.T. Brück [1988] pp. 249f., Smyth also got £100 from both the Royal Societies of London and Edinburgh. Cf. also the draft of a ‘Report on the experiment of September 91 to January 1892, by aid of additions to both optical apparatus and photographic materials obtained by grant from the British Association at Leeds in 1890’. C. Piazzi Smyth's laboratory notebook: ‘Grating spectroscope 1886–92’ (ROE, 18.115), p. 128.

(246) Smyth had written to Rowland on 17 February 1886 (ROE, 15.72, folder R,S), asking for a “second example of your unimitable gratings for my own use”, preferably in the larger size of 4.5 × 7.5” as opposed to the smaller 3.5 × 5” plane grating which he had procured in 1883. Cf. also Rowland's reply of 16 September 1886 (*idem*) which accompanied a high-quality plane grating, although not of the requested size, because Rowland had not yet succeeded in making good large flat gratings. The subsequent Rowland grating with a rule surface of 3.85 inches and 20 000 lines to the inch was sent to Smyth in February 1892. According to H.A. and M.T. Brück [1988] p. 251. Smyth “found it considerably more brilliant than the two which he already possessed.”

(247) See Smyth [1890] p. 750 and Smyth's ms. (cited in footnote 243 above), pp. 8f. The photographic impressions on the plate negatives were limited to a circle of 3.3” diameter, the size of the draw tube—see p. 46 of Smyth's notebook (cited in footnote 245), where exposure times for Fry's special plates are specified at around 20 min for the b linelets, while Fry's 60 × reduced this to 7–8 min; the developer used was hydrokinone.

(248) See Smyth's notebook (footnote 245 above) pp. 128ff. and H.A and M.T. Brück [1988] pp. 250f. about a microdensitometer tracing of a sample region of one of Smyth's last solar ultraviolet-spectrum photographs taken with this optimized instrumentation in May 1892. It shows that the spectral resolution then reached in the near ultraviolet was nearly as good as that of the Utrecht photometric atlas by Minnaert *et al.* [1940].

(249) Piazzi Smyth's 1891 ms. (in footnote 243 above), p. 9.

(250) Among the plates tried we find Edward's isochromatic, Fry's lantern and special, and Swan's Ph.M. Most prints were made on Samuel Fry and Co.’s argentotype Type A 12 × 10 inches Contact Printing Paper with a thin smooth surface, cut down to 16.5 × 25 cm, mounted on thick cardboard, and neatly labeled by hand.

(251) *Op. cit.*, pp. 10f. The only exception to this rule was an anomalous photograph of the spectral region between the very strong H and K lines, which once (on 21 October 1891 at noon) yielded a strangely illuminated space between the two lines instead of the shaded space usually exhibited. Cf. p. 130 (ROE, 18.115 and 18.136) for the set of 18 photographic prints taken from 16 different negatives of this same spectral region in order to settle whether possible changes in the solar spectrum existed. From today's perspective, Smyth's anomalous finding was very likely the effect of solarization.

(252) Piazzi Smyth's 1891 ms. (cf. footnote 243 above), pp. 11f.

(253) C. Piazzi Smyth's notebook (cf. footnote 245 above), pp. 49. 69 and 71 is by far the best documentation of this stage of preparation of spectrum atlases I have found thus far: Smyth discussed various alternatives for overlapping adjacent sections, spacings to allow for labeling, binding, etc.

(254) See C.P. Smyth to P.G. Tait, 25 July 1891 (RSE), courtesy of Dr. Mary T. Bruck, Edinburgh, pp. 4–5. To document this point, Smyth also included a copy of Frank Leslie's *New York Illustrated Newspaper* for 4 July 1891, filling 20 pages with plenty of photomechanically reproduced illustrations, priced 10 cents.

(255) See, e.g., the following entry in C. Piazzi Smyth's laboratory notebook (cf. footnote 245 above), p. 30, written on 18 June 1889, having just received Rowland's pamphlet announcing Rowland [1888]: “Professor H.A. Rowland […] has completed a vastly better Solar Spectrum map than before, on ten photo plates each 19” long. Therefore who would care for my 7 plates each 3.3” long”. Cf. also the entry on 21 June 1889 on pp. 32f., on further technical advantages of Rowland's spectrum atlas, such as longer solar focus and automatic focusing afforded by Rowland's new concave grating.

(256) See H.F.N. [1904] p. xx, H.P.H. [1939] p. 505, and Turner [1905], esp. p. 340: “he always worked alone, never employing an assistant of any kind. […] He not only took all the original negatives himself, but made all the enlarged reproductions of the early work, for distribution. It was only in later years and with obvious reluctance, that he yielded to pressure and enlisted the services of a firm of professional photographers to make these reproductions”.

(257) McClean even continued the numbering sequence, labeling his plates VII to XIII, counting from the section containing D towards the violet. See McClean [1889*a*] p. 122.

(258) *Ibid.*, p. 123.

(259) *Ibid.*, p. 123 and pl. VII, misleadingly labeled ‘The A group of the solar spectrum. Photographed by F. McClean’, thus ignoring W.H. Wesley's lithographic draughting, mentioning only the printing company E. Stanford in London. On Wesley, cf. here p. 148.

(260) See McClean [1889*b*].

(261) See footnote 256 above.

(262) These included platinum, iridium, osmium, palladium, rhodium, ruthenium, gold, and silver, as well as manganese, cobalt, nickel, chromium, aluminium, and copper. See McClean [1890], [1891] and Thollon [1890] as well as here pp. 135 and 102. Cf. also E.C. Pickering's order sent to McClean in Tunbridge Wells, England, 16 December 1890 (HUA, UAV 680.14, box A10, no. 667).

(263) McClean [1891*c*] p. 23.

(264) See the obituaries on Higgs in the issue from Saturday, 19 December 1914, of the Liverpool *Daily Post & Mercury* and the *Liverpool Echo.* Hale [1894], as well as the unpublished masters thesis by Laurie Brock [1996].

(265) According to Perry [1888] p. 388, this set of spectral photographs (a copy donated to the Royal Astronomical Society), consists of four maps, three 12 inches long, and the fourth only 7.76 inches, with an average dispersion of approx. 10 Å/cm.

(266) See in particular Higgs [1891] for his experiments with various sensitizing dyes. According to Watts [1904] p. 127, coerulin is “the colouring substance obtained by heating allein with sulphuric acid; it does not dissolve readily, and is best used in the form of the compound cœrulein-sodium-bisulphite, which is soluble in water. The plates arc stained by bathing them for three or four minutes in a solution of 0.02 g of the cœrulein-bisulphite in 100 c.c. of water with 8 drops of ammonia, and allowing the plates to dry.”

(267) According to Ranyard [1890] p. 212.

(268) Perry [1889] p. 53: Huggins [1891*b*] p. 71 likewise praises the “technical beauty” of Higgs's photographs.

(269) Perry [1888] p. 388.

(270) *Ibid.* According to Brock [1996] p. 25, moving the photographic plate during exposure was just an idea that Higgs never actually put into practice.

(271) According to Ranyard [1890] p. 211 who had visited Higgs in Liverpool “to endeavour to learn something of the means by which Mr Higgs has obtained such sharp definition.”

(272) See, e.g., Glazebrook [1883*e*] pp. 207f., Watts [1904] p. 64, and Hentschel [1993*b*], [1998*a*] chap. 3 about the difference between Rowland's and Higgs's mountings, the latter more commonly known as a Paschen mounting. According to Prof. Alan Bowden (Univ. of Liverpool). Higgs's Rowland-type grating is now part of the Physical Science Collection and on display in the Space Gallery.

(273) See Higgs [1894], 1st series in the original size of the photographic negatives in 15 parts; 2nd series in twofold enlargement in 45 parts, and a 3rd series in four-fold enlargement. In the following I refer to the last, a copy of which I perused in the Wolbach Library at the Harvard/Smithsonian Center for Astrophysics. Cambridge, Mass. A copy of the second is kept in Houghton Library at Harvard. On the distribution see, e.g., W. Wesley to Victor Schumann in Leipzig, 27 April 1894 (HUBL, Schumann papers).

(274) See, e.g., Higgs's letter to Henry Crew, 5 January 1894 (AIP, Crew papers), where he mentions the regular price of £8, £3, and £1, respectively, for the four-fold, two-fold, and one-to-one enlargements of his negatives and expresses his inclination to grant Crew a 20 % rebate for his order.

(275) Ranyard [1890] p. 211 gives as one example of this observation, the interval between the two sodium D lines, within which he counted 22 lines.

(276) Higgs [1897] p. 1. Cf., e.g., [1891*a*] p. 345 about a photograph of the second order around 3300 Å coincident with the red end of the first order.

(277) Higgs [1897] p. 1. Cf. the brief description of Higgs's consecutive wavelength edition in Higgs [1898] p. 86.

(278) “Kurz und gut, der Higgs fängt an, mir fürchterlich zu werden.” V. Schumann to Oskar Simony in Vienna, undated but probably late 1892 (HUBL, Nachlass 208).

(279) George E. Hale to G. Higgs, 28 October 1902 (AIP, Hale correspondence): “Some time ago Prof. Langley kindly offered to lend me a battery [of rock-salt prisms] for the purpose but I was unable to accept the offer. And as they frequently require refacing, it might be preferable to do that part of the work at Washington.”

(280) George E. Hale to G. Higgs, 17 January 1903 (AIP, Hale correspondence). Cf. also the letters of 21 January, 4 February, and 6 August 1903 for further efforts by Hale, E.C. Pickering, S.P. Langley, and others to secure funds for Higgs. According to Brock [1997] p. 96, between 1889 and 1894 Higgs secured four £50 awards by the Government Grant Committee of the Royal Society for the production of his spectrum maps.

(281) See, e.g., Higgs's letter to Henry Crew of 26 November 1906 (AIP, Crew corr.) in reply to another order: “I have been so extremely busy with my ordinary work that a great number of prints are now spoiling for want of toning and I shall have to make the model in overtime as I made the other, so I am afraid it will take a long time.”

(282) During a visit to the Hainberg solar tower of the Göttingen observatory, which was built in 1941 with funds from the Luftwaffe—see Wolfschmidt [1992/93]—I was stunned to see a complete version of the second series of Rowland's photographic map still in use as their only map for the purpose of student instruction.

(283) Quote from Pannekoek [1935] p. 732. See also Babcock [1936*a*] pl. XIV for evidence that by then, slightly better resolution had been reached even in the regions where Rowland's map excelled, although “present instruments have revealed very few new solar lines.”

(284) Trowbridge and Sabine [1887] pp. 291f. Cf., e.g., J.N. Lockyer to E.C. Pickering, 3 May 1887, (HUA, UAV 680.17.8): “I have now made a numerous mass of observations on the coincidence of metallic lines with photographs of the solar spectrum from F to K. These I am about to reduce, using Rowland's map as a base.”

(285) According to an advertisement published as a separate leaflet in 1886 (JHUA, ms. 6, ser. 4, box 35, first series), and according to Rowland [1889*i*] p. 80 as well as *The American Catalogue* of books for the years 1884–1890, referring to the year 1889 and the supplier Nicholas Murray (second series).

(286) Kayser to H. Hertz, 1 December 1890 (DMM, autograph no. 2954).

(287) See, e.g., the letter by Anton K. Grünwald's son to Carl Runge from 1920 (SPK, depository Runge–du Bois-R., 592), in which he informs Runge that his deceased father had bequeathed the Rowland map to Runge (many thanks to Renate Tobies for having pointed out this document to me).

(288) Kayser's research in collaboration with the applied mathematician Carl Runge is discussed in Richenhagen [1985] and in the editorial introduction to Kayser [1936]. Kayser acquired his photographical and photochemical skills during his study years in Berlin; according to H.W. Vogel [1885*c*] p. 197, he had attended courses at a vocational college in Berlin, the Gewerbeakademie.

(289) Kayserto H. Hertz, 1 December 1890 (DMM, autograph no. 2954).

(290) See Kayser and Runge [1888–93], particularly suppl. I of 1888, for their atlas of the iron spectrum which covers the wavelength range 6600–2240 Å, and compare the latter with the plates in Eder and Valenta [1904], and Buisson and Fabry [1908*c*] (covering the wavelength region 6680–2350 Å, reproduced in phototype).

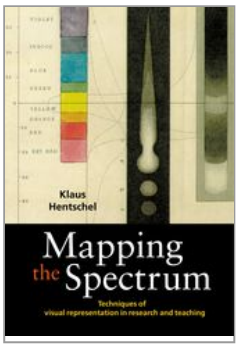
(291) The correspondence between Crew and Brashear, Sept.–Nov. 1892 (AIP, Crew papers) describes the concave grating and other instrumentation obtained through John A. Brashear's Astronomical and Physical Instrument Works in Allegheny, Pennsylvania. Before joining the faculty at Evanston, where he developed a strong interest in the history of physics, Crew had worked as assistant at The Johns Hopkins University in Baltimore, three years at Haverford as professor of physics, and one year at Lick Observatory as spectroscopist: cf. Knowlton [1954].

(292) See on the following Crew [1895], [1896], [1903] and, for the method used, Crew and Tatnall [1894]. Crew's teaching of physics and spectroscopy is discussed here in § 9.8.

(293) Two are located at the MITA: my sincere thanks to Mrs Fran O'Donnell for searching out these two sets.

(294) See Ångström [1868], Cornu [1881*a*], and Thollon [1890].

(295) The most important publication in this respect was the photometric atlas of the solar spectrum by Minnaert, Mulders, and Houtgast [1940]. For details on photometrical methods see, e.g., Hearnshaw [1996]. The concomitant change in theoretical astrophysics, for which quantum mechanics explained not only line positions, but also line profiles, is treated, e.g., by Unsöld [1938], DeVorkin and Kenat [1983], Hufbauer [1991] pp. 96ff.



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
Prof. Dr. Klaus Hentschel

Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

Photochemical Experimentation, Infrared Exploration, and the Turn Towards Photometry

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DOI:10.1093/acprof:oso/9780198509530.003.0007

Abstract and Keywords

Spectroscopy research was tightly intertwined with photochemical experimentation. Hermann Wilhelm Vogel's discovery of sensitizers in 1873, William de Wiveleslie Abney's infrared photography and emulsion, and further improvements in infrared-sensitive emulsions are all cases in point. The introduction of photometry allowed a different gauging of line intensities and a quantification of line profiles that later revolutionized astrophysics.

Keywords: Hermann Wilhelm Vogel, William de Wiveleslie Abney, infrared, photometry, astrophysics

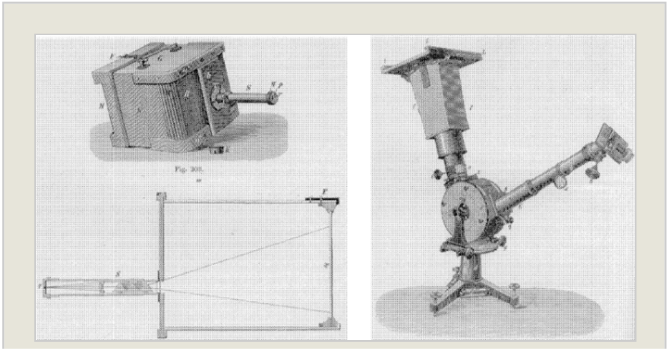
As lithography rapidly gave way to photography in the production of spectral maps, spectroscopists themselves were called more to account for the quality of their final visual representations. Among them, the most qualified photochemical experts frequently held less prominent positions and were unaffiliated with the more prestigious research institutions. As a result, many have been overlooked or under-represented in the historiography, despite the considerable contemporary renown they enjoyed for their work on improving photographic emulsions. In the following we shall look at a few such experimenters, who were, in fact, instrumental in the progress made in spectrography as well.

Our first example will be Hermann Wilhelm Vogel, who taught photochemistry and spectrum analysis at the Royal Prussian Commercial Academy (kgl. Gewerbeakademie) and was famous among photographers in the late nineteenth century as a pioneer in color photography. The second example will be Captain William de Wiveleslie Abney, who gave courses in photography at the Chatham School of Military Engineering. As the world's foremost expert in infrared photography, he explored the very limits of the least refrangible range of the spectrum. Many other spectroscopists like Henry A. Rowland, not wishing to invest the time and effort needed to improve their own photographic plates, first tried the commercially available dry plates in their preliminary work. But in the end, they often had to revert to in-house customization of fine-grain emulsions for the high definition they needed to suit the exact spectral sensitivity to a particular color range.[1] Even after the introduction of orthochromatic and panchromatic plates, practical guides to scientific photography continued to include special sections on how to increase the sensitivity of commercially obtainable plates by means of chemical baths immediately before exposure.[2] Section 7.3 then outlines the increasingly industrialized development of sensitized plates after 1900. Still deeply implicated in spectroscopic explorations into the infrared and ultraviolet, each new and improved emulsion revealed the unfamiliar terrains of hitherto elusive ranges of the spectrum. Later, photometry displaced foregoing methods of registration to predominate in the twentieth century (§ 7.4–7.5).

(p.248) 7.1 Hermann Wilhelm Vogel's discovery of sensitizers in 1873

It was a sensitivity check of commercial plates in the autumn of 1873 that led to a turning point in photochemistry. The Charlottenburg photochemist Hermann Wilhelm Vogel[3] was routinely testing collodion-based silver-bromide dry plates that he had just ordered from Stuart Wortley in England. They seemed to be no different from other plates for photographing normal colored objects, but their sensitivity to the green region proved to be much superior. Closer examination of the plates revealed the presence of a fine yellow powder in the sensitive layer. The manufacturer confirmed that a dye called coralline had been added in order to reduce halation, which is caused by unwanted reflections off the glass backing.[4] Controlled exposure of the same plates with the dye first washed out confirmed that it was indeed the source of the change in spectral sensitivity. Vogel added a bit of this tar-based dye, dissolved in alcohol, to his own wet silver-bromide plates and was astonished to find that the plates became almost as sensitive to the yellow region of the spectrum as to the blue. At first, this discovery was met with incredulity, especially when attempts to replicate Vogel's experiments failed.[5] One anonymous commentator even went so far as to relegate Vogel's claims to the “limbo of photographic abortions”.[6] In his rebuttal, H.W. Vogel pointed to the false assumption by one of his opponents, the Philadelphia lawyer and well-known photographer Matthew Carey Lea (1823–1897), that colored filters could sufficiently imitate a prismatic spectrum;[7] and

he refuted the charge of faulty focusing advanced by the Belgian photographer Désiré Charles Emmanuel van Monckhoven (1834–1882) as likewise unfounded.[8] It did not help that Vogel's initial tests for spectral sensitivity had been done with the aid of a small spectrograph of his own construction, even though it differed from a simple Steinheil camera only by an attached five-prism direct-vision spectroscope (cf. Fig. 7.1, lower left and top left near *S).* He continued to use this handy 'small spectrograph', in conjunction with a Foucault heliostat, for many of his later explorations of absorption spectra; standardized commercial versions of it became quite commonplace in contemporary chemical laboratories.[9] For more detailed examinations, though, its total spectrum length of about 6 cm was clearly insufficient. With Hermann von Helmholtz's support and substantial funds from the Berlin Academy of Sciences,[10] Vogel was able to order a much bigger spectrograph. This instrument, later marketed under the brand name **(p.249)** 'H.W. Vogel's grosser Spectrograph' by the Berlin instrument manufacturer Schmidt & Haensch, had an adjustable photographic plate tray *L* that was movable with respect to the two 60° flint-glass prisms within the round central part *d* (cf. Fig. 7.1, right) so that different regions of the spectrum could be selected. The plate tray could also be tilted to compensate the different focal lengths of various parts of the spectrum. After an exposure, the photographic plate was shifted along the guiding rail *i–i* so several spectra could be taken in succession on a single plate. Optimal orientation of the slit *F* and collimator *C* toward the Sun was achieved by keeping the shadow of a diopter centered on disk *x* marked with concentric circles. For longer exposures, the apparatus had to be readjusted continuously with the two guiding screws *N* and *g.*



These technical improvements, in conjunction with the successes by J. Waterhouse, E. Becquerel, and others in verifying Vogel's findings, eventually led to belated acceptance by the scientific and photographic communities. What followed was a willy-nilly race for better sensitizers at various concentrations and mixtures incorporating the new syntheses being developed by the dye industry. There was a boom in the chemical industry and one Berlin corporation known by its acronym Agfa, for Aktiengesellschaft für Anilinfabrikation vor dem Schlesischen Thore, eventually became, by virtue of its specializing in aniline dyes, one of the leading manufacturers of photographic film in Europe.[11] Others, such as Farb-werke Hoechst, soon jumped aboard the bandwagon, and when the First World War cut **(p.250)** England off from the supply of German dyes, Anglo-American research efforts also intensified.

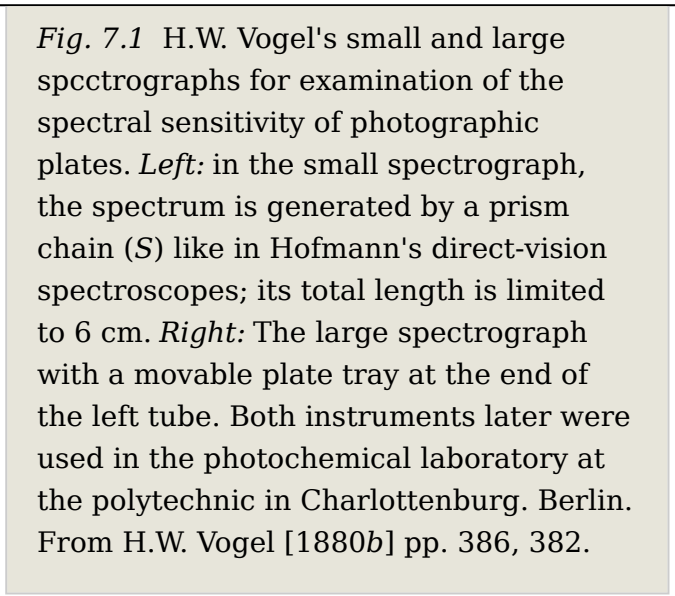


Fig. 7.1 H.W. Vogel's small and large spcctrographs for examination of the spectral sensitivity of photographic plates. *Left:* in the small spectrograph, the spectrum is generated by a prism chain (*S*) like in Hofmann's direct-vision spectroscopes; its total length is limited to 6 cm. *Right:* The large spectrograph with a movable plate tray at the end of the left tube. Both instruments later were used in the photochemical laboratory at the polytechnic in Charlottenburg. Berlin. From H.W. Vogel [1880*b*] pp. 386, 382.

Vogel was optimistic about the prospects of soon accommodating all the spectral colors, yet the early search for sensitizers of silver-iodide or silver-bromide emulsions turned out to be quite haphazard. The many possible combinations and physical constraints were tested in a hit-or-miss fashion until the sought modification in spectral sensitivity was found. One heuristic for this search was Draper's law, according to which absorption of light is a necessary prerequisite for any chemical action.[12] This law, properly understood, however, by no means implied that such a substance causing absorption, say, in the green, also sensitized the silver salt on a wet plate:[13] Sometimes it worked; more often, though, it did not. Nor did Draper's law imply that red absorbents were sensitive to the red region of the spectrum. On the contrary, Vogel had shown that red dyes, such as coralline, naphtalene or roseine, typically led to an increase in sensitivity in the yellow region, while some green aniline dyes sensitized in the red.[14] Once such a substance had been identified, a more systematic study of the variations in sensitivity with sensitizer concentrations could be commenced. For the degree of sensitization closely depended on this ratio. Vogel found, counter-intuitively, that spectral sensitivity did not increase proportionately with admixture. Small amounts tended to yield better results.[15] Another heuristics was provided by Kundt's rule, according to which the positions of the absorption bands of dissolved substances vary systematically with the solvent's refractive index: the greater the dispersion by a solvent, the farther the maximum of absorption is shifted towards the red.[16] Vogel and other photochemists meticulously mapped the absorption spectrum of hundreds of potential optical sensitizers in various solutions. Spectral mapping thus assumed a new importance in the search for the optimal sensitizer.

But even Kundt's phenomenological rule was not totally reliable,[17] so involved series of tests were necessary for each sensitizer. These photochemical explorations were essentially driven by a Baconian-style search for correlations between chemical changes in the collodion or gelatine and changes in spectral sensitivity. An improvement in sensitivity in one region was often coupled with a worsening in another. Fuchsin, for instance, turned silver-bromide plates mainly sensitive to yellow, thus suppressing the usual blue dominance; the sensitivity of silver chloride, however, was hardly changed at all by it. Still no one could claim to understand what was going on either physically or chemically. Some suspected a chemical change in the silver bromide or nitrate induced by the sensitizer, but H.W. Vogel imagined a resonance between the æthereal motion of light waves and the oscillation that **(p.251)** the sensitizer transmitted to the silver-bromide molecules. At a certain critical level of oscillation, the molecules were thought to decompose into silver.[18] But no one could predict which substances might be susceptible to such a mechanical resonance in the æther waves, with the substance at the same time being able to transmit such oscillations to the silver salts. There seemed to be no way of foretelling which substances would combine chemically with the latter in such a way that the resulting compound was sensitive to light of a specific wavelength range.

> The presence of a well-known body (though colourless) changes in a most striking manner the sensibility to colours of the spectrum; nitrate of silver solution, for example, has this effect. Pure dry iodide of silver is but slightly sensitive to ultra-violet and violet rays, more for indigo and blue rays, very little for the others exposed. Iodide of silver under nitrate is more sensitive to ultra-violet, violet and indigo rays than the dry iodide. […]
>
> I mention here that the extension of the action of the spectrum is different at different times, even for the same body. […]. Chloride of silver exposed dry is not very sensitive, but exposed long enough it shows an action to the line B in red. Coloured with naphtalin red, chloride of silver gives a curious result: it becomes most sensitive for yellow rays, less for red and green, and the least for blue. We have here nearly the same proportion in the actinic power as in the sensibility of our eyes. If it were possible to make chloride of silver more sensitive, the coloured salt would be the very body for taking coloured pictures.[19]

But whatever the mysterious underlying mechanism was, the practical impact of ‘Optical sensitizers’, as Vogel called them, or ‘color sensitizers’ as they are now known, was tremendous. As one contemporary put it: Vogel had reinvented photography by bestowing upon it the other half of light.[20] Vogel found out that a treatment with eosine, for instance, on a silver-bromide wet plate, increased its sensitivity by as much as a factor 60 in the yellow range, exactly where traditional plates had been totally ‘blind’.[21] Eosin(e) is a bromo derivative of fluorescein (discovered in 1871 by Baeyer) and was first synthetized by Heinrich Caro at the Badische Anilin- und Sodafabrik (BASF) in 1874, which kept its chemical constitution a company secret to maintain its edge in this fiercely competitive and rapidly expanding branch of the chemical industry.[22] Unlike other dyes, eosine and its derivatives **(p.252)** could also be used to sensitize the gelatine-based dry plates, which increasingly replaced wet plates in the late 1870s and 1880s. For a good sensitizing effect, the dye must be very pure and used only in dilute solution. Consequently commercial dry plates sensitized with eosine only became readily available on the market in 1882.[23] In 1883 Eder found that the eosine derivative erythrosine was a very good sensitizer of gelatine emulsions, superior to eosine particularly in the formerly problematic yellow and green regions so vital in landscape and portrait photography, not to mention spectrum photography.[24] Commercial production of plates sensitized with erythrosine was taken up by the Munich company of Johann Baptist Obernetter (1840–1887) which, incidentally, also specialized in photomechanical reproduction of scientific photographs,[25] valuable documents and historical prints. Obernetter's photographic plates remained in use for many decades under the trade names ‘isochromatic’ or ‘orthochromatic’ plates.[26]

After the discovery of the dye quinoline red in 1882, Vogel also obtained a substantial increase in red-orange sensitivity. His so-called azalin plates, containing a secret sensitizer mixture of quinoline red and its counterpart quinoline blue, also known as cyanine,[27] covered virtually the whole visible range of the spectrum from blue to red-orange.[28] They were sensitive up to 6600 Å with maxima near 5600 and 6200 Å. The dry-plate factories of Johann Sachs and later of Otto Perutz, continued their production past the Great War.[29]

However, ultimate success in the production of truly panchromatic plates had to await the introduction of isocyanines as sensitizers for the red region. This was achieved only in the early twentieth century by Vogel's successors at the Berlin-Charlottenburg Institute for Photochemistry, Adolf Miethe (1862–1927) and Arthur Traube (1878–?), and by his colleagues Josef Maria Eder (1855–1944) and Eduard Valenta (1857–1937), both of whom worked for the Viennese kaiserlich-kÖnigliche Graphische Lehr- und Versuchsanstalt, and taught at the Vienna Polytechnic.[30] Around 1902 they substituted Vogel's cyanine with another **(p. 253)**

dye called ‘ethyl red’, noticing that it gave good green sensitivity without cyanine's tendency to cause foggy and blotchy patches on the plate. Ethyl red belongs to a group of dyes known as ‘isocyanines’, of which various types were being synthetized by Ernst KÖnig (1869–1924) and his co-worker Benno Homolka (1860–1925) at the newly founded photographic research laboratory of the Farbwerke Hoechst near Frankfurt/Main. Distinctive trade names were assigned to their products with the prefix ‘pina’ (for plate), such as pinachrome, pinaverdol, and pinaflavol.[31] KÖnig had acquired the skills necessary for emulsion preparation, sensitization, development, fixing, and sensitivity testing during an extended visit in the laboratories of Eder's Vienna Graphische Versuchsanstalt, where one of Valenta's private assistants and Eder himself showed him many tricks of the trade.[32] By 1904, it had become clear that isocyanines provided far better sensitizers for yellow, green, and orange than any other dyes known hitherto. Hoechst's plans to build a manufacturing **(p.254)** plant for photographic plates sensitized with these new dyes did not materialize however, partly because of the toxic emissions that the dye works would have produced. But others soon filled this gap: Two years later, the established English firm of Wratten & Wainwright in Croydon started manufacturing plates sensitized with a combination of pinacyanol and pinachrome.[33]

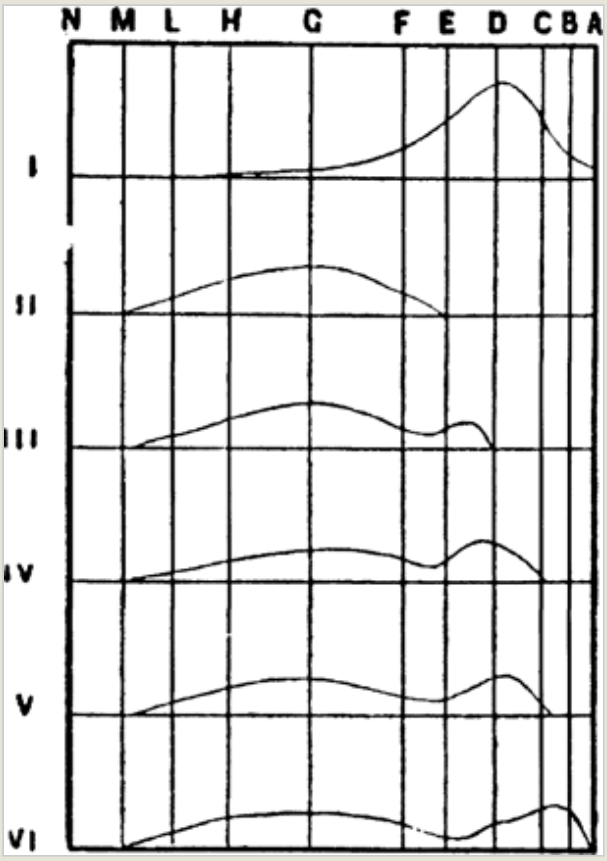


Fig. 7.2 Comparative plot of (I) the optical intensity of the solar spectrum. (II) the sensitivity of a normal dyeless gelatino-bromide plate, and similar plates increasingly sensitized towards the red end of the spectrum (near A) with ammoniacal solutions of (III) eosine. (IV) erythrosine. (V) rose Bengal, and (VI) cyanine. From Watts [1904] p. 126 after Hartley.

7.2 Abney's infrared photographs and emulsions as an art

Few fields have had so chaotic a history as these early investigations in photochemistry. Many discoveries were announced more than once under different trade names and by different persons, serious researchers alongside “busy quacks who relied upon the gullibility of photographers”.[34] Many of the announcements made in the specialized photography journals launched by local associations for both amateurs and professionals,[35] whose numbers began to increase steadily in the 1850s, were later found to be nonreplicable or seriously flawed, and countless legal trials were held over patent infringement disputes.

Nonreplicability due to the influence of unexpected parameters did not help clarify things. John Herschel, for instance, was surprised to find that the sensitivity of various compounds of silver exposed to the solar spectrum crucially depended not only on the precise chemical composition of the samples, but also on the sequence in which these various solutions were layered on the plate's surface.[36] Worse still: William Crookes's attempt to replicate Herschel's results failed. After repeating these experiments several times “with all modifications which ingenuity could suggest, and still to no purpose”, he admitted:

> How ignorant we really are upon the most elementary points of science, when two experimentalists working on the same subject, and with almost the same object in view, arrive at such diametrically opposite conclusions. One states that iodide of silver *is* sensitive to certain rays of light—that it is *always* darkened by them, and produces tangible evidence to bear out the statement. Another states that iodide of silver is *not* sensitive to these rays, and that he has *never* been able to obtain an action by them; and he also brings forward evidence to confirm his statement. Monarchs have gone to war about less important differences than these.[37]

However obvious it may have been for the professional photographer Vogel to distinguish between serious researchers and enterprising quacks, it is far less easy for today's historian attempting to inquire beyond the few names immortalized in photographic folklore.

(p.255) A good illustration of this is the case of William de Wiveleslie Abney, a captain at the Chatham School of Military Engineering previously alluded to. Abney is remembered for his contributions to dry-plate photography; the *Dictionary of Scientific Biography* adds that his ‘albumen beer’ process remained in use until it was superseded by commercial gelatine products.[38] As the following passage from one of his papers shows, though, in his day the production of his infrared-sensitive emulsions was still much more an art than a science:

> My object has been to weight the molecules of silver bromide that they may absorb the red rays. […]. This I first accomplished […] by adding resins to the silver salt and forming what I may call a bromo-resinate of silver. But I am happy to say that I have secured the same end by, I believe, doubling the molecule of the silver bromide. Now this doubling is a matter of manipulation more than of chemical knowledge, and I might describe the process in detail, […] and yet the double molecule would not be obtained unless careful manipulation was attended to—manipulation easy to follow when seen, but difficult to follow from any description. I should therefore prefer to teach practically anyone who is acquainted with silver bromide emulsion making, rather than allow him to be misled by what must be imperfect directions.[39]

This is not simply a recounting of an experimental discovery, but rather a pre-scientific circumscription of an artisanal practice. Its ‘discoverer’ did construe an *ad hoc* atomistic model of what is going on, namely a chemical bonding between the sensitizing substance and the silver bromide: When light hits the compound, a chemical transformation sets in that leads to the decomposition of the sensitizer, which in turn causes the reduction of the silver salt. To bolster his point Abney also postulated a contribution by the fluorescent light supposedly emitted from certain dye sensitizers. His actual practical success certainly was *not* due to this model, however, because—as we now know—Abney's conjectured doubling of silver-salt molecules was utterly confused.[40] Thus it was too soon for the state of the art in ‘scientific’ photography to be translated into a finite set of how-to rules. Even if the method worked in practice, no one really knew why. Besides, often enough it didn't work, especially Abney's mysterious emulsions, whose preparations were so complicated that virtually no one succeeded in reproducing his results.[41] Likewise, the focusing of the spectrum generated by his Rowland concave grating in a special mounting was “rather a matter of guesswork, and trial plates had to be exposed to attain really sharp images in any **(p.256)** part of the ultra-red.”[42] For at least another decade Abney alone could photograph radiation so far into the infrared, although his own estimated limit of 20 000 Å was later corrected down to between 12 000 and 14 000 Å.[43] What happened was that Abney underestimated the amount of diffuse stray light off the surface of the diffraction grating. Abney had been aware of Tyndall's excellent filters made out of a solution of iodine in carbon bisulphide, but for convenience he seems to have mostly used ruby glass, transmitting the red as well as the infrared, but also a minimal portion of light with other frequencies. It was this inconspicuous stray light that caused the appearance of false spectra on his plates in spectral regions beyond c.10 000 Å. Evidence for this hypothesis is provided by the fact that the useful part on his plates always terminates in heavy, uniform fog rather than in complete underexposure as it should have.[44]

Because Abney had reached infrared regions never before photographed, he ran into the trouble of having to coordinate his findings with those of earlier observations obtained by other means, in particular with John Herschel's ingenious thermograph of 1840 (cf. here p. 65 and Fig. 2.28) and Sergei Lamansky's thermopile measurements of 1871 (cf. here Fig. 2.32, p. 73). Reinterpreting the former in terms of absorption lines would mean that the gaps between the circular spots *β, γ, δ*, and *ε* had to be associated with strong absorption bands or relatively dark regions of the solar spectrum, while Herschel's spots themselves were presumably formed by the relatively rapid evaporation of the alcohol on the tissue paper where the continuous parts of the infrared spectrum had been projected. A further complication arose from the fact that Herschel and Lamansky had used prisms to generate their spectra, while Abney had employed a Rutherfurd diffraction grating with 8600 lines to the inch. This meant that his resulting normal spectrum had to be rescaled to prismatic dispersion before any comparison concerning the position of Abney's absorption bands with Herschel's thermographic spots could be made. In doing so, Abney followed a suggestion by Lord Rayleigh in 1877 that the “best representation of the prismatic spectrum for theoretical purposes” was one with ordinates inversely proportional to the squares of the wavelengths of the principal fixed lines. By means of the Cauchy formula $\mu = A + B\lambda^{-2}$, long known as a good approximation of the dependency of the refractive index μ on the wavelength λ, each prismatic spectrum thus translated into a smooth, virtually straight line, whose prolongation cut the ordinate at the limit of refraction.[45] Figure 7.3 displays two such reconstructions of Herschel's prismatic measurements, the one *(S)* pushing *δ* and *ε* beyond the theoretical limit of the spectrum, and thus not very likely, the other *(P)* yielding a very plausible position for the H line at the boundary of the violet end of the visible solar **(p.257)** spectrum and also virtually coinciding with Abney's experimental limit of his prismatic infrared spectra near the label *Q*. The vertical line marked *y* represents the center of the yellow image of the Sun as seen through cobalt glass (row IV, left-most spot), with $l/\lambda^2 = 300$ taken by Herschel as the starting point of his spectrometric measurements.

Abney drew a tentative correlation between his own photographic results (schematically reduced to the main absorption lines and bands in row II of Fig. 7.3) and Herschel's thermograph (see row V). He reasoned that the partial shrinking of the thermograph between α and β was due to the strong Fraunhofer A band, the gap between β *and* γ was due to the three close-lying absorption bands π, ς, and τ, the gap between γ and δ due to the absorption band φ, and finally the one between δ and ε was caused by the dramatic drop in total intensity beyond the absorption band ψ up to *Q*. For Abney this was sufficient explanation of Herschel's findings, long since known but never understood.[46]

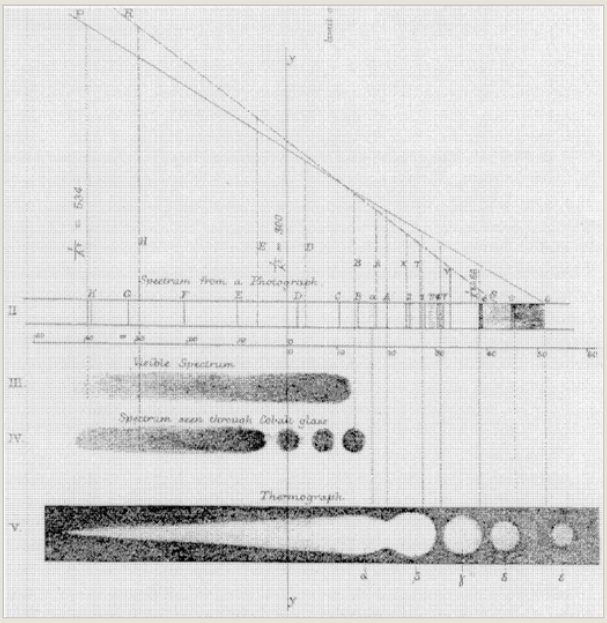


Fig. 7.3 Abney's comparison of Herschel's thermograph (row V) with the main features of his own map of the infrared solar spectrum (row II). From Abney [1880*a*] pl. 32.

(p.258) All these retroconversions of older prismatic measurements remained hypothetical, however, dependent upon the presumed dispersion formula as well as on selected features used for gauging the wavelength scale. It is not surprising that Abney's claims remained controversial, the more so since his photographs simply could not be reproduced by others for years to come, only exacerbating grave doubts: “It has been insinuated that I had never taken the red end at all. I can stand being called anything from a science point of view except untruthful. I was so amazed at the insinuation that I had almost determined never to state anything again but to leave others to find out what had been done.”[47] Even direct inspection of his photographs by the occasional visitor did not necessarily resolve the issue, as the following quote from his Bonn colleague Heinrich Kayser illustrates:

> I also looked up Abney [on the occasion of a trip to England]; he was the first to succeed in penetrating photographically into the ultrared, namely, up to the wavelength 2μ which has never again been achieved. I must say, though, that his exposures, which I saw at that time, did not look very reliable and that neither I nor anyone else has succeeded in producing such plates, even though Abney has provided very detailed instructions. I have all sorts of theoretical misgivings in other respects as well.[48]

This not ‘very reliable’ appearance might have been partly due to the small size of Abney's gratings; and his emulsion had become very course-grained in consequence of his sensitizing procedure. Hence the definition of spectrum lines and the effective spectral resolution must have been poor. As Abney's private correspondence documents, this constant skepticism by other authorities placed a heavy psychological strain on him:

> Were it not that I think one has talents given one to use, I should put twice as a bad mistress. Ever since I took it up I have either been called a liar for publishing my work, or had wrangles as to truth. What would suit me best would be, to do the work and never publish, but it is not fair to one's neighbour tho’ I often think that men of science (particularly abroad) are more like other parties in the parable, than a neighbour.[49]

Retrospectively, it is easy to recognize that Abney's work paved the way to infrared photography, but the above sketch is quite typical of controversies about research of an exploratory character. At such early stages of development replicability is often not possible on the basis of written descriptions alone of the procedure. The results are consequently dismissed as uncertain as long as they remain unconfirmed by means of some other technique or better-understood instrument.

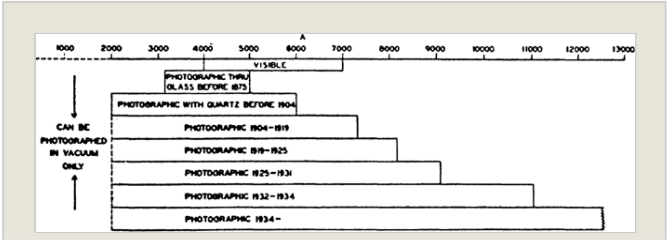
7.3 Further improvements in infrared-sensitive emulsions

How extraordinary Abney's photographic exploration of the infrared spectrum was, judged by the standards of his day, becomes apparent when we compare his work with that of the few of his contemporaries who bothered to experiment so systematically.[50] As soon **(p.259)** as 1880, Abney published a map of the infrared end of the solar spectrum extending to 9825 Å,[51] and two years later Abney co-published with Festing an investigation of the absorption spectra of 52 compounds extending to 12 000 Å (= 1.2μ).[52] By contrast, even several years later, Colonel James Waterhouse[53] (1842–1922), Assistant Surveyor General of India, who worked in Calcutta with dry collodio-bromide of silver plates stained with aniline and **alizarin blue,** merely reached 8400 Å.[54] W.H. Pickering as well as J.C.B. Burbank, who made special preparations of **quinoline blue** (cyanine) and sulphate of quinine at the MIT photographic laboratory, attained 9900 Å.[55] Yet it was not before the twentieth century that infrared-sensitive emulsions became available to more than the happy few personal acquaintances of the pioneers. As already mentioned, in 1904 the dye **cyanine** allowed the sensitization of panchromatic plates up to wavelengths of 7000 Å?[56] A further extension of the spectral range was obtained with the introduction of **cryptocyanine**[57] in 1919 (going up to 8200 Å). By 1925 **neocyanine-**stained plates yielded negatives (for λ up to 9100 Å) free from fog and with brilliant contrast after an ammonia treatment. Because long exposures were necessary, a precondition for success was the prevention of fogging from stray light (as had befallen Abney). An efficient filter for λ ≤ 8000 Å, yet as transparent as was

possible for the intended wavelength range above this threshold, was found to consist of a special variant of the dye neocyanine dissolved in chloroform.[58] **Dicyanine** was introduced as an alternative in 1906 by the Hoechst dye works: it reached 9600 Å and thus recommended itself particularly for spectroscopic explorations of the infrared. But it was far more difficult to handle, because the dye deteriorated rapidly when diluted in water, so the plates had to be dried promptly after sensitizing.[59] Meggers's solar spectrum map from 5500 to 9000 A in the infrared was published in 1920 in the form of enlarged prints from negatives taken at the Allegheny Observatory with Seed 27 plates stained in a bath **(p.260)** of dicyanine.[60] After World War I, Frederick Sumner Brackett's discovery of the infrared series of hydrogen was also achieved with such dicyanine plates, allowing measurements up to 9849 Å.[61] But the sensitivity decreased rapidly beyond 9000 Å and so the necessary exposure times jumped to 6 min for 9300 Å, 12 min for 9500 Å, 20 min for 9600 Å, 40 min for 9800 Å, and more than 60 min for 9900 Å.[62] Because of the considerable amount of attention needed for dicyanine-stained plates, they were “only used by a few workers who had acquired the necessary skill, and it was not practicable to make ready-sensitized plates with it.”[63] The step beyond 10 000 Å became possible with **tricarbocyanine** derived from lepidine (trade name ‘xenocyanine’) in 1932, again using long exposures and the same precautions mentioned before. By 1934 the industrial chemist Charles Edward Kenneth Mees[64] (1882–1960), since 1912 director of research at the newly founded Kodak Research Laboratories in Rochester, New York, developed further derivatives of this dye, called **tetra-** and **pentacarbocyanines,** extending the spectral range to 13 500 Å.[65] The shrinking intervals between successive advances and the rapid gain on a limit of around 13 500 Å, beyond which thermal noise in the emulsion prevents further progress, led Mees to speak of “an almost revolutionary change in the art of photography”.[66] But as a company representative, his words have to be taken accordingly, as some of his colleagues soon realized:

> Don't mind Mees. It is his business to discourage competition with the E K Co. He is a wonder at being able to state with the utmost confidence and conviction anything that he ever heard or thought of, which he believes or wishes to believe. He has his good points undoubtedly but his statements are not always perfectly reliable.[67]

(p.261)



As already mentioned, each of these incremental steps into the infrared spectrum was likely to raise doubts about the photographic results of other researchers, which often were initially irreplicable. In order to minimize this negative reception, close

Fig. 7.4 The stepwise progress of photography of the infrared spectrum after 1900, spurred on by the introduction of the sensitizers pinacyanol in 1904, kryptocyanine in 1919, neocyanine in 1925. xenocyanine in 1932, and tetra- and pentacarbocyanines in 1934. From Mees [1961] p. 125.

collaborations were formed between photochemists and spectroscopists. Prior to the First World War, practically all of the most successful sensitizing dyes had been developed by the large German dye factories. When this supply was cut off, British and especially American agencies started to take up this research agenda. The relevance of infrared photography for long-range vision in aircraft guidance meant that it was handled as a ‘war problem’ by the chemistry section of the Science and Research Division of the Bureau of Aircraft Production, who relayed it to the Color Laboratory of the US Bureau of Chemistry (Dept. of Agriculture). Dyes synthesized in this Color Laboratory were shipped directly to spectroscopists at the Lick Observatory on Mt Hamilton in California.[68] The Kodak photochemists collaborated similarly with two of the most experienced spectroscopists of that time: Harold Delos Babcock[69] (1882–1968) at the Mount Wilson Solar Observatory in California, and William Frederick Meggers[70] (1888–1966) at the National Bureau of Standards (NBS). Only a limited **(p.262)** number of dyes sensitize effectively in this range, but as soon as the company research laboratory at Kodak succeeded in synthesizing one with improved infrared sensitivity and internal test runs had come out positive, test plates were passed on to these two researchers. They exposed them to the solar spectrum as well as to various emission spectra generated by a Fabry-Perot interferometer in the NBS's well-equipped precision laboratories, and reported their results back to the Kodak Company which then decided whether it was a viable product.[71] The demands of these researchers for ever better sensitizers was a constant and welcome challenge for the photochemists at Rochester.[72] The NBS in turn was interested in obtaining this material for two reasons: Apart from the obvious one of being provided with the most up-to-date photographic material useful for its own research, it was also the most appropriate institution for verifying manufacturers’ claims about the spectral sensitivity, contrast and granularity of their new emulsions which determine their resolving power. Thus from time to time, the NBS issued reports on the ‘sensitometry of photographic emulsions and surveys of the characteristics of plates and films of American manufacturers’, with Kodak and the Color Laboratory of the US Bureau of Chemistry as their main dye suppliers. The spectral sensitivity was recorded in the form of wedge spectrograms. These highly symbolic indicators of emulsion sensitivity were made as follows:[73] A sharp angular wedge of black glass was mounted in front of the spectroscope prism or grating (as seen in the left part of Fig. 7.5). The resulting gradient of exposure was thus 1:10 000 all across the whole spectrum. The thin side of the wedge was fitted with a scale indicating wavelength along the length of the

spectrum, and orthogonally to this scale the width of the slit was subdivided into four, corresponding to the regions from 0–10, 10–100, 100–1000, and 1000–10 000 absorption factors of the wedge in proportion to its thickness. When a plate is exposed to a bright continuous spectrum with the wedge interposed between spectroscope and prism, its sensitivity readings are recorded as a curve graph showing the minima of sensitivity marked by dark regions, and its maxima by relatively bright regions as seen in Fig. 7.5 (right). The advantage of this method was that **(p.263)** such a symbolic representation was much easier to print than a full spectrum map, even easier than Bunsen's or Vogel's two-dimensional woodcut representations of spectra discussed on p. 52. All that was needed was the numerical scale (with wavelength numbers represented by their first two digits only, i.e., 52 for 5200 Å), and the varying amounts of blackening. Despite the simplicity of this representation, it carried clear information on the plate's overall range of sensitivity as well as on the location and profile of its maximum (or maxima).

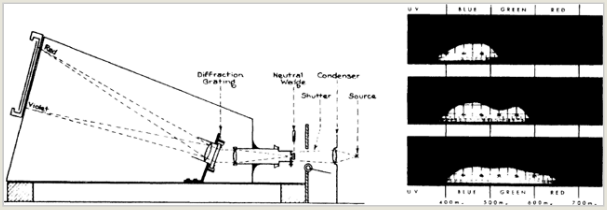
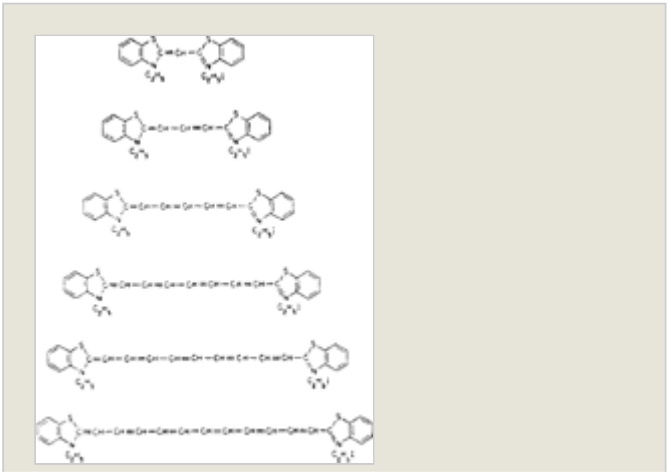


Fig. 7.5 Left: Diagram of simple wedge spectrograph. *Right:* Wedge spectrograms of various types of photographic plates: colorless sensitivity (top), orthochromatic (middle), and panchromatic—sensitive up to 6500 Å (bottom). From Mees [1961] pp. 38, 82.

Our closer look at early spectrum photographs and the incremental improvements made throughout the latter part of the nineteenth century and first half of the twentieth century thus reveals the crucial importance of chemical experimentation with sensitizers for photographic emulsions.[74] Clarity about which chemical components of the gelatine actually induce the chemical processes within the photographic layer, and how sensitizers actually influence them, was gained only in the second quarter of the twentieth century. Much theoretical understanding about how the dye's chemical structure and adsorption to the silver halide influence spectral sensitivity was won through extensive investigations, foremost at the Ilford Laboratories in England and the Eastman Kodak Research Laboratories in Rochester, New York.[75] Only with the introduction of cyanine dyes did it become feasible to find new sensitizers with relatively predictable effects. Dyes from the isocyanine group consist of two nuclei formed of rings of atoms and containing basic nitrogen atoms joined by a chain of methine (=CH-) groups (cf. the following figure). In longer chains, the valency bonds are alternately single and double: …=CH-CH=CH-… The absorption of light is caused by a resonance of the molecule, with valencies exchanging their positions in the chain: =CH-CH=CH- ↔ -CH=CH-CH=. Once Mees and his co-workers realized that **(p.264)** the length of this chain was directly related to the absorption characteristics of the respective dye, chemical ‘reverse engineering’ of sensitizers in wanted color ranges was much simplified: Lengthening the chain of methine groups moved the absorption band towards longer wavelengths—in analogy, lengthening an undulating rope increases the wavelengths of its proper oscillation modes—and this absorption band in turn determined the sensitized region. Thus H.W. Vogel's conjecture was not so far off the mark.



But even once clarity about these basic physico-chemical mechanisms of sensitizing, developing and fixing had been reached,[76] R&D in the laboratories so intimately connected with spectroscopic research continued to keep something of its exploratory touch. In 1947, Kodak's research director applied the dichotomy of art *vs*. science to illustrate this point:

Fig. 7.6 Cyanine dyes with methine chains of increasing length. Top: simple cyanine, second row: carbocyanine with 3 methine groups, third row: dicarbocyanine with 5, fourth row: tricarbocyanine with 7, fifth row: tetracarbocyanine with 9, sixth row: pentacarbocyanine with 11.

> The whole technique of emulsion making is a complicated art, in which practice is in advance of knowledge of the chemical and physical conditions which control the results. Whereas a great deal has been done to reduce this art to a science, nevertheless in a practical industrial laboratory the development of the art itself cannot be neglected, and a large part of the work in the Kodak Research laboratories has been applied to the advancement of the art.[77]

7.4 The introduction of photometry

As we have seen, photography, Talbot's ‘pencil of nature,’ proved to be swayed far more by human bias in the spectroscopic practice than at first admitted. How much retouching and manipulation was still necessary to come away with an acceptable print! Photography and photomechanical printing was thus a long way yet from achieving this ideal of ‘mechanical objectivity’.[78] A more resounding triumph for automatic recording came about in the early **(p.265)** twentieth century with the introduction of photometric and photoelectric registration.[79] Today the use of charge-coupled devices (commonly abbreviated as CCD's) and other fully automated photoelectric recording techniques is so ubiquitous in astronomical and astrophysical research that everything else described here must appear hopelessly primitive to practitioners in these disciplines. In the remaining part of this chapter, I describe the rise of photometric methods which eventually replaced visual and photographic techniques in most branches of spectroscopy.

7.4.1 Gauging the spectral line intensity in the nineteenth century

The call for a more ‘objective’ method of gauging the intensity of spectral lines was made early on. The human eye is capable of judging *relative* intensities fairly well within a surprisingly broad light range, by direct comparison of adjacent fields of view. Thus an order relation can be established of the type ‘this line is stronger than that one; and that one, in turn, is stronger than the third, etc.’, provided that these lines are positioned close enough together and are observed under otherwise identical conditions. This provision for such intensity scaling could not be satisfied in the mapping of major ranges of the spectrum, however. When in the early 1860s Kirchhoff set out to map the solar spectrum with a classification scheme that distinguished between six different line intensities, he and his student Karl Hofmann could only see a small segment of the full prismatic spectrum at a time in the ocular of the telescope.[80] But who could guarantee that the relative comparisons done within this local color range also led to a useful absolute comparison between lines in completely different color regions? Who could guarantee that the patchwork of local intercomparisons led to a workable global standard of line intensity estimates? Given the strong variation in intensity in the continuous spectrum, which Fraunhofer had already plotted in his early map, with the maximum in the yellow-green region,[81] how was one to compare a line in the yellow with a line in the faint violet or in the diffuse red fringes?

The varying sensitivity of the eye to different color regions caused vast problems in efforts to gauge line intensities. While tabulating Kirchhoff's estimates of Fraunhofer lines for several elements, Sir George Johnstone Stoney noted a systematic variation in line intensity with the color of the spectral background. This although he was generally enthusiastic about Kirchhoff's “exquisite” map. For instance, the iron spectrum showed a continuous gradation of intensity from the indigo to the red, with all lines in the violet of intensity 6, a predominance of lines of intensity 6 in the blue, a “struggle between this intense blackness, and the darkest shade short of blackness recorded by Kirchhoff, to which he assigns the number 5”, a prevalence of it in the bluish-green, and then a decrease to line intensities 4 and 3 in the greenish-yellow and orange regions of the spectrum.[82] Stoney tried to **(p.266)** make sense of this gradation by postulating different temperature layers within the solar atmosphere, but others were not so sure whether the observer was not to blame. Ångström multiplied these doubts when he found systematic variations between spectra from light emitted from the center and the rim of the solar disk.[83] Both findings indicated a strong dependence of the intensity estimates on the continuous background. Since this background varied with observing conditions, color range, and areas of the Sun under examination, the ‘objectivity’ of the intensity estimates was called into question.

One late attempt to come to grips with this problem was made by Ludwig Becker[84] (1860–1947) between 1887 and 1889 in Edinburgh in his observations of the solar spectrum at low and medium altitudes. Apparently distrustful of the photographic registration techniques already widely in use at the time (for instance in Rowland's big photographic map of the normal solar spectrum, see above pp. 230ff.), this aspiring “temporary second assistant-astronomer” at the Royal Observatory gauged the line intensities by a subjective method incorporating automated features borrowed from routine astronomical observations. His recording apparatus employed two distinct but synchronized procedures: one magnified the angular motion of the grating with which he dispersed the solar light, the other registered his intensity estimate for each of the lines as it entered the visual field. Turning an endless positioning screw, the observer slowly rotated the grating, “thus causing the lines of the spectrum to move across the field of view. When the line under observation coincides with the intersection of the wires, the fingers of the left hand depress one or more of the needles according to the degree of blackness of the line.”[85] The high dispersion (19.75 inches between the two sodium D lines 6 Å apart, for instance) allowed Becker to obtain a sequence of intensity estimates recorded on a continuous strip of paper 314 feet long covering the full range from 6024 Å to 4861 Å. The grating's normal dispersion made the distances between each recorded line directly proportional to their differences on the wavelength scale. Consequently, using a few reference lines he could construct a map on a normal wavelength scale directly. Rowland's photographic map and wavelength tables, which also included intensity estimates, had been based on many different photographs taken under widely differing conditions and with emulsions and developers especially tuned to the specific spectral sensitivities. Thus his line-intensity base was *heterogeneous.* Becker's intensity scale, on the other hand, was *uniform* in the sense that the apparatus remained at a single setting over the whole spectral range.

Because variations in line intensity were particularly important for discriminating between solar and terrestrial lines in the Fraunhofer spectrum, Becker chose to distinguish as many as 14 degrees of line blackness: 1 for barely visible lines, 3 for the faintest lines just distinctly visible across the whole breadth of the second-order spectrum, 6 and 8 for lines about as dark as each of the two overlying grids of different thicknesses projected into the **(p.267)** field of view, and 9 and higher for even stronger lines than that.[86] Becker's automated continuous recording device never caught on in spectrometry, even though it clearly paralleled those developed by Marey for his physiological experiments and others in the various sciences of the nineteenth century.[87] Such automated photoelectric registration methods only began to gain popularity in the twentieth century (see here § 7.5).

7.4.2 Towards automated recording techniques in the infrared

Another trend leading toward the replacement of standard spectrum photographs or maps by continuous intensity curves emerged from the research on infrared radiation. As detailed in the foregoing sections, for lack of photographic emulsions sensitive to the extreme infrared, which is also invisible to the naked eye, researchers were forced to resort to other types of detectors for recording the spectral lines and their relative intensities. One possibility was to use variations in resistance induced by minute changes in temperature (of the order 10^{-6}°C) within materials exposed to infrared radiation. Essentially, Langley's bolometer (see p. 74) amplified these slight differences in electrical resistance between the two arms of a Wheatstone bridge and thus could record minute variations in spectral intensity extending much further into the infrared region of the solar spectrum than could contemporary photographic emulsions.[88] From the early 1890s on, the electrical signals of an attached galvanometer were recorded photographically, thus adding another dimension to the detection process, that of depersonalized recording:

> Hitherto in his use of the bolometer he [Langley] had depended on successive eye observations of its indications. But now in 1891 he introduced photographic registration. Slow-moving clockwork carried the infrared solar spectrum steadily along over the threadlike bolometer. At the same time a photographic plate 8 by 24 inches in size was moved vertically in front of the sensitive galvanometer which measured the warming and cooling of the bolometer. A little beam of sunlight reflected from the tiny mirror of the galvanometer, no larger than a pinhead, traced the sinuous record of the heat found in the infra-red spectrum. Wherever a line or band of absorption occurred, a jog appeared in the record.[89]

Peaks and valleys in the recorded curve corresponded to maxima and minima of the intercepted radiation, their height and thus the slope of the line profiles could be adjusted by modifying the galvanometer's sensitivity. Scrutiny of his measurement technique and error discussion reveals, though, that the interpretation of the raw data from his bolometer was far from ‘mechanical’ or ‘automatic’. Because of the large fluctuations in amplitude due to ground vibrations, changes in the ambient temperature, air currents, and slight electrical and magnetic disturbances, the galvanometer needle jiggled considerably (see Fig. 7.7). Neither these irregular jiggles nor a more systematic drift in one direction corresponded to any real variation in the signal, but it was hard to suppress this unwanted ‘noise’.

(p.268)

Indeed, to “determine which of the depressions were real, i.a. actually due to absorption lines in the solar spectrum, and which were accidental”,[90] and to try to minimize the “pestiferous little wiggles in the photographic records of the galvanometer” caused only by these “local disturbances” was what Langley and his co-workers ended up investing most of their time and energy on. Each spectrum region was remeasured several times by different laboratory assistants.[91] The scale of the recording strip could also be changed at will by altering the revolving speed of the cylinder (of 60 cm circumference) that transported the film, at a rate of one full revolution every 15 minutes to 2 hours. A typical run thus covered a region, say, between 0.71 and 0.74 μ at a rate of 1 minute of time to 1 minute of arc in the spectrum, or a 2-cm stretch on the holograph.[92]

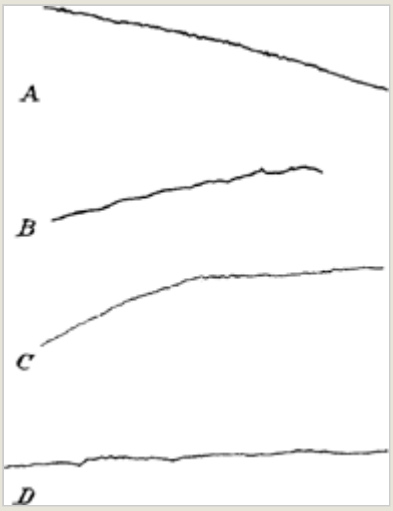


Fig. 7.7 Irregular fluctuations and systematic drift of the galvanometer needle. The speed of the plate is 1 cm per minute. *A:* Daytime record with galvanometer resting directly on a pile of square stones, separated at the corners by rubber, and themselves resting on the pier; *B*: Record taken just after midnight with a calcium light; C: Similar to *A,* but with galvanometer supported on a Julius three-wire suspension; D: Like C, but with inner chamber extended to include the galvanometer. From Langley [1900] pl. xvii (taken between 2 October 1895 and 16 April 1896).

Though the bolometer and galvanometer were substantially improved over a period of 20 years under Langley's directorship, and then in the succeeding three decades under Abbot,[93] this problem could be reduced quantitatively to “accidental deflections” of less than 4/10 of a mm, but never completely eliminated. So the raw data obtained by automatic registration had to be smoothed over, obviously without losing any valuable information on the ‘real’ bolometric curve, which he called a ‘bolograph’. These small-scale tremors and fluctuations were largely absent in the published bolograph (cf. Fig. 7.8).

Note that Langley displayed two such bolometric curves that had been treated similarly but independently, to avoid any skepticism about the results. All features present in both curves were considered to be real. It is interesting, though, that Langley never felt completely **(p.269)** happy with these continuous intensity curves, which looked so drastically different from the conventional representations of spectra in terms of photographic or lithographic maps. Whether in order to satisfy his own expectations or those of his contemporaries, Langley decided to translate his bolographs into diagrams of the spectrum that looked much more like the traditional depictions.[94] The method by which he obtained this ‘conversion to line spectra’ was quite intricate. He blackened-in most of the area under the continuous curve and then photographed the resulting landscape-like pattern using a combination of a spherical and a cylindrical lens, “which draws the blackened-in portion out into regions of greater or lesser shade, according to the linear depth of the blackened-in portion.”[95]

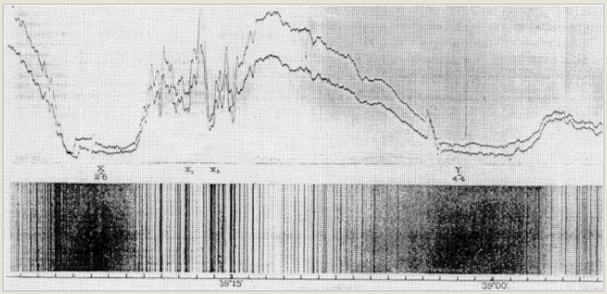


Fig. 7.8 Langley's final bolometric curve of the infrared spectrum, with the disturbing fluctuations illustrated in the previous figure removed: details around line X near 2.6 μ. From Langley 11900] pl. xx.

Neat as this idea may sound in principle, in practice it was quite tricky and by no means “purely automatic”. The spectrum was constructed of one photograph showing the major absorption bands, superimposed on another exhibiting only the fine structure (see also Fig. 7.9). For the first photograph, the whole area under the curve *a* was blackened; for the second, only a shallow dip at the bottom of each depression was filled in, to accentuate the contrast in the finer details, so that the photograph taken with the cylindrical lens could yield a fairly well-defined linear spectrum with dark lines on a bright background, just as on conventional spectrum photographs.

> In the original curve (a) the great elevations represent regions of the greatest heat, and the greatest depressions regions of the greatest cold, and if we fix our attention on these great regions only they can be adequately rendered as in (c) into bright and dark bands, respectively, but the detail is comparatively ill rendered without a special adjustment which would in turn give a false presentation of the great masses of light and shade.

(p.270)

> The difficulty can perhaps not be entirely overcome, but it is otherwise met by fixing the attention primarily upon the smaller inflections of the curves. Thus in (d) and (e) the same curve is shown with a treatment calculated to develop the minor inflections. The result is a linear spectrum where the lines appear distinctly, but now the great absorption bands are no more adequately indicated than are regions of little energy in ordinary photographs of the visible spectrum. If we combine the two treatments, however, by superposing one of these plates upon the other, we get perhaps a result as is attainable, as is shown in (f), and it is by a similar process that the ‘composite’ linear spectrum given in plate XIX is obtained.[96]

Figure 7.9 illustrates the sequence of steps actually taken in this “conversion of bolometric curves to linear spectra": *a* represents the smoothed bolometric curve (bolograph) without “accidental deflections"; *b* the blackened areas above and below it; *c* the resulting photograph of *b* with the cylindrical lens, exhibiting the main absorption bands but without any fine structure; *d* the blackening done to bring out the minor deflections in *a; e* the resulting photograph of the fine structure; and *f* the result of the superpositioning of *c* and *e.*

Producing these composite spectra was such a finicky affair that it was not easy for Langley to find a photographer adept enough to perform the task. As he wrote in a letter to Pickering:

> I think that a great drawback to the work of photographing the infra-red spectrum by the use of the cylindric lens, applied to the bolographic traces, is the lack here of an intelligent photographer, with an aptitude for such work.
>
> The best person would be a young physicist by training, with a special knowledge and interest in photography. I could give such a person a permanent place as Second Assistant, with perhaps a thousand dollars a year, but I want him so urgently at the present time for a task which must be completed before midsummer, that I would pay proportionately considerably more, if necessary, for a brief tenure. L. …] I can command the services of routine, mechanical photographers here, […] it is especially *intelligent* work that I seek.[97]

When about one year later Langley had found one such intelligent photographer, he punctiliously laid down each step of the procedure in a personal letter in order to forestall any deviations from this routine. Langley insisted, for instance, that three bolographs of each spectral region should always be compared; he even developed a special comparator for this arduous task. Only those lines were supposed to be accepted as “veridical […] which were found in exact agreement on all three; exact here meaning something with a maximum error of position of about a tenth of a millimetre.” The best of these three curves was then ‘blocked-in’ following the blackening procedure just described. It was during this stage of the work that personal skill came in most prominently, and as the following quote demonstrates, Langley was deeply troubled by it:

(p.271)

(p.272)

Perhaps the weakest part of our processes in the reproduction of the infra-red, is that small, but essential portion where personality enters, for we desire to make the process purely automatic, and personality, implying a contradiction of this, is, even where reduced to a minimum, so far a defect.

I proposed in a former conversation, to test the effect of this personality, by means of two independent “blockings-in” by two different persons accustomed to the general method, but without sight of each other's work.[98]

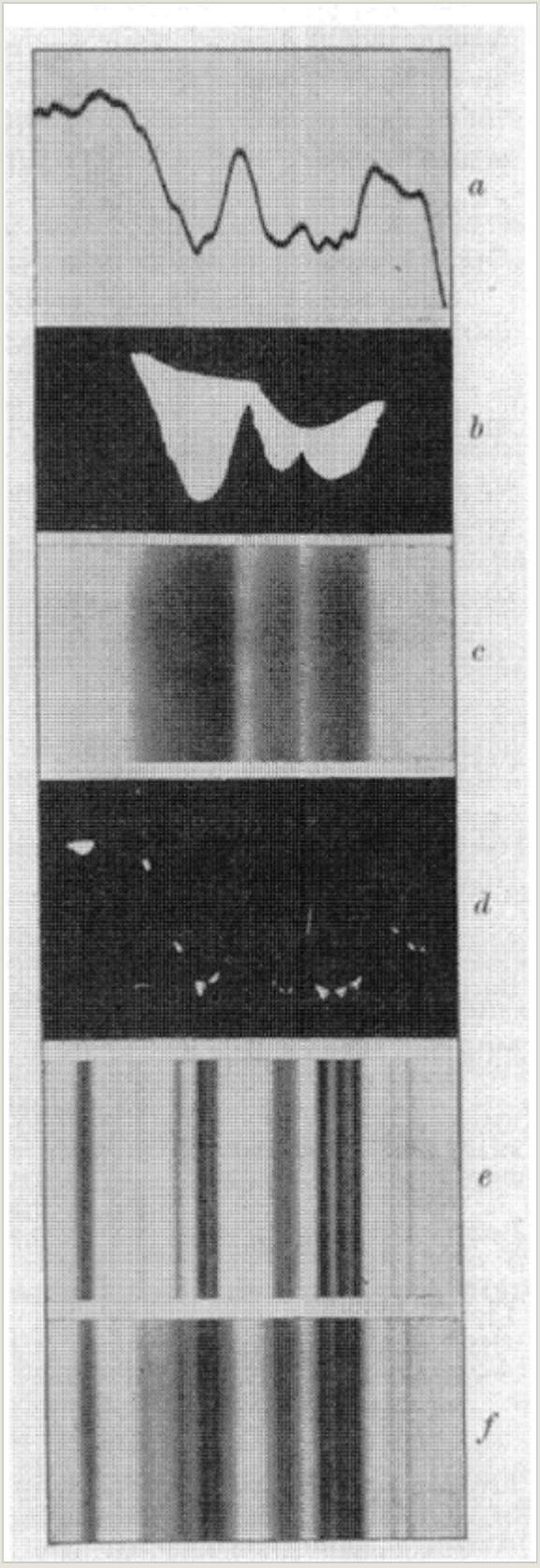


Fig. 7.9 Langley's conversion of bolometric curves (top) to spectra mimicking photographic spectrum maps like Rowland's (bottom); cf. main text. From Langley [1900] p. 73.

The same in-house letter also mentions an instance where, despite all these precautions, the two independently working assistants arrived at great discrepancies in the same region. Not surprisingly, Langley was worried about “the public, [who] will look with doubt either on the finished record, or on the preliminary figure given before the British Association, without some explanation, and I have added to my paper read before it a note to the effect that this figure is not to be considered as typical of the completed work.”[99] Apart from checking the consistency between these independently generated final spectra, Langley also compared them against ones recorded by other techniques, wherever such data existed (esp. Abney's or Higgs's photographic maps of the near-infrared region up to 8600 and 9850 Å, respectively), but he made sure that the preliminary stages of the outside mapping procedures had not been tainted by knowledge from any photographic recordings.[100]

Ironically, notwithstanding these complications in the actual production of the infrared spectra, contemporaries applauded the mechanical reliability of Langley's automated recording technique.[101] Wadsworth could not tolerate for long such constant supervision over every single step of this difficult work, and left. Charles Greeley Abbot (1872–1973) then became Langley's collaborator in 1895.[102]

Seeing how difficult the manufacture of such a map was, it is no wonder that bolographic recording of spectra was not adopted by many other researchers in the nineteenth century. Nonetheless, photoelectrically acquired registration with outputs similar to Langley's bolographs became increasingly common during the first three decades of the twentieth century. Subsequent publications by the Smithsonian Astrophysical Observatory stopped bothering to convert their graphs into line spectra. Abbot and Freeman's plates of the absorption lines in the infrared solar spectrum from 1929, for instance, display basically the same frequency range as Langley's map of thirty years before, recorded with apparatus of much higher resolving power but simply reproducing the three intensity curves actually recorded on moving photographic plates (cf. Fig. 7.10).

(p.273)

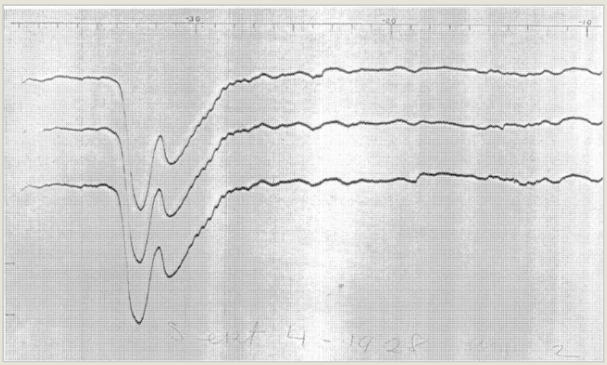


Fig. 7.10 Bolometric curve in region around line A (wavelength region 7600–8600 Å). From Abbot and Freeman [1929], pl. I.

To ease discrimination between the real variations in spectral intensity and accidental deflections, as well as between solar and telluric lines, Abbot and Freeman recorded the same spectral region at least three times, under slightly different observing conditions.[103] The overall close agreement between the three bolometric curves, displayed one above the other, certainly added to confidence in the reproducibility and soundness of their results, and helped discriminate between accidental jiggles and real signals.

7.4.3 Photochemical and photometric registration methods

Langley's bolometric detection of infrared radiation may appear to be an especially problematic case because, apart from Abney's photographs in the near infrared, no other technique existed at the time that yielded any output against which the results could be checked. But as we shall see in the following, this was not the only problem facing photographic technology since its inception: there was also the problem of quantifying the intensity of the chemical action of light on photosensitive materials. As one researcher put it in 1848: “All photographers know by experience that the chemical action is not exactly in proportion to the intensity of the visible light.”[104] Photographic plates, taken as indicators of chemical action, generally first darkened in the indigo-violet range, yet the maximum of the optical spectrum was situated in the yellow-green range which stubbornly refused to leave any imprint on most emulsions available at the time. Thus Bouguet's photometer known since **(p. 274)** the eighteenth century or other photometric devices based on the $1/r^2$ ratio for a decrease in light intensity with increasing distance r, could not be transferred into the new domain of photochemistry.

In 1843, John William Draper designed a device he called a ‘tithonometer’ that made use of the chemical action of radiation on a gas mixture of hydrogen and chlorine. When exposed to a spectrum the gas underwent induced change into hydrochloric acid.[105] When he examined the tithonometer's response as a function of the refrangibility of the spectral rays applied, however, the maximum effect was again not coincident with the optical maximum, but located in the indigo-violet range close to the Fraunhofer line G. This supported Draper's conviction that the chemical rays of the spectrum were of a fundamentally different nature from the optical rays.[106] Other early published curves of actinic intensity confirmed Draper's general location of the maximum of the chemical effect at the violet end of the spectrum, typically somewhere between the Fraunhofer lines G and H.[107] Other ‘photologists’ tried to develop instruments that were closer to the practical needs of photographers. As early as 1839, T.B. Jordan invented a so-called ‘heliograph’ that was later improved and renamed an ‘actinograph’ by the secretary of the Royal Cornwall Polytechnic Society, Robert Hunt. It simply consisted of a rotatable cylinder, positioned parallel to the axis of the ecliptic, and a triangular slit. Chemically sensitized paper was slowly moved along perpendicularly to the slit. Assuming that “the photogenic effect produced upon the paper is in direct proportion to the intensity of the light present”, the length of the trace left on the paper was directly proportional to the intensity of the photochemical action.[108]

This assumption amounted to what Bunsen and Roscoe later called the **reciprocity law,**[109] according to which the photochemical effect E is a function of the product of exposure time t and illumination intensity I: $E \sim f(I \cdot t)$, whether this effect be measured by the amount of chloride gas produced in a setup like Draper's, or whether it be measured by the degree of blackening S of a photographic plate. In other words, illuminating the same photographic paper twice as long with only half the light intensity should lead to the same amount of blackening. One year later, Roscoe applied this new law to photometric measurements of solar limb darkening: he compared the varying degrees of blackening produced by exposure to light from different parts of the Sun's disk on photographic paper against the blackening of the same type of paper in a so-called pendulum photometer that, **(p.275)** by alternately covering and exposing, produced a strip of calibrated variable exposure.[110] However, in the 1880s, sophisticated experiments by Abney and others showed conclusively deviations from this simple law: short exposures with high intensity I_1 yielded a stronger degree of blackening than long exposures of lower intensities I_2, even though $I_1 t_1 = I_2 t_2$, or in other words: the stronger the energy input, the stronger its action.[111] Well-known but strange phenomena like solarization[112] also ran contrary to the simplistic assumption of a direct proportionality between line intensity and degree of blackening on the photographic negative.

A full understanding of the response of photographic plates as a function of light intensity had to await the theoretical analysis by Karl Schwarzschild[113] (1873–1916) in the early twentieth century. This astronomer derived a better approximation of the characteristic curve's dependency on intensity and time of the type $S = \varphi(I \cdot t^p)$, where S is the photographic density (in German: the *Schwärzungszahl)*, indicating the degree of blackening, which is more precisely defined as a quantity proportional to the fraction of illuminating light blocked by the photographic image. P is the so-called Schwarzschild exponent to be determined empirically. Because a short exposure time t_1 for higher intensities I_1 effectively yields stronger blackening than a longer exposure time T_2 for lower intensities I_2 (even though $I_1 \cdot t_1 = I_2 \cdot t_2$), the Schwarzschild exponent p is less than 1 and usually within the range 0.7 and 0.95.[114] One practical consequence of these deviations from the reciprocity law is the practice of pre-fogging. Photographic plates intended for recording faintly illuminated objects can be exposed to very dim light beforehand in order to increase their sensitivity.[115] The interplay of these physico-chemical experiments with the growing sensitometric experience of astronomers with photographic magnitudes of stellar images soon led to considerable refinement of this art of photometry.[116] In the following I am only able to deal with this development insofar as it touches upon spectroscopy.

(p.276) 7.5 Prevalence of photometric techniques in the twentieth century

For spectroscopic purposes, it was essential to be able to detect tiny variations in blackening along a spectrum photograph. The Potsdam astronomer Johannes Hartmann (1865–1936) was the first to design a workable ‘microphotometer’ suitable for this task in 1899.[117] In Hartmann's instrument the blackening on photographic plates was scaled against an optical wedge photographed onto the same plate. The photographed wedge on the plate was first calibrated against a comparison wedge that served as an independent blackening scale. Best comparison is achieved by putting two areas right next to each other and this was done by means of an internal system of reflections in a cleverly designed double-prism arrangement. The precise degree of blackening of a selected area of the photographed wedge on the plate could be determined by careful micrometric positioning of the wedge against the other image in the field of view. A small section of the plate image was then projected onto the (12x) microscope's visual field next to the independent scale. Each reading off the independent comparison wedge could thus be used to interpolate those on the wedge on the plate for a specific degree of blackening. The same procedure was repeated for all interesting areas of the plate under examination. Because both the calibration wedge and the other exposed parts of the same photograph were observed under identical conditions, corresponding position readings off the comparison plate were immediately convertible into degree of blackening S, or equivalently, into degree of light intensity. According to Hartmann, two light sources are photographically equally bright only if they cause an equal degree of blackening on the same photographic plate during the same exposure time.

Aside from potential changes in illumination intensity during measurement of the wedge and the other areas of each negative, the most problematic limitation of Hartmann's microphotometer was its built-in comparison of the relative intensities in areas of the order of 10 µ. The photographic plate's grain had an effect even under moderate magnifications. For a lightly exposed area this could well result in only very few photographic grains being visible under the microscope, and in such a case the observer would be uncertain about whether to judge this section equal to its background. Very narrow spectral lines did not fill this viewing frame, so that a disturbing bright border remained between the line and its comparison field, while in the case of very broad spectral lines, just a cut-out of the line could be observed at a time that was not necessarily representative of the line's overall degree of blackness.[118] The microphotometers constructed in 1910 by Charles Fabry in Marseilles, and in 1920 by William F. Meggers and Paul D. Foote at the National Bureau of Standards in Washington circumvented this problem by deliberately defocusing the exposure so that the observer would not see individual grains. Karl Schwarzschild tried to achieve the same uniform blackening with his *Schraffierkassette* (jiggle-camera), which rendered each stellar image as a uniformly exposed area of 0.25 mm breadth. However, what was won in smooth distribution was lost in photometric resolution.[119] Comparisons **(p.277)** of such micrometrically gauged line intensities with Rowland's visual estimates also—somewhat surprisingly perhaps—generally showed “satisfactory accordance”.[120]

Around 1910, these visual photometers were already being used to examine certain spectroscopic lines of special interest, particularly to study fine Zeeman splittings and other line features that were unresolvable by conventional diffraction gratings.[121] The breakthrough for photometric techniques to gain the upper hand over the competing interferometric analysis[122] happened only when a continually operating photoelectric detector could substitute these subjective methods of registration. The human eye had just too many inherent—and often incorrigible—flaws. Visual comparison of the degree of brightness or blackening of two fields of vision (a) was limited to one percent accuracy, even if the two fields were immediately adjacent to each other (which, as we saw above, was not always possible), (b) demanded sufficiently broad comparison fields, which was problematic for such very small test areas as stellar images or fine spectral lines, (c) required an appropriate level of illumination, as well as (d) spectrum wavelengths adapted to the limited sensitivity of the eye, with a sharp maximum in the yellow-green range.

Certain negatively charged metals exhibit what is called the **Hallwachs effect,** an electrical discharge triggered by impinging light. The effect had first been noticed by Edmond Becquerel in 1839, who had observed electric tension created by solar light directed onto one of the electrodes in an electrolytic solution, and then rediscovered in 1888 by Wilhelm Hallwachs (1859–1922) who took the first quantitative measurements.[123] All early objective registering photometers *(Registrierphotometer)* make use of the approximate proportionality between the intensity of the absorbed electromagnetic waves and the photoelectric current generated, valid for a broad array of wavelengths (from the near infrared through the full visible range into the ultraviolet). The basic arrangement of these devices was as follows: the photographic negative was moved slowly but steadily under the microscope objective. Its degree of blackening, indicated by the varying amounts of photoelectric current produced, was plotted continuously by means of a galvanometer or electrometer. The transport speed of the recording negative (order of magnitude: centimeters per minute) thus determined the resolution factor (somewhere between 1 : 1 and 1 : 500, and usually was set around 1 : 50)—the slower it moved, the finer were the variations on the negative still perceptible by this method (cf. here Fig. 7.13). In order to eliminate systematic errors induced by delays between the transmission of light through the negative and the photoelectric response of the detector, each spectrum negative was usually measured twice, once from left to right and once in the opposite direction.

(p.278) The **photocell,** the most important component of this new type of instrument, worked as follows (cf. Fig. 7.11):[124] Metal that gives off a strong discharge when exposed to electromagnetic waves in the spectral range under study is used as a thin layer opposite the small window at F, inside an evacuated glass bulb coated inside with silver. Light that enters through this window hits the metal, which is connected to the cathode of a 100 volt battery, and releases electrons. These electrons are attracted by the circular anode D and generate a photoelectric current. Disturbing leakage currents in the silver coating are diverted into the protective ring R to prevent them reaching the anode at the bottom of the glass bulb. Typical metals used for the cathode were caesium, potassium, sodium, or cadmium, which have their maximum spectral sensitivities in the green, violet, near and far ultraviolet, respectively. The current coming from the photobattery B_1 often was conducted through an amplifier tube with grating G and cathode K heated by battery B_3 before it reached the galvanometer H (as shown in the right part of Fig. 7.11). An additional current from battery B_5 through the galvanometer was regulated by means of the rheostat W’ in such a way as to fully compensate the anode current, so that the galvanometer effectively only indicated changes in the anode current proportional to the photocurrent.

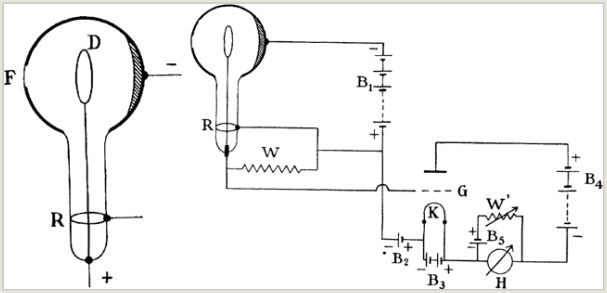


Fig. 7.11 Left: Scheme of a simple photocell, with F: window for incoming radiation, D: circular wire anode, R: ring to shield off leakage currents, shaded area: thin metallic layer. *Right:* Typical electrical amplifying circuit with galvanometer H, anode battery B4, and other elements described in the main text. From Ornstein, Moll, and Burger [1932] pp. 38, 41.

In 1912, the two Wolfenbüttel physics teachers Julius Elster (1854–1920) and Hans F.K. Geitel (1855–1923), had developed workable prototypes of such photocells using very thin leaves of alkaline metal, and had confirmed the proportionality of light intensity and induced **(p.279)** photoelectric current.[125] Soon after, Peter Paul Koch (1879–1945), at that time still working in the Munich laboratory of his doctoral advisor W.C. Röntgen, obtained some potassium cells from them and built the first such recording microphotometer. When he moved to Hamburg, registering photometry became a local specialty there.[126] The arrangement of the various components of Koch's instrument is shown schematically in Fig. 7.12: Light from a Nernst lamp N is projected through the photographic plate P onto a photoelectric cell Z_1, whose cathode K is connected to the negative pole of a battery and to a filament electrometer. Depending on how much light is absorbed or transmitted from the spot on the photographic plate within the focus of the lenses B and M, the photocell will generate more or less current, which is then indicated by the electrometer. Variations in intensity of the Nernst lamp emissions should have no effect, because two more photoelectric cells Z2 and Z3 are also exposed to the same source, whose resistance is then changed synchronously. An automatic transport mechanism slowly carries the photographic plate simultaneously with the registering plate, onto which the deflection of the electrometer needle S is recorded photographically.

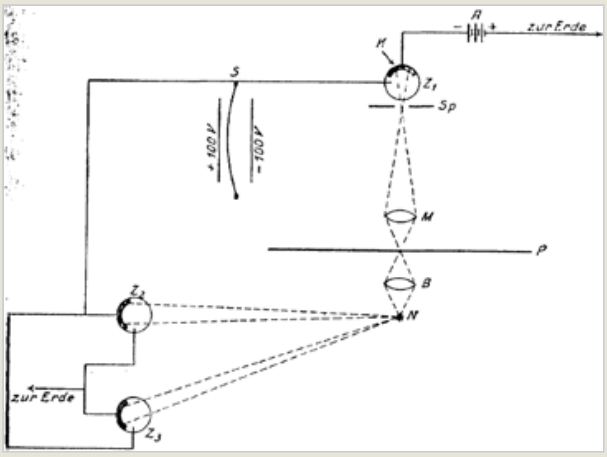


Fig. 7.12 Diagram of Koch's registering microphotometer; for the symbols see the main text. From Koch [1912] p. 707.

This photometer initially had certain drawbacks compared to the Hartmann design, such as the jagged appearance of the photometric curves caused by the toothed-wheel driving mechanism, a considerable delay time (about 0.5 sec) between a change in light intensity and the consequent movement of the electrometer needle, a high sensitivity of the electrometer to ground vibrations, and a more limited range of degrees of blackness that it could handle. Koch nevertheless was able to show that his instrument could reproduce **(p.280)** earlier measurements with a high degree of accuracy.[127] Most importantly: measurements that used to take weeks with the old visual photometric methods could now be done photoelectrically within a matter of hours. By 1920, an improved version of Koch's photometer with a substantially reduced delay had been developed by Fritz Goos (1883–1968), and was manufactured and distributed by the Hamburg instrument maker A. Krüss.[128] The instrument worked so smoothly that in 1922 the physics institute at Hamburg University even welcomed the whole physics community to examine photometrically any important photographic plates in their facilities at no charge.[129] Once this branch of instrumentation had passed the initial stages of exploration, functionally equivalent registering photometers were developed by the Carl Zeiss Company in Jena,[130] and at the Royal Observatory in Edinburgh.[131] Willem Jan Henry Moll (1876–1947) in Utrecht constructed a variant based on thermoelectric detection and galvanometric registration, with a much faster response time, and thus suitable for—but not limited to—infrared detection, because the latter could easily be blocked out by putting a glass plate in front of the thermoelement.[132] As Moll's photometric examinations of Abbe test plates and various spectroscopic fine structures amply demonstrated, his type of registering microphotometer yielded a spatial resolution of at least 0.02 mm, consequently more than even the best photographic plates available with a bromide emulsion.[133]

Figure 7.13 illustrates how such a registering photometer amplifies information about line profiles that is buried in conventional spectrum photographs. By integrating over the width of a spectrum strip and employing a suitably narrow slit, the photometer produces a continuous intensity curve that provides much more structural detail than the photograph. The optimal spectral resolution will depend on the skill of the operator in lining up the photometer slit exactly parallel to the lines, and on the width of the slit which should be as narrow and long as possible. In our example, the registration curve shows the split into five components very clearly, which is otherwise just barely visible, even in ninefold enlargement (as in Fig. 7.13, left). The quintet is revealed as being slightly asymmetric both with respect to position and intensity of the eccentric components (the Paschen-Back effect).

(p.281)

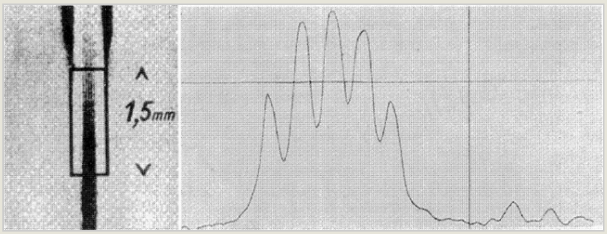


Fig. 7.13 Left: Photometric transformation of a conventional spectrum photograph (taken by P. Zeeman) of a cadmium line at 3610 Å in the near ultraviolet, split into a quintet by the Zeeman effect, with the part selected for photometric analysis in the central frame. *Right:* photometric curve of the central area, enlarged onto a plate of 6.5 × 18 cm. From von Angercr [1931c] pp. 177f.

The photometric method got a significant boost when in the early 1920s it became feasible to reproduce even the finer details of photometric registration curves, such as asymmetries of line profiles, relative heights of line peaks, satellite peaks at the line wings, etc., and to distinguish them clearly from instrumental artefacts. Thus far mainly triggered by advances in instrumentation and experimentation but not much by high theory, photometry now was strengthened by the rapid developments in quantum theory and quantum mechanics. Issues like the quantitative determination of line intensities and the resolution of line profiles suddenly gained importance because in both Bohr's semiclassical theory of electron orbits and Schrödinger's variant of quantum mechanics, it was possible to calculate many of these magnitudes from first principles. In Bohr's quantum theory, **spectral line intensities** are proportional to the total number of different transitions between pairs in differing states of energies E_1 and E_2, which lead to the same observed frequency difference $\Delta\nu = (E_1 - E_2)/h$. How many energetically equivalent transitions exist in turn depends on what is called the multiplicity of the initial and final states (i.e., on the number of electron orbits that normally lead to the same energy level). In an external electrical or magnetic field, each of these different orbits belonging to such a multiplet orients itself differently, which causes a small energetic splitting between them. These phenomena, known as the Stark and Zeeman effects, consequently enabled determination of the mysterious inner quantum numbers that would otherwise have remained unknown to the observer. Following Sommerfeld's convention for counting the inner quantum number J, its multiplicity was $2J + 1$.[134] Schrödinger's quantum mechanics offered similar links between transition probabilities and line intensities. In fact, there was an odd coincidence between the predictions of the older Bohr theory and the new quantum mechanics, even though the derivations in the latter were completely different from those in the former. A comparison of photometric **(p.282)** measurements with quantum mechanical calculations thus allowed a check of theory against experiment.[135]

In order to determine the relative intensities of spectral lines, Thomas Ralph Merton[136] (1888–1969) lecturer in spectroscopy in London, subsequently at Oxford in 1919, and Hen-drik Berend Dorgelo[137] (1894–1961) in the Netherlands, both developed independently of each other spectrophotometric methods based on the use of optical wedges mounted directly onto the spectrograph slit. Spectrum photographs taken with this arrangement showed the lines black at the thin end of the wedge and fading with increasing opacity.

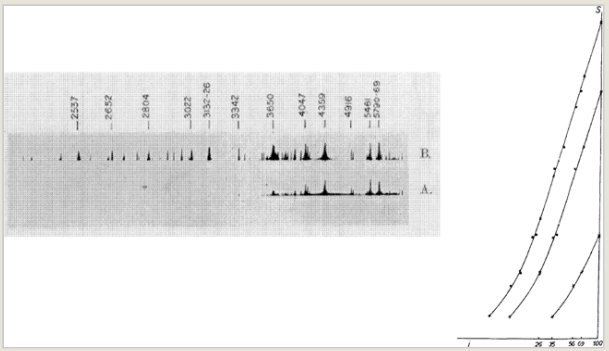


Fig. 7.14 Left: Photograph of the mercury arc spectrum, A: through a glass wedge, and B: through a platinum wedge, from Merton [1924] pi. 7. *Right*: Graph of the degree of blackening S as a function of microphotometer deflection (in units log μ_0/μ) for the Mg triplet lines 5183, 5172, and 5167 ä. From Dorgelo [1925] p. 762.

As the schematic plot on the right-hand side of Fig. 7.14 shows, even though the lines of the magnesium triplet have very different intensities to start with, their relative weakening, caused by insertion of the photographic density wedge, is very similar: all three lines exhibit a similar functional dependency $S(u_0/u)$ of the degree of blackening S on the microphotometer's deflection u. In the figure, S is mapped on the ordinate against the fraction of transmissions through the unexposed u_0 and exposed parts u. Because the latter is plotted **(p.283)** in logarithmic units of u_0/u to account for the general logarithmic dependency between the two magnitudes, there is a generally linear correlation between S and log u_0/u for all relative intensities between 26 and 100%. Merton used a continuously tapering platinum wedge,[138] while Dorgelo relied on discontinuous smoke-glass wedges with a stepwise gradation.[139] In both cases, though, the horizontal displacements between these curves provided an excellent measure of their differences in intensity because they were based on the determinations of several measurements for each line and not, as previously, just on one measurement for the peak intensity.

Another new link between theory and experiment concerned **line profiles.** Based on Heisenberg's uncertainty relation $\Delta E \cdot \Delta t \leq \hbar$, the lifetime Δt of certain quantum states is inversely proportional to the width (ΔE) of the spectrum line generated. Other factors determining spectral line width come from radiation damping, for which Planck had already derived in 1897 the expression for the half-width $\nu' = 8\pi^2 e^2 / (3mck^2)$[140] from what is called collision broadening, and from the Doppler effects induced by the irregular thermal motion of the gas atoms in the solar atmosphere.[141] Measurements of terrestrial spectra readily confirmed that an increase in temperature or pressure broadens the spectrum lines because it amounts to a multiplication of collisions. In the astrophysical context, additional factors influencing the spectral line profiles include Doppler effects due to solar convection, pressure effects, resonance scattering, and differences in the absorption coefficient $n\kappa$ in the various layers of the atmosphere. A useful definition of the intensity i of an absorption line seen against a background of continuous intensity J_0, as a function of wavelength λ, refraction index n, and the length l traversed through the solar atmospheric layer is:

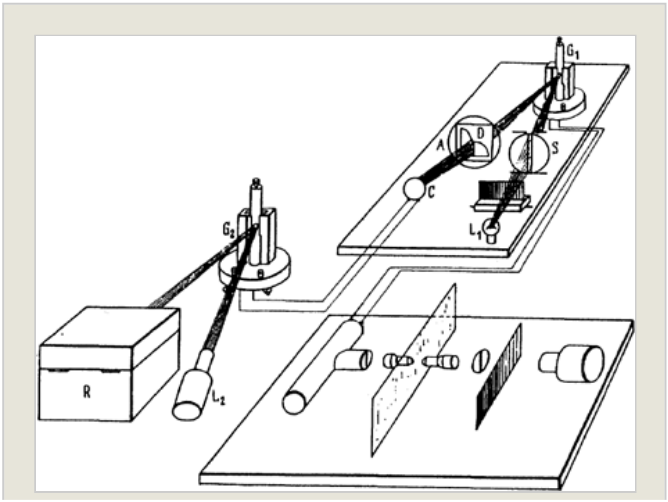
$$i = J_0 e^{-4\pi \cdot n\kappa \cdot l/\lambda}.$$

By analyzing Fraunhofer line profiles in solar spectra, one could now hope to learn more about these processes in the various layers of the solar atmosphere. A detailed account of these developments would go beyond the scope of this study,[142] but allow me to mention the research by Marcel Gilles Jozef Minnaert[143] (1893–1970) and his team at the University of Utrecht, which since Moll's pathfinding research remained one of the prime **(p.284)** centers of photometric research. After completing preliminary experiments on the determination of Fraunhofer line profiles from the mid-1920s, Minnaert and his collaborators finally published their *Photometric Atlas of the Solar Spectrum* from 3612 Å to 8771 Å in 1940.[144] On 176 sheets of coordinate paper the authors reproduced the registration curves obtained with a variant of Moll's microphotometer modified by Jakob Houtgast[145] (1908–1982). This instrument allowed direct registration of the line intensities and thus avoided tedious conversion of the microphotometer record by means of a calibration curve. The thermoelectric current from a tube-shaped Moll microphotometer in the normal setup (at the front, right of Fig. 7.15) is conducted to an auxiliary galvanometer G_1, illuminated by a long luminous slit S. An image of this slit is formed on the diaphragm D, and the transmitted part is led to a photocell C, connected to another galvanometer G2 whose deflections are recorded in the usual manner. The key to this arrangement is to have the diaphragm D shaped in such a way that the light transmitted through it is directly proportional to the intensity I. As Houtgast found out, the way to do this is to form the diaphragm in the shape of the photographic plate's $I(T)$ curve. The transmission I is plotted in the direction in which the galvanometer deflects, intensity / in a direction perpendicular to it.[146]

As the following Fig. 7.16 shows, the vertical axis of the plot represents the intensity as a fraction of the background intensity, which ordinarily is set equal to 100. In order to compensate unavoidable changes in the background intensity in different regions of the spectrum, there is an additional photographic wedge in the front right part of the setup in Fig. 7.15. As the plate is run through the microphotometer, this wedge synchronously is moved horizontally at a speed set to compensate as much as possible (i.e., up to 2–3 %) the general trend of the background intensity on the photographic plate.

To obtain a better dispersion and optimal light intensity, in 1936 one of Minnaert's former doctoral students, Gerardus Franciscus Wilhelmus Mulders (born 1908), installed this microphotometer on the Mt Wilson 150-foot solar tower telescope. It yielded a solar image of 43 cm diameter and an optical spectrum of 15 m length that had to be segmented into about 130 slightly overlapping parts for the photometric analysis subsequently carried out in Utrecht. While the original photographs had been taken at a dispersion of 3 mm/Å, the tracings were recorded at a dispersion of 20 mm/Å.

In an appendix, the three authors extended the wavelength range further into the near ultraviolet up to 3332 Å, based on measurements taken with a concave grating at the Physics Laboratory of the University of Utrecht. According to Minnaert, “the atlas was ready, just **(p.285)** before the Second World War broke out; and the very last airplane which left Portugal for the United States, the last before the five-years-long interruption of communications, carried five copies of our Atlas for the colleagues over there.”[147] Despite the rarity of this first extensive photometric atlas, the Utrecht atlas became a model of its kind for other photometric atlases in solar, stellar, and terrestrial spectroscopy, published after World War II:[148]



(p.286)

Fig. 7.15 Basic design of the Utrecht apparatus for direct intensity recordings, $G_{1,2}$: galvanometers, $L_{1,2}$: strong lamps, S: slit and D: diaphragm, as described in the main text. From Minnaert and Houtgast [1938] p. 355, reproduced by permission of Springer Verlag, Heidelberg.

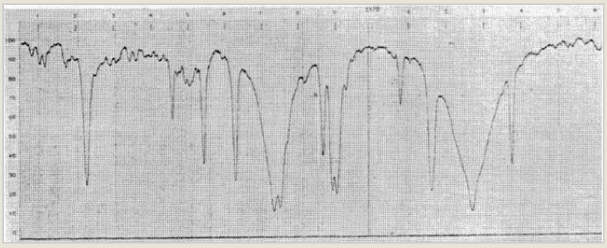


Fig. 7.16 Sample segment around 5170 Å from the Utrecht *Photometric Atlas of the Solar Spectrum*. From Minnaert, Mulders, and Houtgast [1940], by permission of the Sterrekundig Instituut of Utrecht University.

Tab. 7.1 Survey of photometric atlases 1929–1981 Abbreviations: The average density ratio R/L refers to: wavelength region (in k)/length of representation (in cm); in cases of split representation, the regions of minimal overlap of adjacent maps were counted twice; R/L thus gives an approximate measure of the scale of representation.

name	institution	year	type of spectra	λ region R(Å)	# sheets x size L(cm)	R/L Å/cm	instrumentation	remarks
Abbot & Freeman	Astrophys.Obs., Smithsonian	1929	infrared	18200–7600	5×56.4 =282	*5.6*	Vacuum bolometer	Bolographs with c. 1200 identifiable lines
Minnaert, Mulders, Houtgast	Univ. Utrecht	1940	solar spectrum	8771–3612	176×2×35cm	0.5	Houtgast variant of Moll microphotometer, Mt Wilson 150 foot Tower telescope	First large photom. atl. of solar spectrum, direct registration of intensities
Hiltner & Williams	McDonald Obs., Texas	1946	9 stellar spectra	6723–3982 6302–3916	à 20	1–70	Coude spectrograph, 82-inch reflector	Small atlas of stellar spectra

name	institution	year	type of spectra	λ region R(Å)	# sheets x size L(cm)	R/L Å/cm	instrumentation	remarks
Mohler, Peirce, *et al.*	McMath Hulbert Observatory	1950	solar spectrum	25242–8465	117×2×38.7cm	c.3	IF spectrometer with PbS cell, Snow telescope, Babcock grating	Near IF spectrum with c.74000 lines
Migeotte, Neven, Swensson	Liège, Univ. de Louvain	1956/1957	IF solar spectrum	237000–28000	62 x(31×60)		See under Mohler *et al.* [1950]	Continuation of McMath Hulburt Obs. atlas into the far IF, with a gap of 0.3μ because of water vapor absorption in terrestrial atmosphere
Migeotte, Neven, *et al.*	Liège, Univ. de Louvain	1957/1958	IF absorption bands	89000–28000	(25×57)		ditto	Absorption bands of nitrous oxide, methane, and ozone

name	institution	year	type of spectra	λ region R(Å)	# sheets x size L(cm)	R/L Å/cm	instrumentation	remarks
Brückner	Univ. Göttingen	1960	solar spectrum	3629–2988	58×45	0.3	Cassegrain telescope at Gottingen solar tower, Bausch & Lomb concave grating with lin. disp. of 1.25 A/mm	Solar spectrum in near UV
McAllister	Univ. of Colorado, Boulder	1960	solar spectrum	2965–1800	(36×48)		Concave grating rocket spectrograph, flown 6 August 1957	Ultraviolet spectrum
Bass	NBS	1961	absorption bands	5000–3000	20×27			Absorption bands of CH in optical spectrum
Delbouille	Univ. Liège	1963	solar spectrum	12016–7498	84 × (31×61)			infrared solar spectrum

name	institution	year	type of spectra	λ region R(Å)	# sheets x size L(cm)	R/L Å/cm	instrumentation	remarks
Griffin	Cambridge Observatories	1968	Arcturus spectrum	8825–3600	260 × (32×61)	0.3	Mt Wilson 100-inch Coude spectrograph	First detailed stellar spectrum
Hall	Harvard College Observatory	1970	sunspot spectrum	24778–11340	(85×32)			HCO thesis; first photometric atlas of near-IF sunspot spectrum
Brault and Testermann	Kitt Peak Obs.	1972	solar atlas	10014–2942			See below: Delbouille *etal.* [1981]	Preliminary edition
Delbouille, Neven, Roland	Univ. Liège	1973	solar spectrum	10002–3601	108×(45×62)	0.2	Ebert-Fastier spectrometer at Int. Obs. Jungfraujoch	Full spectrum from near UV to near IF
Tousey, Milone, Purcell *et al.*	Naval Research Lab., Washington	1974	solar spectrum	2992–2226	87 x(32×55)		Near vacuum photographs	Near UV spectrum taken during rocket flights

name	institution	year	type of spectra	λ region R(Å)	# sheets x size L(cm)	R/L Å/cm	instrumentation	remarks
Beckers, Gilliam, Bridges	Sacramento Peak Obs.	1976	solar spectrum	7000–3800	165×2×15.3	0.65	Sacramento Peak Obs., Littrow spectrograph, small solar disk	High resolution atlas of integrated sunlight together with identification of Fraunhofer lines
Allan, McAllister, Jefferies	University of Hawaii	1978	solar spectrum	2931–2678	45 x(2×35)	0.2	79 grooves/mm echelle spectrograph, plane grating, digital electronic control system	High resolution atlas of solar spectrum based on rocket echelle spectrogram
Griffin	Cambridge Observatories	1979	Procyon spectrum	7470–5400 5400–3140	182×2(11×46)	0.25	Mt Wilson 100-inch Coude spectrograph	Second detailed stellar spectrum

name	institution	year	type of spectra	λ region R(Å)	# sheets x size L(cm)	R/L Å/cm	instrumentation	remarks
Delbouille, Roland, Brault, Testerman	Kitt Peak Nat. Obs.	1981	solar spectrum	10000-1850 cm^{-1}	169×(22×36)			Continuation of Delbouille *et al.* [1973]
Lamers *et al.*	Space Research Lab., Utrecht	1981	spectra of 220 early-type stars	2880–2060	55×12×7.3cm	15	Orbiting stellar spectrophotometer S59 on board of ESRO satellite TD-1	Mid-ultraviolet stellar spectra with resolution of 1.8A

(p.287) Most of these photometric atlases were based on a continuous recording made with a registering microphotometer that scanned the original photograph at regular fixed intervals. The Royal Observatory in Edinburgh pursued a different approach over a period of several decades. The underlying principle was that one gets much more precise information about line profiles if the intervals at which the spectrum is sampled are smallest in the vicinity of an absorption line; in the continuous parts in-between these lines, the intervals may be much larger. Between 1938 and 1955 William Michael Herbert Greaves (1897–1955) and his chief assistant Edwin Arthur Baker (1891–1980) conducted this program using a manually operated (‘non-recording’) microphotometer constructed in the observatory workshop. Two people were needed to do the measurement: one operator moved the plate incrementally from one part of the spectrum line to the next and read off aloud the blackening at each of the sampling points. An assistant would record these values in a table.[149] Each spectrum thus comprised measurements taken at up to 1500 different wavelengths.

Such a labor-intensive procedure could only be carried out for about 100 stars of type O and B (down to magnitude 5.0), which have relatively few absorption lines. In order to eliminate accidental irregularities due to the grain of the plates or to errors during manual recording, a procedure of numerical averaging of the measures of several spectra of a star—and indeed of those of several stars of the same type—was also introduced. Thus lines too feeble to show up on a single plate against the background intensity could be detected in this way.[150] Greaves's successor as Astronomer Royal for Scotland, Hermann Alexander Brück (1905–2000), changed over to an automated program in which the stellar spectra were scanned by a digitizing microphotometer at small stepped intervals of 12.5 µ. Figure 7.17 illustrates how a line profile **s(x)** prior to digitizing and centered around a is transformed into an output curve **v(x)** by the microphotometer operating with a constant interval set significantly smaller than the line width (**x** being the linear scale of the plate, to good approximation directly proportional to the wavelength, since the spectrograph used in Edinburgh was a grating instrument).

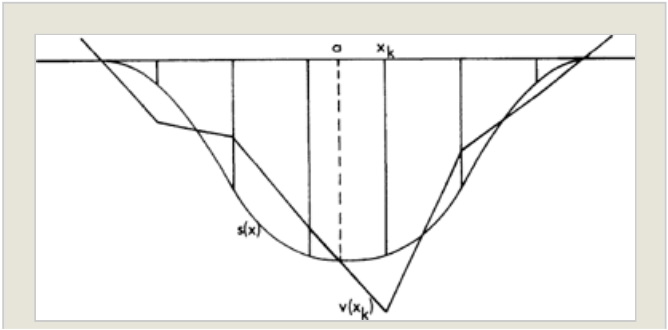


Fig. 7.17 Transformation of a line profile **s(x)** of an isolated line centered around a into a microphotometer output function **v(x)**. From Thompson [1967] p. 248, reproduced by permission of ROE Library and Archives.

(p.288) These measurements **v(x)** were recorded on paper tape for direct computer input, and various programs then executed the involved data analysis, including photometric calibration, noise statistics, correction for overlapping lines, and finally calculation of equivalent widths.[151] I shall have to limit my discussion of these tricky algorithms to the calibration procedure. In the following figure (7.18) the lower curve is the digitized spectrum resulting from the process schematized in the preceding graph. The top curve results after convoluting the spectrum with a function **D(x)** designed to destroy the continuum while not seriously modifying the major lines. The middle curve is the residual continuum obtained by filling in the lines using the computed line areas. It is plotted only to verify that the peak heights of all of these residuals are lower than those of the 'real' spectrum lines. These real lines are depicted in the older iconic mode of representation along the bottom edge of the figure.

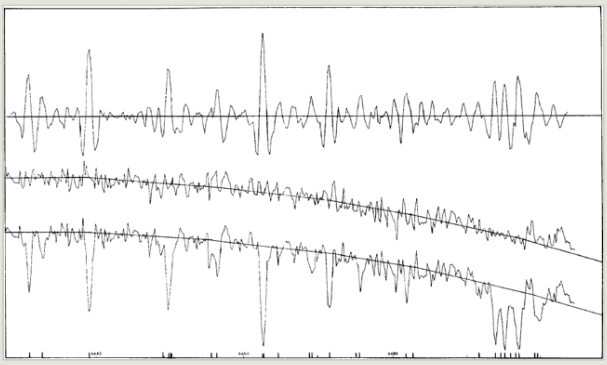


Fig. 7.18 Correction for the change in intensity of the continuous background of a sample line profile, between 6430 and 6510 Å. From Thompson [1971] p. 22, by permission of ROE Library and Archives.

Besides this application in detailed analyses of astrophysical objects, spectrophotometry brought equally dramatic changes to research practice in analytic chemistry and medicine.[152] Davis Baird sees the introduction of (semi)automatic direct-reading spectrophotometers into analytic chemistry as nothing short of a fourth major scientific revolution, "the 'big' scientific instrumentation revolution".[153] Aside from massive changes in the scientific **(p.289)** practice of analytic chemists, this transformation also involved

- the development of a new family of scientific instrument-making companies (such as Beckman Instruments or Baird-Atomic),
- an increasing social differentiation between technicians and analytic chemists,
- a revamping of curricula,
- new levels of expenditure for research and development, for researchers and companies alike, and

• new venues for exchanging information about scientific instruments, such as the MIT summer conferences, the National Instrument Conference and Exhibit, or the Pittsburgh conference (which outgrew its first location in 1968 and is now held elsewhere).[154]

Having thus reached the end of our historical tour through the period considered in this book, we now turn to other aspects of what can reasonably be called the visual culture of spectroscopy: pattern recognition in research (Chapter 8) and its formal inculcation (Chapter 9).

Notes:

(1) On this work in Baltimore, see in particular Jewell [1900*b*] and here p. 232; cf. also H.W. Vogel [1885*a*] pp. 76f. on Rowland's experiments with eosine to increase the sensitivity in the yellow range of the spectrum.

(2) See, e.g., Mees [1931/35] or von Angerer [1931*c*] pp. 52f., esp., pp. 54–9, for a survey of the commercial photographic material available around 1933 and 1950, respectively, for different spectral ranges.

(3) On Vogel see here footnote 61, p. 188. His discovery in 1873 is discussed in H.W. Vogel [1873*a*], [1873/74], [1874*a*] pp. 229ff., Röll [1939] chaps. 15–17, Eder [1945] chap. 64, and Herneck [1984] pp. 71ff.

(4) On halation *(Lichthofbildung)* see, e.g., von Angerer [1931*c*] pp. 44f. and here p. 232.

(5) See, e.g., Monckhoven [1874], Spiller [1874*b*] p. 255, Vogel [1874*f*], and Lea [1874] pp. 109–11, 120–2.

(6) Anon. [1874] p. 268.

(7) H.W. Vogel [1874*d*] pp. 154f., [1874*f,g*]. The counter-argument by Lea [1874] p. 230 that Vogel himself had used filters in the past instead of prisms, was irrelevant because a color filter does not produce pure enough color for precisely this kind of spectral sensitivity test. Nevertheless, his opponent continued to contend two years later that Vogel's sensitizing techniques were “without proof”: see Lea [1876].

(8) See [H.W. Vogel] [1874*f,g*].

(9) See, e.g., H.W. Vogel [1873*a*] p. 454, [1880] pp. 385–7, Schmidt and Haensch [1888] (who distributed this instrument for 80 marks with mounting and prisms included), and Landolt [1899] p. 2.

(10) See, e.g., H.W. Vogel [1880*b*] pp. 380–5, [1885*a*] pp. 9, 23ff.; Herneck [1984] p. 76: a first application in March 1874 drew in 700 thalers, further applications in 1875 and 1876 yielded 450 marks each, another in 1879 for an alteration of the large spectrograph won 710, and one in 1887 for repairs another 150 marks from the Prussian Academy's appropriations board, Geld-Verwendungs-AusschuB.

(11) Founded in 1867. Agfa opened its own film-production plant in Wolfen near Bitterfeld in 1909; see, e.g. Stenger [1939] and Röll [1939] p. 89. The history of dye production in general is also treated in Teltschik [1992] and especially Travis [1993].

(12) On Draper's law and the context of its discovery see, e.g., J.W. Draper [1841], [1843*a*] and Eder [1945] p. 166, who mentions that in 1817 Theodor Grotthuß already hypothesized that only absorbed light rays are agents of chemical change.

(13) On this point, see particularly Eder [1886*c*] pp. 40f.

(14) See, H.W. Vogel [1873*a*] p. 458, [1874*a*] p. 243, and [1877*c*] p. 293, where he defended himself against the false charge by Abney [1876] that he was simply equating absorbent color and sensitizing range.

(15) See, e.g., H.W. Vogel [1874*a*] pp. 233, 246.

(16) See Kundt [1874], [1877/78]; cf. H.W. Vogel [1877*a*] pp. 210ff., [1884*a*] p. 1200, Abney [1885] pp. 835ff.

(17) See, e.g., H.W. Vogel [1878*a*] pp. 1368f.: “Kundt's rule that the absorption bands of a dissolved substance shift farther toward the red, the stronger the fluid's dispersion is in the region of the absorption band, is *not* confirmed in many cases”. Cf. also Röll [1939] pp. 74, 106.

(18) See H.W. Vogel in Abney and H.W. Vogel [1879] p. 95: “The æther's motion is relayed to the absorbent's molecules, thus here initially to the dye. But the latter transfers the motions to the neighboring silver-bromide molecules. If the oscillatory motions are high enough in frequency, splitting, that is, chemical decomposition of the molecules occurs.” On these and other early efforts to develop an underlying theory for photochemistry, see the references in footnote 111, p. 200.

(19) H.W. Vogel [1874*b*] p. 153; see also H.W. Vogel [1877*a*,*b*] Eder [1884], [1885/86], [1945] chaps. 64ff., and H.O. Klein [1910] about the rapid progress made in the last quarter of the nineteenth century.

(20) Eder in a letter to H.W. Vogel, cited by Röll [1939] p. 1.

(21) See H.W. Vogel [1884*a*] pp. 1197f., [1885*a*] pp. 75ff. According to Eder [1945] p. 464, the sensitizing effect of eosine was first noticed by Colonel J. Waterhouse (cf. here footnote 53 below), one of the first photochemists to succeed in confirming Vogel's discovery of sensitizers. They had even met on a British solar eclipse expedition to Bengal in 1875 which Vogel had joined as photographer: see Roll [1939] p. 75. However. Waterhouse [1875] p. 199 only vaguely mentions “plates stained with a blue dye, one of the aniline or an analogous series, obtained in the bazaar” in Calcutta, India, where he was based.

(22) See, e.g., H.W. Vogel [1885*a*] pp. 11 Off. on the chemistry of eosine ($C_{20}Br_4H_8O_5$), first correctly analyzed by A.W. Hofmann in 1875. On secrecy in industrial research, especially in photochemistry, and its drawbacks see Mees [1952], and Galison [1997] 186–91. On BASF, see Telschik [1992], Travis (1993) part III.

(23) According to Mees [1957] p. 289, whose survey of sensitizing dyes I rely on in the following.

(24) For an example of Higgs's successful use of erythrosine-sensitized plates, see here p. 240. Cf. Millochau [1906] for photographs of the infrared spectrum between c. 8000–9350 Å with erythrosine-sensitized plates.

(25) For instance, Obernetter reproduced H.W. Vogel's [1879*b*] plate with photographs of the ultraviolet lines in the hydrogen spectrum. On their technique of *Lichtdruck* see here pp. 158f.

(26) H.W. Vogel himself preferred such terms as ‘color sensitive’ (*farbenempfindlich*), but somehow Eder's ‘Orthochromatic’ (or, correctly colored) prevailed; cf., e.g., H.W. Vogel [1884*b*], [1885*a*] or Abney *et at.* [1896] for early surveys. According to Watts [1904] p. 127, “erythrosine, or iodo-eosine, is the potassium compound of tetraiodo-fluor-escein. The bath must be highly dilute (1:10000) and ammoniacal.”

(27) According to Mees [1937] p. 137, Williams had made cyanine from impure quinoline in 1856, but H.W. Vogel was the first to use it as a sensitizer. Hasselberg [1885], Abney, Rowland, and Schumann all used it to good effect for spectrum photography. A detailed description of the pros and cons of cyanine-sensitized plates is given in an unpublished ms., dated 19 August 1885, by Victor Schumann: ‘Die orthochromatische Platte und die Photographie des Sonnenspectrums’ (HUBL, Nachlass 208), pp. 4–7.

(28) See H.W. Vogel [1885*a*] pp. 102f., and Eder [1945] pp. 460f., according to whom quinoline red had been discovered by the Berlin chemist E. Jakobsen in 1882. Note also that the German spelling of quinoline is ‘Chinoline’, occasionally also appearing so in English texts. According to Watts [1904] p. 127, the cyanine bath is made “by taking 2 c.c. of an alcoholic solution (1 : 400) of cyanine with 100 c.c. water and 1/2 c.c. ammonia. The plates should be prepared and developed in absolute darkness.”

(29) See Röll [1939] pp. 81 ff., 92ff., 98ff. on these commercially not too successful ventures.

(30) These later developments and the Berlin-Charlottenburg Institute for Photochemistry are discussed by H.W. Vogel [1884*b*] Röll [1939] chap. 24, Eder [1945] pp. 473ff., Anon. [1963], and Narath [1964]. On the research at the Viennese Staatsgewcrbeschule, the precursor of the later polytechnic (Technische Hochschule), see Eder and Valenta [1904]. Eder and Valenta established their fame particularly in the area of X-ray photography shortly after Roentgen's discovery in 1896.

(31) Both König and Homolka worked in the photographic research branch of the Hoechst dye works, which was founded in 1902. König had studied in Leipzig under J. Wislicenus and F. Strohmann, entered the dye works of Meister, Lucius & Brüning in Hoechst near Frankfurt in 1893 and advanced to the head of the Hoechst photographic research laboratory (founded in 1902). See Eder [1924], A.H. [1924], Priesner [1980]. Homolka had been assistant to A. von Baeyer in Munich before joining Hoechst in 1886. See Anon. [1925] and Flemming [1972]; the photochemical research at Hoechst is also treated by Flemming (ed.) [1965].

(32) See E. König's letter to Herbert von Meister, 13 October 1903. reprinted in facsimile in Flemming (ed.) [1965] pp. 11–12.

(33) Cf. Mees [1957] p. 290 and [1961] chap. 3. Mees had just become joint managing director of this company, which was bought up by Kodak in 1912, whereupon production of the panchromatic plates was transferred to Rochester, New York, possibly also in part because of less stringent environmental hurdles in the US: on the abandoned Hoechst factory plans owing to this problem, see Flemming (ed.) [1965] p. 36.

(34) H.W. Vogel [1877*a*] pp. 153f.; see also *ibid*, for his advice to any person with a serious interest to join one of the photographic societies, “to protect him from quackery”.

(35) For instance, the *Philadelphia Photographer* (vol. 1, 1864) or the *Photographic News* (vol. 1, 1858). For a list of the most important journals and their years of publication, see Harrison [1886–88*c*] class II (periodicals) pp. 53f., and Johnson [1990] pp. xiii-xv. A list of photographic societies of the late nineteenth century is provided in Welling [1978] pp. 143–73.

(36) See J.F.W. Herschel [1859] p. 229: “it made all the difference in the world which solution was laid on over the other” (original emphasis suppressed).

(37) [Crookes] [1859] p. 267, original emphasis. Crookes surmised that this systematic discrepancy was due to differences in exposure times and intensity.

(38) See Dieke [1970] p. 21. Abney's process used a basic mixture of freshly beaten egg white, liquid ammonia, pyrogallic acid and bitter ale added to ordinary collodion. Since beer could be substituted for the ale and dried albumen for the egg white, the process also came to be known as the beer albumen process. On the Chatham School of Engineering, see here p. 165.

(39) Abney [1878*b*] p. 350; more detailed but not much clearer explanations of his procedures and idiosyncratic atomic model are provided in Abney [1880*a*] and Abney and Festing [1881/82*a*].

(40) Foran early critique of Abney's theory of sensitization, see H.W. Vogel's remarks on the distinction between optical and chemical sensitizers in Abney and H.W. Vogel [1879] with excerpts from their since-lost correspondence.

(41) See, e.g., Ritz [1906] for the first successful attempt to reproduce and even slightly improve upon Abney's results with colloidal silver bromides, and Millochau [1906/07] for another approach with plates dyed with green-malachite and solarized before use. After having just reached 10 750 Å, Babcock [1928*a*] p. 830 admits still then that “in spite of this extension of Abney's limit by nearly 9000 Å, my experience leads to the belief that his emulsion was far more sensitive in this spectral region than any of those now available.”

(42) See Abney [1880*a*] pp. 658–60 as well as Abney to Charles P. Smyth, 24 January 1880 (ROE, 14.64, folder A) on further details of Abney's experimental setup. Abney's mounting was later described in Abney [1886] and by Waterhouse [1889*b*] pp. 286f. Babcock [1934] p. 261 estimated the resolving power of Abney's grating spectrograph to be of the order of 25 000, while his own achieved a resolving power of over 240 000 on the plates. I don't think that originals of Abney's photographs have survived, but according to J. Rand Capron's letter to Piazzi Smyth, 12 April 1878 (ROE, 13.60, folder C), who had seen some of Abney's collodion-based photographs of the red end of the solar spectrum at the instrument maker J. Browning's, the exposure times were about 15 min, the photographs were taken at about 1 p.m., and they reportedly showed the brighter lines as well as the shaded lines of great A well.

(43) See Rubens [1900] p. 144, Coblentz [1905] p. 5, Ritz [1906] p. 167, and Meggers [1918] p. 1.

(44) This explanation for Abney's irreplicable findings was first given by Babcock [1928*a*] p. 830, [1929] pp. 275f.

(45) See Rayleigh [1877] p. 349, Abney [1880*a*] p. 665, Langley [1883*d*] pp. 156–8; for $\lambda \rightarrow \infty : \mu = A = \min$.

(46) Cf., e.g., Abney to C.P. Smyth, 30 March 1878 (ROE, 13.60, folder A): “It strikes me that Sir J. Herschel's thermal spectrum is explained by the group of lines.”

(47) See Abney to C.P. Smyth, 30 March 1878 (ROE, 13.60, folder A). Smyth himself was not totally innocent in this regard: In [1877*c*] p. 46 he had referred to Abney's result in quite skeptical terms: “a recent experimentalist in this country is said to have obtained lines in the photographed spectrum as far beyond A, as A is beyond D, […] but I am not aware of more than the merely verbal statement of that observer having yet been published.” Abney reacted by offering to show his photographs: see his letter to Smyth, 24 December 1877 (ROE, 13.58, folder A). By 1884, Smyth [1884*b*] p. 100 praised Abney in the highest terms, as a “born genius of military engineering”.

(48) Kayser [1936] p. 215 of original pagination. On Kayser, see here pp. 6 and 244.

(49) W. de W. Abney to C.P. Smyth, 24 January 1880 (ROE, 14.64, folder A).

(50) Cf. in this respect Abney [1889] on his distinction between ordinary photography as a ‘common branch of mechanical industry’ practised by thousands of photographers, and scientific photography, limited to a handful.

(51) See Abney [1880*a*] pl. 31. In Abney [1886] the accompanying table continues to 9867 Å. Above the scale value 9900 Å he inserted the text: “at this point there is a continuous spectrum extending as far as wave length 10750 [Å] at which the diffraction Photographs end, but the photographs of the prismatic spectrum show the continuous spectrum as far as wave length 12000.”

(52) See Abney and Festing [1881/82]. However, the enclosed tables only list a lew lines beyond 10 000 Å for each compound, with error margins of ± 50 Å, because wavelength estimates are only given in units of 100 Å.

(53) Waterhouse headed the photographic department for the Surveyor's General Office from 1866 to 1897 and supervised, among other things, the photolithographic reproduction of geographic maps. He consequently had a professional interest in photomechanical processes and photography. Sec. e.g., H.W. Vogel [1885*a*] pp. 52f., Stephenson [1912] p. 281, and Röll [1939] pp. 75f.

(54) See, e.g., Waterhouse [1875], [1889*a*]. Cf. also Higgs [1891] for further details about sensitization with bisulphite compounds of alizarin-blue ($C_{17}H_9NO_4$).

(55) See W.H. Pickering [1884/85*a*], and Burbank [1887]. On W.H. Pickering and his impact as a teacher of photography, see here p. 374.

(56) See, e.g., E.C.C.B. [1926] p. 309, according to whom Ilford was the major producer of such plates. On the increased sensitivity from cyanine, see here Fig. 7.2.

(57) This dye, discovered by Adams and Haller in the Color Laboratory of the US Bureau of Chemistry in 1919, was sensitive between 7000 and 8000 Å and thus actually less sensitive than dicyanine (discussed below).

(58) See Babcock [1927] pp. 140f., [1928*c*] for his experiences with neocyanine used for wavelengths beyond 7300 Å with maximum sensitivity at 8300 Å, and [1929] pp. 275f. on the special filter. Cf. also the correspondence between Meggers and Harlow Shapley (Harvard College Observatory) in December 1925, and Meggers and Keivin Burns (Allegheny Observatory) in March 1926, both of whom asked Meggers to tell them more about this new dye (all at AIP, Meggers papers).

(59) See, e.g. Mees and Wratten [1908] on the skills and tricks necessary to deal with dicyanine-sensitized plates.

(60) These enlarged photographs, taken in 1918 with the Porter Solar Spectrograph, were mounted on cloth and bound together in album form: See Meggers to Frank Schlesinger, 29 December 1919, and 18 January 1920, Schlesinger to Meggers, 12 January 1920 and 1 December 1920, and Meggers to Mr Hershey, The New Era Printing Co., Lancaster, Pa., about the problems of halftone reproduction from the negative and positive plates (all in AIP, Meggers papers, box 1, folders 1919 and 1920).

(61) See Meggers [1918], and Brackett [1921]–[1923]. Brackett (born in 1896) worked as laboratory assistant at the National Bureau of Standards in 1918–19, and as observer at the Mt Wilson Observatory, returning thereafter to the NBS as assistant physicist, also working as instructor of physics at Johns Hopkins University in Baltimore where he took his Ph.D. in 1922. After a career as professor in California, he became director of the division of radiation and organisms of the Smithsonian Institution in 1929, and consultant to various other agencies.

(62) See Burns [1920] p. 64 and Brackett [1921] p. 123, who actually took exposures between 7 and 21 hours, extended over a period as long as three days in a constant-temperature pit at the Mount Wilson solar tower telescope. When exposure times increased beyond 30 min, problems with stray light and Lyman ghosts led to demands for more efficient filters for the region beyond 9000 Å that would function as well as selenium red did for the region 6500–7600 Å. Brackett used a water dilution of malachite green as a filter almost opaque to all wavelengths shorter than 7200 Å.

(63) Quote from Mees [1937] p. 143.

(64) After studying at the University College, London with William Ramsey, graduating with a B.Sc. in 1903 and a D.Sc. in 1906 on the theory of the photographic process, Mees became joint managing director of Wratten & Wainwright in Croydon, England, where he conducted research and development on panchromatic plates and light filters. From 1912 on, he was director of research, since 1923 director of Eastman Kodak in Rochester, NY. Mees received numerous awards (such as the Janssen, Henry Draper, Rumford, and Franklin Medals) and was fellow of many scientific academies and societies. See, e.g., Baines [1961], Clark [1960/61], Anon. [1961], Cf. also Mees [1947], [1961] chaps. 4ff. on the Kodak Research Laboratories which were independent of the factory laboratories, following the role model of German dye works like Baeyer.

(65) See, e.g., Brooker, Hamer, and Mees [1933], Mees [1957] p. 294, [1961] chap. 9, and here Fig. 7.6 for further details of the previously mentioned photochemistry of the dyes.

(66) See Mees [1947] p. 472. Cf. Fehrenbach [1984] p. 167 on the thermal limit of infrared photography.

(67) Paul W. Merrill to W.F. Meggers, 1 March 1920 (AIP, Meggers papers, box 1, folder 1920).

(68) On this collaboration sec, e.g. Burns [1920] p. 65; on the institutional background see W.F. Meggers and F.J. Stimson: ‘Dyes for photographic sensitizing’, unpublished abstract of a paper for the meeting of the Dye section of the American Chemical Society in St Louis, April 1920 (copy in AIR Meggers papers, box 1. April 1920), and Meggers to Stratton, 27 June 1919, enclosing a copy of the first report on ‘photographic researches’ at the NBS with special regard to military aerial photography *(idem*, box XIV).

(69) Babcock enrolled himself at the University of California, Berkeley in 1901; in 1907 he took his B.S. *in absentia*, while a ‘scientific staff member’ of the Washington Bureau of Standards between 1906–08. In 1909 he went to the Mt Wilson Observatory of the Carnegie Institution of Washington where he worked as a full-time physicist from 1948, continuing as a consultant thereafter, specializing in measurements of the Zeeman effect and solar magnetic fields. On Babcock, who was awarded the ‘Bruce Gold Medal’ of the Astronomical Society of the Pacific in 1953, see Bowen [1974].

(70) This farmer's boy studied physics at Ripon College from 1907, where he was appointed ‘instructor of physics’ in 1910/11; he then went to the University of Wisconsin in Madison, also as ‘instructor’ and took his M.A. in 1916, interrupted by a stay in 1912–14 as ‘instructor in physics’ at the Carnegie Institute of Technology. From 1916 on Meggers studied with J.S. Ames at the Johns Hopkins University, where he defended his Ph.D. in 1917. In 1914–16 he was ‘laboratory assistant’, ‘assistant physicist’ until 1919 in the new spectroscopic department of the Washington National Bureau of Standards under Keivin Burns (cf. here p. 329). when he became department head, specializing in interferometric measurements of spectral lines and in spectrochemical applications until 1958. 1935–52 Meggers also headed the commission of standard wavelengths of the International Astronomical Union, 1946–51 he was chairman of the committee on line spectra of the National Research Council, 1950–58 president of the ‘International Joint Commission for Spectroscopy’ and consultant for the Atomic Energy Commission. On Meggers, who was awarded the Mees Medal by the Optical Society of America in 1934, see Foote [1970], Anon. [1971] and Moore [1971].

(71) For two such exchanges of material for expertise, see the correspondence between Mees and Meggers, 3 June 1921 to 22 March 1922 concerning sensitizers similar to pinacyanol and kryptocyanine. The former was eventually placed on the market at a price of $15 per gram (AIP, Meggers papers, box 1, folders 1921 and 1922).

(72) See, e.g., Babcock and Moore [1947] p. 17: “Without the special photographic emulsions supplied by the Research Laboratory of the Eastman Kodak Company the greater part of this work could not have been done. When it has seemed that no further extension into the infrared could be made by photography, the Director, Dr. C.E.K. Mees, has either supplied a new sensitizer or speeded up an existing one.” Kodak's side of the story is described in Mees [1961] pp. 44ff., 269ff. On the later interplay between nuclear physics and Kodak's as well as Ilford's emulsion research see Galison [1997] chap. 3, esp. pp. 186ff.

(73) On the following see, e.g., Mees and Wratten [1907], [1908] p. 27, and Mees [1961] pp. 38f. One sample NBS report making extensive use of these wedge spectrograms is Davis and Walters [1922]. For evidence that the NBS acted as a kind of multiplier of the most recent information on the newest sensitized commercial plates available, see, e.g., W.F. Meggers to C. Fabry, 20 January 1920, which included two such survey papers (AIP, Meggers papers, box 1, folder 1920), and his exchange with Fabry in April 1924 where he asked the Parisian spectroscopist to name the best French plates with respect to high speed, contrast, fine grain, and spectral sensitivity.

(74) To pick out just infrared-sensitive emulsions: see, e.g., Meggers [1919] for the solar spectrum from 6500 to 9000 Å, recorded with plates sensitized with Hoechst's dicyanine plates; Herzberg [1934] for a photograph up to 12 900 Å with Agfa's infrared sensitive plates, and H.D. Babcock [1927], [1928*a*,*c*], [1929], [1934], Meggers [1933], [1935] and Babcock and Moore [1947] for the successive improvements in infrared photography obtained with Eastman I-Z plates.

(75) For good surveys see, e.g., von Angerer [1931*c*] pp. 11ff., and Mees [1937], [1957], [1961].

(76) Compare, for instance, Sheppard and Mees [1906], [1907] or Lea [1908] for the state of the art by 1900, with Mees [1942], [1961] or von Angerer [1931*c*] for later advances.

(77) Mees [1947] p. 471. Even later indications of every stage of emulsion preparation are “infused with craft knowledge”: see Galison [1997] pp. 192f., who also thinks that the Gurney and Mott [1938] quantum theory of latent image production “played absolutely no role in the development of nuclear emulsions.”

(78) For Lorraine Daston's definition of this term, see here pp. 452ff. On even earlier occurrences of the idea to have natural phenomena (such as temperature changes or altering wind directions and strengths) register themselves, see Hoff and Geddes [1959] pp. 8f. who quote Christopher Wren's praise of a graph-tracing thermometer.

(79) On the history of photometric measurements see. e.g., E.C. Pickering [1885], Hearnshaw [1996], and Wolf-schmidt [1989]. For the more recent usage of CCD techniques cf. also DeVorkin [1985], Smith and Tartarewicz [1985], Edgerton and Lynch [1988].

(80) See Kirchhoff [1861/62]. Cf. also Hartley and Ramagc [1897] p. 185 for an example of later refinement of this scaling of line strengths in steel spectra according to a numerical scale of nine gradations.

(81) See Fraunhofer [1815*a*] pl. 2 and here Fig. 2.11, p. 35. Saillard and Cortial [1993] have shown that Fraunhofer's visual estimates for the relative intensities in the spectrum are quite well in accord with today's results for the intensity curve of a body at a temperature of about 6000°, coinciding with the curve of visual efficacity of a normal eye as standardized by the Commission Internationale dc I'9clairage in 1931.

(82) See Stoney [1868] pp. 21ff. and his table II.

(83) See Ångström [1867].

(84) Becker had studied at the Universities of Berlin and Bonn, where he submitted his Ph.D. thesis on problems of classical astronomy in 1882 (written under the guidance of R. Lipschitz and Schönfeld). In 1883 he became assistant at the Astronomisches Recheninstitut of the Berlin observatory, and in 1885 he changed over to an assistant position at the Dunecht Observatory in Scotland. From 1889 to 1893 he was assistant at the Edinburgh Observatory, and 1893–1935 he was Regius professor of astronomy at the University of Glasgow and director of the Glasgow Observatory.

(85) Becker [1890] p. 104.

(86) *Ibid*., p. 105. The coding system used to translate this scale into the five keys for each of the fingers on the left hand is also described.

(87) Cf., e.g. Holmes and Olesko in Wise (ed.) [1995], Hoff and Geddes [1959], [1962].

(88) For a detailed description of Langley's bolometer in its initial form see, e.g., Langley [1881], For later types see Langley [1900], Coblentz [1908] pp. 415ff., and R. Brashear in Bud and Warner (ed.) [1998] pp. 69–71. For a detailed study of Langley's research, based on his laboratory notebooks and other primary sources, see Loettgers [2000].

(89) Abbot [1958] p. 19.

(90) R.T.G. [1901] p. 352.

(91) Some instruction sheets for these assistants have been preserved. See, e.g., S.P. Langley: ‘Instructions for photo-bolometric work’, or entries in Langley's Waste-book no. 5, pp. 26–32. Cf. also Langley to Robert C. Child, 23 October 1895, both in the archives of the Smithsonian Institution, Washington, DC. I am grateful to Andrea Loettgers for having provided me with copies of these documents.

(92) These figures are mentioned in Langley's letter to one of his laboratory aids, R.C. Child, 30 January 1895 Smithsonian Archives (courtesy Dr Loettgers).

(93) See, for instance, Langley [1900] pp. 71ff., 105ff., Abbot [1932], [1958] pp. 19f., 23ff., Coblentz [1908] pp. 424ff. on the construction of sensitive galvanometers, and pp. 435f., 453f. on the physical reasons for the drift.

(94) The argument given in Langley [1900] p. 73: “for the convenience of the reader” is rather vague.

(95) Langley [1900] p. 73. Cf. also R.T.G. [1901] pp. 352f.

(96) Langley [1900] p. 74.

(97) Langley to Edward Charles Pickering, 21 March 1893 (HUA, UAV 630.17.7, box III).

(98) Langley to ‘Dear Sir’, 23 October 1894, Smithsonian Institution (courtesy of Dr Loettgers).

(99) *Ibid.* Fowle was the other assistant besides Wadsworth.

(100) See, e.g., Langley to R.C. Child, 30 January 1895 (Smithsonian Institution), p. 4: “I may mention that the final result is to be exhibited by comparison with the Higgs photograph of this region from the grating spectrum, which will be reduced by photography to the main scale of the bolograph”. For an example of a directive to omit comparison with photographed spectra in the earlier stages, see *idem*, p. 2: “being careful not to familiarize yourself with the region by any inspection of the actual spectrum or photograph of it.”

(101) See, e.g., Huggins [1891*b*] as quoted in Jones [1965] p. 130: “Among the ‘reapers’ of the spectroscopic harvest he mentions particularly Langley and his work on the Sun and the infrared of the spectrum, a map of which, automatically and reliably produced, Langley promised to make one of the first objects of his new observatory”. Cf. also *idem*, pp. 136f. for Langley's and Abbot's own descriptions of their work in similar terms.

(102) Cf. Abbot [1958] p. 19 (here quoted on p. 268), on the tracing of a bolometric graph in terms of a fully automated clockwork.

(103) According to Abbot and Freeman [1929] p. 3, lines were “considered provisionally veridical when found as deflections of similar form and similar setting in three or more holographs”. This comparison was done using a Warner and Swasey comparator, as described in Langley [1900] p. 64.

(104) Claudet [1848] p. 329.

(105) See Draper [1843*e*] pp. 401–15 and the accompanying plate, and Draper [1844*d*]. The underlying chemistry (today we would write it as: $H_2 + Cl_2 + \gamma \rightarrow 2H + 2Cl \rightarrow 2HCl$) had already been explored by Gay-Lussac and Thénard [1811/12]. Later Bunsen and Roscoe [1857–62] modified and improved the instrument under the name ‘actinometer’; see Boberlin [1993].

(106) See Draper [1843*e*] p. 407, [1844*d*] p. 5, table II, and [1844*a*] pp. 44f., 78ff., Boberlin [1993] pp. 58f. and Hentschel [2001*a*] on Draper's interpretation.

(107) See, e.g., Favre and Silbermann [1853] pl. III, fig. 37, who also indicated variations in this curve between the noon sun, a clear morning sky, and hazy evening light. See also Bunsen and Roscoe [1855–62] part 5 (1859), § 5, which indicates a slightly lower second maximum at the line J (in the nomenclature of Stokes [1862], whose map they had obtained prior to publication).

(108) See Jordan [1839], J. Herschel [1840*c*], Hunt [1845], Claudet [1848] pp. 329f. on these instruments as well as on his ‘photographometer’.

(109) See Bunsen and Roscoe [1855–62] part VI (1862), p. 538: “within very broad limits, the products of light intensity and insolation time equal the blackenings on chloride-of-silver paper of equal sensitivity”. Cf. also *idem*, p. 531 on F.P. Malagati and W.G. Hankel, and Boberlin [1993] pp. 195f. on T. von Grotthuß (1818) as precursors.

(110) See Roscoe [1863], and Hearnshaw [1996] p. 114 for this and a few other early astronomical applications of the reciprocity law.

(111) See, e.g., Abney [1882*a*], [1893], [1893/95], H.W. Vogel [1894] vol. II, pp. 65–79, or Angerer [1931*c*] pp. 164ff.

(112) After a certain degree of exposure has been reached, a photographic plate loses its photosensitivity and the contrary process sets in, sometimes leading to strange inversions of heavily exposed parts: see here p. 211 and references there.

(113) Schwarzschild had studied 1891–93 at the University of Strasbourg, and 1893–95 at the University of Munich, where he wrote his Ph.D. thesis under Hugo von Seeliger in 1896. In 1896–99 he was assistant at the Kuffner Observatory near Vienna. In 1899 he habilitated, and 1901–09 was professor of astronomy at the University of Göttingen. In 1909–16 he was director of the Astrophysikalisches Observatorium in Potsdam (succeeding H.C. Vogel). On Schwarzschild, who after the turn of the century studied problems of astrophysics such as formulating the theory governing the solar atmosphere and verifying gravitational redshift, see, e.g., Parkhurst [1916], Eddington [1917*b*], Hertzsprung [1917], Diecke [1975], and H.H. Voigt in Schwarzschild [1992] vol. 1.

(114) Cf. Schwarzschild [1992] vol. 2, part 6 on photographic photometry, esp. pp. 89ff., 273ff. Cf. also Stark [1911], Eberhard [1931], Tolansky [1947] pp. 243f., 258ff., and Habison in Hentschel and Wittmann (eds.) [2000] pp. 112ff.

(115) See, e.g., Wood [1908] for a practice-oriented description of this procedure which was already known to Piazzi Smyth and other spectrum photography pioneers in the late nineteenth century.

(116) See, e.g., von Angerer [1931*c*] pp. 164ff. for the details and refinements in the law of photochemical darkening; Brück [1936], Weaver [1946], Wolfschmidt [1989], Hearnshaw [1996] on the development of astronomical photometry; and Herrmann and Hoffmann [1976] on the interplay of photometry with the industrial developments in lighting engineering.

(117) See Hartmann [1899], esp. pp. 99ff. as well as Berl [1923] pp. 125f. and Eberhard [1931] pp. 440ff. on the built-in Lummer–Brodhun double-prism. Hartmann's microphotometer was built and distributed by Otto Toepfer in Potsdam, whose company merged with the Askania works in Berlin in 1919, which also sold this type of instrument: see Wolfschmidt [1989] p. 261.

(118) On this complaint, and a subsequent technical improvement of Hartmann's design, see Lehmann [1911].

(119) See Fabry [1910], whose apparatus was originally developed to determine the intrinsic brightness of the starlit sky, Meggers and Foote [1920], Dorgelo [1925] pp. 775f., von Angerer [1931*c*] p. 175, Hearnshaw [1996] pp. 149–60, and Habison in Hentschel and Wittmann (ed.) [2000] for some astronomical applications of this extrafocal photometry.

(120) See, e.g., Babcock and Moore [1947] pp. 4ff. for a tabular comparison of their scales of intensities differing by one unit for Rowland's classes 2, 3, and 8 for wavelengths ≤ 6300 Å.

(121) See, e.g., Brotherus [1911] on the hydrogen H_α and on the sodium D lines, or Koch [1911], [1913] on the cadmium line 6439 Å, and the Zeeman-split mercury line 5790 Å.

(122) See, e.g., Michelson [1891/921, [1903], Koch [1911] for a comparison of both measurement types, and Hentschel [1998*a*] § 5.4, for further literature.

(123) On the history of photoelectric effects see E. Becquerel's [1839*a*], Hallwachs [1888], Ostwald [1896] pp. 1084–7, Lange [1940] vol. 1, pp. 8–27, Rappaport [1959], Wiederkehr [1973], Wheaton [1978], Büttner [1999] chap. 9, and the references to primary literature given there.

(124) On the following see, e.g., Ornstein, Moll, and Burger [1932] pp. 38ff. Later types of spectrophotometers are described in Twyman [1951] chap. 5, Bud and Warner (ed.) [1998] pp. 458f.

(125) Their progress on photoelectric response in the ultraviolet and infrared spectrum range is delineated, e.g., in Elster and Geitel [1904], [1912], respectively, and [1914] provides their experimental demonstration of linear response. Cf. also Schweidler [1915], Wiederkehr [1973] pp. 98–100. On their biographies and their other researches, e.g., in atmospheric electricity, see also Wiechert [1921], Pohl [1923/24], and Fricke [1992].

(126) See Koch [1912], Dorgelo [1925] p. 776, and Ornstein, Moll, and Burger [1932] pp. 58–60. This early type of instrument initially was manufactured by Otto Toepfer in Potsdam, later also by the Askania works in Berlin-Friedenau and by A. Krüss in Hamburg: see also Wolfschmidt [1989] pp. 263f. and footnote 128 below.

(127) See Koch [1912] pp. 737–41 for various photometric curves taken from the same overexposed photographic plate before and after a chemical reduction in the overall degree of blackening, and *idem*, pp. 741ff. for his comparison of photometric curves of Fabry-Perot rings, generated with the Koch and the Hartmann microphotometers.

(128) See Goos [1921*b*] pp. 648f. On Goos's work in precision spectroscopy see also Hentschel [1997*c*] or [1998*a*] chap. 6; cf. also Hentschel [1992] or [1998] pp. 526ff. for Leonard Grebe's and Albert Bachem's application of this instrument in the experimental verification of gravitational redshift.

(129) See Koch and Goos [1922], This offer was made at the request of the Notgemeinschaft der Deutschen Wissenschaft in exchange for a generous grant given to the Hamburg department.

(130) See, e.g., Strohmeier [1937] or Wolfschmidt [1989] pp. 265f.

(131) See Baker [1924]. For examples of its use to estimate the continuous spectrum of stars and the effective temperatures of stars, see Sampson [1923], [1925], and here footnote 149 below.

(132) See, e.g., Moll [1913], and Ornstein, Moll, and Burger [1932] pp. 4–18 on the rapid-response Moll moving-coil galvanometer and his thermoelements; *idem*, pp. 60ff., Moll [1919], Dorgelo [1925] p. 777, and von Angerer [1931*c*] pp. 175ff. on Moll's microphotometer which was distributed by Kipp & Zonen in Delft as well as by E. Leybold's Nachfolger in Cologne.

(133) See again Ornstein, Moll, and Burger [1932] pp. 68–76. Koch [1913] pp. 121f. even quotes an error margin of ±0.001 mm for the determination of the center of a spectrum line, compared against the optimum of ±0.002 mm for visual registration.

(134) See, e.g., Kramers [1919], Landé [1921] (whose conventions lead to 2*j* for the multiplicity of *J*); Sommerfeld and Heisenberg [1922], Dorgelo [1925], esp. p. 784 on four intensity rules, Sommerfeld [1919*c*] pp. 580f., 649ff., and Sommerfeld and Hönl [1925] on these quantum theoretical calculations.

(135) On the predictions from wave mechanics see, e.g., Hönl [1925], Schrödinger [1926] 3rd notice, pp. 457ff., Sommerfeld [1929*b*] pp. 97ff. On the intensifying interplay between theory and experiment since 1915 see, e.g., Kragh [1984/85], and Hentschel [1998*a*] chap. 6.

(136) Merton had studied at Balliol College, Oxford, becoming lecturer for spectroscopy at King's College, London University 1916–19, then reader 1919–22, and professor 1923–35 of spectroscopy at Oxford, and fellow of Balliol College. After some research and work on inventions for the Royal Air Force during World War II, Merton became fellow of Eaton College at the University of Oxford 1945–63; he was also vice-president of the Royal Society, London 1941–56. On Merton see Hartley and Gabor [1970].

(137) Dorgelo studied under L.S. Ornstein at the University of Utrecht, became physics teacher at a Utrecht Gymnasium in 1920, then took a research position at Philips Gloeilampenfabrik in 1924, and was professor at the Delft Polytechnic 1927–56.

(138) See, e.g., Merton [1924], esp. p. 379 on the methods of preparing platinum wedges of such uniform density gradation, and on their absorption characteristics between 6000 and 2000 Å, von Angerer [1931*c*] pp. 172–4.

(139) See Dorgelo [1925] pp. 759ff., or Ornstein, Moll, and Burger [1932] pp. 77ff.

(140) In Planck's derivation, *e* is the electron's charge, *m* its mass, *c* the velocity of light. For wavelengths λ of visible light, the order of magnitude of this factor is approximately 10^{-4} in accordance with experimental results, such as, by Wilhelm Wien (1924).

(141) For derivations by Lorentz (1906), Lippich (1870), Pfaundler (1877), Rayleigh (1899), see the references in later survey articles by von Klüber [1927] and Redman [1938]

(142) For a good introductory textbook see Unsöld [1938] and further references there; for a semipopular account see Minnaert [1963] pp. 6ff. Among the later experimental contributions on spectrophotometry within astrophysics, let me just mention von Klüber [1927], Unsöld [1928]. Kienle [1930], ten Bruggencate [1939], [1944/47], ten Bruggencate and Houtgast [1939], [1940], Redman [1935], [1937], Thackeray [1935], Allen [1937], [1938], Shane [1941]. Cf. also the overviews by Brück [1936].

(143) Minnaert had first studied biology at the University of Ghent, then physics at Leyden and Utrecht, mostly under W.H. Julius and L.S. Ornstein. After the latter's death in 1924, Minnaert assumed the main responsibility for solar research at Utrecht, and defended his thesis on irregular refraction of light in 1925. From 1926 on he was ‘Privatdocent’ for astrophysics, and in 1937 he became professor of astronomy, as well as director of the university's observatory, a position he held until 1963. Minnaert, an active member of the International Astronomical Union, was awarded the Gold Medal of the Royal Astronomical Society in 1947 and the Bruce Medal of the Astronomical Society of the Pacific in 1951; see Minnaert [1963], de Jager [1970/71], [1974], Buning [1979].

(144) See Minnaert, Mulders, and Houtgast [1940]. On the preliminary studies see Minnaert [1927], Minnaert and Assenbergh [1929] containing the first curve of growth for Fraunhofer lines, Minnaert and Mulders [1930], [1931] on the effects of damping and Doppler shifts on line profiles, Minnaert and Houtgast [1936], [1938] on direct registration, and the retrospective account in Minnaert [1963] pp. 4ff.

(145) Houtgast had worked at the Philips Natuurk. Lab. in Eindhoven from 1927 to 1930, then decided to study physics at the University of Utrecht, 1930–37. From 1938 up to the outbreak of World War II he held an assistantship at the astrophysical observatory at Potsdam where he cooperated with Paul ten Bruggencate. In 1942 he submitted his Ph.D. dissertation on the variation of solar line profiles along the radius of the solar disk to Utrecht University where he later became lector in astronomy.

(146) See Minnaert and Houtgast [1938], esp. pp. 357f. Of course, T is by definition 1 if the transmission is 100%, and 0 if it is 0%.

(147) Minnaert [1963] p. 4. The *National Union Catalogue* lists at least 12 copies of Minnaert's atlas currently in the US: at UC Berkeley; Bloomington, Indiana; Charlotteville, Virginia; Haverford College; Univ. of Chicago; Univ. of Wisconsin, Madison; Library of Congress, and Smithsonian Institution, both in Washington, DC; and finally at Princeton University and Yale; another copy, not listed, is at the Harvard College Observatory Library.

(148) For explicit acknowledgment of the Utrecht atlas as a paradigm see, e.g. Griffin [1979] sheets ii, v.

(149) The preceding is based, e.g., on the summaries in Baker [1950], Greaves *et al.* [1955] as well as on a detailed note by Mary T. Brück to the author, dated May 2001. On Greaves, who became Astronomer Royal for Scotland and professor of astronomy at the University of Edinburgh in 1938, see also Jackson [1956], esp. pp. 148f. Baker had obtained his B.Sc. in 1912 at University College in Reading, and worked as assistant at the Royal Observatory of Edinburgh from 1913 until 1952; see Brück [1981]. On the photometer and densitometer, see above p. 280.

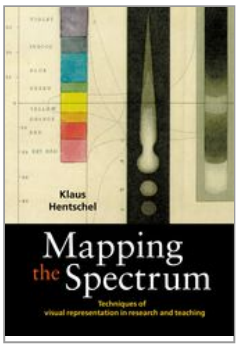
(150) An assistant in Edinburgh, Robert Wilson (born 1927), now emeritus professor of astronomy at the University College, London, discovered a hitherto undetected series of shallow helium lines, originating in the fifth quantum level in the spectra of Draper type Oe5: See Baker [1950], Wilson [1955], and Jackson [1956] p. 149.

(151) For a survey of this automated spectrophotometry in Edinburgh, see Thompson [1967], [1971].

(152) For surveys of chemistry and medicine, see Baird [1993] and Büttner [1999] chap. 10, respectively. Quantitative spectrochemistry is discussed here in § 8.7.

(153) On the following see Baird [1993] quoting its title; for a case study cf. Baird [1990], and Sturchio and Thackray [1988]. About the equally effective impact on analytic practice within medicine: Büttner [1999] chap. 10.

(154) According to Baird [1993] p. 287, the National Instrument Conference of 1947 had an attendance of 7000 persons and offered 139 instrument exhibits. Cf. here pp. 339 about the MIT event and the enormous scale reached by PITTCON in recent years.



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
Prof. Dr. Klaus Hentschel

Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

Research Applications: Pattern Recognition

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DOI:10.1093/acprof:oso/9780198509530.003.0008

Abstract and Keywords

Qualitative spectrum analysis was born in late 1859 through the cooperation of a first-class analytic chemist, Robert W. Bunsen, and a first-class physicist, Gustav R. Kirchhoff, in Heidelberg. Early spectrum maps displaying the fingerprints of the elements, especially alkaline and alkaline earth metals, are reproduced. The discovery of various new elements with this new analytic technique is also covered. The search for homologous spectra and the efforts to decipher the structures in series spectra, band spectra and stellar spectra are dealt with. Johann Jakob Balmer's creative transfer of perspectival Gestalt-vision is analysed in depth on the basis of hitherto unpublished sources from his papers in Basel. Finally, the much less straightforward development of quantitative emission spectroscopy is documented, which only became feasible in the 20th century.

Keywords: Robert W. Bunsen, Gustav R. Kirchhoff, Johann Jakob Balmer, series spectra, band spectra, qualitative spectrum analysis, quantitative spectrum analysis, stellar spectroscopy, homology

We have now arrived at the second part of the book that undertakes a more systematic analysis of the multifarious uses of the meticulous spectrum maps described thus far. This chapter will look at the skill of pattern recognition, which all practitioners in spectroscopy learned to master. The immense importance of this activity was felt well beyond the confines of spectroscopy proper. Spectrum analysis, series identification, and classification of stellar spectra all proved crucial for theoretical physics, analytic chemistry, and astrophysics in the early twentieth century.

8.1 Qualitative spectrum analysis: element identification

The dramatic success of spectrum analysis in 1859/60 caused this analytic technique to make quick inroads into the chemist’s or pharmacist’s laboratory, the astronomer’s observatory, the physician’s hospital, and even the judge’s court. Such multifarious applications as blood and steel analysis ultimately generated the need for attention to the new field in lab courses at high school and university. Typically this transfer from the research frontier to the school bench takes a decade or longer. In the case of qualitative spectrum analysis, it took considerably less. The most notable use of the new technique involved identifying the presence of the various elements. It led to the surprising finding that the metal lithium, for instance, hitherto considered quite rare, was among the more ubiquituous chemical elements. This example is given in a popular exposition of spectrum analysis by the then President of the British Association for the Advancement of Science, William B. Carpenter, in *Good Words*, a widely distributed religious journal.[155] Such rapid dissemination was certainly powered by the enthusiastic tone of the many introductory texts addressed to groups of all kinds after 1860 (see § 9.8 below). The news that now it was possible to decipher the chemical composition of the Sun and ultimately also of the stars spread fast: Who could fail to be impressed by the fact that only microscopic amounts of sodium ($3 \cdot 10^{-9}$g) were needed for detection of its characteristic yellow D lines in a Bunsen flame?[156] Or put in more familiar proportions: a mere teaspoon of salt in a full swimming pool. Now, using a simple pocket spectroscope, a steel caster could easily identify the exact instant **(p.291)** of decarbonization of molten steel, just before it loses its fluidity.[157] Previously, considerable skill had been required to ‘see’ a subtle change in color of the red-hot metal inside its vessel. All one had to do was notice when the CO bands in the spectrum were at the point of vanishing from among the many iron lines, just at the completion of the decarbonization process.[158] Similarly, chemical analysis of various gases and absorbing fluids like blood simply required the ability to distinguish the patterns formed by their line and band spectra.[159] Unharmful substances such as lithium, when injected into the bloodstream of a guinea pig, for instance, are easily detected spectroscopically. The spectroscope thus could be used to trace the lithium’s passage into the vascular and nonvascular tissue, thus greatly assisting physiological experimentation.[160]

This skill of pattern recognition had to be learned, and the primary medium was the spectral plate or map. Bunsen's map of the characteristic lines of six to ten elements, for instance, was frequently reprinted on a reduced scale in the many papers and books on spectrum analysis published since 1860.[161] It was also distributed in poster form by the publisher and manufacturer of chemical, pharmaceutical, and physical instruments George André Lenoir.[162] This large-scale version displaying the pure spectra of several of the chemical elements was intended for the laboratory wall so that a single glance at it from the spectroscope would suffice for comparison against the spectrum in the Bunsen flame. Lenoir's poster version found widespread distribution not only on the Continent. It also served as a welcome substitute for the original plates in the UK and in the US, where the original volumes or their plates were frequently unavailable.[163] The London instrument manufacturer John Browning also sold a whole list of different 'coloured charts' of spectra at a price between 3 shillings 6 pence for a black-and-white map and 7 shillings 6 pence for one in **(p.292)** color.[164] So did the scientific instrument makers E. Leybolds Nachfolger in Cologne, and Max Kohl in Chemnitz around 1913.[165] Around 1870, another London instrument maker, William Ladd, distributed a color map of the solar spectrum displaying about 500 absorption lines, many of them only discernible with a magnifying glass.[166] Some wall posters have survived as a part of instrument collections. Harvard still has one copy of Lenoir's color map of the alkaline spectra as well as a color chart of stellar spectra as recorded by Sir William Huggins, also printed by Lenoir with German captions. In its handsome glazed wooden framing, language obviously did not matter as much as the map itself.[167] Unfortunately, not many of these posters were transferred to archives or saved when a laboratory was refurbished and its maps discharged from active service. As is evident from photographs dating back to the 1890s (cf. Fig. 9.2 on p. 373), MIT, for instance, most certainly had quite a few of them, but apparently did not keep any.[168] A recent catalogue of a major American scientific instrument supplier confirms that even today these charts are still being sold, under the rubric Educational Optics.[169]

The crude print quality, comparatively speaking, of these wall-hanging representations is indicative. The point of these ‘charts’ was *not* to improve the accuracy of the representation (as was the case before, in the section on enlarging) but convenience. It freed experimenters from continually groping for a comparison spectrum map as a part of the laboratory routine. Few scientific representations have acquired such a canonical status in the laboratory (among them the periodic table in chemistry and physics, or the geological time scale with the sequence of eras in the geo-sciences) and few so often reproduced within such a short period.[170] Each of the various applications of spectrum analysis also developed its own traditional standard map. Whereas the map width as well as the number of depicted spectra depended much on the dispersion of the refractive instruments used in each specific subfield, common among all of them was the effort to emulate the general style of Bunsen’s chart.[171] The omnipresence of the Bunsen chart and other spectrum representations in the laboratories of the industrialized world made the spectrum into a symbol of a new **(p.293)** age. The technique of spectrum analysis was truly modern in the sense that it minimized actual contact with the material. While requiring only miniscule samples, it afforded hitherto undreamt-of sensitivity. Most spectacular perhaps was the new research avenue of solar and stellar chemistry, something that the philosopher Auguste Comte (1798–1857) had categorically excluded as impossible in principle, just a few decades before, in 1834.[172] And this all in one step instead of after a long and complicated series of traditional chemical analysis. This physicalization of chemical and—in part—medical research practice thus “in effect extend[ed] the senses and allow[ed] the analyst to observe molecular structure without the crudity of picking the molecule apart”.[173]

An initial wave of unrestrained enthusiasm, fueled by the discovery of several new elements which had revealed their presence as otherwise unidentifiable lines in mineral water and other samples,[174] was soon dampened when it became clear that it was not so easy to trace all the chemical elements. Sodium, lithium, strontium, or calcium were rather exceptional in already displaying their spectra in volatilized samples of a few hundred-thousandths of a microgram. The extreme sensitivity of some elements were bewildering enough for chemists. It was no less strange that others (including fluorine, chlorine, bromine, iodine, oxygen, nitrogen, sulphur, and selenium) failed to show any clear spectral fingerprint at all.[175] Another confusing factor was that the spectra changed drastically, depending on how they were generated, whether volatilized in a flame, an arc, or spark. When early efforts failed to transform the hitherto purely qualitative spectrum analysis into a quantitative technique, most chemists turned their backs on the field. Thus it remained the playground of physicists and astrophysicists for the next few decades, and the trend only swung back again after the belated breakthrough of quantitative spectrochemistry in the mid-1920s (see here § 8.7).

8.2 Strategies for series identification: Hinrichs, Balmer, and Rydberg

Speculative considerations about the distribution of lines in the spectra date nearly as far back as the observations themselves. Even at the very beginning of our narrative, in 1802, Wollaston justified his interpretation of the dark lines in the solar spectrum with their nearly regular distribution (see above, p. 33). Half a century later, in 1848, John William Draper thought he had found a clue to the physical cause of these Fraunhofer lines. Tabulating the wavelengths of the major dark lines from A to H in the solar spectrum (which were not **(p.294)** very accurately known at the time), he observed that the differences between them “are obviously very nearly as the whole numbers 1, 2, 4, 6, 7, 9, 10. This coincidence is far too striking to be merely accidental”. Because of the similarity of this series to an overtone series, he concluded that “the cause, whatever it may be, that produces these fixed lines is periodic in its action”.[176] Later also, in Victorian times, the search for the key to unlock the secret code of these strange line patterns remained a favorite pastime of many who concerned themselves with spectra. Despite several setbacks, such as Arthur Schuster’s demonstration in 1881 that the search for simple harmonic relations in spectra (which would have supported the optico-acoustical analogy) had utterly failed, fascination with the topic remained strong throughout the nineteenth century. In the following, I shall discuss two examples of the search for groups of related lines, or series as they were eventually called, one of which proved successful.

News about “the great discovery of Kirchhoff and Bunsen” traveled fast and during transmission it was adapted to local preferences and tastes. When it reached Gustav Dethlef Hinrichs (1836–1923) at Iowa State University, who today is best remembered for his somewhat speculative publications on *Absolute Atomic Weights and the Unity of Matter*, he became interested in the topic.[177] Hinrichs felt “sure that the dark lines of the elements would prove to be distributed according to simple laws, and that these laws might lead us to a knowledge of *the relative dimensions of the atoms*”[178] After a colleague lent him Kirchhoff’s two maps of 1861 and 1862 to study in more detail, he found his prior conviction confirmed. Not that Hinrichs ignored Kirchhoff’s caution about the arbitrariness of the scale used, but he discussed it away with the argument that for any realistic dispersion curve, a straight line fit would be a sufficient approximation as long as the wavelength interval was not too large: “within a small range equal differences on this scale must correspond to equal differences in wave length, for whatever the curve may be […], representing the wave-length as a function of Kirchhoff’s millimetre-scale, within such narrow limits the curve will coincide with its tangent.” Thus, in Hinrichs’s opinion, differences of wavelengths could be measured equally well in terms of differences between Kirchhoff’s scale numbers (in the following abbreviated as k followed by the number of Kirchhoff’s scale), so he worked with the latter from the very beginning.

He searched for groups of lines exhibiting “any order”. Given the open-mindedness of this approach, it is not surprising that he found many candidates. For instance, a certain group of lines identified by Kirchhoff as calcium lines and all of intensity 4 or 5, the lines K 2869.7, 2864.7, 2854.7, and 2834.2 had the intervals 5.0, 10.0, and 20.5, respectively, that is a relation of very nearly 1 : 2 : 4. As to the deviation of the last line’s k value, he commented as follows: “We see, the error is almost nothing—the last one might easily be conceived as the result of the increased range. Hence we find that the group is very regular, having a **(p.295)** principal difference of 5.0, or a simple multiple (here successive duplication) thereof.” After two other examples had also revealed similar relations of approximately 1 : 2, 1 : 3 : 2 : 8, and 2 : 2 : 1 : 4 : 1, he felt safe enough to make his first generalization: “The mutual distances of the different lines in each separate group are multiples of the smallest distance in such group.” Intercomparison among several such groups in the calcium spectrum then suggested a second generalization, that these intervals may be expressed in very simple (integral) numbers, and a third, which specified these differences to be the same if measured in terms of wavelengths “throughout the whole spectrum”.

Without further elaboration it is already clear that Hinrichs drew far-reaching generalizations on the basis of fairly skimpy empirical evidence. Cases that would have weakened or refuted the argument were repeatedly discussed away (“the spectrum of strontium, as given by Kirchhoff, is too deficient yet to be of any consequence”), and subsets that fit the ground rules were apparently selected at will (“the barium spectrum is more complete, but we have too few lines to discern the physical groups; therefore it seems best to rely on the more intense lines as corresponding ones”). However, even though Hinrichs’s tentative generalizations obviously did not hit the mark, I don’t think that it would be good history simply to dismiss his case as bad science. Not only was Hinrichs’s case typical of the contemporary research practice in that field and reasonably well received at the time,[179] but occasionally this strategy even worked quite well. Hinrichs’s rules are very similar to ones suggested in 1907 by Carl Runge to describe in a phenomenological way the many complicated magnetic line splittings known as the Zeeman effect. This time it turned out to be right, and amazingly so, since no one then had even an inkling as to how this anomalous effect came about.[180] So, contrary to the ‘disciplinary memory’ of Whig history, which has only preserved the few success stories, we must take Hinrichs’s efforts as an early example of a research strategy in frequent use in the late nineteenth century.[181] Hinrichs’s efforts turned out to be premature because his empirical basis was not yet firm enough; he also happened to choose the misleading Kirchhoff scale as a basis for his numerological trials.

Our second example regards a Swiss mathematics schoolteacher, Johann Jakob Balmer[182] (1825–1898). When the hydrogen spectrum was published in 1884, it was long taken to be a striking example of numerology, a lucky guess, a *Zahlenwunder*. Contrary to what is often asserted, however, Balmer did not simply borrow the purely numerological heuristics governing earlier approaches in order to interpret the hydrogen lines as optical harmonics.[183] Unlike physicists such as Stoney, who had been nurtured on the analogy of acoustics in optics **(p.296)** (cf. the following section), Balmer embarked on his analysis of series spectra from an entirely different mind set. It was precisely because he was free from this deeply engrained prejudice that he was able to see a different *Gestalt* in the meagre data initially available to him.[184] Balmer approached spectra with the eye of a geometrician used to teaching the rules of perspective. He chose a geometric construction based on the similar appearance of a spectral series to perspectivally shortened equidistant columns viewed from the side.[185] Thus his was not the mind of a Fourier analyst in search of optical analogies to harmonic overtone series. From his geometric vantage point, the convergence was located at the shortest wavelength λ_0, which is a clear *Gestalt* switch, an entirely new way of seeing these series.

Balmer probably started with a conventional plot of the four wavelengths λ_{1-4} of the hydrogen spectrum known to him from the literature.[186] Ångström's original determinations of the first four lines had been 6562.10, 4860.74, 4340.1, and 4101.2 × 10^{-10} m (only later did a local physicist inform Balmer about various other contemporary measurements).[187] Ignoring the decimal places for the moment, these four lines yielded decreasing intervals of roughly 1702, 520, and 239 units. To most people, these numbers would not have suggested any straightforward algebraic relation, but George Johnstone Stoney had already suggested in 1871 that the wavelengths of H_α, H_β, and H_δ were related by the factors 1/20, 1/27, and 1/32 of a fundamental line. Multiplying these by 36 yields: 36/20 = 9/5, 36/27 = 4/3, and 36/32 = 9/8. In addition, Balmer found out that the fourth line, H_λ, could also be linked to the other three if interpreted as 25/21 times a fundamental wavelength of 3645.6 Å.

The difference between the hydrogen wavelengths listed by Ångström in 1868, and the four wavelengths calculated according to this *Ansatz* came to less than 0.1 Å (i.e., 1/40 000 of the wavelength) and was thus well within the margin of error for these wavelength determinations. This sequence of four fractions (9/5, 4/3, 25/21, and 9/8) was not easily interpretable at first. But by multiplying the second and fourth of these fractions by 4/4, a numerical regularity emerged, hence: 9/5, 16/12, 25/21, and 36/32. All numerators became the squares of integers, and the respective denominators were obtained by subtracting 4 from each of these squares. Balmer thus wrote the fractions algebraically as

$$\frac{m^2}{(m^2 - n^2)}, \qquad (8.1)$$

where $n = 2$ and m = 3, 4, 5, and 6. From a purely numerical approach, this was quite far off the beaten track. From a geometric approach, however, these squared expressions and **(p.297)** reinterpreting 4 as 2^2 was quite natural.

At this point Balmer abandoned the one-dimensional numerical analysis of such intervals universally practiced by researchers up to that point. He turned instead to a two-dimensional, geometric reconceptualization: could these numbers λ_i be interpreted as the sides of quasi-Pythagorean triangles? As is shown in Figure 8.1, Balmer introduced a series of overlying right triangles. Their shared vertical side, or leg, is fixed at λ_0 and corresponds to the radius r of a circle whose center is the common origin of their upper acute angles.[188] The question was, what radius r allowed all the triangles to be drawn as quasi-Pythagorean triangles such that $\lambda_0^2 + \lambda_i^2 = \lambda^2$, with all λ_is multiples of a fundamental length λ_0? Could these multiplication factors be related to the ominous factors from the above analysis of hydrogen wavelengths?

Guided by this Pythagorean approach, Balmer linked the four known hydrogen lines H_α, H_β, H_γ, and H_δ to a single fundamental length, the "fundamental number of hydrogen" *(Grundzahl) h* = 3645.6 A by showing that $\lambda_i = f \cdot h$, where f = 9/5, 4/3, 25/21, and 9/8. Defining the base lengths from 0 to λ_1 as λ, and similarly to λ_2 as λ', etc., one obtains:

$$(\lambda)^2 = \lambda_0^2 + \lambda_1^2$$
$$(\lambda')^2 = \lambda_0^2 + \lambda_2^2$$
$$(\lambda'')^2 = \lambda_0^2 + \lambda_3^2,$$

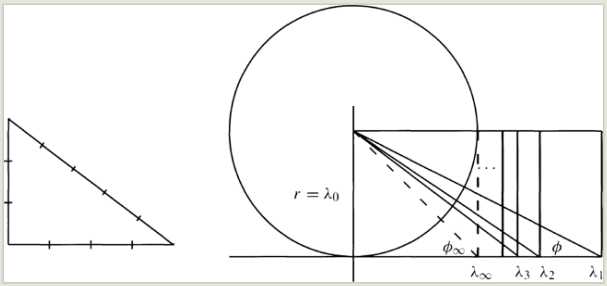


Fig. 8.1 Balmer's Pythagoraen approach to series lines. *Left:* Pythagorean triangle with the length of its leg 3 units, its base 4, and its hypotenus 5. *Right:* geometric reimerpretation of the hydrogen series, with the four known wavelengths λ_i plotted as bases of right triangles, whose acute angles originate from the focus of a circle of unknown radius and a point on the tangential base axis.

(p.298) and so on for the other values of λ_i obtained by observation. Thus the various coefficients mentioned above were easily reinterpretable as $(1/\cos)^2 = \sec^2$ of the angle ϕ between the x axis tangent to the circle and the hypotenuses of the various triangles cutting through the circle's center: $\sec^2(\phi) = \lambda^2/\lambda_1^2 = \lambda^2/(\lambda^2 - \lambda_0^2)$. Rename $\lambda_0 = n$ and $\lambda = m$ and you get: $\sec^2(\phi) = m^2/(m^2 - n^2)$, and thus precisely the form of Balmer's term (eqn 8.1). The change of angle ϕ up to the limiting value of $\phi_\infty = 90°$ and the corresponding series limit (the dashed vertical line tangential to the circle in Fig. 8.1) are easily visualizable and comprehensible within Balmer's geometric scheme.

Because eqn (8.1) worked so astonishingly well for m running up to 6, it was too tempting not to try it out for higher values of m as well and other values of n. The latter option is significant insofar as it implies that already in 1885 Balmer had envisioned the possibility of series other than the one with $n = 2$ (which was later renamed the Balmer series): “Hydrogen lines to which the equation $n =$ 3,4, etc. would apply and which might be designated as lines of third, fourth order, etc., do not appear in any of the spectra published until now; to become detectible, they would have to develop under entirely new temperature and pressure conditions.”[189] Thus a lack of data for the frequency ranges into which other values of n lead compelled Balmer to set this option aside.[190] Concentrating on the variation of m, he obtained:

$$\lambda_m = h \cdot m^2/(m^2 - 4). \qquad (8.2)$$

The wavelengths λ_m resulting from increasing integer values for m indicated spectrum lines not yet tabulated in any of the standard tables of the solar spectrum and to a theoretical series limit of $\lambda_\infty =: h = 3645.6$ Å in the ultraviolet. When Balmer turned to a local physicist, Prof Jacob Eduard Hagenbach-Bischoff (1833–1910), for help, the latter recalled two pertinent publications from around 1880. The stellar spectroscopist William Huggins had obtained gelatine dry-plate photographs of the spectra of white stars like *a* Lyrae, which exhibited twelve “very strong lines” in “remarkable agreement” not only in appearance, but also in their relative distances, which between any two adjacent lines decreased with increasing refrangibility. The backdrop of Huggins’s results was that he could not be sure whether all of these lines were emitted by one and the same substance—not even to speak of attributing them all to hydrogen. All that Huggins could say was: “The group possesses a distinctly symmetrical character. The suggestion presents itself whether these lines are not intimately connected with each other, and present the spectrum of one substance.”[191]

The photochemist Hermann Wilhelm Vogel, on the other hand, had found similar regularities in the ultraviolet part of hydrogen spectra excited by electrical discharge in a Geissler tube. To make sure that these new lines outside the spectral range covered in Ångström's atlas really belonged to the hydrogen spectrum, he filled the Geissler tube with **(p.299)** the purest form of hydrogen available (electrolytically produced) and took all due precautions to avoid contamination of the tube.[192] Despite the vast differences between the two light sources, Huggins's and Vogel's determinations of wavelengths agreed to within 0.5 Å on the first four new lines. They were recorded on gelatine dry plates, which according to Vogel were about 15 times as sensitive as the previously used wet plates. Huggins's measurements added six more lines because he had used quartz lenses and quartz or Iceland spar prisms whereas Vogel's normal flint-glass prism had absorbed the lines in the ultraviolet range.[193] Although the fit between their observations and Balmer's values, derived from the still somewhat speculative eqn (8.1), was far from perfect, the differences were reasonably small—in most cases less than 1 Å for Vogel's values, and up to 3.9 Å for Huggins's wavelengths.[194] By 1886, both Alfred Cornu in Paris and Gustav Müller at the Astrophysical Observatory in Potsdam had redetermined the wavelengths of hydrogen series lines with increased precision. Balmer's friend Hagenbach was quick to point out the astonishing fit between these accurate measurements and Balmer's calculations,[195] which, incidentally, withstood later, more accurate tests as well.

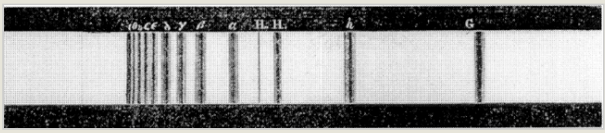


Fig. 8.2 Huggins's representation of the hydrogen series with twelve lines in the spectrum of α Lyrae as a frequency plot (highest wavelength leftmost). Wood engraving. From Huggins [1879*b*] p. 270.

A decade later, Balmer published another geometric interpretation of the law for the hydrogen series he had found a dozen years before (cf. Fig. 8.3). A series of equidistant points 0 to 10 are plotted on a line X', tangential to a circle at point O with a radius of two units. A series of lines through these points, all tangential to this same circle, touch the vertical axis running through O and A at points l_i, with $i \geq 3$ (the line H is parallel to the Y axis). The wavelengths λ_i, $i \geq 3$ are easily read off the diagram as proportional to the distances $a\alpha = \lambda_3$, $b\beta = \lambda_4$, etc. The diameter of the circle becomes the series' limit λ_∞.

Imagine an observer moving away from a column with diameter $A\ O$ along the X axis. Because of perspectival shortening, the apparent extension of the column in direction Y will decrease the farther the observer moves away from the column. Balmer 'saw' the sequence of progressively smaller intervals l_3, l_4, l_5 (measured along the Y axis from point O) in analogy to the decreasing wavelengths converging to a minimum wavelength λ_0 **(p.300)** equal to the diameter $O\ A$ of the column. *Qualitatively*, Fig. 8.3 immediately 'explains' the convergence of the sequence of intervals l with increasing distance from the column. But Balmer's geometric discovery was that the ratios of successive shortenings of the intervals l^i could be obtained *quantitatively* by the construction shown in the upper right quadrant of Fig. 8.3, with the radius of the circle set to 2 units, and the steps along the X axis increasing in integer units m from 3 on (the vertical dotted line at $m = 2$ indicates the tangent to the circle not intersecting at any point with the Y axis). In the upper left quadrant of the figure, Balmer plotted the resulting wavelengths α, β, γ, etc., as vertical lines rising from the X axis, and geometrically constructed their inverse values to obtain the frequencies α′, β′, γ′, etc., which, of course, increase as the wavelengths decrease, because $\upsilon = c/\lambda$. Whereas this geometric approach to the hydrogen series might appear as a tardy afterthought, published more than ten years after the actual discovery, unpublished sheets in the Balmer papers show that this geometric construction was more than a geometric reinterpretation of a result found otherwise. In one of them (see fig. 8.4 left), he was still experimenting with the **(p.301)** precise placement of the projection lines, whether they should not be tangential to an inner circle. In the figure to the right, he had already settled on the final form, but still calculated the various lengths in a rather involved manner, using squares and square roots of the right triangle's sides instead of the much easier method based on the secant and tangent of its inscribed angle θ. Also note that the radius of the larger of the two circles on the left part of Fig. 8.4 already has been assigned the value of 1823.8, i.e., $\lambda_0 = 3647.6$ Å, whereas the diameter of the circle on the right side of Fig. 8.4 has been assigned the value of 3421.091, which is 24.5 units lower than the estimate for the wavelength limit λ_0 published in his celebrated paper submitted to the Basel Naturforschende Gesellschaft. These two details indicate the likelihood that this sheet is one of the final stepping stones on the way to his series formula and thus dates from 1884.

In a later section on visual thinking I shall return to this topic and demonstrate that this construction was the direct result of Balmer's visual analogy, applying his technique of drawing perspectively shortened circles to the problem of the hydrogen lines (see here § 10.6, esp. Fig. 10.4, p. 444 on Balmer's tangent method). This geometric version of Balmer's law was, of course, still far removed from any real physical understanding of "the mysterious phenomena of the spectral lines". Balmer himself most readily admitted that "the final impression, which our mind involuntarily receives in contemplating these fundamental relations is that of a wonderful mechanism of nature, the functions of which are performed with never-failing certainty, though the mind can follow them only with **(p.302)** difficulty and with a humiliating sense of the incompleteness of its perception."[196]

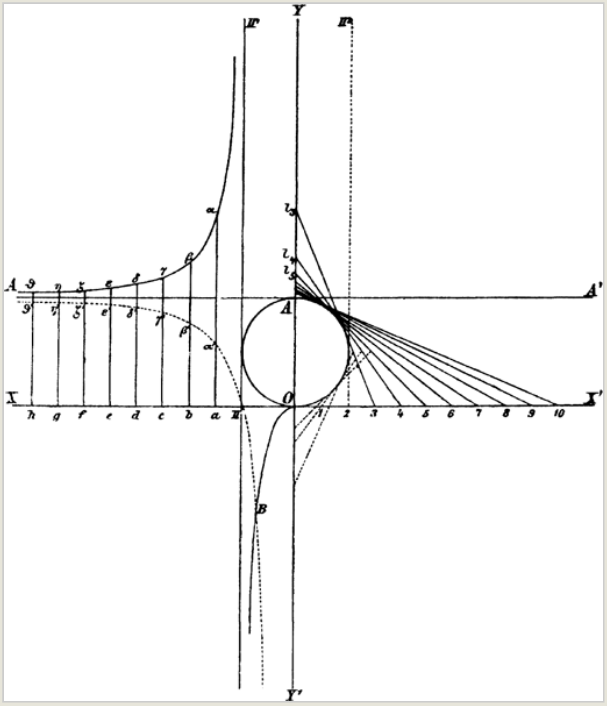


Fig. 8.3 A geometric approach to series lines. For details see the main text. From Balmer [1897] pl. VIII.

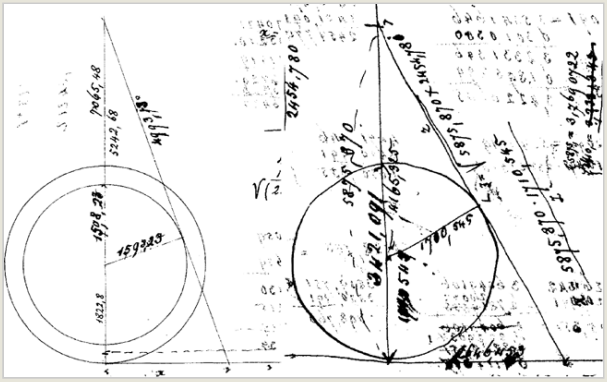


Fig. 8.4 Two hitherto unpublished sketches on a larger sheet from the Balmer papers with a bleed-through of unrelated calculations from the verso, undated. For commentary see the main text. From BÖB, Nachlass 133, folder no. 12, reproduced by permission.

In November 1889, the Swedish physicist Janne (Johannes) Rydberg (1854–1919) presented to the Stockholm Academy of Sciences the results of his examination of various relatively simple line spectra of alkali metals and alkaline earths. Notwithstanding the relatively poor quality of the spectroscopic data at his disposal,[197] his tabular surveys of differences between inverse wavelengths independently confirmed and extended Hartley's law of constant wave-number differences for various doublet and triplet lines of sodium, potassium, thallium, magnesium, calcium, zinc, cadmium and mercury. In order to get a better overview of the abundant data available, Rydberg changed his research strategy: he plotted the wave numbers of various line groups on millimeter graph paper, always paying special attention to the multiplet character of the spectral lines (cf. Fig. 8.5 for an example). Thus Rydberg collated series of lines with common characteristics, and distinguished three species of series: sharp (S), principal (P), and diffuse (D),[198] normally superimposed in one spectrum. The members of each series were double for alkalis and either single or triple for alkaline earths. Plotting the wave numbers n of these series lines along the ordinate as a function of a running number m on the abscissa revealed striking geometric regularities: neat parabolic curves resulted, which could be fitted to the following general formula:

$$n = n_0 - \frac{N_0}{(m + \mu)^2}, \qquad (8.3)$$

where N_0 = 109 721.6 cm^{-1}, and no, μ are fitting parameters differing for each series.[199] Because the second term diminishes with increasing m, no acts as a so-called series limit, against which higher terms in each series converge for $m \to \infty$. As Fig. 8.5 also illustrates, the various parabolic curves exhibit family resemblances in that several could be transformed into one another by a simple shift in the x or y direction.[200]

(p.303)

(p.304) Figure 8.5 exemplifies a visual approach employing large-scale graphics that led Ryd-berg to find the series formula (eqn 8.3) which happened to work amazingly well even for series he had not taken into consideration when first suggesting it in 1889. It is amazing that Rydberg's procedure was quite similar to the one that Balmer had recommended in an—unpublished—manuscript on the hydrogen series. In a passage that dealt with the question of how to extend his hydrogen series formula to other elements, Balmer suggested drawing the hydrogen series as well as the wavelengths of prospective series of other elements on graph paper using a logarithmic scale. Both drawings should then be shifted relative to each other until anticipated coincidences emerged. In order not to fall into the trap of accidental fits, Balmer recommended that these drawings be 1 meter in size.[201] Rydberg worked with wave numbers, i.e., in a mode of representation proportional to frequency, whereas Balmer always adhered to the wavelength mode. Yet they agreed in their pursuit of visual strategies for detecting correspondences between the series of hydrogen-like substances.

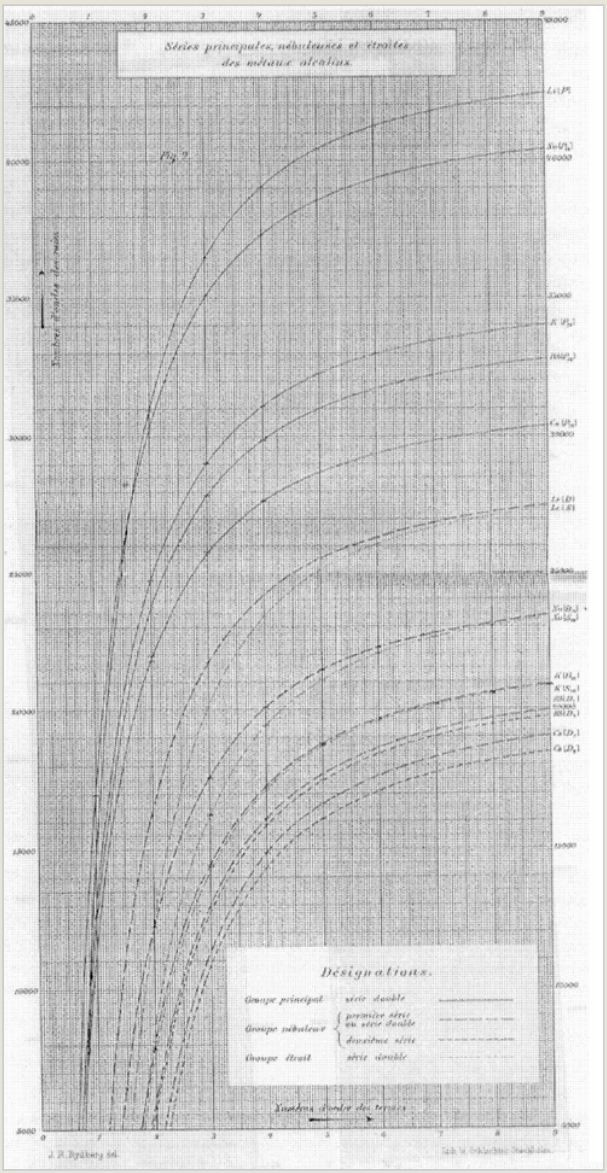


Fig. 8.5 Next page: Rydberg's plot of the wave numbers *n* of spectrum lines for the alkaline metal series as a function of a running term *m*. D: diffuse, S: sharp, and P: principal series. Known wave numbers (in units $10^8/\lambda$) are entered as short horizontal lines. Lithograph by W. Schlachter. From Rydberg [1889/90] pl. I.

Further progress was made with even more generalized phenomenological series formulas, to which Heinrich Kayser, Friedrich Paschen and Carl Runge in Germany, and Henri Deslandres in Paris also contributed. In his Gottingen Ph.D. dissertation, the Swiss physicist Walther Ritz (1878–1909) formulated his combination principle, according to which all frequencies of series lines could be written as the difference between two terms characterizing two other series lines.[202] But deeper understanding of this strange finding, as well as of *series* spectra in a more general sense, remained at an impasse until the rise of quantum theory in the twentieth century.[203] As late as 1908, Arno Bergmann identified new series in the infrared spectra of various alkaline emission spectra by applying a combination of phenomenological strategies:[204]

> • erasure of all known series lines from his spectrum photograph, thereby forming a kind of residual class of unexplained lines;
> • close visual inspection of the features of these residual lines (line strength, doublet or triplet structures, satellites) with the aim of singling out a subclass of lines sharing several common characteristics;
> • checking for series relations among recurrent line pairs, or for other regularities in the line distributions;
> • numerical testing of candidate spectrum series by applying the standard formulas of Balmer, Rydberg, Kayser-Runge, and Ritz; and finally
> • optimization of the various constants allowed in these formulas, once one was found to fit the regularities overall in a satisfactory way.

Until 1913 the decisive step in this process of series identification in carefully recorded and measured spectra remained visual inspection and *Gestalt* recognition. Calculation only confirmed and strengthened the regularities found by eye. It was, so to speak, a perfect example of ‘visual reasoning’ in the sense of Arnheim:

(p.305)

> The six newly measured caesium lines […] form three pairs whose differences in vibration I have found to be the values 96, 93.4, 97.5, which may be considered constant within the margin of measurement error. In the ultrared caesium spectrum another line pair […] exists that does not fit into any of the existing series either, but whose vibration difference comes to 93.3, in excellent agreement with the above values. If one adds this pair, *the regular sequence of the four pairs immediately strikes the eye, upon looking at the spectrograms.* As in the series, the diffuseness of the lines increases towards the shorter wavelengths while the intervals between the pairs regularly diminish. It was therefore probable that we were dealing with a new series […] The calculations have confirmed this suspicion.[205]

Up to now I have been emphasizing the phenomenological aspects of the search for series spectra. This was in conscious counterpoint to the standard accounts, which usually portray all the work on spectrum series as intimately linked to the effort to crack the constitution of the atom. Although overemphasized, these efforts undoubtedly did exist, and to understand them properly we must go back three or four decades.

8.3 Stoney's search for harmonics and wavelength reciprocals

The idea that the lines in the spectra of gases are somehow correlated with the periodic motions of the individual molecules or atoms had occurred to several researchers in the 1860s and 1870s. It was George Johnstone Stoney (1826–1911), formerly professor of natural philosophy at Queen's College in Galway and, at the time when he first espoused the idea in 1868, Secretary of Queen's University in Ireland, who embarked on the most serious inquiry.[206] A pupil of the Dublin school of mathematical physics, he employed the calculational techniques imported to Ireland from the École Polytechnique.[207] In the mode of a Fourier-analysis he decomposed the complex motion of a gas molecule into a sum of terms of the type $C_n \sin(nx + \alpha_n)$ where C_n is the amplitude to the nth order of vibration, x an abbreviation for $2\pi t/\tau$, τ being the period of one complete revolution of a single oscillation, and α_n the phase shift of the nth harmonic. In 1871 Stoney came to the conclusion that "one periodic motion in the molecules of the incandescent gas may be the source of a whole series of lines in the spectrum of the gas […] these vibrations will coexist in a state of mechanical independence of one another, if the disturbance be not too violent for the legitimate employment of the principle of the superposition of small motions."[208] There only remained explaining why some—in fact the overwhelming majority—of the coefficients of the Fourier decomposition C_n vanished. As a consequence no spectrum was a regular sequence of a fundamental tone (i.e., base line) plus all subsequent harmonics, just a small subset of the harmonics. After reduction to vacuum values, for instance, the hydrogen series spectrum, the three known lines h = 4102.37 Å, F = 4862.11 Å, and C = **(p.306)** 6563.93 Å, could be interpreted as the "32nd, 27th and 20th harmonics of a fundamental vibration whose wave-length in vacuo is 0.13127714 of a millimetre."[209]

To investigate this question, Stoney launched a major research program to systematically map “interrupted” (i.e., band) spectra. Their copious supply of lines and obvious but as yet unexplained regular spacings, held much promise. In his spare time, he and his assistant James Emerson Reynolds (1843–1920), then keeper at the mineralogy department and analyzer at the Royal Dublin Society, measured the absorption and emission spectra of various gases. Their equipment included the Society’s multi-prism spectroscope and other laboratory apparatus “for keeping an abundant supply of the ox[y]hydrogen lime light”, the continuous light source for generating the absorption spectra.[210] But they encountered an unexpected obstacle: Several gaseous absorption spectra had just too many extremely closely lying lines, and there seemed to be several distinct superpositionings, so that it was hard to follow the “apparently confused maze of lines, from which it is difficult to pick out those that are to be referred to any one motion in the gas.” They finally settled on the absorption spectrum of chlorochromic anhydride (CrO_2Cl_2) which gave a spectrum of the “required simplicity”. To plot their findings, Stoney hit upon the ingenious idea of using the reciprocals of the wavelengths, because “this scale of inverse wave-lengths has the great convenience for our present purposes that a system of lines with periodic times that are harmonics of one periodic time will be equidistant upon it; it has also the minor convenience that it much more closely resembles the spectrum, as seen, than the scale of direct wavelengths used by Ångström in his classic map.” Such an inverse-wavelength graph would reveal most clearly any hint of harmonic relations of the type Stoney was looking for, in the form of equidistant intervals between adjacent lines. This is because in this scale the nth harmonic i_n will simply equal $(n + 1) \cdot k$, with $1/k$ standing for the wavelength of the fundamental motion. Needless to say, Stoney succeeded in interpreting a good 31 absorption lines, measured to 0.1 Å, as harmonics of one fundamental line at the low end of the inverse wavelengths. The order of the harmonics ranged between 5 and 105, and all outstanding differences between measurement and calculation fell within the limits of observational error, between +0.7 and —0.9 Å. More regularities were present in the distribution of line intensities within the full spectrum of 105 lines, with repeated occurrences of a particular pattern “consisting of five lines, a very dark one followed by a very light one, then two of medium intensity, and then another very light one”.

Stoney’s review of the advantages of an inverse scale at a meeting of the British Association for the Advancement of Science in 1871 prompted the formation of a committee, consisting of William Huggins, Warren De La Rue, Norman Lockyer, William Marshall Watts, and George Johnstone Stoney, to compile a catalogue of tables of such ‘wave numbers’ for all major lines of the spectrum. This task took eight years to complete. Of course, this major effort was invested because others besides Stoney were also convinced of the **(p.307)** possibility of detecting “harmonic relations” in maps plotted according to these oscillation or wave numbers, as they were also called; “for rays that are harmonically related are therein represented in the simplest form that is practicable […] in the map by a series of equidistant lines.”[211] Enthusiasm was so great that the few skeptics preferred to remain silent about any reservations, at least in public.[212]

But just as this compilation was coming to an end, the Manchester physicist Arthur Schuster raised serious doubts about the prospects of the search for harmonic relations in the spectrum, in which he himself had been enrolled in the past.[213] He could demonstrate mathematically that for any set of random numbers it would always be possible to ‘reduce’ them to subsets of harmonic overtones, provided the harmonics were allowed to run into the hundreds and thousands, as they did during the quite inflationary use of this method during the 1870s. While his papers certainly did not immediately halt all efforts of linking these mysterious spectra to the atomic structure, it certainly applied the brakes on the then so assiduous hunt for simple harmonic series:[214]

> We know a great deal more about the forces which produce the vibrations of sound than about those which produce the vibrations of light. To find out the different tunes sent out by a vibrating system is a problem which may or may not be solvable in certain special cases, but it would baffle the most skilful mathematician to solve the inverse problem and to find out the shape of a bell by means of the sounds which it is capable of sending out. And this is the problem which ultimately spectroscopy hopes to solve in the case of light.[215]

8.4 Homologous spectra: Lecoq de Boisbaudran, Ciamician, and Hartley

The search for patterns discussed in the last two sections related to series lines in one and the same spectrum. This endeavor, slightly discredited though it was by 1880, was but one example of pattern searches. What about similarities between the spectra of the different elements? This question guided the contemporary researches of the French spectroscopist Paul Émile Lecoq de Boisbaudran[216] (1838–1912). He was struck by the similarities between the characteristic spectra of alkaline and alkaline earth metals, as depicted in Kirchhoff and Bunsen's color plate. Most notably, the spectrum of rubidium seemed to be exactly **(p.308)** like that of potassium with a slight shift towards the red. Two years later, after studying the chemical spectra of various elements, he deposited a sealed note at the Parisian Académie des Sciences in which he defined a general rule that the higher the chemical element's atomic weight was, the farther the corresponding spectral lines moved toward the red.[217] The main purpose of such a *pli cacheté* was to ensure priority of a specific discovery without having to disclose it to rival researchers until it was deemed ripe for publication. In this case another five years elapsed before this tentative rule appeared in the *Comptes Rendus* of the Paris Academy.[218]

Lecoq de Boisbaudran described this type of similarity between the spectra of different elements as 'homologous,' defined as 'possessing an affinity depending on structure or constitution'. Being theoretically minded, he did not confine himself to expounding this empirical rule. He developed a model to explain why such a shift in wavelength should occur in relation to atomic weight. According to it, a molecule is analogous to a pendulum, with the molecule's mass corresponding to the pendulum length which determines the eigenfrequency of its characteristic oscillation modes:

> So the molecule plays the role of a pendulum, and like the latter, returns to its position of equilibrium with greater rapidity, the greater is the interval. But the force tending to return the molecule to its center of motion is the æther's reaction to the molecule, which reaction is constant for equivalent molecular masses but which varies when the ratio between the masses, the æther, and the molecule have changed. […] The result is that a heavier molecule will be returned to its center of equilibrium with less energy than another and consequently it will take more time to complete one oscillation around this point: its wavelength will be larger.[219]

Atoms of different weights do indeed differ in their modes of vibration, and do so quite differently from molecular systems: “Light, which arrives to us from the depths of space, brings us the table of reactions of these bodies which we do not possess and perhaps never shall! It is up to us to learn to read it.”[220] Seen in this light, spectra suddenly gain new importance as a key to the atomic constitution of luminescent matter—a key for which the lock still had to be found. As a first step in this direction, Lecoq de Boisbaudran tried to identify the ‘elementary’ line groups as the ones retaining their overall *Gestalt* in homologous spectra despite displacement, augmentation, diminution, and possibly also truncation. The following sample sketches in Fig. 8.6 reveal how strongly his perception was molded by theory: the band spectrum of nitrogen gas *{azote)* and the line spectrum barium chloride. The observed band spectrum agreed with the predicted one only to the extent that the supposed third and fourth harmonics were in the same spectrum range but differed widely with respect to line spacing. But that apparently did not worry him much; **(p.309)** nor did the absence of the third harmonic of the line pattern labeled γ, α, δ, β, and ε of BaCl, as calculated from the observed grouping interpreted as its fourth harmonic. It was sufficient proof for him that at least *some* spectrum lines appeared where he had predicted, based on theoretical calculations.[221] And he was by no means alone in entertaining this optimistic view. In 1872 the Academy of Sciences awarded him the Prix Bordin (valued at 3000 francs) for experimental or analytical work contributing the most toward establishing the theory behind spectrum lines.[222]

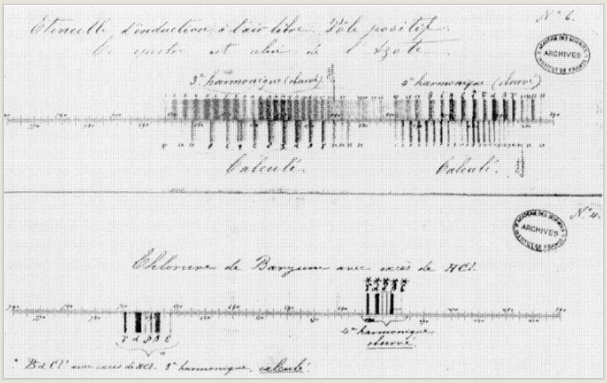


Fig. 8.6 Lecoq de Boisbaudran's pencil and ink sketches of the N2 band spectrum (top) and BaCl line spectrum (bottom). From AASP, dossier Prix Bordin 1872, reproduced by permission.

These ‘raies primitives’ (labeled with Greek characters) and their purported harmonics (usually indicated with a prime or asterisk) also feature in Lecoq’s meticulous atlas of luminous spectra which appeared in 1874. However, this atlas and accompanying text volume omitted most of the theoretical modeling and interpretation of his findings, in conformance with the then prevailing style of presenting empirical results.[223] Gone are the graphical **(p.310)** comparisons between calculated and observed features; it is only their phenomenological appearance that is portrayed in—outstanding—engravings made by the Academy’s specialist Pierre Dulos (see here Fig. 4.6, p. 118 for one example of his masterful work, and p. 143 on the engraver). Lecoq’s atlas was widely praised as an extraordinarily faithful representation of the appearance of spectra at the low dispersion available to chemists and others using only simple single-prism spectroscopes. It also helped that Lecoq scrupulously recorded the spectra of each element then known under various observing conditions for flame, spark, and absorption spectra.[224] In a sense, then, Lecoq de Boisbaudran’s *Spectres lumineux* marked the fusion of the spectroscopic traditions of condensing (cf. here § 3.3) and portraiture (cf. here § 4.5), aiming at the most abstract depiction possible of the observer’s field of view.

Following the discovery of gallium in 1875, Lecoq de Boisbaudran himself turned to mineralogical and chemical applications of spectroscopy,[225] possibly partly in response to declining enthusiasm for his claims and growing skepticism about his hypotheses.[226] But the tree he had planted bore fruit elsewhere. His work inspired the Italian chemist Giacomo Luigi Ciamician[227] (1857–1922), at that time a doctoral student at the physical laboratory of the Vienna Polytechnic. Initially he had taken up spectroscopy in order to contribute to the ongoing discussions about the differences and similarities between emission spectra of the elements and their chemical compounds.[228] But he could do no more than confirm the view of Helmholtz and several others, who had already linked line spectra with atoms, and band spectra with molecules.[229] Ciamician was struck by the surprising similarities between the spectra of different elements such as zinc and cadmium, which both exhibit a second-order emission spectrum composed of four strong lines of similar distribution. Isolated similarities of this sort had already been pointed to earlier, most notably by Mitscherlich and Lecoq de Boisbaudran, but Ciamician was able to systematize the earlier **(p.311)** observations and avoid being trapped by too superficial regularities that later proved not to hold generally. Most importantly, Ciamician could not confirm Lecoq de Boisbaudran’s rule in all its simplicity, as these shifts were not only variant in degree, but in some cases even in direction. Nevertheless, he was able to qualify the rule by claiming that the degree of shift depended not on the atomic weight, but on the respective element’s free chemical energy.

Ciamician's **law of homology** thus stated that *grosso modo* spectra of chemical elements in one and the same group of Mendeleev's periodic table exhibit similar spectra only differently shifted towards one of the extremes, even though in some cases certain lines or line groups seemed to be omitted.[230] Remarkably, the existing maps of emission spectra, published by Huggins and Thalén for metallic elements and by Salet for nonmetallic elements, were insufficient for Ciamician's purposes. Lines he identified as characteristic for a given element group were missing, others were of the wrong intensity, but most disturbing was the presence of other lines Ciamician deemed irrelevant. What he needed were charts limited to his characteristic line groups, listed in homological order to highlight the similarities—all this was very much in the spirit of Bunsen and Kirchhoff's spectroscopic fingerprints discussed earlier (cf. pp. 47 and 290).[231]

He found, for instance, that carbon, boron, and magnesium all have the same typical line spectrum, i.e., three strong lines, the middle one a triplet, appearing on the chief fluted band of their low-temperature spectrum (which incidentally was also similar for all three elements). Likewise, the oxygen group (O, S, Se, Te) yielded a characteristic line pattern, although a much more complex one in that it was composed of 15 little spectrum line groups. With increasing atomic weight, this pattern of 30–40 lines simply shifted towards one end of the spectrum, with the spectra of selenium and tellurium almost indistinguishable. Ciamician could identify only one characteristic line feature for the nitrogen group (N, P, As, Sb), with nitrogen itself showing some additional superstructure not recurring in the heavier elements of its group, but strangely similar to the more refrangible part of the oxygen spectrum. He identified fluorine as the prototype for the halogen group, whose spectrum most clearly showed the characteristic line pattern of this column in the periodic system, with four red lines labeled α to δ so precisely alike for Fl, Cl, Br, and I, that it was scarcely necessary to redraw them but for the slight displacement. δ constituted two strong lines occurring in all the elements within this chemical family, which with increasing atomic weight likewise exhibited diminishing features of oxygen-like line patterns.

By 1880 he had extended these homologies to the spectra of 20 elements and a great many of their compounds.[232] Time and again, characteristic line groups from the oxygen **(p.312)** spectrum were mixed within the emission line spectra of other elements.[233] Thus a special role was attributed to this element of atomic number 16, quite in line with the rule of multiples of 8 at the core of the periodic table.[234] Hence Ciamician's 'law of homology' went beyond superficial analogies between the spectra of various elements, suggesting a more profound connection between all the elements still awaiting exploration by the chemists of the day. The spectroscope, Ciamician hoped, might not only serve as a handy tool for rapid identification of chemical substances, but also as the key to clues about the composition of the atom (which was perhaps not as indivisible as commonly thought) and its types of motion.[235] His enthusiasm was not catching, though. In an obituary of Ciamician we read that "his conclusions were far in advance of their time, and it is small wonder that even Mendeleev and W[ilhel]m Ostwald judged them as fanciful."[236]

The Irish chemist Walter Noel Hartley[237] (1846–1913), demonstrator and later professor of chemistry at the Royal College of Science in Dublin, also enrolled in this research program in the early 1880s. The central part of the optical spectrum having already been exploited, he decided to devote closer examination to the ultraviolet range of the spectrum, which had just been explored photographically by a handful of researchers, including Cornu, Adeney, Liveing, Dewar, and himself.[238] One of his papers contains three plates displaying spectrum photographs in their original length of 10 cm, reproduced by the Woodbury Type Printing Company in London. They give an excellent idea of the obtainable quality at the time, including the unevenness of the lines, residual problems with focus, and the poor sensitivity of dry plates in the visible part of the spectrum. Nevertheless, Hartley decided to have some of the best spectra enlarged to the gigantic size of 36 × 28 inches.[239] Comparing these substantially enlarged photographs of the ultraviolet spectrum of the "elementary bodies", Hartley discovered remarkable homologies between the line groups in the spectra of a handful of chemical elements. Since these homologies showed a recurrent pattern of spectral line groups with interstices between adjacent lines diminishing **(p.313)** as the wavelength decreased, Hartley deviated from the practice of his precursors Lecoq de Boisbaudran and Ciamician, who had mapped prismatic spectra either without any further transformation or according to wavelength. Hartley chose instead to apply reciprocals of the wavelength λ. Using the Oscillation frequencies' $\upsilon = c/\lambda$ already advocated by Stoney (see the previous section), he expected that these successive interstices would be of the same order of magnitude.[240] This suspicion was to some degree confirmed in his paper of 1883 for the elements magnesium, zinc, copper, silver, silicon, boron, and aluminium, relying on his own measurements as far as possible, and otherwise referring *inter alia* to those of Lecoq de Boisbaudran or Mascart, as well as to a recently compiled table of

oscillation frequencies published in the *Report of the British Association* for 1878. Quite similarly to Hinrichs two decades earlier, Hartley then calculated the consecutive differences between adjacent pairs of spectral lines for each series and came up with a whole slew of homology relations, some of them very convincing—such as those between magnesium and cadmium whose intervals for a quintuplet group related as follows: Mg – 2 : 2 : 3 : 1 and Cd – 44 : 48 : 74 : 20. Other spectra, though, were riddled with anomalies and discrepancies: zinc and silicon, for instance, which also had such a quintuplet group and were chemically related, had quite different intervals: Zn – 18 : 21 : 14 : 4 and Si – 8 : 8 : 7 : 12. Despite these occasional deviations, there were still many striking homologies between specific line groups within the spectra of certain "natural groups of chemical elements" he had singled out on the basis of their "peculiar spectrum [with] certain lines and groups of lines recur[ring] with decrease or increase of wave-length for differences in the spectra of different elements of any one group."[241] Thus copper and silver, as well as magnesium, zinc, and cadmium formed such natural groups of the elements, because of their characteristic sequences of singlets, doublets, triplets, "quadruples," and "quintuplets" in their spectra (cf. line groups a, b, c, d, and e in Fig. 8.7). As Lecoq de Boisbaudran had observed before him, within each natural family of elements, as the atomic weight increased, the characteristic groups seemed to shift more and more towards the red end of the spectrum.[242]

Besides these homologies between spectra of different elements, Hartley also noted some striking recurrent patterns within the spectrum of a single element: most notably the three similar triplets in the cadmium spectrum (b_1, b_2, and b_3 in Fig. 8.7). Hartley consequently felt confident enough to evaluate his paper as "a considerable addition to the body of evidence in support of the view that elements whose atomic weights differ by a constant quantity, and whose chemical character is similar, are truly homologous, or in other words, are the same kind of matter in different states of condensation."[243] Put otherwise, he suspected that these iterative line groups in the spectrum of a chemical element indicated resonances of certain subatomic constituents, not unlike the 'proto-elements' postulated in Lockyer's contemporary (nonstandard) dissociation theory, to which Hartley alluded in **(p.314)** his closing words.[244] These speculations about a subatomic structure of the chemical elements were premature, of course, and led nowhere at the time. Hartley's law of constant wave-number differences, and his attention to the multiplet structure of these lines as another criterion for their grouping in 'series', however, proved instrumental in the continued search for patterns in line spectra. But its deeper theoretical underpinnings had to wait another 30 years.[245]

8.5 The green CO band: Piazzi Smyth and Alexander Herschel 1883

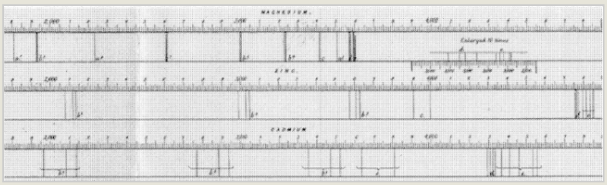
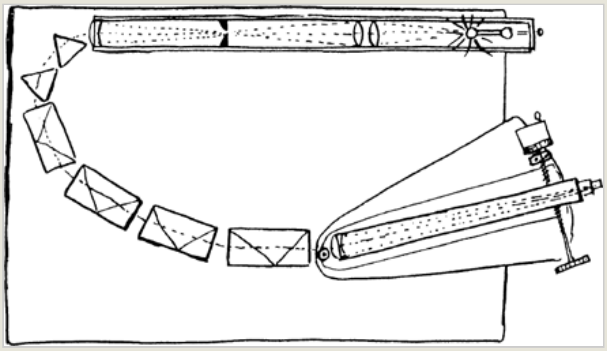


Fig. 8.7 Homologies in the spectra of magnesium, zinc, and cadmium: a refers to singlets, c to doublets, b to triplets, d to quartets, and e to quintets. From Hartley [1883*b*] pl. 1. Note that the scale refers to “oscillation frequencies” in units of 10 oscillations per mm.

A new, detailed representation of an interesting segment of the spectrum could cause quite a stir. This is evident in Alexander Stewart Herschel’s[246] (1836–1907) response to Charles Piazzi Smyth’s micrometric measures of gaseous spectra under very high dispersion. The spectroscope used was composed of nine carbon-bisulphide fluid prisms. Unfortunately, their refractive index is highly temperature sensitive, so Piazzi Smyth was disappointed to find that his wavelength measures were not reproducible.[247] Fortunately, his *relative* measures of the various line distances in the CO band were less affected by this uncertainty in the absolute wavelength values.

(p.315) From one of his notebooks, we learn a great deal more about his telescope micrometer and the attached recording barrel. It was rotated by means of a small handle (the little ring-shaped attachment off the rim of the barrel in Fig. 8.8) in a plane perpendicular to the drawing plane.[248]



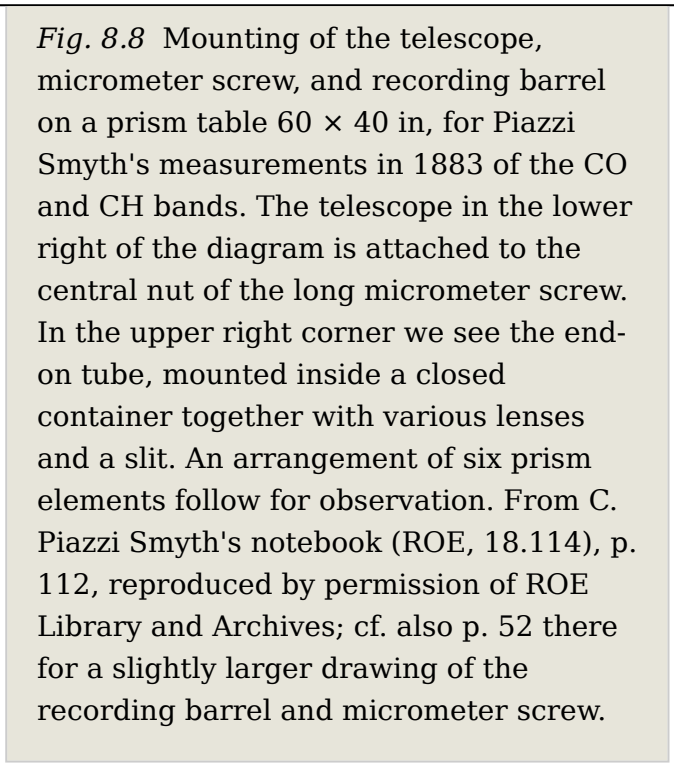


Fig. 8.8 Mounting of the telescope, micrometer screw, and recording barrel on a prism table 60 × 40 in, for Piazzi Smyth's measurements in 1883 of the CO and CH bands. The telescope in the lower right of the diagram is attached to the central nut of the long micrometer screw. In the upper right corner we see the end-on tube, mounted inside a closed container together with various lenses and a slit. An arrangement of six prism elements follow for observation. From C. Piazzi Smyth's notebook (ROE, 18.114), p. 112, reproduced by permission of ROE Library and Archives; cf. also p. 52 there for a slightly larger drawing of the recording barrel and micrometer screw.

The prism arrangements were usually set “in the morning to any desired part of the spectrum, intended to be looked at, at night, and are then well covered up with gilded wood covers and thick cloth and left to settle and acquire equal temperatures, before observing.”[249] This setup was so sensitive that a change of 1 degree angular deflection (i.e., nearly twice the field of view in the telescope, but only one 1/60 of the total dispersion of approx. 60° from A to H), corresponded to 2.3 full revolutions of the micrometer screw.[250] The error margin for the readings was estimated to be in the order of 0.005 revolutions of the screw, but Piazzi Smyth was also aware that “the variations from day to day (probably from temp.)” were much higher, namely in the order of 0.020 revolutions.[251] Although a **(p.316)** source of serious concern for precision spectrometry up to the early twentieth century, it was irrelevant when measurements were restricted to a short time interval at approximately constant temperature. The disadvantage of this high-resolution setup was that only relatively short segments of the spectrum could be measured: the reading barrel was only 3.4 inches long which limited it to 16 revolutions in one direction, corresponding to less than seven degrees. Thus it was out of the question to map longer regions of the solar spectrum, and Piazzi Smyth concluded that “the most useful cases of micrometrical differences to be observed with it at this time, are the linelets composing the bands of CO and CH; and each of these bands is generally comprised within 5 revolutions of the screw.”[252] Despite this high dispersion the light intensity was sufficient because of the specially designed end-on vacuum tube, whose electrically generated light was not ‘spectralysed’ (as Herschel wrote) from the side as in conventional Geissler tubes,[253] but aligned with the tube’s main axis, thus substantially intensifying the total amount of available light. These end-on tubes were initially built by the Paris instrument maker Jules Salleron.[254] By 1883, his main supplier for gas tubes was the instrument maker Louis Paschal Casella (1838–1901) in London, the actual manufacture of the fragile tubes being done by his son Charles F. Casella.[255]

Unfortunately, no further details about Piazzi Smyth's measurements of these bands have been preserved; presumably these notebook pages had been torn out for mailing, as several pages in the notebook are missing.[256] Upon seeing Piazzi Smyth's raw data recording taken with this high-resolution instrument in November 1883, Herschel, at that time professor of physics at Durham College in Newcastle, wrote an enthusiastic letter about **(p.317)** the green band of CO (at 5813 Å or 49 000 wave numbers per British inch), which was appended to Piazzi Smyth's paper eventually published in the *Transactions of the Royal Society of Edinburgh* in 1887:

> The chart of the green band's lines is beautiful; it is quite a page of the spectrum itself much more clearly laid down, I am sure, than I have ever seen the tribe of linelets, and I'm astonished how you can have both discovered and plotted so many perfectly.
>
> You have far surpassed the sight you gave me last, I find, of the CO band, by dividing 'broad' and plenty of the fine lines too, into pairs and triplets. This is a real triumph, that I couldn't well believe possible, when I discovered it by trying to recognize your new map in the drawing and measures that I took […] There is a profusion of new dissections of the band that you have managed now to supply for its anatomy![257]

But far more was involved than the aesthetic pleasure of resolving the details of something that had previously been vaguely described as 'broad', 'winged', or at best as a 'united pair'. This aesthetic thrill certainly was Piazzi Smyth's motive (cf. § 10.9) for "unravelling the mazy linelet systems of those familiar spectra's bands". But Alexander Herschel, grandson of the world-renowned astronomer William Herschel, went for something bigger. When he entered spectroscopy in the late 1860s, he seems to have been mostly interested in spectra as a tool for chemical identification. By 1880 he was attracted by the prospect of finding homologies between the emission spectra of elements belonging to the same group in Mendeleev's periodic system,[258] or between the many spectrum bands of compound gases such as CO, CH, or CN.[259] In an undated fragmentary letter (most likely written in mid-April 1880), we read that Herschel suspected a common difference or modulus in these bands, which were so striking in appearance from the perfect regularity in the spacings between adjacent linelets:

> The intervals themselves between the 5 strong lines of the Citron group are not equal. But the three differences of the four intervals are 74, 52 & 28, which is near enough to 75, 50 & 25 to answer very satisfactorily to the supposed common base of wave-frequency of 12.5 or 12.6 in the linelets of the band. The interval itself between the last two of the five lines is 250 wave nos. to an inch (or 10 intervals of 25), and the wave nos. of all the five lines are within one or two units of either a round hundred or one if its quarters 25, 50 or 75. The same ‘base’ of 25 is noticeable pretty distinctly in the two intervals between the three strong ‘green-band’ lines of the Blow-pipe flame.

But his hopes of finding an indubitable example of the long-sought harmonics in spectra were in vain, and by 17 April he had to admit: “As to the theory of relations among wave numbers of a given substance’s spectrum lines, I believe that it is wholly unapproached yet and that a very large field of observations lies open to discover what they really are; perhaps an almost insurmountable one; and it is pretty plain at all events that it is [a] well **(p.318)** nigh inexhaustible theme to follow out!”[260] In 1883, Herschel was still hunting for the supposedly in-built, but hidden mathematical rule that would connect the various lines of a spectrum band. And in this search for patterns he ultimately succeeded:

> And then Io TRIUMPHE! in searching over the spaces of my ‘readings’ to identify your lines with, I lighted luckily *on the key* of the construction, which is simplicity itself, and couldn’t well be exceeded in the exactness with which your new map reveals it. *Lux in tenebris*, what a happy and glorious release you have disclosed to all our uncertainties![261]

Two essential ingredients in the mix led to this success: (i) Herschel's tenacious talent for pattern recognition and (ii) the high resolution of Piazzi Smyth's map. As to the second point, Piazzi Smyth had measured and plotted the b group at an unprecedented resolution and, following the British tradition inspired by the earlier searches for harmonic ratios,[262] according to wave numbers ~ 1/λ, not wavelengths λ.[263] Of equal importance was Piazzi Smyth's distinction between two different groups of lines within the CO band, namely fairly intense main lines and fainter split lines interspersed in-between. As I have argued earlier (cf. § 4.5), this skill of identifying family resemblances among spectrum lines was closely linked to the tradition of spectroscopic 'portraiture', of which Piazzi Smyth was such an outspoken exponent. At any rate, this differentiation between singlets and doublets, as they are now termed, was the 'open sesame' to identification of the pattern, because as soon as Herschel focused on the main lines, he spotted a very regular increase in the interspacings that could actually be described as a stepwise widening of the interval between each line n and its immediate neighbor $n + 1$, as n times the interval between line numbers 1 and 2 (if numbered from the left, that is, from the red end of the band). Having once incorporated all the main lines into such a scheme, he could concentrate on the split lines, whereupon it became fairly obvious that they too were distributed according to a similar rule, just shifted slightly towards the red relative to the main lines. In Herschel's words: "the 'leaders' form a scale in chief by themselves, and a little distance preceding it is just another such scale of fainter twins, overlying the former scale."[264]

In his effusive and jubilant communication to Piazzi Smyth about this discovery, Herschel even devised a neat way of illustrating this pattern, which was molded by the calculational techniques of his time. As Andrew Warwick has shown in an informative paper about the calculational techniques used in the late nineteenth century, straight-edge rulers **(p.319)** played an important part in the daily practice of both theoreticians and applied scientists. It is precisely this kind of graphic method of problem-solving that lay behind the technology Herschel used to illustrate the structural pattern of the CO band. He took a strip of cardboard as long as Piazzi Smyth's detailed drawing of the CO band, aligned it along the lower edge of the spectrum, and marked on it all the positions of the prominent main lines. He thus copied the pattern of regularly increasing line distances as integral multiples of the smallest distance. Next he shifted the cardboard towards the left along the spectral map and suddenly, at one point, its marks matched up with all the remaining split lines:

> The result was, to my joyful surprise that it *accounts instantly and in toto for every* single line of the band laid down on your map. The band is *simply two exactly similar* single-rank line progressions laid over each other displacing one of them slightly on the other; while one consists of single strong lines, the other is formed of fainter, closely double ones.[265]

This is a nice example of a *Gestalt* switch or a restructuring, as psychologists also call it.[266] A spectral region that had always been considered messy and ill-understood was suddenly transformed into a rigidly structured pattern of superimposed grids, each of which obeyed a very simple rule of constitution. The impenetrable jungle of the b band had turned into what experimental psychologists call a 'good' *Gestalt*,[267] i.e., an easily recognizable configuration of lines with a 'simple' inner structure:

> Instead of being, therefore, a linelet band of the most curiously involved *complexity*, as it at first sight looks by its 'crossing' lines and close pack of crowded lines near the front edge, the ruled CO green band is really *the very simplest* in its mode of construction that I *think* has yet been met in spectroscopy. The way in which your sharp resolution of the two 'crossing' lines themselves into a minute triplet and a minute doublet respectively agrees with the conjunction is by itself a wonderful corroboration of the structure. But without the clear and *precise* resolution *of all its lines throughout* with the most accurate autographic measurement that you have effected, it would evidently have been quite impossible to recognize and establish it in its microscopic mixture.[268]

As Herschel's cardboard ruler certainly could not be included in the Edinburgh *Transactions*, Piazzi Smyth had to resort to a different, more static means of conveying an idea of Herschel's pattern decoding. His plate 31 included the observational spectrum plotted as a function of wave number, not wavelength (thus following Hartley's advice, see above p. 313). Furthermore, he indicated the arithmetic progression of both the series of strong **(p.320)** main lines and faint split lines above and below this full spectrum, as would follow if the intervals were precisely integral multiples of the distance between line nos. 1 and 2. In addition, in the lowest part of the map, he plotted both parts of the spectrum one above the other (that is with the main lines reset ten units back). This last plot is particularly helpful in illustrating both the 'homology' of the two line groups and the remaining minor discrepancies, such as slight shifts between lines. Despite these remaining discrepancies, the plot made abundantly clear how good the overall fit was between the split spectrum and the main line spectrum, with several of the doublets even in the 15th and 16th ordinal still perfectly symmetrically placed as compared with the main spectrum singlets.

Taken as a difference equation, the geometric law governing the increase in line distances, gauged to a frequency scale, translates into the following functional relation:

$$\frac{\Delta \nu[m]}{\Delta m} \simeq \frac{\Delta \frac{1}{\lambda[m]}}{\Delta m} \sim m \Rightarrow \nu[m] = a + bm^2,$$

with m as a running number, and b a constant coefficient, whose sign determines whether the band develops into high or low frequencies. This is precisely the first law of band spectra as established independently by Henri Deslandres (1853–1948) in Paris in 1886 for the band systems of N_2, NO, CN, O_2, OH, and CH.[269] When measuring the precise location of various band heads, Deslandres noted further that they in turn were quadratically spaced: $v[n] = A - Cn^2$, with A the frequency to which the bands of this system converged, and C a uniform second difference. Even though it remained a mystery why these empirical regularities held in fair enough approximation for many band spectra, they served as a kind of “sorting device”, bringing about “a sense of organization to a structure which outwardly was just a jumble of lines.”[270]

8.6 The oxygen band doublets: George Higgs 1893

Alexander Herschel’s unveiling of the hidden rule governing the sequence of lines in the green CO band was a strong incentive for others to pursue this avenue of research as well. One example is the amateur astronomer George Higgs, whom we have encountered in the context of photographic maps of the solar spectrum (see here p. 239). For his atlas of more than 100 photographs of all regions of the visible spectrum with its infrared and ultraviolet extensions,[271] he chose not Herschel’s wave-number plot, but a wavelength plot. The reason for this was simply that his work did not stem from the Victorian tradition of harmonic relations. It sprung from the tradition of ‘normal’ photographic maps of the solar spectrum, originating with Ångström’s map and climaxing in Rowland’s celebrated photographic map issued in 1886 and 1888 (see here § 6.9).

(p.321) Unlike Rowland, who had also studied the B and D lines as well as the carbon bands in the solar spectrum but never published any of his attempts to ‘rationalize’ the band structure,[272] Higgs could not resist this temptation. He supplemented his elaborate photographic atlas with a plate linking his *extensive* endeavor to the *intensive* search for patterns occupying so many of his contemporaries. Plate 89 of Higgs’s set from 1894 provides a “representation of the geometrical construction of the oxygen bands in the solar spectrum” which actually shared many things in common with Herschel’s analysis from about ten years earlier. The oxygen band (Fraunhofer’s B), depicted in a wavelength plot in the upper part of his diagram, is divided into two different line categories: a primary series of stronger doublets, and a “secondary train of thinner, sharply defined doublets”, which could be “traced on the photographic print [only] to about the 12th position [and] was not previously known to exist.”[273] In both series the intervals between consecutively numbered lines increase steadily. To illustrate this (see Fig. 8.9), he plotted the wavelengths of the components of the atmospheric oxygen band at 690 nm as a function of their ordinal number and linked the points by means of a parabolic curve with the vertex at the origin of the band near 6867 Å. So once again a geometrical mode of representation paved the way towards the phenomenological fitting formula for each series,

$$\lambda = V + \frac{(2n + c)^2}{L}, \qquad (8.4)$$

with V the vertex of the parabolic curve, n a running number, c a constant depending on the wavelength values of V and the first line of a series, and L a constant determining the parabola's shape. Each band was decomposed into its head and train, each composed of doublet lines, thus into four series altogether. Higgs's plate gives only a numerical comparison between measured wavelengths and those calculated on the basis of eqn (8.4) for about 23 lines. The accompanying paper applied this formula to about 200 other lines belonging to the oxygen bands A, B, and α. He claimed an excellent match between 'theory' (that is, his phenomenological formula), and experiment (i.e., his own micrometric measurements of wavelengths up to 0.01 Å), with the discrepancies between computed and observed positions not exceeding 0.015 Å for the α and B bands, and 0.05 Å for the A band.[274]

Well, spectroscopists with heavy experimentalist leanings had a quite different opinion about the validity of Higgs's claims. In their view, too much hinged on the precision of the wavelength values. According to Heinrich Kayser, Higgs and the many other spectroscopists who followed this research avenue, relied far too much on the absolute correctness of these values, which practitioners like himself knew enough not to trust, especially with respect to the absolute values. When confronted with a similarly speculative paper by another British spectroscopist in Edinburgh around 1910, Kayser reacted skeptically:

(p.322)

> I just want to say one thing: I warned Mr Hicks *[sic]* about relying too much on Kayser's figures. No one knows better than I that they are of very mediocre accuracy; as they are, to a large part, my first efforts in this field and only gradually does one learn how to take measurements. In any event, it would seem very questionable to me if he considered the hundredths of Ångström correct, let alone take into account the thousandths.– Because Hicks builds his hypothesis precisely on these latter entirely tentative figures, the decision was, if never explicitly stated, already made for knowledgeable persons.[275]

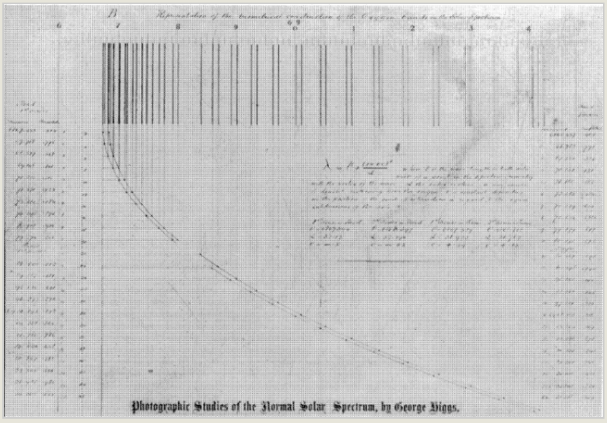


Fig. 8.9 Higgs's wavelength plot of the oxygen band at 6900 Å. The top row is scaled between 6867 and 6948 in normal wavelength mode. Underneath, the respective positions of the doublet lines are plotted as a function of a running variable from 2 to 46, thus revealing the neat parabolic shape of the resulting curve. See the main text about the formula in the center. From Higgs [1894] pl. 89.

Quite apart from the issue of numerical precision in wavelength determinations, Higgs's analysis downplayed the problem of the gap in the band structure below $n = 22$ by simply skipping to a different series of running numbers at this position. As fastidious in his measurements as Rowland was, he certainly noticed this gap, and unlike Higgs, was not willing to accept that the lines on one side of a gap formed a series which, if continued, lay in-between the lines on the other side. Whereas Deslandres (just as Fortrat, 25 years later) nevertheless tried to fit a continuous series, Rowland preferred to drop the issue, publishing his photographs, but never offering *any* interpretation of this band's structure.[276]

(p.323) If we recast Higgs's formula (eqn 8.4) in terms of a 1 /λ expression, we come up with a power series expansion like

$$\frac{1}{\lambda} = \frac{1}{V + \frac{(2n+c)^2}{L}} \simeq C + \frac{C'}{\lambda^2} + \frac{C''}{\lambda^4} + \cdots \qquad (8.5)$$

which is certainly far less simple than Herschel's geometrical composition rule molded in terms of his wave-number plot. Historians of science want to understand their actors in the light of their own time, so we must suppress our retrospective preference for the wave-number plot (or equivalently, the frequency plot) because of its direct relation to the energy levels via $E = h\nu$, which neither Higgs nor Herschel could have known about. But we see how much the tradition of representation, in which the search for patterns in spectra is embedded, actually affected the conclusions ultimately reached. Both Higgs and Herschel attempted to arrive at 'simple' construction rules for the spectral bands studied, and both ended up with fitting formulas of the type: distance ~ const + const′/n^2. They just happened to differ in the modes of representation chosen—Higgs opting for a δ-plot, and Herschel for a 1 /λ-plot. This conflict resurfaced time and again.[277] Higgs and Rowland counted among those who wanted to minimize the transitional steps between the photographic recording of the spectrum lines and the production of the map; because diffraction gratings yield normal spectra, they opted for the wavelength plot. On the other hand there were the "series men", who wanted to use these maps solely for detecting series relations. Because they suspected the existence of harmonic overtones analogous to those found in acoustics, these spectroscopists preferred a 1 /λ-plot, or wave-number plot, proportional to the frequencies $\nu = c/\lambda$.

Let me clarify one point with regard to the physical interpretation of band spectra: by no means did A. Herschel's explication of the constitution of the green CO band, nor Higgs's account of the "geometric construction" of the oxygen A, B, and α bands in any way imply an understanding of what the physical origin of these band structures might be. Nevertheless, their analyses constituted a major improvement in the phenomenological description in many areas of spectroscopy. A more profound explanatory theory had to await the twentieth century.[278]

8.7 Quantitative emission spectroscopy

Whereas *qualitative* spectrum analysis got a head start in the early years of the 1860s (see above pp. 45ff. and 290ff.), its *quantitative* counterpart had a much more difficult time of it. As late as 1910, the doyen of German spectroscopy, Heinrich Kayser, pronounced all foregoing efforts futile.[279] This despite the simplicity of its underlying idea: that the **(p.324)** intensity of the spectrum lines of each chemical element (or of the spectrum bands of each molecule) is, *ceteris paribus*, dependent on the number of radiation-emitting atoms (or molecules).[280] If a test substance contains two or more different chemicals, each of them will (under suitable conditions of excitation) emit its own set of spectrum lines or bands. Four different strategies grew out of this basic idea for inferring the chemical concentrations of the constituent elements in the spectrum of an unknown substance:

(1) determining the absolute intensity of emission or absorption lines of a selected element in the spectrum;
(2) measuring the time span during which certain spectral lines appear in the flame or arc spectrum before vanishing again upon complete volatilization of the material;
(3) analyzing the exact shape of characteristic spectrum lines (e.g., total width, apparent length, asymmetry, inversion, or wavelength shifts);
(4) comparing the test spectrum against a set of prepared composite spectra of a reference substance with differing known amounts of other admixtures.

Strategy (1) is, historically speaking, the oldest of the three, and also the most straightforward way of implementing the basic idea. Just two years after the breakthrough of qualitative spectrum analysis, W.A. Miller, at that time an assayer of the Royal Mint in London, tried to photograph the spectra of slightly different alloys of gold and silver in the hope of finding a practicable way of assaying gold.[281] Strategies (2) and (3) soon proved too unreliable and were discarded by 1880.[282] Strategy (1), on the contrary, was taken up repeatedly by various spectroscopists and chemists, who worked on mineralogical specimens, determining the mineral content of drinking water, or the analysis of steel.[283] Interest grew after 1884 when the professor of chemistry at the Royal College of Science in Dublin, Walter Noel Hartley, whom we have already met in the discussion about homologous spectra (see p. 312), experimentally confirmed a monotonic decrease in the number of spectrum lines with a corresponding lowering of the chemical's concentration in the spark.[284] Hartley's result was valid as long as the electric parameters for the generation of the spark, the distance **(p.325)** between his graphite electrodes, and all other instrumental conditions were faithfully retained. Hartley invested great energy in optimizing his spectrograph, in order to document his findings as clearly as possible. He devised a "method of photographing the ultraviolet spectra of metals, including on one plate, accurately focused and sharp impressions of all lines lying between the least and the most refrangible rays capable of acting on bromide of

silver."[285] The key to his quartz spectrograph design, which was adopted in all later spectrographic work in the ultraviolet, was tilting the photographic plate. Instead of mounting it perpendicular to the optical axis (as was the general practice), Hartley took into account that within his recording range the difference in focal length between a ray in the green region of the visible spectrum, and one at the end of the near-ultraviolet (approximately 2200 Å) was as much as six inches. He knew from a paper by Stokes that, in principle, the locus of the foci formed "the arc of a curve, or nearly a straight line, lying very obliquely to the axles of the pencils coming through the lens".[286] Even so, experiments showed that, in order to obtain an image in good focus, it was sufficient to pivot the photographic plane around its central vertical axis, without any further bending necessary. The precise angle of this "side-swing", which varied between 19° and 21° for quartz prisms of 60°, had to be found experimentally by means of trial exposures.[287] From his gelatino-bromide photographs of the blue, violet, and near-ultraviolet spark spectra generated off graphite electrodes soaked in a saline solution, Hartley was able to conclude that "the effect of diluting solutions of metallic salts is first to weaken and attenuate the metallic lines, then with a more extensive dilution to shorten them, the length of the longest and strongest lines generally decreasing until they finally disappear."[288] Thus, the spectrum lines of a given chemical element did not diminish equally upon dilution. Weak lines disappeared relatively soon, while a few others remained visible until the last detectable chemical traces of the element were gone. These last lines to vanish, usually among the strongest in an element's line spectrum, he termed "persistent lines". By a stepwise reduction of the concentration of 14 metals dissolved in hydrochloric acid, Hartley could identify and tabulate the barely visible spectrum lines, and the ones just disappeared (for each concentration). Any spectrum of a sample with an unknown amount of these metals, generated under the same spark conditions, could thus easily be compared to identify the respective level of concentration yielding the most closely similar spectrum. Because of the roughly logarithmic ratio of line intensity to quantity, a great range of concentrations could be covered, from 1 % to 0.000 000 01 % (or 1 part in 10 000 000 000 of solution) for magnesium, and between 1 % and 0.001 or at least **(p.326)** 0.01 % for all the other metal solutions.[289] The Dublin chemist James Holms Pollok[290] (1868–1916) developed an elaborate nomenclature for the sensitive spectrum strong solutions lines of metals in solution, to indicate the minimum concentration in which they were still visible when photographed with a medium-size quartz spectrograph:

Tab. 8.1 Pollok's nomenclature for the sensitive spectrum lines of metals in solution, as photographed with a medium quartz spectrograph. Based on Pollok [1907] p. 189.

line	still visible with –	but not visible with –
τ	metal	strong solutions
σ	strong solutions	1 % solutions
φ	1 % solutions	0.1% solutions
χ	0.1 % solutions	0.01 % solutions
ψ	0.01 % solutions	0.001 % solutions
ω	0.001 % solutions	

Slightly later, in 1894, totally independently of Hartley, Comte Arnaud (Antoine Alfred Xavier Louis) de Gramont[291] (1861–1923) also started to work along these lines. While conducting spectroscopic examinations of mineralogical samples for his thesis, he noticed a strange effect when he added condensers (in order of magnitude 0.02 to 0.002 μ*F*) to the ac circuit generating the spark. The spectra of sparks off the surface of alloys or off fused pulverized masses did not display any of the metalloid bands, consisting only of superposed line spectra of the various other constituent elements.[292] Around the turn of the century he realized that a further simplification of this ‘dissociation spectrum’ (as he called these superpositioned spectra) could be obtained by adding a self-induction coil to the electric circuit generating the short spark. A suitably chosen self-inductance very effectively suppresses the strong band spectrum of air, which is otherwise disturbingly superposed on the spectrogram.[293] Having begun to analyze these spectra purely by eye, he continued using photography, which extended the spectral range into the line-rich near-ultraviolet.[294] Solid samples were mounted on a specially designed spark stand to make them into the actual electrodes. De Gramont’s spark stand had plenty of regulating screws for adjustment of the spark, in order to limit its length to 2 mm and to assure its coaxial ity with the optical axis of the spectroscope and slit. When spectroscopically examining liquids, he generated the sparks between drops formed at the extremities of two intricate capillary tubes, thus avoiding **(p.327)** unwanted spectrum lines from electrode material.[295] Nonconducting substances were examined in the form of fused salts: that is, the sample was pulverized and mixed with an alkaline salt, then compressed and put into a powerfully heated small crucible which served as the second electrode for the spark. Much of his work seems to have been done with a large crown-glass spectrograph custom-manufactured at Adam Hilger’s instrument workshop in London according to de Gramont’s own specifications. But de Gramont developed other prototypes as well, including a simple spectroscope with a double prism and an ocular that could be exchanged with a photographic plate,[296] and medium-size spectrographs with quartz and Icelandic calcite prisms, suitable for work in the near ultraviolet at low dispersion.[297] The Hilger spectrograph with optics made out of a special type of crown glass called ‘uviol’ permitted spectroscopic photography up to the lead line 3176.6 Å. De Gramont’s quartz-optics

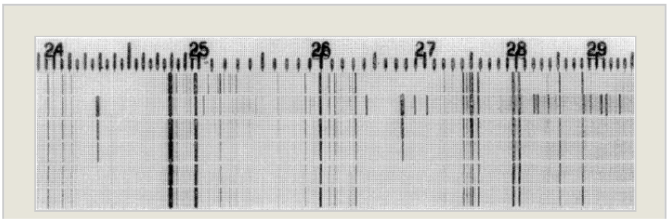
spectrograph, by comparison, could reach the ultimate lines of aluminium at 1862 and 1864 Å.[298] Starting in 1906, de Gramont methodically recorded the detectability of large numbers of such characteristic lines at low concentrations. The few spectrum lines that remained visible as long as any trace of a substance was ascertainable spectroscopically he called “raies ultimes"—‘ultimate’ or ‘residuary’ lines. For 83 different elements including, besides most metals, a great many rare earths and nonconducting elements, de Gramont listed the low number of 307 ultimate and penultimate lines. They were also referred to as “raies sensitives” because they were the most reliable indicators of the presence of the respective chemical element in a sample.[299] Thus these lists of sensitive spectrum lines comprised a small, carefully selected subset of the larger groups of Lockyer’s ‘long lines’ and Hartley’s ‘persistent’ lines mentioned above.[300] As was already noted at the time, these lists formed an odd mixture of flame, arc, and spark lines: They were compiled exclusively on the basis of tireless empirical trials; quantitative spectroscopy was thoroughly within the realm of ‘virgin practice’.[301] The reason for de **(p.328)** Gramont’s more radical reduction is found in his primary aim. At that time his purpose was to aid investigators who needed quick qualitative statements about the presence of a certain chemical element in a given specimen. If the small set of ultimate spectrum lines of a certain substance appeared in a spectrum, one could be certain of its presence in the sample. Otherwise it could be safely ruled out. In addition, their relative strengths with respect to other lines in de Gramont’s ‘spectres de dissociation’ also gave clues about their approximate concentrations. But this was only a secondary issue for him, whereas it had been Hartley’s primary motive. At any rate, the exclusion or inclusion of certain elements helped immensely in rapid qualitative analysis of minerals, steel melts, and other applications on continuous production lines. For instance, four French steel mills for which de Gramont regularly analyzed samples, could successfully improve their production because spectroscopic analysis readily informed them about the presence and approximate concentrations of aluminium, boron, cobalt, chromium, copper, manganese, molybdenum, nickel, silicon, titanium, vanadium, and tungsten in their steel. Not surprisingly, during World War I, de Gramont and a few assistants used his method in a broad array of military applications. Among them were fast and efficient analyses of the structural frames or valves of zeppelins, shrapnel from long-range guns, or magneto ignitors of aircraft.[302] However, even under such ‘favorable’ conditions, the Count seems to have encountered difficulties in institutionalizing his method: shortly before his death, in January 1923, he wrote to one of the few colleagues who had published a paper along similar lines:

> I am happy that you sent me a copy, […] as it defends and approves the methods of analysis which I have tried to popularize in France since 1895 […] Unfortunately, the routinish spirit and backwardness of our country shows itself there again; the French chemists have an indolent dread of spectral analysis. In Paris, only the Municipal Laboratory of chemistry and the Mineralogical Laboratory of the National Museum of Natural History, where I have made pupils employ with success spectral analysis by means of spark spectra. M. Urbain and his pupils refuse to employ anything but arc spectra. M. LeChatelier and his pupils even refuse to inform themselves about spectral analysis of any kind whatsoever. As to the faculty of Pharmacie, M. Daniel Berthelot, who teaches physics there has declared publicly that ever since Bunsen and Kirchhoff, spectra analysis has been a deception (!) and has made no progress from a practical point of view.
>
> However, the University of Liége (Belgium) is installing my method of dissociation spectra in its laboratories of metallurgical chemistry, and the great manufacturer of munitions d'Herstal near Liége has sent someone to see my installation in the laboratory of the Faculty of Sciences (Sorbonne). It must be added that all the apparatus and instruments are my property, and have been installed at my expense. The Faculty furnishes me only water, gas, electricity and compressed air. My assistant [Émile Dureuil] is paid entirely by myself; I instructed him entirely and he has never passed any examinations except those of primary school. As regards the spectrographic installation of the laboratory of mineralogy in the Museum which I mentioned, I donated all this to that institution.[303]

(p.329) The New World became acquainted with de Gramont's techniques through an American astrophysicist by the name of Keivin Burns[304] (1881–1958). He was introduced to these techniques of precision spectroscopy while visiting the Universities of Bonn and Marseilles as a postdoctoral student, and imported into the US his general confidence in quantitative spectroscopy. The spectroscopic laboratory of the National Bureau of Standards (NBS) in Washington was among the very first to take over de Gramont's method of 'practical spectrographic analysis'. After the war, William F. Meggers[305] and some of his colleagues applied it to the chemical analysis and quality control of pure noble metals, such as gold and platinum, for the US Mint in San Francisco.[306] Their implementation was already much more involved, quantitatively approximating the amount of impurities even though they too only used a comparator microscope to gauge the intensities of the ultimate lines on their photographs.[307] Promising pioneering work was also done in applying quantitative spectroscopy to analytical and metallurgical tasks at the American Brass Co., in Waterbury, Connecticut, as well as in a few other industrial laboratories.[308]

Thus, strategy (1) did produce striking local successes, due to the experience and skill of the few spectroscopists involved in this research branch.[309] But it did not lead to a real breakthrough. In retrospect it is easy to see why the gauging of absolute line intensities could not lead to a globally reproducible and practicable form of quantitative chemical analysis.[310] Line intensities are dependent not only on the absolute number of luminescent atoms but also, to a considerable extent, on the type of excitation. As was already well known by the 1860s, other spectrum lines are excited less in flames than in the electric arc **(p.330)** or spark.[311] Since the emergence of Bohr's quantum theory, these differences could be explained in terms of the excitation potentials for the different electron jumps. Flame spectra are caused mainly by transitions between energetically low states of the neutral atom, arc lines reach into higher states of excitation, and spark spectra mainly exhibit the spectrum lines of singly or multiply ionized atoms. But even assuming the conditions of energetic excitation could be held absolutely constant, other factors also affect the measurements of spectrum line intensity: dissociation temperatures, vapor pressure of the electrode material in the electric arc or spark, light absorption in the spectroscope optics, and not least, spectral sensitivity of the registering eye or recording photographic plate. All these factors differ widely, making it very hard, if not impossible, to compare results obtained at one laboratory against those at others with other sets of instruments and standards. These difficulties inherent in the measurement of absolute line intensity left room only for the last of the four strategies outlined above (cf. p. 324) ultimately to lead to the belated breakthrough of quantitative spectroscopy in the mid-1920s.

Despite the obvious importance of de Gramont's work for the French war machine, strangely enough, the Germans did not implement anything remotely similar. It is indicative that a plenary lecture on quantitative spectroscopy before the 88th meeting of the Gesellschaft deutscher Naturforscher und Ärzte in Innsbruck in September 1924 bore the title: "a forgotten method".[312] It's speaker, Carl Friedrich (called Fritz) Löwe[313] (1874–1955), was one of the most active promoters of its industrial applications among chemists and physicians. Löwe's frank allusion to the missed opportunities during the recent—and lost—World War was certainly effective in arousing renewed interest in the method. His promotion of instruments by the Zeiss Company in Jena reached German-speaking audiences. Frank Twyman[314] (1870–1959) fulfilled a similar function toward the Anglo-Saxon world for his company, Adam Hilger Limited in London.[315] From 1925 there was a rapidly **(p.331)** mounting stream of published papers on the method. The initial skepticism, still very much perceptible in Heinrich Konen's talk at the Naturforscherversammlung in Düsseldorf two years later, soon gave way to enthusiasm about its many applications,[316] embracing mineralogy, biochemistry, plant physiology, and agricultural chemistry. The Stockholm professor of experimental biology Henrik Gunnar Lundegårdh (1888–1969) particularly stressed these latter three fields. His procedure consisted in feeding a liquid through an atomizer into the air supply of an acetylene-oxygen flame. Being much hotter than a Bunsen burner, this flame emitted more lines of higher excitation potential and allowed determinations of 34 different chemical elements.[317] During the next two decades spectrochemistry advanced to one of the most important analytical techniques in the metallurgical industry.[318] In 1928, Löwe's indefatigable efforts culminated in an acclaimed photographic atlas of the ultimate lines of 47 elements most responsive to this method.[319] Löwe indicated only the wavelength regions in which the ultimate lines were located. Besides providing the dry-carbon spark spectrum for each element, Löwe also took spectrograms of acidic solutions in concentrations of 1 %, 0.1, 0.01, and 0.001 %. These were arranged underneath a wavelength scale allowing visual estimates of ±1 Å (cf. Fig. 8.10).



(p.332) In the German context, Löwe's work was seconded by Walther Gerlach[320] (1889–1979) and his co-workers. Inspired in 1924 by Löwe's talk, Gerlach initiated his own research program, the first that was clearly not based on the first two strategies but on the fourth. Gerlach argued that previous efforts to determine *absolute* changes in the intensity or appearance of spectrum lines were too riddled with problems arising from inevitable deviations in the conditions of the electric circuit generating the spark, differing absorption by the optics, and/or inconsistent registration on the photographic plates. His way out was to

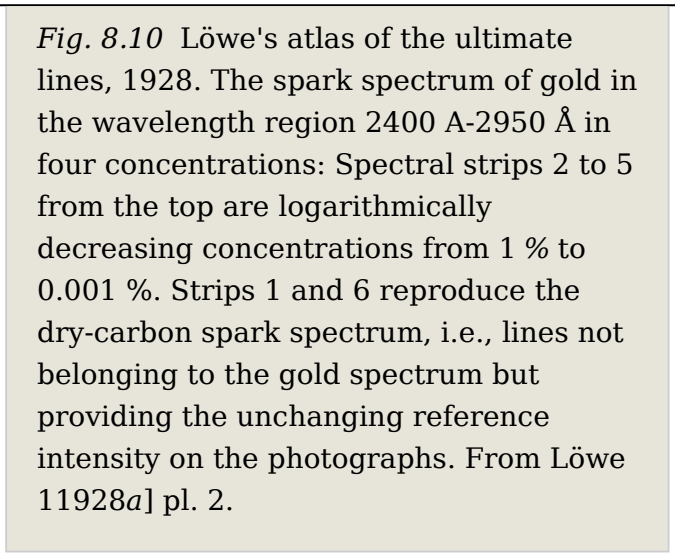


Fig. 8.10 Löwe's atlas of the ultimate lines, 1928. The spark spectrum of gold in the wavelength region 2400 A-2950 Å in four concentrations: Spectral strips 2 to 5 from the top are logarithmically decreasing concentrations from 1 % to 0.001 %. Strips 1 and 6 reproduce the dry-carbon spark spectrum, i.e., lines not belonging to the gold spectrum but providing the unchanging reference intensity on the photographs. From Löwe 11928*a*] pl. 2.

measure only *relative* intensities of one or more lines of an impurity B compared with one or more spectral lines of a reference substance A situated as closely as possible to those of B. Assume that three lines λ_1, λ_2, and λ_3 of an otherwise pure reference substance A are located close to an ultimate spectrum line λ_B of impurity B. Gauging photographs of various known concentrations of B in A show that the intensity of line λ_B is equal to λ_1 for 1 % concentration, equal to λ_2 for 0.2 %, and equal to λ_3 for 0.05 % concentration. This spectrogram gauging makes it possible to determine the relative brightness of λ_B compared with λ_i, of A from any additional photograph of a dissociation spectrum showing lines from A and B in a sample A + *x* %B (with *?* unknown). Thus in the example depicted to the right, λB’S intensity falls midway between the gauging spectrograms for concentrations 0.2 % and 0.05 %. Because of the roughly logarithmic dependency of line intensity on concentration, it is justified to assume for this sample. Because these estimates are relative and made within a very small wavelength range, they remain independent of the sensitivity of the photographic plate. The only condition was that the lines be neither too weak nor too intense, because otherwise solarization effects or other deviations from the Roscoe and Bunsen photometric law would set in. In this case, one could always alter the exposure time to increase or reduce the overall line intensity One might argue that the relative intensities of the three A lines and λ_B might be affected by changes in the electric excitation conditions. This is generally true, but the craft of Gerlach’s variant of quantitative spectroscopy consisted in choosing precisely those pairs of spectrum lines substances A and B whose relative intensities were demonstrably *not* affected by any feasible changes of the electric **(p.333)** parameters.[321] Such line pairs, which differed for each combination of two chemical elements A and B, were dubbed ‘homologous lines’.[322] This very basic diagram captures one of the essential characteristics of the bulk of future quantitative spectroscopic studies: In the period 1855–1925, i.e., after general consensus on a horizontal depiction of spectra had been reached, most diagrams focused on the absolute or relative positions of spectrum lines in this ordered array. Thereafter we encounter a new scopic regime. Wavelengths are now known, tabulated, and unproblematic (within a certain range), because qualitative detection of a certain element by its most characteristic lines had become an easy matter. It was no longer their precise positions in terms of Å that counted, with as many digits behind the decimal point as possible (which is

what Ångström, Cornu, Rowland, Kayser, and a whole generation of spectroscopists had been after). The tables and atlases for spectrochemists only gave figures for ultimate lines rounded off to 0.1 Å. What was now relevant was the intensity, more precisely: the relative strengths of a very limited set of spectrum lines of each element as compared with a few select lines of the reference substance, both displayed on the same spectrogram. In foregoing decades, absolute precision and full detail were called for, now only choice features or sensitive lines were sought. And the quantitative spectro-scopist's glance no longer darted from side to side along such a carefully mapped spectrum, but up and down among the spectrogram strips (see Fig. 8.10 on p. 331), which reiterate a relatively small wavelength range in poor resolution and quality for a single substance, with the only variation being the impurity concentrations. A true atlas of ultimate lines like Löwe's was a good guide for beginners and experts alike, because it displayed the line locations, appearance, and strengths against their spectral neighbors. After some practice, a spectroscopist would form a mental image, or *Gestalt*, of closely neighboring lines in sensitive regions, which facilitated quick orientation within the "thicket of lines." Experience with a particular type of sample even obviated constant reference to such guides altogether for quite accurate visual estimates of chemical concentrations.[323] A scanning of the spectrum of a sample of unknown composition required switching back and forth between atlas and tables. Several tables listed the immediately adjacent sensitive lines for any given element, so any suspected ingredient could be easily checked by moving from one area where a candidate sensitive line had appeared to the next in which a sensitive line of that element ought also to be present.[324]

The particular skill that had to be cultivated within this new practice was reliable gauging of the relative intensities of various closely neighboring spectrum lines, particularly **(p. 334)** any perfect—or sufficiently perfect—equalities and certain gradations between the scales provided by the gauging spectrograms on file. In our example above (cf. Fig. 8.10), the unknown sample, case no. IV, lay comfortably midway between the gauge spectrograms II and III, but other cases in-between might also be conceivable. According to Gerlach, this visual assessment of intensities “can be ascertained subjectively to a high degree of reliability; intermediary concentrations can be estimated” within a wide range of concentrations from 1 to 0.01 %. For many metals, impurities could be gauged in four or more intervals within each order of magnitude, thus any sample may be subdivided into concentration ranges of, say, 0.1–0.07 %, and so on, for 0.05, 0.03, 0.02, 0.015, and 0.01 %, for instance.[325]

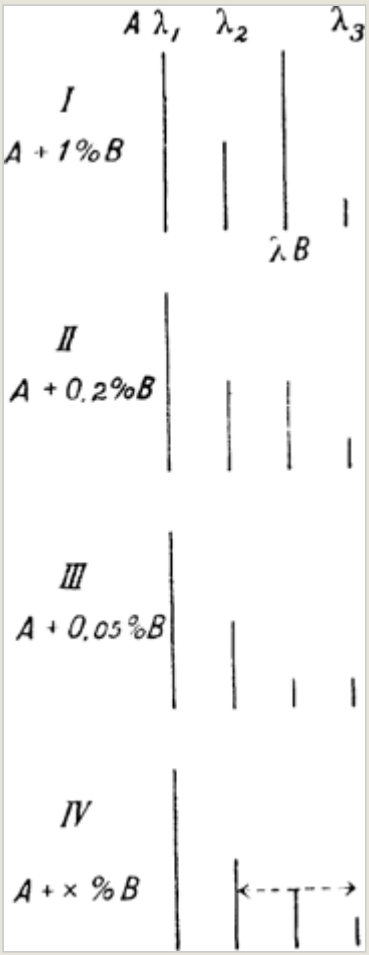


Fig. 8.11 Diagram illustrating Gerlach's relative determination of the concentration of an impurity B in a sample of reference substance A. From Gerlach [1925] p. 388.

Figure 8.12 shows how such a set of gauging spectrograms is obtained. It illustrates the search for pairs of spectrum lines of equal intensity, one of which belongs to the basic substance (here Sn), and the other to the impurity (Pb). The various concentrations are 10 % in the uppermost spectrum under the wavelength scale, and 4.3 %, 1.4 %, 0.47 %, 0.16 %, 0.05 %, and 0.02 % in the successive lower spectrograms. The lead lines clearly decrease in intensity in proportion to concentration to the point of being barely visible at all, in this reproduction at least, while the tin lines remain unchanged. The handwritten brackets added to these exposures indicate various lead percentages that the spectrochemist M. Keller in Jena tried to identify by their ultimate lines having the same intensity as certain lines of tin as the reference substance. It is not as if such cases were rare. For instance, the 4058 line of Pb is estimated to have the same intensity as the line 3801 of Sn at 2 %, i.e., somewhere midway between strips two and three of the gauging spectrograms, whereas the Pb line 2802 is estimated to be equal in intensity to Sn 2765 at 0.1 %, i.e., midway between strips 5 and 6, and Pb line 2873 is considered to be equal to the same reference line of Sn at 0.6 %, i.e., slightly above the level photographed as strip 4. Proceeding in this way, one obtains from such a set of gauging photographs for seven different degrees of impurities a table with one or two pairs of spectrum lines for eight different concentrations between 10 % and 0.02 %.

Once the relative sensitivities of one of these ultimate lines had been experimentally ascertained within a certain range of concentrations and spectrographically gauged, it was possible to extrapolate further for concentrations for which no comparison spectrograms were yet available: thus a known decrease in intensity between 1 and 0.1 % enabled an experienced spectroscopist to extrapolate into the next lower order of magnitude of 0.01 %.[326] By 1930 Gerlach could claim: “We have trained a whole range of physicists in this analytical method and have immediately found that this faculty for correct estimations is easily learned.”[327] This was confirmed when some visual estimates were compared with photometrically analyzed blackening curves of spectrograms that in a chemical laboratory had **(p.335)** been carefully prepared in small increments of decreasing concentrations.[328] Around 1930, practitioners of this craft limited the relative accuracy obtainable with such visual estimates to ±10 % (for lead in gold, for instance), and this error bracket could be reduced further by a factor 2 if photometric techniques were used to determine the line intensities.[329] Later improvements in the standardization of light sources reduced the error margins, even for visual estimates, to no more than ±3 % for routine work and 1.5 % for precision analyses by 1939, to ±0.7 % by 1942, and eventually into the ppm range (parts per million), well below the standard deviations common in wet chemical methods.[330]

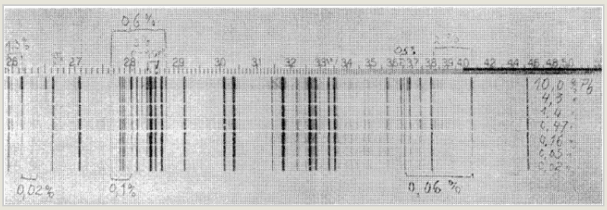


Fig. 8.12 Practical example of identifying pairs of equally intense spectrum lines at various concentrations of a lead impurity in tin. Exposures taken with a small spectrograph for chemists by M. Keller in Jena. From Löwe [1929] p. 674.

Despite these impressive results, spectrochemical practitioners never intended to overthrow or replace the refined standard ‘wet’ methods of analytical chemistry. In fact, they readily acknowledged their dependence on the latter. In preparing gauging spectrograms, for instance, no estimates of unknown samples were possible without it. The new method was rather conceived as complementary to traditional chemical techniques:[331]

- It was much more efficient than the long and involved series of chemical analyses.
- It allowed analysis of all the components of a mixture, alloy, or composite at one time, because practically all were effectively separated chemically in the high-power electric spark.

(p.336)

- It required only tiny sample amounts (in order of magnitude 10^{-6} to 10^{-9} g),[332] which was important for irreplaceable specimens like grenade fragments, or metallic archeological artefacts.[333]
- The relative error in quantitative determinations was nearly independent of the concentrations, over a wide range down to very low values of $2 \cdot 10^{-5}$ % or absolute amounts of $2 \cdot 10^{-3}$ mg for traces of gold, for instance. This put spectrochemical methods at a particular advantage over traditional techniques in the region of low concentrations.[334]
- Finally, most samples could be examined without altering them in any noticeable way, because they could usually be simply mounted at the end of one of the two spark electrodes.

In terms of efficiency, in the early 1920s, controls for impurities of a dozen tin samples (for Cu, Pb, Fe, Zn, Ni, Ag, Bi) performed in the traditional manner of chemical analysis at the chemical laboratory of the NBS, took about two days, as compared with two hours spectrochemically.[335] By 1930, a typical spectrochemical procedure took no more than 20 minutes (including development of the photographic plate). If more precise wavelength measurements had to be taken of the spectrograms using a plate-measuring microscope in order to read closely neighboring lines, it could also take up to one hour. Even so, this was a major gain. Less than a decade later, the industrial pressure for ever higher production rates had “super-speed analysts"—as Meggers called them—reduce this time to a minute or two. The Ford Motor Company laboratories, for instance, carried out large numbers of analyses at high speed: samples were sent by pneumatic tube from the foundry to the spectrographic laboratory, and within a few minutes after receipt of the sample the results were available again on the factory floor.[336]

The fact that a sample was virtually unscathed by this method allowed one to examine local differences of various parts of its surface, or of various layers. Wet chemical analysis, by contrast, inevitably yielded average results because the sample had to be analyzed in solution.[337] A limited set of gauging photographs were all that was needed for series examinations of the same type of sample, with slightly differing amounts of impurities. The more general problem, however, involved quick identification of all the sensitive lines of an unknown number of elements in a given sample. To simplify the tediously long chains of spectrographic comparisons, two British spectrochemists developed what was known **(p.337)** as ‘RU (raies ultimes) powder’.[338] It was basically a compound of zinc, magnesium, and calcium oxides to which were added small quantities of about 50 elements. They were proportioned in such a way that the spectrograms normally recorded only the most important or sensitive lines of each element. According to this method, three spectrograms are taken underneath each other: first a line-rich iron spectrum, and then immediately beneath it on the same negative the spectrum of the unknown sample, and below that, one of the RU powder. This juxtaposition, in combination with a chart of the ultimate lines of these 50 elements, made it easy to identify the chemical elements in the unknown sample, all at once. The next step involved quantitative spectrochemical analysis of their respective concentrations following the methods outlined above. Other applications of spectrochemical analysis after 1930 include:[339]

- absorption spectrophotometry of organic solutions for identification of hormones, vitamins, and other complicated substances;
- testing for silver or boron content in the mining industry;
- routine quality control in the metallurgical and chemical industries, including monitoring of isolation or separation processes;
- soil analysis for agriculture and plant physiology,

• applications in the food packing industry (e.g., checking how fast the inner coating of a can dissolves, by measuring two or three parts of aluminum or lead per ten million, or testing chocolate or chewing gum wrappers, and whiskey distilling vats);
• forensic analyses or autopsies for detection of trace amounts of toxins (e.g., thallium from rat poison, which is ascertainable in hair samples);
• analysis of fusible alloys of tin for safety valves or fire sprinklers, to trace impurities such as lead and zinc, which may raise the melting point by undesirable amounts if present in proportions of as little as one part in ten thousand;
• archaeometric comparisons of the precise composition of metals and alloys from various locations, sometimes enabling archeologists to infer where a certain piece had been manufactured, or conclusions about the geographic and temporal spread of certain technologies or skills;[340]
• and, of course, plentiful applications in mineralogical analysis which (as we have seen in the case of de Gramont) had initiated some of the earliest efforts in quantitative spectrochemical analysis.

The cathode-layer technique, developed by Victor Moritz Goldschmidt (1888–1947), Rein-hold Mannkopff (1894–1978), and his assistant Clemens Peters (born in 1902) at the mineralogy department of the University of Göttingen in the early 1930s, was capable of detecting most elements in concentrations down to 0.001 % or even less.[341] The plethora of **(p.338)** possibilities turned spectrochemical analysis into a vibrant and popular field. The industrial world embraced it in the following decades, setting up thousands of spectrochemical laboratories.[342] The boom in this field of research can be gauged somewhat by publication statistics in spectrochemistry: 1467 books and papers, and half a dozen treatises were indexed in the first part of William F. Meggers and Bourdon F. Scribner’s bibliographic survey, covering the years 1920–39. 1044 contributions were made in the short period of World War II 1940–15, another 1264 in the next five postwar years, and 1866 in the period 1951–55. A true explosion in the literature followed, with an exponential growth in many scientific fields leading to an estimated total of 10 000 spectrochemical publications by 1963.[343] The annual statistics in Table 8.2 show that the irregular drip of contributions each year in the early 1920s changed into a steady flow by the end of that decade. From the early 1930s on, the field swelled substantially, slowing only during the five years in which the US entered the World War against Germany and Japan. Between 1950 and 1954, it reached a stable plateau of around 300 publications per year before joining the rapid stream of publications from all the sciences in 1955.

Tab. 8.2 Annual statistics on publications in spectrochemical analysis between 1920 and 1955. Based on Meggers and Scribner [1940], Scribner and Meggers [1946], [1954], [1959]. These bibliographies have running entry numbers, but last-minute additions and interspersed a's and b's make their index totals somewhat misleading.

year	**1920**	**'21**	**'22**	**'23**	**'24**	**'25**	**'26**	**'27**	**'28**	**'29**
no.	5	13	**9**	**18**	12	11	**24**	**34**	**34**	**44**
	1930	**'31**	**'32**	**'33**	**'34**	**'35**	**'36**	**'37**	**'38**	**'39**
	44	**70**	**82**	104	125	158	152	161	193	209
	1940	**'41**	**'42**	**'43**	**'44**	**'45**	**'46**	**'47**	**'48**	**'49**
	255	274	133	157	136	179	129	226	261	247
	1950	**'51**	**'52**	**'53**	**'54**	**'55**				
	319	298	335	333	332	578				

Various other atlases and wavelength tables designed primarily to serve spectrographers also appeared.[344] For instance, Fritz Gössler's atlas of the arc and spark spectra of iron and **(p.339)** the ultimate lines of most of the chemical elements was designed to be used in conjunction with a spectrum projector.[345] A test spectrum, assumed to have been taken with the same standard Zeiss Q24 spectrograph as the one used by Gössler (an employee of the Zeiss Werke, of course!), is projected onto the appropriate cardboard-mounted plate from his atlas. The projector's magnification was adjustable so that the test iron spectrum could be made to coincide with the iron lines on the plate. Any other line coincidences in the test spectrum with the labeled ultimate lines on the plate immediately revealed the presence of that element. This example also shows quite nicely how improvements in convenience and speed in practical applications of spectrochemical methods went hand in hand with an effective marketing strategy by the major spectrograph manufacturers such as Zeiss, Hilger, or Fuess. Visual resources like these atlases were an integrated part of their full program: proper use of the atlas required a Zeiss spectrograph providing the exact same magnification, hence guaranteeing a growing customer base for the company. The most ambitious inventorization effort was the famous MIT table of 100 000 wavelengths. It was compiled with specially developed spectrophotometers capable of automatically measuring, computing, and recording the wavelengths of spectrum lines, thus speeding up these operations some two hundred-fold.[346]

As one of the major teaching and research centers for spectroscopy (cf. here pp. 368ff.), MIT started to host annual summer conferences on spectroscopy in 1933. An initial attendance of 69 persons in the first year increased to 233 in 1938, 250 in 1939, and 302 in 1942. The series was interrupted for the remaining war years but resumed thereafter.[347] The rapidly expanding market for spectrographs and spectrometers led to the initiation of specialized events such as the National Instrument Conference and Exhibit. An overlapping interest in spectrochemical instrumentation and techniques motivated the Society for Analytical Chemistry of Pittsburgh (SACP, founded in 1943) and the Spectroscopy Society of Pittsburgh (SSP, founded in 1946) to combine their annual meetings in 1949. The joint meetings of these hitherto moderately sized societies, held every March since 1950 under the acronym PITTCON (Pittsburgh Conference and Exposition on Analytical Chemistry and Applied Spectroscopy), transformed spectrochemistry to the point that the convention eventually outgrew this steel-producing city and its organizers were forced to find other locations. Whereas the first Pittsburgh Conference offered 56 presentations and 14 exhibits by commercial instrument makers, the 1990 conference (held at the Jacob Javits Center in New York) coordinated more than 1200 talks and 25 symposia, over 3000 instrument exhibits by over 800 commercial instrument makers, and 12 500 hotel bookings.[348]

(p.340) The first journal dealing exclusively with spectrochemical issues, *Spectrochimica Acta*, was launched in 1939. Its editorial board was international.[349] Publication was temporarily interrupted by World War II but continued in 1947 with its third volume. Divided since into two subseries in 1967, it is still thriving today. A *Spectrographer's News-Letter*, issued by the Applied Research Laboratories, began to appear in 1943, and *Applied Spectroscopy* followed in 1947, published by the newly founded New York Society for Applied Spectroscopy.[350]

Both the high demand for spectrochemical techniques during World War II and the ubiquitous pressure for ever faster results led inevitably to increased substitution of quasi-instantaneous photoelectric detection in photographic recording and thus to a merging with a strand of research discussed here in § 7.4 (pp. 264ff.). This elimination of photographic development and densitometry in favor of photomultipliers and electronic automation was pushed particularly in the United States in companies like Dow Chemical Co. in Midland, Michigan, Perkin Elmer in Boston, Baird Associates (BA) in Cambridge, Massachusetts, Applied Research Laboratories (ARL) in Glendale, California, and National Technical Laboratories, renamed Beckman Instruments in 1950, whose direct-reading spectrometers flooded the international market in the 1950s.[351] Advertisers claimed these 'analysis automats' made "all routine spectrochemical analyses with dispatch and precision", and in the 1950s and 1960s they eventually did.[352] The considerable price asked for these refinements in instrumentation and automation apparently was not a problem, once industry had become interested in methods of spectrochemical analysis.[353] With these improvements came a rapid expansion of the potential applications especially in infrared spectroscopy. During World War II, it had mostly been used for prompt analysis of fuels and synthetic rubber, but in the succeeding decades chemical applications of (infrared) spectroscopy burst into the vast territory of characteristic band spectra for every kind of organic molecule.[354]

(p.341) Before entering the Second World War, America only had four infrared spectrometers in commercial use; shortly after the war their numbers had already increased to over 400[355]

In retrospect, one of the most striking questions raised by this development of quantitative spectroscopy is why it took so long for the breakthrough to occur. Local implementations of the basic ideas by Hartley and de Gramont were successful already in the late nineteenth century. Yet more than three decades had to pass before a first wave of recognition set in during the mid-1920s. And it was another one or two decades more before these techniques were really used on a broad scale in fields as disparate as agriculture and metallurgy, forensic science, and quality control in manufacturing. One explanation for this delay may be the decidedly empirical orientation of most of the researchers involved. This resulted in an excessive variety of ‘methods’, all closely related, but differing in important details like preferred light sources, electric parameters, spectrograph models, photographic materials, and calibration methods.[356] The choice of excitation conditions was of particular importance: Lundegardh and his school preferred the acetylene-oxygen flame, most quantitative spectrochemists used various types of spark-generating devices, but a few analysts preferred the electric arc because of the higher intensity of its spectrum.[357] Notwithstanding this bewildering profusion of instrumentation details, the disputes among spectrochemists about which sensitive lines to choose for identification and quantitative determinations revealed a theoretical deficit that was often noted by more theoretically inclined physicists.[358]

The disagreement between de Gramont and Gerlach on whether or not the ‘raies ul-times’ were actually the strongest lines of the spectrum is indicative of this disciplinary boundary. In various publications, de Gramont had explicitly cautioned against mistaking his ultimate lines for the “ ‘Hauptlinien’ des physiciens allemands”. As one of the latter’s advocates,[359] Gerlach deemed ultimate lines quite definitely as the strongest and most persistent (in absolute terms), simply by virtue of their maximum intensity. But practically speaking, other factors like the proximity of adjacent lines from other elements, a too strong tendency for self-reversal, or bad photographic sensitivity in the relevant spectral region might prevent them from also serving as the most sensitive lines for the purposes of quantitative spectrochemistry. With the arrival of Bohr’s quantum theory, it became evident that most ultimate lines indeed originate from the lowest atomic energy level and thus correspond **(p.342)** to the first terms of the main series.[360] Penultimate lines originate from the next lowest level and antepenultimate from higher ones. Because of the sharp drop in probability that electrons be in higher states of excitation, transitions between the energetically lowest states correspond to the strongest lines for moderate states of atomic excitation, and unless these strongest lines happened to fall within the far ultraviolet and are thus not easily registered, they also constitute the ‘raies ultimes’ in de Gramont’s phenomenological sense. However, these theoretical foundations gleaned from the insights of practitioners like Hartley or de Gramont came only as an afterthought of a development that had been guided almost exclusively by purely empirical constraints. This striking dominance of empirical trial and error over theoretical considerations was often noted in the survey literature of the time. Lowe still hoped in 1927 that profound physical insight would eventually penetrate the practical realm of spectrochemistry, but a quarter of a century later his colleague Twyman was considerably less optimistic: “the practising spectroscopist may even doubt if theory has added anything appreciable to the knowledge laboriously accumulated by Gramont and his followers […]; for one thing the theoretical *rale ultime* may occur in a part of the spectrum difficult to observe and so be of little use.”[361] Likewise, his German colleague Heinrich Kaiser[362] (1907–1976), at that time physicist at the state agency for materials testing in Dortmund, wrote about the tension between physical method and the research approach of chemists:

> So spectrochemistry—as this boundary discipline is recently being called—falls between two stools. Nobody is quite responsible. These methods are to a large part unfamiliar to chemists. They are sometimes very suspicious, and because they do not have a full command of the technical measurement conditions, they are unable to assess the great possibilities of this procedure and the assistance it could offer them. Added to that is the worry about a daily livelihood: What would happen in terms of staffing and jobs if one were to introduce this efficient method on a large scale? Physicists, on the other hand, are in most cases completely at a loss. They might know about the theoretical and experimental foundations of spectrochemistry, but as to solving a concrete problem, they don't know what to do either.[363]

(p.343) It was thus a mere coincidence that the troubled course of spectrochemistry began to turn more favorably during the critical period of the mid-1920s, when quantum theory was on the threshold of quantum mechanics. By no means was it the result of any fruitful interaction between theory and experimental practice. Quite the contrary: "It appears that the *applied spectroscopists* (excluding astrophysicists) have scarcely taken any notice of the great advances in knowledge concerning the origin and interpretation of atomic spectra which the *fundamental spectroscopists* brought forth in the period of decline of spectro-chemical analysis, 1885 to 1925."[364]

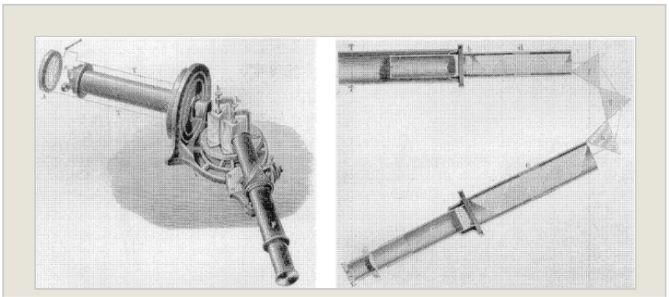
8.8 Stellar spectroscopy

A study of visual representations in the extensive field of stellar spectroscopy could easily fill a whole book. So let us limit the discussion here to some brief remarks about its historical development, emphasizing the distinguishing features between stellar spectral plates and the maps discussed thus far. As will be shown, one of the key devices used to treat this drastically different subject matter is familiar: The comparative diagram of several types of stellar spectra is actually similar to the ones we have just encountered in the previous section on quantitative spectroscopy. Another interesting aspect of this subfield, namely the training of its practitioners, will be taken up in § 9.6.

Stellar spectroscopy developed somewhat later than solar and terrestrial spectroscopy, because the light received on Earth from the stars, even of the first magnitude, is only about a seventy-thousand-millionth part of that received from the Sun.[365] It is more surprising that observations of stellar spectra date far back to Fraunhofer's pioneering researches. Already in 1814, he was able to confirm the existence of at least the strongest dark lines of the solar spectrum in the light reflected from the Moon and from Venus. In 1823, he presented his results obtained with an objective-prism spectrometer of considerable size (10.8 cm aperture, flint prism with a refracting angle 37°40' and an average deflecting angle of 26°). With it he also checked whether there were any relative positional changes in the spectral lines of different stars. But his prismatic analysis of light from some of the brightest fixed stars (Sirius, Procyon, Capella, and Betelgeuse) unexpectedly yielded spectra quite unlike those of the Sun. Only the lines D, E, and b seemed to be present, indicating the presence of sodium, iron, and magnesium. Some other lines, however, could not be correlated at all with any of the dark solar lines.[366] Under normal conditions, the image of a fixed star in the telescope is a tiny point that when dispersed by a prism is stretched out into a fine line. Elongating the point-shaped stellar image into a line is achieved with a cylindrical lens, and this image is then spectrally decomposed to yield a two-dimensional spectrum of the familiar shape formed by more extended light sources such as the Sun, a flame, or a larger planet whose images may be projected directly onto the slit of a spectroscope.

(p.344) The uncertainty of these first forays into stellar spectra is revealed by the fact that when Giovan Battista Donati (1826–1873) later published 15 such drawings with three to four distinct lines per spectrum, their positions did not even roughly concur with Fraunhofer's findings.[367] After Kirchhoff and Bunsen opened up an avenue for systematically identifying dark absorption lines with bright emission lines, therefore chemical analysis of all kinds of light sources, stellar spectroscopy also received a boost of attention. In the wake of their discovery, the gentleman scientist William Huggins[368] (1824–1910) initiated a program of spectroscopic research in the early 1860s. His private observatory was then equipped with an 8-inch refracting telescope by Alvan Clark in an equatorial mounting by Cooke. The stellar light was prismatically decomposed by two high-quality 60° flint-glass prisms (cf. here the left part of Fig. 8.13), and the comparison spectra were generated with an induction spark off electrodes of different metals.[369] By 1866, Huggins had acquired altogether 14 different prisms, also including some made of quartz, Iceland spar and rock crystal, which extended his wavelength range into the near ultraviolet and infrared.[370]

In order to obtain terrestrial emission spectra for comparison, Huggins needed pure samples of many different chemical elements, so he struck up a collaboration with the chemist William Allen Miller, who happened to be a neighbor close by, on Upper Tulse Hill Road, at that time still considered on the outskirts of London.[371] Upon Miller's untimely death Huggins had to look for another assistant; Margaret Lindsay Murray (1848–1915), whom he married in 1875, took on this role and soon became his "complementary collaborative partner".[372] In February 1863, Huggins and Miller were ready to communicate their **(p.345)** first measurements of the lines in Sirius, Aldebaran, and *a* Orionis to the Royal Society. A year later, in a much more detailed paper for the *Philosophical Transactions* that included a discussion of some fifty different stellar spectra, they could already claim to have proved the presence of about a dozen chemical elements in the spectra of Aldebaran and Betel-geuse *(a* Orionis).[373] Huggins had modified his telescopic spectroscope in order to ease systematic comparison of these unknown spectra with various emission spectra of incandescent metals and gases: pressing a button brought a projected image of a comparison spectrum into its field of view. Thus he could immediately see whether or not a particular set of characteristic lines were present in the stellar spectrum under examination.[374] In only two out of fifty stars examined (namely *a* Orionis and *?* Pegasi) were the lines of hydrogen, C and F, found to be absent, and all stellar spectra examined until then exhibited dark lines. An early general outcome of this "stellar chemistry" was the insight that altogether "the physical constitution of the fixed stars resembles that of the sun."[375] But by 1864 Huggins also knew that the spectra of the celestial bodies known as planetary nebulae consisted of bright lines on a dark background, thus lacking a continuous spectrum. Inferring from emission spectra observed under laboratory conditions, these nebulae had to be relatively thinly distributed luminous gases. They were thus totally unlike the Sun, presumed to have a white-hot nucleus emitting a continuous spectrum and a surrounding outer atmosphere containing the vapors of particular metals which produce the absorption lines. But they also differed from the stellar conglomerates that astronomers had hitherto expected.[376]



(p.346) Such endeavors were typical of the emerging field of stellar spectroscopy which at first was espoused only by a handful of unabashed enthusiasts on the margins of professional astronomy. Besides Huggins and Secchi, the names G. Battista Donati and Lewis M. Rutherfurd come to mind. Both of them mapped stellar spectra in relatively peripheral settings.[377] In 1897 Huggins recalled his motivation for entering the field. With the construction of his observatory completed in 1856, he “commenced work on the usual lines, taking transits, observing and making drawings of planets” but was quickly bored with conventional astronomy. “I soon became a little dissatisfied with the routine character of ordinary astronomical work, and in a vague way sought about in my mind for the possibility of research upon the heavens in a new direction or by new methods.” When Kirchhoff’s and Bunsen’s discovery made headlines in England, the thought occurred to him to apply it to the analysis of starlight: “this news was to me like the coming upon a spring of water in a dry and thirsty land. Here at last presented itself the very order of work for which in an indefinite way I was looking—namely to extend his novel methods of research upon the sun to the other heavenly bodies.”[378]

Fig. 8.13 Left: Huggins's first star spectroscope with two flint-glass prisms and a cylinder lens A, freely adjustable along the dashed tube TT. *Right:* Huggins's high-dispersion star spectroscope with two direct-vision prism chains from J.G. Hofmann and three simple prisms. From Schellen 11870/72*b*] pp. 446. 455.

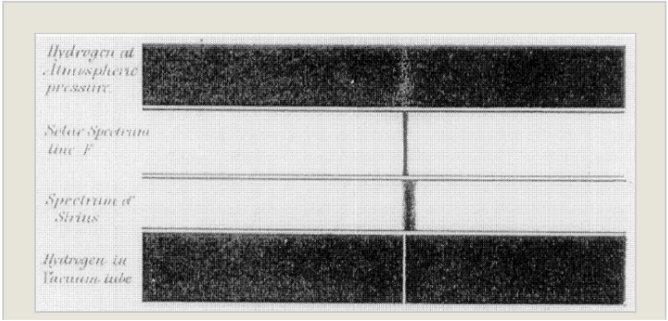
Another ardent advocate and practitioner of stellar spectroscopy was Father Angelo Secchi[379] (1818–1878) at the Collegio Romano. Altogether, he examined more than 500 stars with a direct-vision spectroscope mounted on his 24-cm equatorially mounted refractor by Merz. After having classified more than 300 stellar spectra, Secchi concluded that above half of them were bluish or white (like Sirius) and displayed little besides the hydrogen lines, less than half were yellow (like the Sun), with numerous fine dark lines like the Fraunhofer solar spectrum, while the small remainder constituted orange-to-red and deep red stars, with spectra incorporating both bright and dark lines (cf. here color Plate IV).[380]

Even though Secchi's superior instrumentation allowed him to reach the highest dispersion in the stellar spectroscopy of the time, it was Huggins who first applied the Doppler principle to measurements of radial stellar velocities relative to a terrestrial observer.[381] Using **(p.347)** a specially constructed high-dispersion spectroscope that combined two direct-vision spectroscopes of the Hofmann design with another chain of three simple prisms (see here the right part of Fig. 8.13), he compared the locations of strong lines such as H_β in the spectrum of Sirius with the hydrogen spectrum produced with a Geissler tube. He noticed a persistent shift in the starlight (cf. Fig. 8.14 below). Assuming that this shift was due to a Doppler effect, a radial velocity of this bright fixed star relative to the Earth of around 40 km/s resulted, corresponding to a wavelength shift of 1 A. Such velocities were so inconceivably high for his contemporaries that many were willing to dismiss Doppler's theory, or at least its validity to optical radiation, if that was its implication. Because Huggins's observations contradicted common consensus about an essentially static universe, he was particularly careful about how he put forward his claim at the meeting of the Royal Society on 23 April 1868. The more so since just one month previously, Secchi had reported to the Paris Academy of Sciences a *negative* result from a similar search for relative shifts among stellar spectrum lines and laboratory emission spectra.[382] Huggins affirmed:

> The observation of the comparison of the lines was made many times, and I am certain that the narrow line of hydrogen, though it appeared projected upon the dark line of Sirius, did not coincide with the middle of that line, but crossed it at a distance from the middle, which may be represented by saying that the want of coincidence was *apparently* equal to about one-third or one-fourth of the interval separating the components of the double line D. […11 have not been able to detect any probable source of error in this result, and it may therefore, I believe, be received as representing a relative motion of recession between Sirius and the Earth.[383]

To back up his interpretation of the observed line shifts as a Doppler effect, Huggins turned to no lesser an authority than James Clerk Maxwell. He quoted from a letter in which Maxwell theoretically derived the effect of relative motion on wavelength shifts.[384] Figure 8.14, taken from Huggins's first major publication of his novel findings, gives an idealized version of the faint impressions that he really saw in his star spectroscope with its movable cylindrical lens for adjustment of the height of the broadened stellar image.

From his preserved notebook, we learn more about his struggle in first convincing himself that these displacements, at the very limit of observability, were more than artefacts. Even with his high-dispersion stellar spectroscope, Huggins's readings for wavelength shifts were essentially limited by the division of his micrometer screw head to a minimum of 2 A.[385] Huggins's early instrumental means limited his power of detection to motions greater than 25 miles per second, precisely at the limit of the relative radial motions **(p.348)** of objects like Sirius (40 km/s). So it is not too surprising that his visual estimates were but approximations. In early March 1868, he wrote about his comparison of the F line in Sirius with the hydrogen emission line: "Made the comparison at least 20 times, but without absolute certainty. Upon the whole, my impression was that of coincidence, but if there was any difference [then the] line of H [is] on [the] more refrangible side."[386] A few days later, another series of observations with one of the two Hofmann compound prisms removed, and hence with less dispersion but better light intensity, seemed to indicate a slight shift, albeit of less than half the width of the Fraunhofer line F. But yet another alteration of the spectroscope changed the position of the comparison H line so that it seemed to be on the less refrangible side of the corresponding line in the Sirius spectrum. It was only towards the end of March that he slowly gained confidence in the reality of a slight redshift of the Sirius spectrum relative to the terrestrial hydrogen spectrum.[387] It is telling that some of these measurements —including his earliest estimate for the radial motion of Sirius—even had to be corrected in sign, thus effectively inverting his former statement about a recession to an approach of the same object.[388] Even though this did not help to increase overall trust in the mindboggling results of this new branch of spectroscopy, Secchi and other spectro-scopists who had thought of such measurements independently were nevertheless able at **(p.349)** least to confirm the existence—albeit not the magnitude—of such Doppler effects in stellar spectra.[389] It was only after Hermann Carl Vogel in Potsdam, William H.M. Christie in Greenwich, and other specialists at the Lick Observatory and elsewhere started taking visual Doppler shift measurements with much improved instrumentation that the data began to agree.[390]



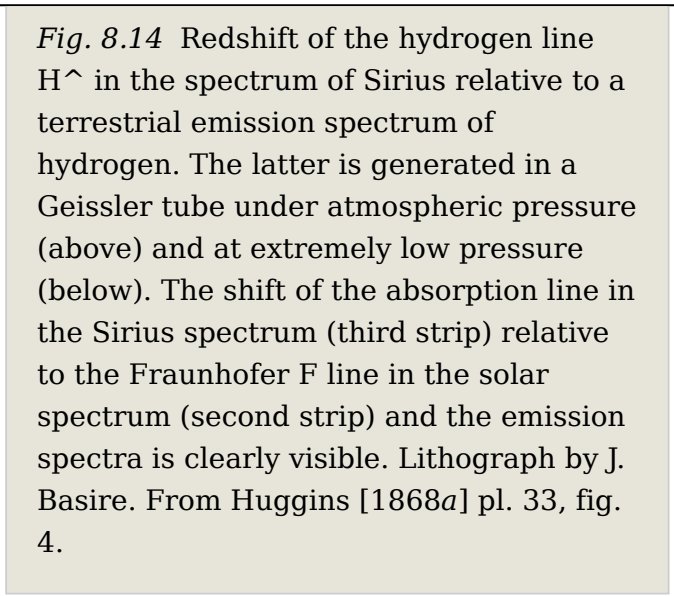


Fig. 8.14 Redshift of the hydrogen line H^ in the spectrum of Sirius relative to a terrestrial emission spectrum of hydrogen. The latter is generated in a Geissler tube under atmospheric pressure (above) and at extremely low pressure (below). The shift of the absorption line in the Sirius spectrum (third strip) relative to the Fraunhofer F line in the solar spectrum (second strip) and the emission spectra is clearly visible. Lithograph by J. Basire. From Huggins [1868*a*] pl. 33, fig. 4.

The visually obtained pioneering measurements were extraordinarily difficult and riddled with systematic errors. The extreme faintness of the spectrally dispersed light was weakened further by the elongation of the spectral widths by means of the cylinder lens. Nor were the terrestrial comparison spectra so easily projected into the field of view so as to be precisely coincident with the particular stellar spectrum under examination. They were also much more intense and overpowered the faint stellar images by many orders of magnitude.[391] Reliable determinations of stellar radial velocities relative to the Earth and precise to at least 3 km/s could only be made once it had become feasible to photograph stellar spectra as opposed to just observing them visually without producing any direct permanent records.

Quite early on, in 1863, Huggins had tried to photograph the faint stellar spectrum of Sirius, but the limited sensitivity of his wet collodion on a glass plate and problems with the clockwork mechanism guiding his telescope resulted in only a faint continuum without any spectrum lines.[392] The dry collodion available since 1854 was not sufficiently sensitive and wet collodion dried much too quickly for the prolonged exposure times necessary for the faint stellar spectra. Various efforts to prolong the exposure times of wet collodion by adding all kinds of substances (like albumen, honey, glycerine, or beer) failed to satisfy the finicky demands of spectroscopists.[393]

(p.350) The first satisfactory photograph of a stellar spectrum (showing four spectrum lines of α Lyrae, also called Vega) was obtained in August 1872 by Henry Draper,[394] whom we have encountered in § 6.7 with his first photomechanical reproduction of a solar spectrum.[395] In photographing Vega, Draper had refrained from using a slit or collimating lenses, employing only one quartz prism, placed just within the focus of the small diagonal mirror of his silvered reflecting telescope. At the recommendation of Huggins, whose observatory he had visited in the spring of 1879, Draper then tried out the commercially available gelatino-bromide dry plates manufactured by Wratten & Wainwright, which combined a high spectral sensitivity with the convenience of indefinite storageability. Assisted by his wife, Anna Palmer Draper (1839–1914), he still had to expose the film for up to two hours, in order to accumulate enough light with his relatively powerful telescopes in Hastings-on-Hudson, 20 miles north of New York City.[396] But such long exposure times demanded perfect precision of his telescope's driving mechanism.[397] Given the extreme narrowness of his slit, at a width of one-three-hundred-fiftieth (1/350) of an inch, keeping the stellar image positioned on the slit was a highly nontrivial affair and called for "a system of continuous supervision, and instant control by hand when necessary."[398] Also, before the method of sensitizing these gelatino-bromide plates for wavelengths below the line F had become widespread (see here § 7.1), stellar photography was limited to the more refrangible region of the blue, violet, and near ultraviolet. Visual observations, on the other hand, were limited to the red-to-green region of the spectrum. Draper was enough of a pragmatist to use this fortunate complementarity, this "mutual assistance",[399] to its fullest, and several other stellar spectroscopists, albeit still mostly amateurs, soon followed suit.

(p.351) At least one professional astronomer also foresaw good prospects for celestial photography: Draper’s fellow American Edward C. Pickering, from 1877 until 1919 director of the Harvard College Observatory (HCO) in Cambridge, Massachusetts.[400] Assisted by his brother William H. Pickering, then instructor of photography at the nearby MIT, and supported financially by the Rumford Fund of the American Academy of Sciences and the Bache Fund of the National Academy of Sciences, he initiated a series of systematic experiments. Following up an idea of Secchi, they mounted a large 13° prism *before* the objective lens of the telescope and broadened the resulting spectrum stripe by means of a cylindrical lens. In 1885 Pickering acquired a new telescope with a Voigtlander portrait lens, specially designed for photographic analysis of stellar spectra. A second one arrived in the early 1890s. Like all the larger optical instruments used at Harvard for spectroscopic analysis of starlight, these instruments were made by Alvan Clark & Sons. A battery of up to four large prisms could be mounted in front of the 11-inch telescope, for dispersion of light from the brighter stars. The resulting length of the spectra increased from a quarter of an inch to nearly five inches. The telescope driver was controlled electrically by a clock whose rate could be reset by means of weights on its pendulum. Around this time the sensitivity of photographic plates used was being steadily improved as well. So the resulting stellar spectrum photographs were significantly sharper and yielded a rich spectrum of sometimes as many as 500 lines.[401]

This ‘objective-prism method’ had previously been used by Father Angelo Secchi for visual observations of about 400 star spectra. Pickering adapted it for obtaining spectra of stars brighter than the sixth magnitude. By photographing a field of stars with this method, one photographic plate yielded hundreds of stellar spectra, all photographed under the same conditions and hence easily comparable (see Fig. 8.15). Secchi’s classification into four star types soon proved inadequate to the task of distinguishing the many variations among the stellar spectra recorded at the Harvard College Observatory, even after Pickering had added a fifth class reserved for strange spectra composed mainly of bright lines.[402] So a different, “purely empirical” Harvard system of classification was developed (see here Table 8.3), assigning the letters A to Q of the alphabet (except J) to stellar spectra. After working with this classification, it became evident that a reorganization was necessary. Some of the assigned classes (such as C and D) had to be dropped. After Cecilia Payne-Gaposchkin[403] (1900–1979) demonstrated that the spectral differences arise primarily from variations in temperature or density, the sequence of the different classes was rearranged roughly in the order of decreasing stellar temperatures: O [later renamed W], B, A, F, G, K, M, extended by the new classes R, N, and S. Because this sequence was—erroneously, **(p.352)** as we now know—also taken to be an evolutionary one, the classes B and A were also referred to as ‘early’, F and G ‘medium’, and K to S ‘late’ spectral classes. For further differentiation, each class was subdivided by 10, indicated by an arabic numeral between 0 and 9. More recently, a couple of these subclasses (such as B4, or K6–9) have been deleted, and various suffixes and prefixes have been added to signify other characteristics.[404]

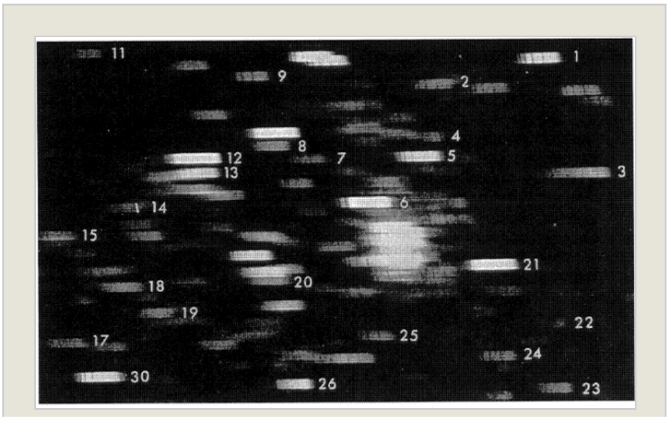


Fig. 8.15 Small segment of a photograph of the *?* Carinae region taken by the objective-prism method in a 140-minute exposure on 13 May 1893: each of the stellar images is elongated by means of a cylindrical lens and decomposed into a spectrum strip by means of one or several 15° prisms mounted before the objective lens of the 8-inch Bache refractor. From Harvard College Observatory Archives.

For an idea of the quantities of stellar spectra involved here: The first installment of the *Draper Catalogue of Stellar Spectra* published in 1890 contained 10 351 stars north of —25° declination, down to about the eighth magnitude;[405] an additional volume published in 1897 included the southern stars. The *Henry Draper Catalogue* published between 1918 and 1924 originally included 225 300 stars,[406] and two supplements published by 1949 increased that total to 359 082 stars. They had all been classified by one expert, Annie Jump Cannon[407] (1863–1941), who had thus classified a total approaching 400 000 spectra. **(p.353)** Even though she had several assistants—averaging about five at any time—the final classification, revision, and supervision of the whole catalogue rested solely on her shoulders. Cannon was famed for her “keen eye and extraordinary visual memory” and even more for her conscientious abstention from attempting any form of interpretation, a virtue that members of the next generation of astrophysicists had difficulty fully appreciating. Cecilia Payne-Gaposchkin’s reminiscences are a good example:

Tab. 8.3 Translation between the Secchi classification and its differentiation by H.C. Vogel into the classification adopted by E.C. Pickering and colleagues for the Henry Draper Catalogue (Harvard System): see Secchi [1868*a*], [1870*d*], Pickering [J89l*a*] pp. 176f, [1891*b*] for class V, Hoffleit [1991] p. 121, Kaler [1989] pp. 62ff.

Secchi	Vogel	HD	Remarks
I	Ia	A	bluish or white stars with little more than strong hydrogen lines
	Ib	B	like class A, but with added ‘Orion lines’, later identified as due
		C	to neutral helium doubled hydrogen lines
	Ic	D	emission lines present
II	Ila	E	yellow stars with numerous metallic lines; Fraunhofer H, K, and Hβ lines present
		F	similar to class E, but all hydrogen lines present

Secchi	Vogel	HD	Remarks
	IIa	G	same as F, but additional lines (like the solar spectrum)
	IIa	H	same as F, but drop in intensity in blue part of spectrum
	IIa	I	like class H, but with additional lines
	IIa	K	TiO band visible, G band strongest
	IIb	L	peculiar variations
III	IIIa	M	orange stars with prominent Ti bands, each getting darker towards the blue; also metallic lines of type II
IV	IIIb	N	red stars with carbon bands that shade in the other direction
V	IIIb	0	spectra with bright continuum and emission lines (including Wolf-Rayet stars, later separated as class W)
	IIIb	P	gaseous nebulae
IV		Q	all other spectra (later changed to designate novae)
		R	stars showing strong CN and CO bands
		S	stellar spectra with strong ZrO bands

> Miss Cannon was extraordinarily kind to me. She might well have resented a young and inexperienced student who was presumptuous enough to interpret the spectra that had been her own preserve for many years. She never gave a sign of doing so. […] I had even permitted myself to wonder how anyone who had worked with stellar spectra for so long could have refrained from drawing any conclusions from them. She was a pure observer, she did not attempt to interpret.[408]

(p.354) Cannon’s achievement thus lay in consistently applying a set pattern of spectroscopic *Gestalten* to what was essentially a continuum of all kinds of spectra, many of which were little more than smudgy patches of light on plates like Fig. 8.15, containing many spectra photographed at once using Pickering’s objective-prism spectrogram technique.

When Payne-Gaposchkin first inspected the plates upon which the Henry Draper classification was based, she was flabbergasted:

> The spectra looked like tiny little smears, not like the beautiful pictures in Sir William Huggins' atlas or even the spectra from which Miss Cannon and Miss Maury had made Volume 28 of the *Harvard Annals.* It seemed impossible that anyone could see enough in those tiny smears to classify the spectra. Sometimes, indeed, I would find one of Miss Cannon's numbers in a spot where I could see nothing but a faint blur. Several times I brought her a plate that she had classified years before and asked her to verify a spectral class. Not once did her re-examination produce anything different from her original estimate.[409]

Fig. 8.16 A.J. Cannon at a plate stand, inspecting a stellar spectrum photographic negative luminated from behind, c. 1940. From [Cannon] [1949] frontispiece.

But while other observers could not refrain from combining this classification with some type of analysis, Annie Jump Cannon performed her function without reference to any ‘theory’ whatsoever, and without aiming at any kind of theoretical understanding. Her task was solely the phenomenological classification of these stellar spectra into one of the various spectral classes (see Table 8.3) and their ten subcategories. Needless to say, her 45 years practice while working for the Harvard College Observatory greatly enhanced her efficiency. In 1896, when she started examining her first plate with an objective-prism photograph of a rich stellar field in the *?* Carinae region (see Fig. 8.15 for a small segment), she needed three days for 62 A stars, 11 G stars, 5 M stars, and one K star (at that time still without numerical subclasses). When she returned to that region 17 years later for the *Henry Draper Catalogue*, her record book reveals that she only needed 19 minutes for 64 **(p.355)** stars, then going on with an adjacent region to classify 139 stars within another 40 minutes, thus at a rate of more than three stellar spectra per minute.[410] Checks against earlier plates verified that her classification was reproducible to an astonishing degree. Moreover, there was no leap from classification to analysis or further even, to speculation about physical differences or stellar evolution which had motivated Lockyer’s premature efforts.[411] Likewise AntoniaC. deP.P. Maury (1866–1952), a granddaughter of John William Draper and niece of Henry Draper, who devised a more elaborate two-dimensional system of classification distinguishing between different luminosity classes.[412] Cannon’s extraordinary skill at *Gestalt* recognition was not based on any definable rules that might easily be transformed into a finite set of explicit algorithms—this was tacit knowledge, pure and simple. The following anecdote, reported by Cecilia Payne-Gaposchkin, underscores this:

> In the last years of Miss Cannon’s life, Henry Norris Russell used to say: ‘Somebody ought to find out from Miss Cannon exactly how she classifies each spectral type’. I argued with him that she would not be able to tell them because *she did not know.* She was like a person with a phenomenal memory for faces. She had amazing visual recall, but it was not based on reasoning. She did not think about the spectra as she classified them—she simply recognized them. This was. in fact, one of the strengths of *the Catalogue.*[413]

The peculiar social setting in which this classification was done has often been described, recently also from the feminist perspective. Female employees and voluntary aids were hired expressly for this task. For one, they were cheaper than their male colleagues: Edward Pickering, director of the Harvard College Observatory, paid most of the ‘women assistants[414] only between 25 and 35 cents an hour to sort photographs of stellar spectra. Thus it was no major investment to hire 20 such assistants between 1885 and 1900, three of them college graduates.[415] The woman in charge of the hiring and supervision of the female assistants, Williamina Paton Fleming (1857–1911), a former domestic servant, earned just $1500 a year (compared to about $2500 for a male assistant), a low salary that caused her great personal discomfort.[416] This change in the labor force, from fewer—male—observers in exchange for more—female—assistants, to tackle the massive amounts of data generated **(p.356)** in photographic stellar spectroscopy has been called ‘proletariatization’ because it allowed the job to be downgraded. The Harvard College Observatory has even been likened to a data factory whose output was maximized through strategic de-skilling of the work force, as was a prevalent trend in industrial manufacturing of the time. But in a sense, because of their education with a stronger emphasis on skills like drawing, female assistants were also better prepared to do this kind of job, for which pattern recognition, visual memory, patience, and diligence were essential (cf. here § 9.5 and 9.6 with a case study on Wellesley College). “Energy, perseverance and loyalty”, not ‘genius, intelligence, and career’ were the key words that appeared in the obituaries of the most prominent among these ‘women assistants’. If they published anything of their own (like Mrs Williamina Fleming’s address entitled A field for women’s work in astronomy’ at the World Columbian Exposition in Chicago in 1893), it was likely that they too praised the stereotypical “feminine skills” of ‘untiring zeal, patience, perseverance, and method’.[417]

Having dwelt on the classification of spectra, allow me to close this section with a striking parallel that draws spectroscopy in relation to another field more traditionally populated by women. An analogy often made by turn-of-the-century astrophysicists in reflective statements about their own work links spectroscopy to botany. Both disciplines rest on a huge material basis, and in both, classification plays a vital role in the early stages of their development, well in advance of high-brow theory that might lead to an understanding about why the many different species—whether plants or spectra—occur. Efforts to classify the suffocating volume of data are a necessary first step. These tentative clusters, groupings, types, classes, species, or whatever else you will call them are the grids upon which theoretical understanding is shaped. ‘Mere classification’ without any effort at deeper analysis or theoretical interpretation is often looked down upon by experimentalists and theoreticians alike. Payne-Gaposchkin, for instance, reported having once “heard Rutherford refer to the latter [spectroscopy] in disparaging terms as ‘descriptive botany’ “. Interestingly enough she did not agree with this assessment: “the phrase grated on me, for I still had a respect for descriptive botany”.[418] More recently, in the early 1920s, Arnold Sommerfeld and Ernst Back referred to ‘Zeeman zoology’ and ‘term botany’ in the context of mounting problems with the old quantum theory. These metaphors had an ironic twist, alluding to avid Baconian-style collecting of facts as well as to the strangeness of regularly observing theoretically inexplicable patterns. These were just barely describable by the *ad hoc* solutions proposed by Lande and others, involving half-quantum numbers and other strange features not understood at the time.[419] In this sense, classification certainly preceded theory in both botany and spectroscopy, as well as in many other conceivable examples.[420]

(p.357) It is for this reason that Cannon's "dispassionate and unbiased" restraint from theoretical reasoning was so vital to the success of the *Henry Draper Catalogue:* theory had to wait until the empirical basis of classified spectra had become broad enough to allow educated guesses about the physical reasons for the many different traits of stellar spectra (temperature, luminosity, age, chemical composition, nuclear processes, etc.). As Pickering phrased it in the foreword to the *Henry Draper Catalogue:* "In the development of any department of astronomy, the first step is to accumulate the facts on which its progress will depend."[421] Thus not only does experimentation have a life of its own (as Hacking's by now apodictic slogan tells us), but phenomenological classification as well. Despite the rapidly developing theory of stellar atmospheres, this is also true of the famous atlas published in 1943 by William Wilson Morgan (1906–1994), Philip Childs Keenan (1908–2000), and Edith Kellman (born in 1911).[422] Morgan and Keenan decided which spectrograms would go into the atlas. Kellman then made enlargements of them on paper prints and cut, trimmed, and mounted them for the photographic reproduction on 8x10 inch plates. A first edition of only 100 copies of the atlas, containing 55 plates, appeared in January 1943. with only a few copies distributed outside North America.[423] With such low print runs and scrupulous quality control in the photographic or photomechanical reproductions, many atlases made even later retained the look and feel of custom manufacture.[424] This care was all the more important because the so-called MKK classification (later revised into the better known MG classification)[425] emphasized luminosity effects, thus sorting stellar spectra both according to a general progression of spectral type (abscissa) and luminosity (ordinate). The latter was divided into 6 classes of decreasing luminosity, from class I, the supergiants, to class VI, the subdwarfs. The continuum of spectra in this two-dimensional scheme were then sorted into a finite array of discrete cells. The sun, for instance, (spectral type G2 and luminosity class V) was assigned the MK type 'G2 V. Concerning their guidelines, the originators of this two-dimensional classification scheme wrote:

(p.358)

> There appears to be, in a sense, a sort of indefiniteness connected with the determination of spectral type and luminosity from a simple inspection of a spectrogram. Nothing is measured, no quantitative value is put on any spectral feature. This indefinite-ness is, however, only apparent. The observer makes his classification from a variety of considerations—the relative intensity of certain pairs of lines, the extension of the wings of the hydrogen lines, the intensity of a band—even a characteristic irregularity of a number of blended features in a certain spectral region. To make a quantitative measure of these diverse criteria is a difficult and unnecessary undertaking. In essence the process of classification is in recognizing similarities in the spectrogram being classified to certain standard spectra.[426]

While Morgan specialized in the hotter, early types of stars, Keenan concentrated on stars cooler than the Sun, but they both shared a morphological approach to the classification of stellar spectra. Arranging their specimens in the order indicated by the observed form, they ended up with well-defined clusters of morphological types. By basing their scheme on carefully chosen ‘normal stars’ as standards, Morgan and his colleagues avoided the trap of choosing criteria that might change as more was learned about stellar atmospheres and the physical conditions in their interiors. Had they opted to classify according to temperature estimates, as Lockyer or Huggins had tried shortly before 1900, their classification would soon have been rendered worthless. Morgan’s ‘normal stars’, however, being an assemblage of real samples, sorted purely phenomenologically, were immune to theoretical evolution. The MK system was simply defined by a list of standard stars published by Johnson and Morgan in 1953. With any change in the theory of stellar atmospheres, “the standard stars remain the same; only the calibration changes.”[427] The term ‘phenomenological’—already used quite frequently throughout this chapter—is particularly fitting here, because in some of his later writings Morgan himself alluded to Edmund Husserl’s phenomenology with its slogan: ‘back to the things’:

> The ‘thing itself, whether breathing or not, growing or not, has a fundamental property or existence far deeper than any conceptual construction. […] It induces a very deep feeling of respect for those things for themselves, as independent structures of nature.[428]

Elsewhere, Morgan defined the MK system as “a phenomenology of spectral lines, blends, and bands”, emphasizing that the standard reference points did “not depend on values of any specific line intensities or ratios of intensities, [but] by the appearance of the totality of lines, blends, and bands in the ordinary photographic region.”[429] Because any effort to define such a classification system in theoretical terms or in a finite set of line ratios is doomed to failure, Morgan and company argued: “In the final analysis there is only one **(p.359)** meaningful approach we can adopt in the empirical system: *to define it in terms of real objects, without comment.”*[430] Morgan’s classification, like Fleming’s before, was thus quasi-holistic and intentionally autonomous from any theoretical models—the attempt to create a ‘picture-language’, a morphology of classes rooted in the things themselves. Morgan was later successful in establishing similar morphological classifications in other fields as well, most notably for the optical shapes of galaxies.[431]

Table 8.4 lists some of the most important atlases of stellar spectra to appear between 1890 and 1978. Their main aim was to provide representative cases of the various stellar spectra for instructive use by advanced students and young researchers (for more on the teaching of stellar spectroscopy see here § 9.6 on p. 393). Quite in line with what has just been said about the underlying intention of the Morgan, Keenan, and Kellman atlas—which became paradigmatic for most of the later ones—the central function of these stellar spectrum atlases was (and is) to aid in finding the right class for a given sample. In order to achieve this goal, virtually all of them display several related but slightly different stellar spectra on one plate, with a gradient of specific *Gestalt* qualities, such as the intensity of one characteristic line against another. In the simplest case, a stellar spectrum is classified based on the judgment about whether it is 'like' or 'not like' one of the spectra in the array of standard stars. In practice, a systematic comparison of several printed standard spectra with the one under examination will yield either the particular spectrum class closest to the unclassified sample, or two standard spectra between which the given sample should be ordered. Indices like the numerals 0 to 9 are introduced to help in the final steps of this one or two-dimensional ordering.[432] Here is an example of the modern classification along the second dimension of luminosity classes (ranked I-V, progressing towards the brightest stars) among A0 stars:

> Balmer lines of hydrogen show a prominent negative luminosity effect. Thus, the wings of Balmer lines can be used for assigning classes la—111. It is, however, not easy to distinguish among classes III, IV, and V by the aid of Balmer lines alone. Ionized metals except for Ca II K and probably Mg II 4481 and Ti II-Fe II 4173 show positive luminosity effects. Hence the following line ratios can also be used:
>
> Si II 3856/Ca II K Fe II 4233/Mg II 4481, and Si II 4128.31/Mg II 4481. The last one seems to be the most sensitive at A0 for separating classes III, IV and V.[433]

Precisely because there is, in general, no *single*, unique criterion, but always several ratios of line intensities that should be taken into account, which all too often even point to slightly different classifications, the final decision is based not on a strictly algorithmic procedure but on a holistic *Gestalt* classification of the overall appearance. Whereas Galison has readily acknowledged, and indeed emphasized this prevalence of subjective judgment **(p.360)** over a purely mechanical ordering for the later period of stellar atlases, he has construed the earlier endeavors of Cannon *et al.* as following an older ideal of mechanical objectivity.[434] I think that Galison's periodization scheme has led him to overemphasize the differences and to undervalue the many common traits in the longterm endeavor of stellar spectral classification. Despite the positivist data-gathering attitude governing the early efforts at the Harvard College Observatory, as we have seen, the success of the Harvard classification crucially depended on Cannon's extraordinary skill in classifying, far beyond anything resembling mechanical routine. We have also seen that three decades later W.W. Morgan at the Yerkes Observatory was as keen to go 'back to the things themselves'. I thus rather see great continuity in the overall research strand of stellar spectral classification, which from the very beginning was a bonanza of pattern recognition and visually triggered judgments. Altogether, the typical atlas of stellar spectra has similarities with the gauging photographs of quantitative spectroscopy in that we find arrays of samples directly above each other with specified gradients of line intensities. We are once again in the realm of visual comparisons. But unlike Lowe's or Gerlach's gauging photographs, in which spectra of different concentrations of a single substance are compared, which thus decrease monoton-ically in intensity with diminishing concentration, the gradients of stellar spectral classes go in both directions: as one line or band (such as, for instance, the TiO band) strengthens, if we go from classes E to G (where they are virtually not present) to classes I to M (where they are strongest), the FraunhoferH, K, and *Hα* lines weaken correspondingly. Ultimately, however, observers in both research areas weigh family resemblances, basing this skilled judgment on a good visual memory and close comparisons with the representative samples for the various classes displayed in atlases like the ones listed in Table 8.4.

(p.361)

Tab. 8.4 Survey of atlases of stellar spectra 1890–1978. Abbreviations in col. /: HCO: Harvard College Observatory; col. 6 with the average density R/L refers to the fraction ‘wavelength region (in A)/length of representation (in cm)’; in cases of split representation, the regions of minimal overlap of adjacent maps were counted twice; R/L thus gives an approximate measure of the scale of representation.

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
W.P.Fleming & Pickering (HCO)	1890	10 351	4500–3800			objective-prism method. 8-inch aperture Voigtlander lens. 13° prism	16 classes of stellar spectra, designated by letters A-Q (omitting J) in alphabetical order north of-25° declination and down to about 6th magnitude

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
Pickering & Fleming (HCO)	1896		4500–3800			8-inch telescope	Dropping of categories C. D. L. and I. moving K closer to G. reversing F and F. Suppl. with spectra of a southern cluster

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
A. Maury (HCO)	1897	681				11-inch photographic telescope with 153-inch focal length. 4 prisms (high dispersion)	New scheme with 22 groups, identified in Roman numerals together with the lettered sequence. B preceding A; group XXII related to bright-line class O first in sequence. First two-dimensional scheme with additional labels for line strength: a for average, b for hazy and indistinct. c for narrow sharp lines

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
Huggins	1899	12 plates	4050–3625	6 25	100 17.5	Tulse Hill Obs.	Speculative evolutional'} temperature sequence: representative stellar spectra: one plate with “historical spectra” 1876–82

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
A.J.Cannon (HCO)	1901	1122	4500–3800			13-inch Boyden telescope in Arequipa	Refinement of Pickering/ Fleming (Harvard) system with decimalization *oi* the categories (i.e.. K5). subtypes a-c indicating unusually broad lines, d and e weaker emissions. Cannon's system soon became standard and replaced Maury s system

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
Cannon & E.Pickering(HCO)	1918–1924	225 300	4500–3800	c.ll	c.7()	8-inch telescopes at Cambridge. Mass. and Arequipa	*Henry Draper Catalogue:* spectral classification of virtually all stars brighter than 9th or 10th
Cannon & E.Pickering(HCO)	1925–1949	133 782		"	"		magnitude by A.J. Cannon and assistants Extensions of the *Henry Draper Catalogue.* again by Cannon and assistants

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
Morgan, Keenan & Kellman(U.Michigan)	1943	55	3920–4900	c.13	c.75	one-prism spectrograph. 40-inch refractor. 125 A/mm prismatic dispersion: Fastman process and Cramer Hi-speed Special plates	Six MK(K) luminosity classes and redefinition of each Harvard subclass bv the spectrum of a selected star similar to Draper description, for stars up to 12th or 13th magnitude; emphasis on luminosity effects

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
Hiltner & Williams (McDonald Obs., Texas)	1946	9	3982–6723 3916–6302	c.2()	1 70	Coude' spectrograph of the 82-inch reflector. Fastman I03a-0 emulsion	*a* Bootis K2 pec. *a* Cygni la. *[1* Orionis B8 la. *a* Lyrae AO V. *a* Canis Majoris AI V. *a* Canis Minoris F5 IV. *a* Persei F5 lb. *a* Orionis M2 lb: photometric atlas
Abt.Meinel, Morgan & Tapscott	1968	13×61×3	5000–3500	17.7	c. 83	128 A/mm grating dispersion of 36-inch Kitt Peak reflector	Arrays of standards in four sequences. Low dispersion grating stellar spectra of classes B-O and supergiants B-M: 3 metallic line stars

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
Seitter (Bonn Obs.)	1970	24 × (6–8)3×1 32×(2–5)	3500–8665 3340–8640	c.19 c.3()	340 220	Schmidt mirror at Obs. Hoher List. 240 A/mm dispersion at H_γ	MK classification of c. 300 objective-prism stellar spectra in 3 series, and 6 photometric registration curves
Houk.	1974	13×(6–7)	5180–3850	15.5-	c.80	Curtis Schmidt telescope at Cerro Tololo.	Two-dimensional spectral types for 82 objective-prism stellar spectra, accompanying Michigan Catalogue
Irvine & Rosenbush (Michigan)				19		Chile, with 4° plus 6° prism. 108 A/mm disp. at H_y. Ila-O plates	

observer & institution	year	# of spectra	λ region **R(A)**	length L (cm)	R/L	instrumentation	classification & remarks
Keenan & McNeil.	1976	32	3900–4900	37	c.50	photogr. processes Ortho and Fktapan	Revised MK classification for cooler stars. classes G. K. M. S. and C
Perkins Obs. Yamashita *et al.* (Tokyo)	1977	129×5–8	5170–3870 4930–3790	c. 28	c.4()	Ila-O emulsion; single-prism Cassegrain spectrograph. 73 A/mm; 36-inch telescope. Okayama Observatory	Representative stellar spectra of MK standard stars and various peculiar spectra
Morgan. Abt & Tapscott	1978	32×(2–5)	extended to 3500 A	32	40	dispersion of 63 A/mm - 125 A/mm	Revised MK classification; effects of luminosity and line intensity for stars earlier than the Sun, classes O. B. A. F

Notes:

(155) See Carpenter [1873] pp. 415f.; on the importance of this journal—costing only 6 pence an issue—which catered to a wide readership of 70 000 (Margaret Lindsay Huggins was one of its subscribers), see Becker [1994] pp. 250ff.

(156) This feature, already known to Swan [1853/57], was underscored in Kirchhoff and Bunsen's 1860 paper (see Bunsen [1904] vol. 3, p. 235) and often reiterated in the literature since, e.g., by Miller [1862*a*] p. 407 and Roscoe [1868], Another effective rhetorical device was Kirchhoff's [1861/62*d*] p. 19 clever calculation that the more than 60 coincidences between the bright lines in the iron spectrum and dark lines in the Sun's spectrum are statistically improbable and therefore not accidental. Cf., e.g., Anon. [1862] pp. 54–6, A.S. Herschel [1869] p. 157.

(157) A pocket spectroscope with five prisms, three of flint glass, two of crown glass is described, e.g. by Stein [1877] pp.276f.

(158) On the early application of spectroscopy in Bessemer steel production, see *ibid*., pp. 280ff., Lielegg [1867], Watts [1867], [1871], Lorscheid [1870] pp. 116f., Silliman [1870], Parker [1871], Roscoe [1871] pp. 182ff., Alleyne [1875], Browning [1878*a*] pp. 27–9, and the historical survey by Turner [1994]. Stoughton [1911] p. 88 points out that problems occurred in particular when more than one vessel was being blasted at the same time, since light reflected from one interfered with spectroscopic indications of the others. Cf. *idem*, pp. 85ff., Morison [1966] pp. 13If. or Gordon and Malone [1994] p. 279 about recarburizing spiegeleisen with a known amount of manganese to create high-quality steel.

(159) On early applications of spectroscopy in blood analysis, see, e.g., Hoppe-Seyler [1862], [1868], Sorby [1865], [1867], [1875], [1876], Thudichum [1867], Fumouze [1870], and further literature listed in Schellen [1870/72*b*] p. 661, Tuckermann [1888] pp. 165–7, 174, Formanek [1905], Hawk [1907*b*] pp. 215–18, Löwe [1928/33], and Büttner [1999] chap. 6.

(160) See e.g., Jones [1865]; several other applications for physicians and physiologists are discussed in Valentin [1863].

(161) Cf., e.g., Lockyer [1870], Miller [1855*c*] p. 151, J.H.J. Müller [1847*d*] pl. IIIa, Jamin [1858–66] vol. 3. Daguin [1855/79] 3rd edn, vol. IV, opposite 199, Hoppe-Seyler [1868] frontispiece, Roscoe [1869]; Secchi [1870*c*] p. 238, Schellen [1870/72] frontispiece, Browning [1874] frontispiece, Stein [1877] p. 272, etc.

(162) “Besitzer der Fabrik und Handlung chemischer, pharmazeutischer, physikalischer Apparate von G.A. Lenoir”. The spectral map is entitled “Sonnenspektrum und Spektren der Alkalien und alkalischen Erden nach der Originalzeichnung” and measures 63.5 × 93 cm.

(163) See, e.g., Simmler [1861] p. 8 who ordered Lenoir’s “chromatische Wandtabelle” because Poggendorff’s *Annalen* were not accessible to him for longer periods on loan. Roscoe [1868*a*] p. 378 still mentions this distributor of the wall-hanging map in his survey article for a British dictionary of chemistry (see footnote 13 below).

(164) See, e.g., Browning [1874] pp. 28 and 42, [1878*a*] p. 48; cf. also the frontispiece to Browning [1878], and Anon. [1930] p. 360 on Browning’s primary interest in the spectroscope and its applications.

(165) See, e.g., Rosenberg [1908/10*b*] vol. 2, p. 456 who quotes the price of 10 marks for one of four posters, two with chemical spectra per Bunsen and Kirchhoff, and two with astronomical spectra following H.C. Vogel. On Leybolds Nachfolger see also Dunkel [1973].

(166) See G.J.W. [1870], quoting a price of only 7 s 6 d. Ladd had presumably financed the chromolithograph as advertisement for his prisms and spectroscopes: see Clifton [1995] p. 161.

(167) These two items have no registration numbers so it is not clear from which lab they originate. For a fascinating glimpse at the Harvard collection of scientific instruments I am indebted to its curator, William J.H. Andrewes.

(168) I am grateful to the curator of Historical Collections at the MIT Museum, Michael Yeates, for his help in finding at least photographic documentation of earlier usage of such posters in education.

(169) See *ES: Edmund Scientific Industrial Optics Division. 1996/97 – Optics and Optical Instruments Catalog*, pp. 89 and 239.

(170) Other evidence of poster use in laboratories is provided, e.g., by the frontispiece in Gissing [1910], a laboratory arranged for taking spark spectra.

(171) For instance, the representation of haemoglobin in Stokes [1864*b*] p. 356, in various stages of chemical treatment was one often-reproduced spectrum chart in blood analysis (cf., e.g., Sorby [1865*b*] p. 195 or Schellen [1870/72*b*] p. 197). A particularly impressive emulation of the Bunsen chart, adapted to depict 18 different blood spectra (reproduced as chromolithographs and compared against the Fraunhofer solar spectrum at the top) is published in Fumouze [1870] pl. 2 and reproduced in Büttner [1999] p. 48.

(172) See, e.g.,Roscoe [1868*a*] pp. 394ff., or Huggins [1891*b*] pp. 77f., and contrast with Comte [1851–54] vol. 2, 19th lecture (3rd edn 1869), p. 6; written in September 1834 as part of *La philosophic astronomique:* "There are some things of which the human race must forever remain in ignorance, for example the chemical constitution of the heavenly bodies."

(173) B.L. Clarke in *Industrial and Engineering Chemistry. Analytical Edition*, **19** (1947) p. 822, quoted from Baird [1993] p. 277. He locates the 'big' revolution with the introduction of direct-reading spectrometers in the 1940s. However the impact of spectrum analysis on chemical practice can be traced back to the nineteenth century.

(174) See, e.g., Bunsen [1860], [1861*a*], [1863*a-c*] on caesium, [1861*a*], [1862] on rubidium. Lamy [1862], Crookes [1863], [1864*a-c*] and James [1981] [1984] on thallium. Reich and Richter [1863] on indium. Lecoq de Boisbaudran [1875] on gallium, and Rayleigh [1895], Rayleigh and Ramsey [1895], Ramsey [1895] on helium. However, cf. also Junkes [1962] p. 18, Karpenko [1980], and James [1988] about the many false claims on the basis of this methodology.

(175) See, e.g., Meggers, Kiess, and Stimson [1922] p. 240. According to Kaiser [1949] pp. 35f. by then 70 elements could be traced qualitatively in arc and spark spectra, with relative limits of detectability around 10^{-4} *c/c*.

(176) See J.W. Draper [1848] pp. 113f.

(177) Hinrichs's book of this title was published in St Louis in 1901. Born in Holstein, Hinrichs studied at the University of Copenhagen where he obtained his Ph.D. in medicine. In 1861 he migrated to the US where he became professor of physics and chemistry two years later. Between 1866 and 1868 he was also working as chemist for the Geological Survey, and since 1878 as director of the Iowa Weather Service, which he had founded. Between 1889 and 1907 he then became professor of chemistry in St Louis. Hinrichs's work on atomic weights and the periodic system is the subject of a study by Eric Scerri (in prep.).

(178) For the following quotes see Hinrichs [1864] pp. 31–6.

(179) See, e.g., H. Draper [1865] p. 395.

(180) See Runge [1907]; cf. also Jammer [1966], pp. 118–33.

(181) For many other examples of Hinrichs's strategy see, e.g., McGucken [1969] and Maier [1964/81].

(182) The son of a farmer and tilery owner studied at Basel University, Karlsruhe Polytechnic, and Berlin University, and taught at various technical schools before being employed at the Höhere Töchterschule in Basel with a teaching load of 17 hours per week. He submitted his dissertation to Basel University in 1849 where he also wrote his habilitation in 1865. He was then qualified to offer lectures as a Privatdozent but had to cancel many for lack of enrollees. The annual report containing Balmer [1884] lists on pp. 15–21 the assignments of all teachers at the Buergi school for girls in Basel during the school year 1883/84. Balmer, who is listed among the teachers of the Untere Töchterschule, taught simple drawing with straight lines in grade I, mathematical fractions as well as Latin and Gothic script in grade III. On Balmer's life and work see, e.g., Hagenbach [1921], Hartmann [1949], H. Balmer [1961], McGucken [1969] pp. 131–3, and MacLean [1972] pp. 132–7.

(183) See Balmer [1885]. On the search for overtone series, see here pp. 307f.

(184) On reconstructions of this *Gestalt-switch* or 'restructuration'—as the Gestalt psychologist Karl Duncker [1945] called it—from a numerical analysis of the problem to a geometric one, see Banet [1970] and the following main text. For further literature on restructuring see here footnote 112, p. 319.

(185) See the remarks in Riggenbach [1898] col. 2. H. Balmer [1961] also confirms that perspective was one of J. Balmer's favorite topics.

(186) See, e.g., A. Hagenbach [1921] or H. Balmer [1961] p. 57. According to the latter, Balmer had first heard about the issue in a lecture on optics by the Basel professor of physics Jacob Eduard Hagenbach-Bischoff. Balmer [1885] p. 80 only writes that he had been "encouraged" in his endeavors by Hagenbach.

(187) See Balmer [1885] p. 83, quoting Ditscheiner [1864], Mascart [1864*b*], [1867], [1868], van der Willigen [1866/68], Ångström [1868/691, Mendenhall [1881], Huggins [1879*b*], and H.W. Vogel [1880*a*]. Banet's [1966] algebraic reconstruction of Balmer's heuristics is revoked in Banet [1970].

(188) As will become clearer in § 10.6, this move was motivated heuristically by a visual analogy with Thibault's construction of perspectivally shortened circles by means of inscribed right triangles, for which the Pythagorean proportions are valid (see Fig. 8.1). In 1884 Balmer published a paper on circle perspective in which he also discussed Thibault's method.

(189) Balmerf 1885*b*] p. 84.

(190) However, among Balmer's unpublished papers (BÖB, Nachlass 133, folder 12) there is one sheet with a tabular survey of the wavelengths of hydrogen lines from the first to the eighth order (in his nomenclature) calculated on the basis of his general formula (eqn 8.1) with h = 3645.6. One of the first persons to remember Balmer's foresight was Ritz [1903] p. 272.

(191) See Huggins [1879*b*] p. 270, [1880*a*] p. 678. Cf. also McGucken [1969] pp. 118f., O'Hara [1993] pp. 14f., and here pp. 305ff. on Huggins's data and Stoney's interpretation of them.

(192) See H.W. Vogel [1879], [1880*a*] p. 193. H.W. Vogel's biography is outlined in footnote 61 on p. 188 above.

(193) See H.W. Vogel [1880*a*] p. 194 on the mutual agreement of their wavelength determinations, and [1879*a*] p. 116 as well as here p. 187 on the higher sensitivity of dry plates.

(194) See the postscript in Balmer [1885*b*] p. 86 for a detailed comparison between theory and experiment for values of m from 5 to 16, and p. 82: "the agreement must astonish one to the highest degree." Cf. also a slightly later unpublished manuscript 'Ueber Huggins's Messungen der Wasserstofflinien weiβer Sterne' among Balmer's papers (BÖB, Nachlass 133, folder no. 12), with values of m from 5 to 17.

(195) See Hagenbach [1886/90] based on data from Cornu [1886*c*], and Müller and Kempf [1886].

(196) Balmer [1897] p. 209. Cf. similar passages in a manuscript 'Die Notwendigkeit der mechanischen Naturer-klärung' (BÖB, Nachlass 133, folder no. 11) which formed the basis of Balmer [1891], esp. pp. 29f.

(197) See Rydberg [1889/90] p. 13 (note) for some of these sources and their errors. Rydberg had studied at Lund University, where he also became *docent* in physics in 1882, and head of the department in 1901; cf. Meggers [1954], Maier [1976], and especially Hamilton [1993].

(198) See Rydberg [1889/90] pp. 27f. The later nomenclature of S, P, D, F, G, H, and I terms in quantum theory, corresponding to azimuthal quantum numbers k = 1, 2, 3, etc., ultimately derives from Rydberg's phenomenological distinction between the appearances of various spectral series.

(199) See Rydberg [1889/90] p. 42. Rydberg's wave numbers were calculated as the inverse of the wavelength (given in units of Å), and then multiplied by 10^8 to yield numbers with fewer digits after the decimal point. Today both eqn (8.3) above and the constant $N_0 =: R$ are named after Rydberg; the latter is related to Balmer's *Grundzahl, h* (in eqn 8.2) via $R = 4/h$ = 109 721.4 cm^{-1}.

(200) See Rydberg [1889/90] p. 152.

(201) See Balmer’s manuscript, ‘Wellenlänge der Spektrallinien des Wasserstoffs’ (BÖB, Nachlass 133, folder no. 12). Unfortunately, none of these large-scale drawings seem to have been preserved among Balmer’s papers.

(202) See Ritz [1903] pp. 270f., [1908]; cf. Hagenbach [1921] pp. 453–5 and P. Weiss in Ritz [1911].

(203) See, e.g., Kayser and Runge [1888–93], Deslandres [1886]. Cf. also Baly [1905*c*] vol. 3, pp. 4–18, McGucken [1969] pp. 142ff., Brand [1995] chap. 7, and the introduction to Kayser [1936].

(204) For the following, cf. Bergmann [1908] pp. 161ff.: ‘Die neuen Serien’.

(205) Bergmann [1908] p. 161, my emphasis.

(206) On the context of Stoney’s research, see e.g., McGucken [1969] pp. 41ff., 1l0ff., MacLean [1972] pp. 124–9, and O’Hara [1991].

(207) On the Dublin school of mathematical physics, see O’Hara [1979]. For discussions on the role of the Ecole Polytechnique as a master model for the Dublin curriculum see, e.g., Belhoste, Dalmedico, and Picon (ed.) [1994].

(208) See Stoney [1871] p. 293. Cf. also [1891] p. 575 where he makes a similar attempt at ‘explaining’ doublet lines as the result of “elliptic partials of the motion going on in the molecules”.

(209) *Ibid.*, p. 295. When Huggins had found even more components of the hydrogen series, Stoney [1880] repeated this harmonic analysis and had to admit that the lines were not quite, but nearly “harmonically connected”; cf., e.g., McGucken [1969] pp. 118ff.

(210) Stoney [1871] p. 41. This instrument, manufactured by the Dublin instrument makers Howard and Thomas Grubb (1838–1878), was modified with an automatic mechanism for adjusting the prism chain to the position of minimal deflection which, according to Stoney, “almost made of the spectroscope a new physical instrument”; *idem*, p. 44. For the following quotes see also pp. 41, 42, and 46 there.

(211) See Stoney [1871], and Stoney *et al*. [1878] p. 38, and, e.g., Soret [1871] as well as Lecoq de Boisbaudran [1869/71]; cf. also O’Hara [1991] p. 13.

(212) See, e.g., Lecoq de Boisbaudran to the *Secrétaire perpétuel de I'Académie des Sciences*, Paris, 24 May 1874 (AASP, dossier Lecoq de Boisbaudran) on the "really very vague correlations indicated primarily by Mr Stoney, who adopts such high numbers for his harmonic orders that in almost all spectra one can find numerical relations which, in my opinion, do not have very great scientific value. […] this remains entirely between you and me."

(213) See Schuster [1879], [1881*a*], and [1882] pp. 121ff.; cf. also McGucken [1969] pp. 122ft. and MacLean [1972] pp. 129ff.

(214) At the meeting of 12 June 1885 of the Berlin Physical Society, which is summarized in *Nature*, Kayser reported: "the attempt to find such simple harmonic relations was abandoned after the question had been discussed by Schuster." See Anon. [1885] p. 312; cf. alsoCornu [1885] who also declared this search for harmonic overtones useless, and McGucken [1969] p. 125.

(215) Schuster[1882]pp. 120f.

(216) On his oeuvre see, e.g., Urbain [1912], Ramsay [1913], Gramont [1913], and Lecoq de Boisbaudran and Gramont [1923] vol. 1, pp. xi-liv, Marché [1958], Schacher (1970), Courtin [1971], Dhombres [1995], and Lange [1997].

(217) See Lecoq de Boisbaudran [1869/71] vol. 71, p. 659 for the publication of an excerpt of this sealed note from 1865: "The spectral lines of the alkaline (and alkaline earth) metals, classified by their refrangibilities, are arranged, as are the chemical properties, according to the order of the atomic weights."

(218) See Lecoq de Boisbaudran [1869/71] p. 974: "for alkaline metals and alkaline-earth chlorides, a substitution of the metal by an analogous [heavier] metal produced an increase in the mean wavelength of the spectrum that was noticeably proportional to the increase in molecular weight." See also Brian and Demeulenaere (ed.) [1996] pp. 73f. about the 'plis cachetés'.

(219) Lecoqde Boisbaudran [1869/71] p. 659, vol. 71 (quoted in 1871 from the *pli cacheté of* 1865).

(220) *Ibid.*, p. 660.

(221) See, e.g., Lecoq's letter dated 24 May 1874 to the Secretary of the Paris Academy of Sciences (AASP, personal dossier Lecoq de Boisbaudran) in which he mentions his findings on the "homology of the lines […] These relations are at least curious, I think; they allowed me to calculate in advance the λ of some hitherto unknown and since found lines."

(222) See the dossier ‘872 Prix Bordin-Théorie des raies du spectre’ (AASP) for the official advertisement and Lecoq’s application. The commission consisted of the astronomer Charles-Eugéne Delaunay (as rapporteur), Ch. Carley, M. Serret. J. Liouville. and Edmond Becquerel. In 1878, Lecoq was elected corresponding member, in 1880 he received the Academy’s Prix La Caze of 10 000 francs, and in 1879 the London Royal Society awarded him the Davy Medal, but all of these acknowledged his chemical work (see below).

(223) The subtitle of Lecoq de Boisbaudran’s [1874] text volume of about 200 pages is: *destinée aux recherches de chimie minérale*, and it seems that applied chemists and mineralogists were initially the main intended audience. This tendency already emerged in an amendment to his Bordin prize application from 1872 (AASP): “My aim being to facilitate for chemists the spectral research of principle mineral substances. The present work is exclusively observational and experimental, it is completely independent of my theoretical researches on the constitution of luminous spectra.”

(224) See, e.g., Urbain [1912*b*] p. 929: “If one observes the spectra in a spectroscope as used by Lecoq de Boisbaudran, and compares them with his drawings, one is surprised by the extraordinary accuracy of the latter, not only regarding the positions of the lines in the spectrum, but also regarding their relative intensities.”

(225) Lecoq’s chemical studies led to the identification of four more elements (dysprosium, samarium, terbium, and europium). The interplay of these studies with his careful research on their spark, absorption, and phosphorescence band spectra are discussed, e.g., by Gramont [1913] and Urbain [1912].

(226) Ditte [1871] drew earlier analogies between the spectra of S, Se, and Te. Troost and Hautefeuille [1871], between C, B, Si, Ti, and Zi. On the many problems related to the empirical verification of Lecoq’s “speculations” after more precise measurements by Thalén and others, see the critical review by Schuster [1882] pp. 121, 138f.: “some of the relations traced no doubt are interesting and deserve further attention, but most of them are farfetched, and will probably be proved to have no foundation in fact.”

(227) Ciamician later became professor of general chemistry in Padua in 1887, and Bologna in 1889, where he and his assistant Paolo Silber later focused on the photochemistry of carbonyl molecules. See Bruni [1922/23], Jacobson [1922], McPherson [1922], Thorpe [1922], Timeus [1925], Nasini [1926], Fabré [1927], Costa [1972], and further biographical references there.

(228) See, e.g., Gladstone [1857], Mitscherlich [1864], Plücker and Hittorf [1865], Diacon [1867], Moser [1877].

(229) See Ciamician [1877*a*] pp. 502f., where he distinguishes room-temperature absorption spectra of complex compounds in solutions, emission spectra of first order at moderately low temperatures and indicative of simple compounds, and emission spectra of second order, generated by atoms at higher temperatures.

(230) *Ibid.*, pp. 506f., and 513f.: “Accordingly, every natural group of the elements has its own spectrum, which seems to differ among the individual members of the group only in that the homologous lines or groups of lines appear shifted toward one or the other end, that is, an increase or decrease in wavelength and also that certain lines or line groups retire.”

(231) See *ibid.*, p. 507 as well as the accompanying plates, which additionally label the characteristic line groups in each spectrum. Another photomechanically reproduced pl. V in Ciamician [1880], intended to emphasize the homologies between C, Mg, Ca, and Sr, is unconvincing in my opinion. For the earlier maps of these same spectra see Huggins [1864*a*], Thalén [1868], and G. Salet [1873].

(232) For the foregoing see Ciamician [1877], (1878), and [1880]; cf. also Schuster [1882] pp. 140–2 and A.S. Herschel to C.P. Smyth, 16 November 1880 (ROE, 13.58, folder H) for a good summary of Ciamician’s findings, ending thus: “What a grand speculation he has broached and grounded I think on very good proofs of observation!”

(233) Ciamician [1880] pp. 445ff. compared the least refrangible parts of the oxygen spectrum with those of Si, Al, and the alkaline earth metals, and the more refrangible parts of the oxygen spectrum with Cl, Br, I, P, As, and Sb.

(234) *Ibid.*, pp. 451–5. For the context of Mendeleev’s and Lothar Meyer’s discovery of the periodic system and its precursors see, e.g., Brock [1992] chap. 9 or Ihde [1984] chap. 9.

(235) See Ciamician [1877*a*] pp. 517, and 504f. for more details about his model of the types of oscillations performed by atoms and their alteration in compounds.

(236) Quoted from Nasini [1926] p. 997. Bruni [1922/23] p. 28 reports: “Responding to a question by the author, Mendeleev hastened to repudiate these compromising fancies which Wilhelm Ostwald had heftily criticized as transgressing the limits of serious science.”

(237) Hartley completed his studies in Edinburgh, spent the winter of 1864–65 working in Kolbe's chemical laboratory at Marburg, became assistant to Thudichum at the Bartholomaeus Hospital Medical School in London and to Odling at the Royal Institution, advancing in 1871 to senior demonstrator at King's College in London. He held the chair in chemistry at the Royal College of Science in Dublin since 1879. On Hartley, who received the Longstaff Medal from the Chemical Society in 1906, see Adeney [1913], [1914].

(238) See, e.g., Cornu [1874/80], [1889*a*], Hartley and Adeney [1884], Liveing and Dewar [1882*a*] for lithographically or photomechanically reproduced maps, and Kayser [1900] pp. 603ff., 736–40 for a survey of the literature. Cf. also Hartley [1882*b*] for a progress report of a committee, composed of Hartley, Huntington, and Odling, appointed by the British Association for the Advancement of Science to investigate the spark spectra of metallic elements and their compounds under varying conditions.

(239) See Hartley [1882*a*] p. 89 where he announces that these enlargements "will ultimately be published by the Autotype Company, 531 Oxford Street, London". No such publication seems to have appeared.

(240) See Hartley [1883*b*] p. 391: "In order that harmonic relations between lines and groups of lines may he conveniently studied, it is necessary to map spectra according to their inverse wavelengths or oscillation frequencies instead of in the usual manner."

(241) *Ibid.*, p. 390.

(242) See above, p. 308. Similar tendencies were later reconfirmed by de Gramont [1915] p. 280 for his 'ultimate lines' (see p. 327 below).

(243) Hartley [1883*b*] p. 398.

(244) See *ibid.* and Hartley [1891] p. 360: "these elements [belonging to one family] are composed of the same kind of matter in different states of condensation, the molecules having similar modes, but different rates of vibration"; cf. Lockyer [1873], [1874*c*], [1878*a*], [1879*c*], [1880], [1887], [1888*a*], [1897*a*], etc. Lockyer's atomic model assumed that low (flame) temperatures would just yield the spectra of compound bodies, at high temperatures the latter could be decomposed either into smaller molecules of the same element, or into distinct elements even more elementary than the chemically familiar ones on Earth: cf. also H.W. Vogel [1883], McGucken [1969] pp. 83ff., Maier [1964/81] chap. 4, Meadows [1972], North [1969], Wilkins [1994], and Leone and Robotti [2000].

(245) Hartley [1883*b*], p. 397. For the first such observation of the approximate equality of line distances in the sodium doublet and magnesium triplet, see also Mascart [1869]; cf. Meggers [1947] p. 10, Maier [1964/81] pp. 81–3.

(246) The son of the photographic pioneer John Herschel had been appointed professor of mechanical and experimental physics at the University of Glasgow in 1866, and from 1871 until 1886 was professor of physics at Durham College, Newcastle, England. See Turner [1908] and Millman [1980] part III particularly on A.S. Herschel's work on meteor spectra.

(247) See Piazzi Smyth's notebook 'Solar-Spectroscope February 1882–1885' (ROE, 18.114), p. 120, entry for 5 November 1883, where a change of one degree Celcius in temperature for bisulphide prisms is estimated to cause a change of 257 units of wavenormals (waves per British inch), or equivalently a shift of 0.31°, i.e., half the field of view in his viewing telescope!

(248) A perspectival diagram of this type of micrometer is given in Watts f 1875*b*] p. 82. It moves only one half of a telescope lens in the manner of a heliometer. The positions could be read off very precisely from the graduated head (far right of the figure) and a counter (the small horizontal disk left of the counter).

(249) C. Piazzi Smyth's notebook (ROE, 18.114), p. 112; cf. notebook (ROE, 18.113) p. 9 for a clear overview of the various prism arrangements used for observations of different color regions of the spectrum.

(250) About this setup, Arthur Schuster wrote to Smyth on 16 January 1882 (ROE, 15.67, folder S): "let me congratulate on the definition of your spectroscope. I know pretty well, what the different spectroscopes in this country and abroad can do, and there can be only very few indeed that could resolve these lines.– In one sense this is rather discouraging to me. I was just going to start a series of measurements, but as my definition can be so much improved upon I think I shall wait till I can command a better spectroscope."

(251) Quote from C. Piazzi Smyth's notebook 'Aurora spectroscope Prism 2' (ROE, 18.116), p. 21, where he also provided a sketch of how micrometer lines, direct spectrum, and reference spectrum appear in the field of view; cf. Hentschel [1998*c*] for a case in which such micrometric errors played an essential role.

(252) C. Piazzi Smyth's notebook 'Solar-Spectroscope February 1882–1885' (ROE, 18.114), entry for 14 July 1883, p. 52, where he also outlines the relative positions of the six CH bands and the nine CO bands. By October 1883, Smyth seems to have experimented with photographic recording of these features as well, using quarto-sized bichromated plates prepared "with great excellence" by M. Alfred in London: "Every CO band spectrum repeated with the illumination of the sparks of these larger plates (through the coil) gives such a much larger range of lines in place of haze, that it is well worth having installed", *idem*, p. 116.

(253) Piazzi Smyth's correspondence with the instrument maker Thomas Cooke & Sons in York documents that in 1877 he was still experimenting with Geissler tubes, which Cooke tried to obtain directly from Geissler in Bonn, because not many glass blowers mastered the skill of manufacturing such thin tubes. On the Cooke dynasty of instrument makers see Williams [1994] pp. 110f., Clifton [1995] pp. 64f.

(254) See Smyth f 1879*a*], in particular pp. 167, 189f., [1880*a*] pp. 224f., and [1883] p. 94 on Monckhoven's [1877] priority in the invention of end-on tubes. Cf., e.g., Ångström and Thalén [1875], Schuster [1879], Liveing and Dewar [1880], Smyth [1883], [1887], A.S. Herschel [1900] pp. 162–4, and the latter's correspondence in 1880 (ROE, 14.64) for scientific and technological details about these experiments and the production of the tubes.

(255) See C. Piazzi Smyth's notebooks (ROE, 18.106), entry April 1882 about the retirement of J. Salleron, recommending A. Démichel as his successor at the same address in Paris, and (ROE, 18.114), p. 116 about his new "chief maker", as well as the entry of 27 November 1883, pp. 122f., for a transcript of Charles F. Casella's letter to Smyth, dated 31 August 1883, in which he specifies how he had generated the various gases with which he filled the end-on tubes. CO and CO_2 were prepared by "heating crystallized oxalic acid with concentrated sulphuric acid." On the Casella dynasty of instrument makers, between 1875 and 1901 residing at 147 Holborn Bars in London, see Williams [1994] pp. 24–6, Clifton [1995] pp. 51f.

(256) However, C. Piazzi Smyth's notebook of 1878 (ROE, 18.113) contains various handdrawn charts of bands like the Fraunhofer B line, which give an idea of how his chart of the green CO band may have looked. Right under the conventional mapping of this region, he added a two-dimensional graph, with wave numbers along the abscissa, and micrometer readings along the ordinate, for a diagonal array of points (or rather crosses), each for a line in the band. Orthogonally to the line connecting all the crosses, he drew lines with lengths indicating the intensity of each component. Regularly distanced line doublets were then numbered consecutively (from 1 to 11 and 1 to 12 in the case of the solar B band).

(257) A.S. Herschel [1883/87] p. 454. On A. Herschel's work in spectroscopy see also McGucken [1969] pp. 134f.

(258) See A.S. Herschel [1869], and his letters to C.P. Smyth, dated 19 May 1877 and 16 November 1880 (ROE, 13.58 and 14.64), the latter containing an enthusiastic summary of the recent findings by Ciamician [1880], discussed here on pp. 310f.

(259) See, e.g., A.S. Herschel to C.P. Smyth, 9 April 1880 (ROE, 14.64): "1 must go carefully over the two sets of measures and see if anything like resemblance and connection can be made out between them."

(260) The foregoing two quotes from A.S. Herschel to C.P. Smyth, April 1880 (ROE, 14.64). The undated fragment also mentions that Herschel actually worked from Smyth's micrometric readings to remain "strictly with the measurements", and not from his calculated wave numbers, as the latter sometimes contained small errors of two or three wave-number units up or down, from "curve-reading' (i.e., graphical interpolation).

(261) A.S. Herschel [1883/87], original emphasis.

(262) This tradition had been initiated with Stoney [1868*b*], Mascart [1869], Lecoq de Boisbaudran [1869/71], [1870], and Soret [1871]; see, e.g., McGucken [1969], Maier [1964/81], and MacLean [1972].

(263) Cf. here p. 59 and A.S. Herschel to C.P. Smyth, 17 April 1880 (ROE, 14.64) for further details on wave-number plots. In a commentary on Ångström's normal map of the solar spectrum, A.S. Herschel [1869] p. 157 had argued for the use of the wave-number scale in practical terms: "if, however, in place of the wave length the number of impulses in a second, or their scale of pitch, as in musical notes, were employed for projecting the Fraunhofer lines, a nearly natural representation of the prismatic spectrum would be obtained."

(264) A.S. Herschel [1883/87] p. 455. A similar feature had in fact also been described by Schuster [1882] p. 126 as a "curious change and transformation" of fluted bands in spectra.

(265) A.S. Herschel [1883/87] p. 455, original emphasis.

(266) See, e.g., Duncker [1945], Kuhn [1962/70], Miller [1996] pp. 151–3, 158f., and 298f., and Kaufmann [1980] pp. 98, 114ff., and I42f. where he claims that among problem-solving operations, restructuring involves most visual components. Whether there is any link between the prominence of *Gestalt* pattern recognition as practiced in spectroscopy and the emergence of *Gestalt* psychology is beyond the scope of this book, but I am grateful to Kathryn Olesko for raising this point in discussion with me. On the history of *Gestalt* psychology see Ash [1995] and Harrington [1996] chap. 4.

(267) See, e.g., experimental data from Z.W. Pylyshyn—discussed in Kaufmann [1980] pp. 95–7. 115, and Miller [1996] pp. 286f.—which demonstrate the difference between the recognition of good and bad *Gestalten* after they have been turned.

(268) A.S. Herschel [1883/87] p. 455, original emphasis.

(269) See Deslandres [1886].

(270) Brand [1995] p. 177; on p. 159, Brand explains the general attribution of this law to Deslandres as a consequence of Piazzi Smyth's "joyous abuse of speculation", his "tireless" polemics and "guerilla warfare with established science", which had "alienated practically all his colleagues". On Deslandres's other laws, see also Baly [1905*c*] vol. 3, Kayser [1902] pp. 470–91.

(271) See Higgs [1894], issued in three different series: the first in original size in 15 parts, the second in twofold enlargement in 45 parts, and a third in fourfold enlargement in 44 parts. In the following I always refer to the last, a copy of which I saw at the Wolbach Library of the Harvard/Smithsonian Center for Astrophysics, Cambridge, Mass.; a copy of the second is available in the Houghton Library at Harvard.

(272) See Rowland [1889e] for his detailed photographic map of these regions, which makes no comment at all about its interpretation, and Ames [1890], Deslandres [1886*a*] for evidence that Rowland tried unsuccessfully to fit a quadratic formula to the series.

(273) Higgs [1893/94] p. 202. An explicit link between Higgs's and A. Herschel's plots is made in A.S. Herschel [1900] p. 164; cf. also Brand [1995] pp. 178ff.

(274) See Higgs [1893/94] p. 202 and [1896] pl. 89. Cf. also the later debate between Lester [1904] and Higgs [1905] over the degree to which Higgs's values agreed with Rowland's and the proper way of dividing all the bands into series.

(275) Kayser [1936] p. 290; in the 1996 edition, pp. 264f.

(276) See Rowland [1889*i*], Deslandres [1886], Fortrat [1912], and Brand [1995] p. 178.

(277) See, e.g., here footnote 57 on p. 307 as well as the letter by George E. Hale to Edward C. Pickering, 21 September 1897 (HUA, UAV 630.17.7, box 2) for a similar discussion of this issue between Hale, Schuster, and Runge who "will here represent the "series" men, who are the strongest objectors to our present arrangement".

(278) See, in particular, Brand [1995] chaps. 9–12.

(279) See, e.g., Kayser [1910] p. 27: “In summing up all the investigations discussed, I draw the conclusion that quantitative spectroscopic analysis has proved impracticable.” Cf. also Hartley [1911], Konen [1925] p. 619, [1926] p. 1109, Löwe [1925*a*] pp. 38ff., [1929] pp. 669ff., Lecoq de Boisbaudran and de Gramont [1923], and Görlich [1960] pp. 16f., on the problematic start of quantitative spectrum analysis in the nineteenth century.

(280) According to thermodynamic reasoning on the basis of Boltzmann statistics, the dependence of intensity on the number of atoms cannot be expected to be linear, but logarithmic. As discussed below, this was readily confirmed in the pioneering studies of the 1920s.

(281) See W.A. Miller [1862*c*]. On Miller, see here pp. 42, 367, and 399ff.

(282) Compare the claims by Truchot [1875], concerning (2), with the devastating criticism by Ballmann [1875] p. 297: “the duration of the luminous emission is not a reliable gauge, for, as numerous scrupulously performed experiments have convinced me, often even the *same* solution produces different results.” Ballmann’s alternative, his so-called extinction method, in which a lithium solution is diluted by degrees until its strongest *a* line vanishes, is actually a methodological precursor of de Gramont’s method of ‘raies ultimes’ (see p. 327 below). Ballmann used flame spectra with their ill-defined temperatures, however, whereas de Gramont and Hartley preferred spark spectra. Concerning (3) see, e.g., Liveing and Dewar [1879], who tried to correlate the width of the D band with quantities of sodium and other metals, or Lockyer and Roberts [1874], Lockyer [1873/74*a*] pp. 261, 655, 481ff., who noted that as the quantity of an element diminishes its spectrum lines shorten until all but the longest lines disappear. For a later revival of Lockyer’s idea see Scheibe and Neuhausser [1928], Twyman [1951] pp. 269ff.

(283) For examples see Janssen [1870], Champion, Pellet, and Greniet [1873], Truchot [1875], or Alleyne [1875]; Vierordt [1873], H.W. Vogel [1877*a*], [1878*a*], and Formánek [1905] pioneered quantitative techniques of absorption spectroscopy.

(284) See Hartley [1884], [1907*b*]. More precise measurements were published by Reis [1926] clearly showing to good approximation the logarithmic dependency of line intensity (or photographic blackening) on chemical concentration.

(285) Hartley [1881] p. 96. On the same page. Hartley thoroughly criticized the only other photographs of the ultraviolet region published thus far, namely those of W.A. Miller [1862*c*], as “executed with too wide a slit” and “defective in being almost entirely out of focus” (see here pp. 209f.). In 1883/84, his own photographs were reproduced as lithographed plates in negative, i.e., bright emission lines shown in dark on a white background.

(286) See Stokes [1862] p. 605. Cf. on the following Hartley [1881] pp. 97ff. Independently, William Huggins had also implemented this idea in his stellar spectrograph: see Huggins [1880*a*] p. 671. fig. 1.

(287) Hartley's quartz spectrographs and details about his experimental setup and photographic processes are described, e.g., in Hartley [1880], [1881], [1882*a*], and Hartley and Huntington [1879].

(288) Hartley [1884*a*] p. 62; cf. p. 52 there for a sketch of his graphite electrodes. The lower one had deep vertical grooves and was mounted in a U-shaped tube and kept moist by capillary attraction. He also argued that unavoidable accidental differences in the passage of the spark or in the exposure time did not matter as long as they were between half a minute to five minutes; for further tips on the positioning of the spark with respect to the collimator and slit, see Schweitzer [1927*a*] pp. 132–4.

(289) Hartley [1884*a*] pp. 326ff. More extensive tables very much in the same spirit were later published by Pollok [1907], Pollok and Leonard [1907], who used gold electrodes, and Twyman [1923].

(290) Pollok had studied at Albany and Glasgow, had earned the degree of D.Sc. and was lecturer at the Dublin Royal College of Science.

(291) De Gramont had studied under the mineralogist and chemist Charles Friedel, and was elected member of the Paris Académie des Sciences in 1913, but remained an independent researcher; see Branly [1913], Fabry [1924], Haller [1924], Zwaardemaker [1924], Payen [1975], and Tétry [1985].

(292) See de Gramont [1895].

(293) The optimization of the electric circuit by means of self-inductance was done in collaboration with C. de Watteville and Gustav-Adolphus Hemsalech: see, e.g., Schuster and Hemsalech [1899], Hemsalech [1901], and Lecoq de Boisbaudran and de Gramont [1923] text vol., pp. 225–32; cf. also Meggers *et al.* [1922] pp. 238, 241f., Löwe [1929] pp. 670ff., and Lundegårdh [1929/34] vol. 1, pp. 87ff.

(294) Standard gelatino-bromide plates were sufficient for recording the region most useful for spectrochemical analysis, 4800–2230 Å (covering blue, violet, and the near ultraviolet). To go further into the red, de Gramont used Wratten & Wainwright panchromatic plates, and from 1921 on, Lumiére Chroma V.R.: see Lecoq de Boisbaudran and de Gramont [1923] text vol., pp. 210–12.

(295) See *ibid.*, pp. 233ff., and Löwe [1929] pp. 670ff. or Lundegårdh [1929/34] vol. 1, pp. 91ff. for the improved Zeiss version of de Gramont's spark stand, and Hilger [1936] pp. 50f. on the Hilger variant.

(296) This device was useful for exploratory orientation and for rapid recording of the actual field of vision. It was manufactured by the Paris instrument maker Ph. Pellin, who continued the business of Jules Duboscq.

(297) On de Gramont's instrumentation, see de Gramont [1922*b*] and esp. the richly illustrated volume Lecoq de Boisbaudran and Gramont [1923] text vol., part ii, which is confined to describing de Gramont's apparatus in various laboratories.

(298) ibid., text vol., pp. 209–21. Other spectrographs then available on the instrument market that could attain the near ultraviolet included models by R. Fuess (Berlin) and Zeiss (Jena): for a comparative description of all three, see Gerlach and Schweitzer [1930*a*] vol. 1, p. 37. Gratings were not used in early quantitative spectroscopy because of the low overall light intensity of their spectra. This tendency would only reverse itself in 1935 with R.W. Wood's invention of blazed gratings, which channeled most of the diffracted light into one order to yield much better intensities: see, e.g., Harrison [1939*b*] p. 388, [1942] p. 386, Göβler [1946], Kaiser [1949] pp. 41f., and Fitzer [1952] pp. 4–7 for a comparison of the dispersions of various types of prism and grating spectrographs.

(299) See de Gramont [1914], [1922*a*]. Because the different absorption characteristics of the three types of spectroscopes de Gramont used (visual, crown glass, and quartz) changed the overall appearance of the spectra, his tables of ultimate lines in Lecoq de Boisbaudran and de Gramont [1923] pp. 294f. list them separately, both by instrument type and by chemical element.

(300) Altogether, Hartley listed in various papers 1067 lines for just 29 elements. For a detailed critique of some of Hartley's choices, see de Gramont [1914] pp. 6ff.; cf. also here p. 341.

(301) See Konen [1926] pp. 1113f.: "At the moment the list of residual lines has an overwhelmingly empirical character; it belongs very much to pure practice." Theoretically based redefinitions of ultimate lines as a combination of the lowest spectral term with the next higher, nonmetastable term of the same spectral series, with a preference for the $\Delta l = 1$ term, were first suggested by Meggers, Kiess, and Walters [1924] and Laporte and Meggers [1925].

(302) See de Gramont [1920], [1922*b*], and Löwe [1924] p. 568, who somewhat enviously noted a lack of their use by the other side.

(303) A. de Gramont to W.F. Meggers, 13 January 1923 (AIP, Meggers papers, box 2, folder 1923). A partial, but in places incomplete English translation of de Gramont's letter has been published in Meggers and Scribner [1941] pp. 3–4 (the omitted names and places have been reinstated here). Meggers responded by averring: "I was deeply interested in your remarks on the difficulties in getting any recognition for practical spectrographic analysis in France. We have the same difficulty in this country." For a detailed description and illustrations of de Gramont's instruments, see Lecoq de Boisbaudran and Gramont [1923] text vol. part ii. The spectroscopic instrumentation of the Parisian municipal laboratory of chemistry is also discussed in Kling and Lassieur [1921].

(304) Burns graduated in astronomy at the University of Minnesota, from 1913 to 1919 worked as the NBS's first staff spectroscopist in Washington, later becoming director of the Allegheny Observatory in Pittsburgh; see Warga [1958], Anon. [1958], and Hentschel [1998*a*] pp. 567ft.

(305) 305 Meggers (cf. here p. 261, footnote 70) had visited de Gramont's Sorbonne laboratory in September 1921: see W.F. Meggers to A. de Gramont, 19 September 1921 (AIP, Meggers papers, box I, correspondence 1921).

(306) See Meggers, Kiess, and Stimson [1922] pp. 248ff.; cf. also Meggers and Scribner [1941] p. 3. and Meggers [1939] for retrospective accounts of the early spectrochemical work at the NBS.

(307) See, e.g., W.F. Meggers to W.F. Koch of the Materials Branch. US Army Air Corps, Wright field, Dayton, Ohio, 7 February 1930 (AIP, Meggers papers, box 3) for a brief description of the work on spectrochemical analysis at the NBS. His point (9) mentions the exclusive use of an, albeit high-resolution comparator microscope: "The extra cost and labor of obtaining and interpreting microphotometer records would not be justifiable except in very rare instances." A photograph of the W. Gaertner & Co. microscope used at the NBS is stored in a small gray box with his photo collection (AIP, Meggers papers).

(308) See Bassett and Davis [1923] for their still mostly qualitative results obtained with a Hilger quartz D spectrograph, and the subsequent discussion with remarks from other American spectrochemical pioneers. Cf. also Williams [1994] p. 152 and Menzies [1959] p. 271 on the importance of these early customers, and the latter ref. on Zeiss and Bausch & Lomb subsidizing researchers at universities to use their instruments.

(309) See, for instance, Hartley [1906] pp. 162–4, [1911] for an examination of the mineral constituents of a dusty atmosphere. It was sensitive to such minute amounts as 0.000 05 mg of Cu or 0.000 03 mg Mn volatilized in the spark per second, and was thus more sensitive than the famous sodium test by the yellow flame in the Bunsen burner (see here p. 290).

(310) For a caution in this regard see. e.g., Konen [1926] pp. 1112f.

(311) See, e.g., Plücker and Hittorf [1865] p. 6, Konen [1926] p. 1113, and Gerlach and Schweitzer [1930*a*] vol. 1, pp. 5f. Both Hartley and Moss [1912] p. 38, and de Gramont [1915] pp. 277f. ordered the various light sources according to decreasing temperature: condensed spark, with or without self-inductance, spark without condenser, arc, acetylene-oxygen flame, oxyhydrogen flame, Bunsen burner. For historical details, see James [1983*b*], and Hentschel [1998*a*] chap. 5. For a comparison of the physical conditions in arc and spark: Fitzer [1952] pp. If.

(312) See Löwe [1924]. Cf. also Gerlach [1925] p. 383: “strangely forgotten … exhumed by the physicist of the Zeiss works, Doctor Löwe”. The great impact of Löwe’s talk is also asserted by Görlich [1960] p. 18.

(313) Löwe studied at the Universities of Leipzig and Berlin, wrote his dissertation under Paul Drude, and joined the Zeiss Optical Company in Jena in 1899. He started as assistant to Carl Pulfrich (1858–1927) in the metrology department. In 1902 Löwe was made responsible for the research and development of refractometers and spectrometers, later also of interferometers and spectrographs. In 1927 he became head of the Zeiss metrology department. This widely known popularizer of the new experimental technique also offered lectures on optical measurement since 1946 at the University of Jena. On Löwe, see Jobst [1955], Lucas [1955].

(314) The son of a ropemaker studied electrical engineering at Finsbury Technical College and then won a scholarship to the Central Technical College (later to form part of Imperial College, London). From 1897 on, Twyman worked as a cable tester for the Fowler Wiring Cables Co. before joining the instrument manufacturer Otto Hilger in 1898, where he advanced to managing director (1904–46). After the amalgamation of Adam Hilger Ltd. with E.R. Watts Ltd. in 1948, he served as director until 1952, and later as technical advisor. Twyman was elected Fellow of the Royal Society in 1924, and awarded the Wetherill Medal of The Franklin Institute in Philadelphia in 1926, the Duddell Medal of the London Physical Society in 1927, and the Gold Medal of the Society for Applied Spectroscopy in 1956. See, e.g., Anon. [1959], Menzies [1959], Williams [1994] pp. 110f., 126, 135, 151ff.

(315) According to Menzies [1959*a*] p. 270, the father of the Hilger brothers had been master of the Mint at Darmstadt. Adam Hilger had worked for a time in Paris at the Observatory under the direct supervision of Foucault, came to London in 1870 and worked as foreman for John Browning until he set up his own business in 1874. After Adam Hilger's death in 1897, his brother Otto took over; he had worked as mechanic for Lord Blythswood during the construction of a ruling engine for diffraction gratings. Aside from Twyman [1923], [1927], [1929]. [1932],]1941], and [1951] see also various unsigned company brochures on spectrographic apparatus offered by Adam Hilger Ltd., such as Hilger [I936], [1946].

(316) See Konen [1926], followed by Reis [1926] and two other contributions, all three positively disposed towards quantitative spectroscopy.

(317) See, e.g., Lundegardh [1929/34], [1936] for his spectrophotometrical examinations of flame spectra of enzymes, peroxidase in plants, or soils, and Hilger [1936] pp. 50f., Twyman [1951] pp. 172f. for the design details of later variants of Lundegardh's instrumentation. Lundegårdh studied at Stockholm, spent a post-doctoral year, in 1912, at the Universities of Leipzig (with Wilhelm Pfeffer) and Heidelberg, becoming assistant three years later and professor in 1918 at the botanical institute in Lund; see, e.g., Burstrom [1970/71].

(318) On contemporary applications of spectrochemical techniques in steel production see Kellermann [1927], [1929], Vincent and Sawyer [1937], Harrison [1938*a*] pp. 15f., Sawyer and Vincent [1940], Kaiser [1941*a*].

(319) See Löwe [1928].

(320) Gerlach studied at Tübingen and wrote his dissertation under F. Paschen. He was lecturer at the Universities of Tübingen, Göttingen, and Frankfurt, where he was promoted to associate professor of physics in 1921 and discovered space quantization in a magnetic field (together with Otto Stern). In 1925 he was appointed full professor of experimental physics at Tübingen, and at Munich University 1929–45. He returned to his position in Munich 1948–57. From 1944 to 1945 he was also nominated plenipotentiary of nuclear physics. See, e.g., Stierstadt [1980], Nida-Rümelin [1982], Heinrich and Bachmann (ed.) [1989], and FüBI [1998].

(321) In order to reduce the instrumental variance, the optimal conditions for the electric spark circuit were also spectroscopically determined by means of a fixation couple, i.e., one arc and one spark spectrum line of the reference substance, which had to be equal in intensity: see, e.g., Gerlach and Schweitzer [1930*a*] vol. 1, pp. 62ff.

(322) See Schweitzer [1927*a*] p. 130, Gerlach and Schweitzer [1930*a*] vol. 1, pp. 61ff. and Twyman [1951] pp. 56ff., 266f. This term should not to be confused with Hartley's unfortunate homonym relating to his comparisons of series spectra discussed above on pp. 312ft.

(323) See, e.g., Löwe [1929] p. 664, and Meggers, Kiess. and Stimson [1922] p. 252: "The relative intensities of the lines can, after some practice, be estimated visually with a high degree of exactness, so that the use of a microphotometer is required only for work of the utmost refinement. With these, and especially with simple types of spectra, a trained observer, who becomes familiar with the relative positions occupied by the sensitive lines, can entirely dispense with auxiliary apparatus and interpret the spectrogram quickly and accurately".

(324) On this alternating perusal of atlas and wavelength table, see Urbain's preface in Bardet [1926], and Löwe [1928*a*] p. 10.

(325) See Gerlach [1928]; cf. Löwe's [1929] p. 673 warning about visual interpolation between different degrees of blackening.

(326) Gerlach and Schweitzer [1930*a*] vol. 1, pp. 97f.: "For one can apply the knowledge that the subjectively estimated change in intensity of a spectrum line of Z changes approximately evenly over a succession of powers of ten of Z percentages. […] From the reduction in line intensity between 1 and 0.1 % one can then quite safely estimate intermediary steps between 0.1 % and 0.01 %. Some experience is needed, but that is easily acquired."

(327) *Ibid.*, p. 98.

(328) See Reis [1926] and Gerlach and Schweitzer [1930*a*] vol. 1, pp. 19–22 for one experimental test of this procedure, based on successive dilutions by a factor of 1 : 1.5 for a concentration range of Pb in Au between 1 % and 0.003 %.

(329) Scheibe and Neuhäusser [1928], Twyman and Simeon [1930], and Slavin [1933] positioned a logarithmic wedge sector immediately before the slit of their spectroscope, and then used the length of the spectrum lines as an indicator of intensity. Others used photoelectric methods: see the surveys by Twyman [1939] and Kaiser [1941*b*]; cf. also here pp. 264ff.

(330) See, e.g., Harrison [1939*b*] p. 389, quoting results by Heinrich Kaiser [1936], who had shown the reproducibility of his quantitative estimates for an antimony-lead allow within 2.64% of the mean; cf. Meggers [1946] p. 441, Kaiser [1949] p. 36, and Harrison [1942]. According to the latter, contemporary standards for wet analysis were ±2 % for concentrations around 1 %, provided a sufficiently large sample was available, rising to ±100 % for lower concentrations.

(331) On the following cf., e.g., Gerlach [1928] p. 1319, Gerlach and Schweitzer [1930*a*] vol. 1, pp. 7ff.

(332) For gold and lead, respectively, according to Gerlach [1928] p. 1319 or Bayle and Amy [1927] p. 270. Jolibois and Bossuet [1925] suggested an electrolytic method of depositing samples on electrodes to reduce sensitivity levels even further, and specialized firms developed increasingly purified carbon or metal electrodes, which were essential for obtaining such low sensitivity levels.

(333) For the results of one early examination comparing old Greek, Roman, and French coins, see Hartley [1906] p. 162. Wet chemical analysis usually needs samples of at least 10 g.

(334) These figures according to Jolibois and Bossuet [1925] p. 1300, who report that it was thus possible to trace concentrations as low as 20 mg per ton in minerals. Cf. also Brownsdon and van Someren [1931], Kaiser [1952] pp. 56, 58.

(335) See Meggers, Kiess, and Stimson [1922] p. 248.

(336) On some of the techniques used at this site, see Vincent and Sawyer [1937], Kaiser [1941*b*], [1952] p. 59, and Harrison [1939*b*] p. 388.

(337) Nice examples, including the spectroscopic proof that Pb weakens the grain boundaries in gold, are discussed in Gerlach and Schweitzer [1930*a*] vol. 1, chap. 7.

(338) On the following see Ryde and Jenkins [1930]. RU powder was distributed in particular by Adam Hilger Ltd, together with enlarged charts of the prismatic spectrum of the powder. Cf. also Crook [1935] p. 21, who used this method for metallurgical spectrum analysis.

(339) Examples are given in Lundegårdh [1929/34], [1936], Harrison [1938*a*], [1939*b*], [1942]. A Czech case study from c. 1900 is provided by Kuba [1974] pp. 174–81.

(340) For examples, see Werner [1972] and folder 131–4 in DMM, NL-80 (Gerlach-papers).

(341) See, e.g., Mannkopf and Peters [1931], Strock [1936], Goldschmidt [1939] pp. 83–4. On Mannkopff and Peters cf. also Mannkopff’s file (UAG, RA) as well as 4 November 1930 (UAG, Kur. XVI. V. C.q.2. vol. 1).

(342) It is hard to quantify this more precisely, but the international estimate of several thousand spectrochemical laboratories, based on sales figures for large spectrographs and direct-reading spectrometers, is given both by Kaiser [1949] p. 37 and Meggers and Tech [I960] p. 1038. According to Kaiser [1952] p. 60, in the early 1950s, the price of these high-end 'quantometers' lay between $20 000 and $40 000. Based on sales figures of Hilger Ltd. as detailed in Hilger [1936] pp. 55–61, Twyman [1951] p. v estimates that by 1945, 500 spectrographic facilities were in operation in Great Britain alone.

(343) See Meggers and Scribner [1941], Scribner and Meggers [1946], [1954], [1959] covering publications in Dutch, English, French, German, Italian, Russian, and Spanish, and Meggers [1963] p. 662. Cf. also the *Spectrochemical Abstracts*, issued in 19 installments by A. Hilger in London between 1933 and 1973, and the *Spectrographic Abstracts*, issued by the London Ministry of Supply: vol. 1 (1954) – vol. 5 (1961). For earlier statistics on the spectroscopic literature between 1800 and 1930 see Kayser [1938], which records a steady increase in the number of papers on general spectroscopy between 1920 (197 items) until 1928 (642 items), followed by a slight drop to 544 in 1930, most likely the result of the growing popularity of quantum mechanics.

(344) There is a flood of relevant literature. I mention only the tables by Kayser and Ritschl [1926], reissued in 1939, and by D.M. Smith [1928], reissued in expanded form in 1952; the atlas of arc and spark spectra by Bardet [1926], the atlas and tables of flame and spark spectra for various metals in salt solutions in Lundegårdh [1929/34], the arc spectrum atlas for metallurgical spectrum analysis by Crook [1935], Gössler's [1942] atlas of arc and spark spectra of iron as obtained with the widely used Zeiss Q24 spectrograph, and the extensive series of high-dispersion atlases and tables of arc and spark spectra by Gatterer and Junkes [1935*a*], [1937], [1945], [1949].

(345) On the following, see Gössler [1942] text vol., p. 7 and folder 233–2 in DMM, NL-80 (Gerlach-papers).

(346) See Harrison (ed.) [1939], as well as [1934], [1935], and [1938/?! for the techniques involved in this automated measurement reduction.

(347) See the Harrison papers (MITA, MC 60, box 2, folder conferences) and Harrison [1933*b*], [1939*c*], [1942]. According to Harrison [1933*b*] p. 111, the 1932 summer school was attended by about 120 scientific and industrial spectroscopists, coming from all parts of the US and even from England and Canada. Harrison [1939*b*] p. 387 also reports of participants from Germany for the 1939 conference.

(348) Data according to Baird [1993] p. 287. Cf. also the webpages of the two societies at www.sacp.org/about.html and www.ssp-pgh.org/about.html

(349) Vols. 1 (1939–41) and 2 (1942–44) still carry the German subtitle: *Ein Forschungsarchiv* and were published by Springer in Berlin. The editorial board of these first two volumes was composed of R. Breckpot (Louvain), A. Gatterer (Vatican Astrophysical Observatory), W. Gerlach and G. Scheibe (both Munich), and F. Twyman (Hilger, London). 25 contributing editors represented most other contemporary centers of spectrochemical research.

(350) From vol. 12 (1958) on, the same journal was published under the auspices of the National Federation of Spectroscopic Societies (formed in March 1956 in Pittsburgh), since 1966 by the American Institute of Physics, of which the Society became an affiliated member, but the editorial management belonged to the Society for Applied Spectroscopy: see their webpage at www.s-a-s.org/const/History.html

(351) See Saunderson *et al.* [1945], and Baird *et al.* [1947] for descriptions of some of the first working prototypes of such direct-reading spectrometers. According to Baird [2000] p. 6, BA bought the license for commercial manufacture and sale of this instrument in 1947; ARL sold their instrument under the brand name ‘quantome-ter’. On Beckman Instruments, see Beckman *et al.* [1977], Stephens [1985], Sturchio and Thackray [1988], and Thackray and Myers [2000]. Prototypes of Perkin Elmer spectrometers are presented in Ossadnik [2000]. On the contemporary photomultipliers, see Traynard [1950].

(352) See Meggers and Tech [1960] p. 1038. Saunderson *et al.* [1945] mention that with their prototype roughly 20 000 quantitative determinations of magnesium alloys were done within one year of use in a commercial alloy plant. For surveys with further references, cf. Löwe [1950] pp. 399f., Fitzer [1952] pp. 34ff., Jaruntowski *et al.* [1992], and Ossadnik [2000].

(353) According to Menzies [1959*a*] p. 270, the elaborate direct-reading spectrometers cost as much as £15 000, against the simple Hilger spectroscopes from 1896 which had cost only £10.

(354) A brief survey of applications with references is given by Schrader [1999]. According to Ossadnik [2000] p. 13, the oil and Buna industries depended mostly on infrared spectrometers for fast and precise analysis of C4-carbohydrates, and for monitoring of the styrene-butadiene reaction.

(355) See Barnes *et al.* [1966] p. 115. Cf. also Barnes and Bonner [1937/38]. Wright [1941], Jones [1981], Rabkin [1987] on quantitative aspects of the dissemination of infrared spectroscopy among chemists, and Lenoir [1997] pp. 241, 288ff. for further implications on the role of instrument makers in the process of discipline formation.

(356) Cf. Meggers [1946] p. 440 for a list of three dozen methods for performing quantitative spectrochemical analyses. Along a similar vein, Hodge [1943] and Junkes [1962] p. 25 complained that spectrochemical data were still too often determined through trial and error by inexperienced workers and without a sufficient effort at standardization.

(357) Because of the very short discharge period of 10^{-5} sec, the line intensities in spark spectra are lower than in the steadier electric arc: see Kaiser and Wallraff [1939], Kaiser [1949] pp. 39–41, Werner [1948], and Fitzer [1952] pp. If. about the many options of electric excitation then available. Despite better reproducibility of the spark, during the late 1940s and early 1950s, the arc started to displace it in most applications.

(358) Löwe [1929] p. 670 provides us with a nice example: “Physicists will regard with suspicion the procedure devised by the mentioned chemists of what is, in a sense, a quantitative method of spectral analysis as long as they do not know about the physical conditions under which a spark is formed.”

(359) See, e.g., de Gramont [1914] p. 6, Lecoq de Boisbaudran and de Gramont [1923] p. 277,. vs. Gerlach [1925] p. 385, Gerlach and Schweitzer [1930*a*] pp. 11f.

(360) See, e.g., Lecoq de Boisbaudran and de Gramont [1923] pp. 286–93, Laporte and Meggers [1925], Negresco [1927], Russell [1925] p. 225, [1927] pp. 212ff. for the iron group, Löwe [1929] p. 669, Candler [1937] pp. 121f., 187, 260ff.

(361) Twyman [1951] p. 56. Analogously, Meggers [1946] p. 441, and Löwe [1928*a*] p. 11. Löwe [1929] p. 669, added: “There is hope that the criticism in physics will further illuminate the findings made by chemists.”

(362) After studying physics, mathematics, and chemistry in Münster, Freiburg, and Cologne, where he took his doctorate in physics, Kaiser worked in the physical laboratories of Zeiss in Jena between 1934–45. He was subsequently employed at the Staatliche Materialprüfungsamt in Dortmund from 1947 to 1952 while he continued to fulfill the requirements of his academic status as *Privatdozent* at the University of Bonn, becoming founding director of the Dortmund Institute for Spectrochemistry in 1952. In 1954 he was nominated extraordinary professor, and in 1968 full professor at the University of Bonn, retiring in 1975. The Society for Applied Spectroscopy acknowledged Kaiser’s work in spectrochemistry with the Hasler award.

(363) Kaiser [1952] p. 51. The unambiguous message of this talk before the Arbeitsgemeinschaft fur Forschung des Landes Nordrhein-Westfalen was well received. This regional science policy council founded a promotional association, Gesellschaft zur Förderung der Spektrochemie und angewandten Spektroskopie e.V., which in turn founded the Dortmund Institute for Spectrochemistry and Applied Spectroscopy all in the same year. On the early history of this institute see Kaiser [1966].

(364) Meggers [1947] p. 10, original emphasis. One good example among these exceptional astrophysicists is Henry Norris Russell (1877–1957), who published a list of ultimate and penultimate lines of astrophysical interest in 1925, and continued to discuss these issues with some of the spectrochemists involved: see esp. his correspondence with W.F. Meggers in October 1927 (AIP, Meggers papers, box VII).

(365) The figure refers to light in the blue (photographic) and is even higher in the visual. For a detailed general survey of the history of stellar spectroscopy, see Hearnshaw [1986].

(366) On the preceding see Fraunhofer [1815] pp. 220f. and [1823*b*] pp. 142–4; cf. also E.H. Geyer in Sterken and Staubermann (eds.) [2000] pp. 39f.

(367) Fraunhofer [1815*a*] pp. 220f. reported having discerned three broad lines in the spectrum of Sirius, one of them in the green, and two in the blue range of the spectrum. See Donati [1862*a*] p. 292, Merz [1862] p. 654, and Hearnshaw [1986] pp. 51–7. A graduate of the Scuola normale in Pisa and student of Mossotti, Donati became adjunct and professor of astronomy at the observatory in Florence, ‘La Specola’. After Donati’s nomination as director and successor of Giambattista Amici in 1864, the observatory moved from Florence to Arcetri in 1869. On Donati see also Anon. [1874*d*], E.D. [1874], Bonelli [1971].

(368) Huggins was the only surviving child of a London silk mercer and linen draper. After receiving private tutoring, he attended the City of London school 1837–39, whose curriculum deviated from the classical one at public schools. While running his father's business, he took an interest in microscopy, and was elected member of the Royal Microscopical Society in 1852. After the family retired from commercial life, he built up a private observatory in their new residence on Tulse Hill near London. In 1854 Huggins joined the Royal Astronomical Society, for which he later fulfilled the functions of secretary 1867–70, vice-president 1870–73, president 1876–79, and foreign secretary 1873–76 and 1878–1910. From 1865 on, he was Fellow of the Royal Society in London, which conferred upon him the Royal Medal in 1866, the Rumford Medal in 1880 and the Copley Medal in 1898 for his work on stellar spectra, and was elected president from 1900 to 1905. For his discovery of the Doppler effect in stellar spectra, he received the Gold Medal of the Royal Astronomical Society in 1885 and further honors. On Huggins see: Pritchard [1867], Huggins [1897*b*], Kayser [1901], Campbell [1910], Scheiner [1910], R.A.G. [1910], H.F.N. [1911], Dyson [1911/12], Hollins [1912], Hale [1913*a*], Maunder [1913], Mills and Brooke [1936], Dingle [1972], and Becker [1994].

(369) The instrumentation of Huggins's private observatory are described in Huggins [1856], Huggins and Miller [1864*a*] pp. 415–17, and Becker [1994] pp. 39f., 217f., 225ff. For various other types of star spectroscopes, some of which were later also employed by Huggins, see Schellen [1870/72*b*] pp. 442–58.

(370) See the list of equipment, dated 1866, in Huggins's Observatory Book 1866–1889 (WCSP).

(371) W.A. Miller is mentioned here on pp. 42 and 367. On their joint research results in the early 1860s see, e.g., Roscoe [1868*a*] pp. 394ff., and Becker [1994] pp. 85ff., 122ff.

(372) Lady Huggins's collaboration with William is the subject of Becker [1994] p. iii and chap. 4. Cf. also Cannon [1915*b*], Whiting [1915], Newall [1916], Brück [1991] pp. 70–4, 210f., and M.B. Ogilvie in Abir-Am and Outram (ed.) [1987] pp. 110ff.

(373) See Huggins and Miller [1863], [1864], and Huggins [1866*b*] frontispiece. Cf. also Roscoe [1868*a*] pp. 394f. and Becker [1994] pp. 108–17.

(374) This device is mentioned, e.g., in Carpenter [1873] p. 466, and described further by Huggins and Miller [1864*a*] pp. 417f. and pl. X, including the precautions taken in positioning the comparison spectrum.

(375) Quote from Roscoe [1868*a*] p. 395; see also here Fig. 8.2 on p. 299 for his wood engraving of the hydrogen spectrum of α Lyrae, Huggins [1891*b*] pp. 75f. for later qualifications of the “almost infinite diversification” of stellar spectra, and [1891*a*], pp. 7ff., [1865/66], [1869*c*] for Huggins’s models of stellar constitution and evolution.

(376) See Huggins [1864*c*], [1865*a*], [1891*b*] pp. 85ff.; cf. Roscoe [1868*a*] p. 396. Hirsh [1979] pp. 198f.. and Becker [1994] pp. 126–40.

(377) See Donati [1862], [1863], and Rutherfurd [1863], and here pp. 344 and 209. Cf. also Lankford [1981] p. 277 on amateurs as the “risk-takers of science”, and Becker [1994] pp. 73–5 on the concept of ‘peripheral’ as opposed to ‘marginal’.

(378) Quotes from Huggins [1897*b*], see also Mills and Brooke [1936] p. 23.

(379) The son of a carpenter underwent Jesuit training at the Collegio Romano since 1835, where he already specialized in mathematics and physics. From 1841 on, he taught these fields at a Jesuit college in Loreto, 1844–48 he was assistant to F. de Vico at the observatory of the Collegio Romano. During the temporary condemnation of Jesuits by Rome in 1848 Secchi went first to Stonyhurst, England, and then to the George Washington University in Washington, DC, where he became assistant to the astronomer P. Curley. When the ban on Jesuits was lifted again a year later, in 1849, Secchi returned to the Collegio Romano, where he initiated an extensive research program in solar physics in 1851. Aside from his classification scheme of stellar spectra, Secchi also published on solar physics, planets, comets, and gaseous nebulae, and co-founded the Societá degli Spettroscopisti Italiani—see Angot [1878], Bricarelli [1888], Abetti [1975], Brück [1979], and McCarthy in Corbally *et al.* (ed.) [1994].

(380) On the distinction between these four types of stars, which formed the basis of the Secchi classification of stellar spectra (cf. here Table 8.3), see Secchi [1863] about the first two types, [1866] for the third type, and [1868*a*] for the fourth); for summaries see Secchi [1870*d*], H.C. Vogel and Wilsing [1899] pp. 258–329, Brück [1979*a*] p. 12, Houziaux [1979], Hearnshaw [1986] pp. 57–66. Cf. also Secchi’s high-resolution drawing of the spectrum of *a* Orionis, dated 9 February 1866 and covering the full range of the visible spectrum in a detailed pencil drawing of c. 50 cm length, sent to Huggins and preserved as a loose sheet in Huggins’s notebook 2 (WCSP).

(381) On the prehistory of this effect in acoustics, and on earlier theoretical speculations about an analogous optical Doppler effect, see Kayser [1902] § 290ff., Hearnshaw [1986] chaps. 4ff., Hentschel [1998*a*] pp. 380ff. and further references there.

(382) See Secchi [1867] p. 979, [1868*a*] pp. 375f., and p. 401: “for stars of the Sirius type there is, according to my measurement instruments, no appreciable displacement.”

(383) Huggins [1868*a*] p. 547, original emphasis. Cf. Huggins [1872] for an improved estimate, and Hearnshaw [1986] p. 74.

(384) For this long excerpt from a letter by J.C. Maxwell to Huggins of 12 June 1867, see Huggins [1868*a*] pp. 532–5. Maxwell also mentioned his own failed attempts to verify experimentally any influence of terrestrial motion on spectra.

(385) See Huggins and Miller [1864*a*] pp. 416f. and Becker [1994] p. 191 on the micrometer; *idem*, pp. 193f. and Huggins [1868*a*] p. 536 on the high-dispersion star spectroscope; and Huggins [1891*b*] pp. 92f. with his later apologies for this lack of agreement and accuracy of his earlier measurements.

(386) William Huggins notebook no. 2 (WCSP), entry on 6 March 1868, facsimile in Becker [1994] p. 196.

(387) See *ibid.*, entries of 10 March (“almost certain”), 12 March (“the opposite”), 18 March (“I had almost the impression that they were more nearly coincident. I am not sure of this, but certainly when line best seen”, and 30 March (“on the more refrangible side […1 certainly confirmatory”), likewise in facsimile in Becker [1994] p. 199.

(388) See Huggins [1872] pp. 360f., where he reduced his original estimate of Sirius’s recession velocity from 26 to 18–22 miles per second. It is now known that Sirius is not receding from the solar system at 26 mi/s as originally estimated in Huggins [1869*b*] p. 219 but approaching it at 5–8 mi/s. Cf. Hearnshaw [1986] p. 74.

(389) On the associated priority dispute see Huggins [1876] vs. Secchi [1876]; cf. also Kayser [1902] §292. Secchi conceded the existence of Doppler effects in stellar spectra in Secchi [1868*c*] and [1868] pp. 168ff.

(390) See for instance the comparison of contemporary estimates for stellar radial velocity by researchers in Potsdam and Greenwich in Cornu [1891] p. D3I. Cf. also Secchi [1876*b*] about contradictory estimates, Maunder [1885] pp. 167f., Kayser [1902] § 294, pp. 393f. on the various sources of error, and Hearnshaw [1986] pp. 147f. on the superiority of Vogel’s photographic measurements over the Greenwich visual estimates with typical probable errors of ±22 km/s.

(391) This “kill” effect and the complicated instrumental devices needed to overcome it (e.g., by displaying the terrestrial comparison spectrum only for a very brief instant) is discussed, e.g., by Maunder [1885] PP. 119ff. who also indicated the achievable precision and pointed to further sources of systematic error, *idem*, pp. 164f.

(392) Cf. here p. 189 for a quote from Huggins [1880*a*] about this transition from wet collodion to gelatine dry plates, and furthermore Clerke [1902] p. 382, Becker [1994] pp. 260–71. A few of Huggins's early efforts have been preserved (in the storage facilities of the NMAH—my thanks to Deborah Warner for showing me some of them in 1997), presumably because Huggins later gave some of his sample plates to Henry Draper, who glued a few developed collodion films, stripped from their glass backings, into his notebooks (see here Fig. 6.1 1 on p. 215).

(393) See here p. 185 for further commentary and references. As has been pointed out by Becker [1994] p. 260, the second edition of the chemistry textbook by Huggins's collaborator W.A. Miller [1860] included an extensive discussion of the then available photographic methods. Lady Huggins later took over the photographic research: see their list of photographs taken, some of which were later reproduced in W. and M. Huggins [1899] pl. II. Cf. also their notes at the end of their notebook 2 (WCSP) on "experiments in photography to determine the relative sensitiveness of plates", and his notebook 4 for notes on gelatine films and various recipes (also WCSP, c. 1878).

(394) According to H. Draper [1877], these first photographs were 1/2 an inch long and 1/32 inch wide. These earliest spectra seem to have been lost, but according to Herczeg and Kinney [1982] pp. 333f., the New York University Archives include a fine set of eleven slit spectra of the Moon, Jupiter, Arcturus, and Antares, taken from 1879 to 1881.

(395) On Henry Draper, the son of John William Draper, see here pp. 213ff. For excerpts from a since lost laboratory notebook by Henry Draper covering the crucial period starting 29 May 1872, see the posthumous article [Draper] [1884] pp. 237ff. All of Henry Draper's photographic records prior to mid-1879 are wet collodion-based, with exposure times between 320 seconds and 10 minutes.

(396) For a detailed description of Henry Draper's 15 1/2-inch and 28-inch reflectors, see H. Draper [1864], and Plotkin [1972] pp. 15ff. His other instrumentation included a 12-inch refractor, a siderostat built by Alvan Clark & Sons and a strong Rühmkorff coil generating one thousand ten-inch sparks per minute, a Rutherfurd grating, a direct-vision spectroscope allowing use of three to nine prisms, and a Huggins-type star spectroscope with two 60° prisms (both spectroscopes manufactured by Browning): See [H. Draper] [1884], Plotkin [1972] pp. 26f., 36–53, and here pp. 213f. Anna Palmer was the daughter of a wealthy businessman from New York. She assisted Draper with the coating of wet collodion photographic plates, even accompanying her husband on a solar eclipse expedition. After his sudden death she funded the Henry Draper memorial, see Cannon [1915*a*], and Plotkin [1972] pp. 23ff., 119ff.

(397) According to H. Draper [1879*c*] p. 84, seven different driving clocks were tested before a satisfactory one was found. Huggins [1879*b*] p. 269 likewise reported success only after obtaining a driving clock manufactured by Grubb in 1875. These two examples nicely support my general claim that experimental breakthroughs are triggered by developments in instrumentation.

(398) Quote from Huggins [1879*b*] p. 269, an abstract of a paper read before the Royal Society in London on 18 December 1879. It was stimulated by Henry Draper's [1879*b*] publication, read before the National Academy of Sciences on 28 October 1879 (cf. Draper [1879*c*] p. 83 for another description of the same guiding problem). Draper admitted *(idem*, on p. 84) to having visited Huggins's observatory in the spring of 1879 and gleaned various tips, including a recommendation of the commercial plates by Wratten & Wainwright.

(399) H. Draper [1879*c*] p. 83.

(400) On the HCO see in particular Jones and Boyd [1971] and the special issue of the *Journal for the History of Astronomy*, **21** (1990) pp. 3–106. Pickering's work there is discussed in Plotkin [1978], Hoffleit [1991].

(401) 'For more detailed descriptions of the instrumentation and recording techniques see E.C. Pickering [1884/85], [1891*a*] pp. viii, xii-xvi, xix-xx, and Hoffleit [1991] pp. 110ff. The optical workshop of Alvan Clark & Sons is mentioned in Warner [1968], pp. 57f., 68f.

(402) See Secchi [1868*a*], [1870*d*], Pickering [1891*b*], and Maunder [1913] pp. 33f. Today these stars are called Wolf-Rayet stars.

(403) After completing undergraduate studies at Newnham College in Cambridge, she left England to do research at the HCO. Radcliffe College awarded her the first Ph.D. in astronomy ever granted to a student at the HCO for a thesis on stellar atmospheres. She became Philips Astronomer in 1938 and professor of astronomy, and chair of the department of astronomy in 1956, retiring in 1965. See Haramundanis (ed.) [1984].

(404) On the early history of the Draper classification see, e.g., Cannon [1915*c*], reprinted in H. Shapley (ed.) [1960], pp. 149–58, esp. pp. 151f., Gingerich [1964], [1982] pp. 318ff., Plotkin [1972] pp. 137–48, Hoffleit [1991] pp. 120ff., and the modern textbook surveys in, e.g., Kaler [1989] chap. 3, Kitchin [1995] chaps. 1 and 11.

(405) See the *Annals of the Astronomical Observatory of Harvard College*, **27** (1890).

(406) See *the Annals of the Astronomical Observatory of Harvard College*, **91** (1918)-**99** (1924), esp. Cannon and Pickering [1918], and [Cannon] [1949] for the extension of the Henry Draper atlas.

(407) The daughter of a Delaware state senator graduated at Wellesley College in 1884. After spending the next 10 years at home in Denver, she returned to Wellesley as a postgraduate assistant in 1894, also enrolled as a special student in astronomy at Radcliffe College in 1895. One year later Cannon joined the staff at the HCO and worked there for the rest of her life. From 1911 to 1938 she was curator of the astronomical photographs, and then became the William Cranch Bond Astronomer at the HCO. Among her many distinctions are an honorary doctorate awarded by Oxford University (the first ever awarded to a woman), and the Draper Gold Medal from the National Academy of Sciences. See, e.g., Brück [1941], Campbell [1941], Payne-Gaposchkin [1941], Shapley in [Cannon] [1949], Gingerich [1972], and Hoffleit [1991] pp. 129ff, 142ff.

(408) See Payne-Gaposchkin in Haramundanis (ed.) [1984], p. 149, 139 written in the 1970s, privately printed in 1979, first published in 1984. Cf. also Gingerich [1980] p. 50, Galison [1998] p. 343.

(409) Payne-Gaposchkin in Haramundanis (ed.) [1984], p. 150: part of Cannon’s secret seems to have been that she did not rely on the line spectrum, especially in the case of very faint stars, but on the distribution of energy in the continuum. See Gingerich [1964] for examples.

(410) For the precise times in her logbook and further details about this example, see Gingerich [1964] p. 82.

(411) See Lockyer [1888], [1897*a*], [1902].

(412) Maury had graduated from Vassar College in 1887. and was research assistant at the HCO 1888–1935. She introduced a second dimension to this classification system by noting conspicuous differences in the width of spectral lines, adding the labels a, b, and c, to refer to broad, intermediate, and narrow lines. On the Maury classification see, e.g., Struve and Zebergs 11962] chap. 10. Plotkin [1972] pp. 143f., DeVorkin [1981], Hearnshaw [1986] pp. 111ff., Hoffleit [1991] pp. 126ff., and Corbally *et al.* (ed.) [1994].

(413) Payne-Gaposchkin [1984] p. 150, original emphasis.

(414) Altogether 44 between 1877 and 1919 with terms of employment between one and 46 years, according to Hoffleit [1994] pp. 13f.

(415) On the contemporary education of American women astronomers, see Warner [1979], Rossiter [1982] pp. 53ff., 136ff., 170ff., Hoffleit [1994] pp. If., and Lankford [1997] chap. 9. According to Dorrit Hoffleit, only 16 of the roughly 2500 high schools existing in the US in 1890 offered astronomy—of these 16, ten were open to girls. On the situation in Greenwich and Edinburgh, see Brück [1995], [1998]; on France see Bigg in Hentschel and Wittmann (ed.) [2000].

(416) See Fleming's diary of 1900 as quoted in Rossiter [1982] pp. 56f., cf. also pp. 53f., Cannon [1911], and Hoffleit [1991] pp. 117f., 124f., and 138ff.

(417) See Fleming [1893]; cf. also Whitney [1882], Rossiter [1982] pp. 53f., Kidwell [1986], Lankford and Slavings [1990], Mack [1990], Lankford [1997] chap. 10, and Ogilvie in Abir-Am and Outram (ed.) [1987], According to Payne-Gaposchkin [1984], p. 147, Pickering had chosen Fleming after discovering her talent for recognizing spectra; two others (including Maury) were deaf.

(418) See Payne-Gaposchkin [1984] p. 161. Cf. also Wead [1884] p. 97 in which G.D. Liveing is quoted as conceiving the "classificatory sciences, botany and zoology" as the only ones possible for introduction into elementary school curricula.

(419) Sommerfeld and Back [1921]; cf. also Forman [1968], [1970], Hentschel [1996*a*] on Zeeman spectroscopy in this period, and Hentschel [1998*b*] or Kojevnikov (in prep.) on the crisis of the old quantum theory.

(420) See, e.g., Secord [1986] p. 33 for an interesting parallel between geology and stellar astronomy as 'classificatory enterprises'. For a further embedding of classification within a sequence of typical research strategies, see Hentschel [1998*a*] chap. 11, [1993*a*], [1996*b*].

(421) See Cannon and E.C. Pickering [1918] p. iii; on the hidden association of female 'unskilled' workers with machines, as a "tacit guarantee that these data were not the figment of a scientist's imagination or philosophical commitments", sec Galison [1998], pp. 342f.

(422) Morgan lived and worked at the Yerkes Observatory for 68 years and received numerous awards for his work centering on morphological classification techniques; see Garrison [1995]. Keenan also worked at the Yerkes Observatory and later at the Perkins Observatory of Ohio State University: see Boeshaar [2000]. Osterbrock in Corbally *et al.* (ed.) [1994] is the only historical article also including remarks about Edith Kellman. who graduated from Wheaton College in 1933 and became Morgan's assistant in 1934. According to Morgan [1988] pp. 4f. Kellman became a science teacher at Williams Bay High School in 1943. Donald Osterbrock tells me that "she kept in close touch with Morgan, and recommended her best students to him for part-time summer jobs at the Observatory" (personal communication, 18 June 2001).

(423) On these manufacturing details see Osterbrock in Corbally *el al.* (ed.) [1994] pp. 211f.

(424) See, e.g., Morgan in Garrison (ed.) [1984] p. 25 with respect to Morgan. Abt. and Tapscott [1978]: “It was a good thing that we got the Atlas out when we did, because Joe Tapscott died soon after that. He supervised the printing very closely, stopping it after each 100 prints to check how things were going.”

(425) The MKK classification refers to the atlas by Morgan, Keenan. and Kellman **[1943];** the MK classification refers to the list of standard stars published by Johnson and Morgan [1953], and later revisions by Morgan and Keenan [1973] and Morgan, Abt, and Tapscott [1978] are referred to as ‘revised MK’. For surveys and discussion of these schemes, sec Garrison (ed.) [1984] and Corbally *el al*. (ed.) [1994].

(426) Morgan, Keenan, and Kellman [1943] pp. 4f.; cf. also Galison [1998] pp. 338–43.

(427) See Garrison [1995] p. 509, who also points out the similarity to Wittgenstein’s thoughts about classification by specimen.

(428) Morgan [1988] p. 3.

(429) Morgan and Keenan [1973] p. 30; cf. also the remarks by Garrison, Keenan, and Hoek in McCarthy *et al.* (ed.) [1979] pp. 38, 49, 55 about the importance of visual inspection of actual spectra, not just a reliance on a small number of line ratios.

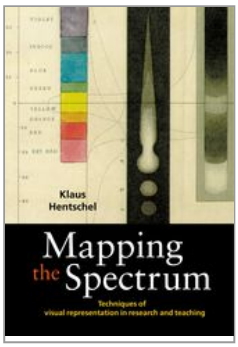
(430) Statement by Dimitri Mihalas as quoted in Morgan and Keenan [1973] p. 31.

(431) See Morgan [1988] pp. 3–9 on these other classification schemes, and Morgan’s as well as Mihalas’s contributions to Garrison (ed.) [1984] about the basic approach of the ‘MK process’, defined as the general methodology to construct autonomous systems of classification defined solely on particular observed characteristics of selected specimens.

(432) Whereas the original Secchi, Vogel, and Harvard classifications are one-dimensional, the MK classification of Morgan, Keenan, and Kellman [1943] is two-dimensional because it orders both into star types and luminosity classes.

(433) Yamashita *et al.* [1977] p. 50; cf. also the accompanying plate on p. 51.

(434) On the latter see Daston and Galison [1992] and here pp. 450ff.



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
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Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

In the Classroom Laboratory

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DOI:10.1093/acprof:oso/9780198509530.003.0009

Abstract and Keywords

Visual science cultures only stabilize if routine methods of teaching Gestalt-seeing, pattern recognition, and other visual skills are taught effectively in the classroom, in laboratory sessions or other practical courses. This chapter documents these pedagogical efforts based on a few exceptionally well documented case studies, most notably the Harvard Student Astronomical Laboratory, and classes at MIT and Wellesley College. Edward Charles Pickering's and William H. Pickering's courses at MIT as well as Sarah Whiting's courses at Wellesley permit tracing the training methods for young practitioners of spectroscopy to memorize the characteristic lines in emission spectra or the various classes of stellar spectra. Further dissemination of spectroscopic techniques and skills into high schools, Gymnasien, etc. was achieved by widely distributed wall posters or charts and simple instruments for generating spectra, such as direct-vision spectroscopes.

Keywords: pedagogy, MIT, Wellesley College, Harvard Student Astronomical Laboratory, Sarah Whiting, Edward Charles Pickering, William H. Pickering, direct-vision spectroscope, wall-hanging poster

> It is wholly beyond question that to him who desires to become a physicist, Practical Laboratory Work is absolutely essential. Thorough knowledge must be drunk in by the eyes and the ears, and absorbed by the finger-tips. A. Daniell [1884] p. vi.

The spectroscopic research applications dealt with in the last chapter presuppose practical proficiency. Education is the means by which skills, including the visual skill of pattern recognition and mastery of various modes of representation are disseminated within a community. How were the many types of visual representation of spectra we have encountered here—maps, plates, photographs, and drawings—actually used in teaching? What role did photography play in the practical education of aspiring astronomers, physicists, and chemists? To what extent were the famous maps of the solar and terrestrial spectra also useful for teaching purposes? How did a beginner use the large poster on the classroom wall or small-scale reproductions in his or her textbook and laboratory manual to find a specific line? How did a more advanced student learn to recognize spectroscopic features like reversion and line splitting, or specific patterns like a spectral series or the identifying spectrum lines of a chemical element? How were practitioners trained to draw these features during observation in the laboratory? Did these teaching methods differ by country—I glance at Britain, France, Germany, and the United States—or by scientific discipline—chemistry, physics, astronomy? What popularization techniques were used in the surprisingly rapid diffusion of spectroscopic knowledge among the general public since the 1860s? These questions will be addressed in the following.

Historians and sociologists of science alike have emphasized the crucial importance of institutionalized teaching for the formation and stabilization of disciplines. The history of scientific instruction in general, and more particularly, the teaching methods in specific subject areas have occupied historians of science[1] ever since Thomas S. Kuhn pointed out the importance of new recruits and the transmission of knowledge and skills to coming generations for the stability and efficiency of ‘normal science’. The social historian of science Lewis Pyenson even went so far as to say that “a strong teaching program may even be more important than high-quality original research in launching a scientific discipline.”[2]

(p.363) One of the most momentous social changes for the scientific enterprise during the nineteenth century was the emergence of scientific and teaching laboratories. Contrary to what is commonly thought today, physics and other sciences (such as geology, physiology, and engineering) borrowed the concept of the research lab from chemistry relatively late in the game. Hence, before we can have teaching laboratories, the ‘laboratory revolution’ must have completed its redefinition of the material circumstances under which research is conducted. This process is linked to the rising professionalization and specialization that ultimately led to the split of physics into theoretical and experimental physics as independent subdisciplines.[3] It was only after the transition to physical research laboratories had been completed that this discipline could start to introduce specific teaching laboratories. Chemists had already achieved this, with Liebig in Giessen, Bunsen in Heidelberg, and Wöhler in Göttingen, to name the most prominent German examples attracting many foreign students and serving as an international model.[4] At Harvard the first real laboratory course for chemists was introduced in the autumn of 1870, and “elective laboratory exercises in physics” first appeared in the curriculum of 1871/72.[5] At the University College, London, laboratory training in chemistry had a tradition going back to Alexander Williamson’s reform of chemical teaching in the mid-1850s.[6] The first engineering laboratory specifically for teaching was set up in 1878, however, and it took until 1894 for physics to acquire satisfactory teaching laboratories. Formerly, “the professor of this science [had been] but indifferently lodged. His classes had not room enough […] and were so ill fitted to the requirements of physical observation and experiment that there was no room in his department where the equilibrium of a delicate balance would remain undisturbed if any one walked across the floor!”[7] In the weekly *Science* journal of 1884 we read:

> The material circumstances under which scientific discovery is prosecuted have been completely revolutionized during the last forty years. […] Forty years ago there were very few, more properly no laboratories which we of to-day would consider even tolerable. Now every university of importance and repute, the world over, has large suites of rooms for each department of science, and often numerous great buildings within whose walls thousands and thousands of students are daily brought face to face with the facts and laws of nature.[8]

(p.364) By 1900, only one fifth of some 250 major institutions of higher learning, employing about 500 professors and 800 assistants, in Europe, the United States, and Australia, did not offer any laboratory courses to an approximate total of 25 000 students. According to a contemporary survey, many students actually spent an average of 8 hours per week over three semesters working on some 60 different exercises, often including one or two spectroscopic topics.[9] Considerable attention has been given, within different national and institutional contexts, to the emergence of laboratories from private professorial collections of apparatus and materials (such as, those of the physiologist Purkinje in Breslau, the physicist Magnus in Berlin, or the chemist Liebig in Giessen) and from instrument collections in museums (such as the Boerhaave in Leyden or the Muséum d'histoire naturelle in Paris). But to my knowledge no in-depth study exists on the practical laboratory and classroom training of spectroscopists, and *a fortiori* none with a comparative perspective on different national contexts.[10]

I start this chapter with a survey of spectroscopic textbooks since the mid-nineteenth century, initially focusing on Germany. This will give an idea of the level, the overall breadth, and the specific topics covered in lecture courses. In due course these traditional *Vorlesungen* were supplanted by practical instruction in special student laboratories. Based on laboratory manuals and some student notebooks I discuss spectroscopic classroom and laboratory exercises in astronomy and physics, and to a lesser extent in chemistry (§ 9.4), as well as the popularization of spectroscopy for broader audiences (§ 9.8). Special case studies are made of the spectroscopy courses at MIT, the Harvard Students Laboratory, Wellesley College, and the École Polytechnique in Paris.

9.1 Textbooks and laboratory course manuals

Textbooks are an important form of knowledge transmission. Their primary audience is students, many of whom later become practitioners and, in some cases, professors or teachers in the field, thus effecting a further multiplication of knowledge acquired during their training.[11] Textbooks are printed in fairly large runs, often go through several editions, **(p.365)** sometimes are also translated, and are frequently revised to keep at bay the chronic threat of becoming obsolete.[12] Comparing various editions can thus yield important insights into the changes in emphasis on certain topics. Likewise a comparison of contemporary textbooks of different origins points to regional and national differences in the curriculum.

One interesting example is the influential textbook on physics and meteorology by the physics professor at Freiburg Johann Heinrich Jacob Müller. It originated as a German translation of C.S.M. Pouillet's *Éléments de physique experimentale et de météorologie*. The first German edition of 1844 is a rather loose rewriting of the French original, and later editions only barely resemble it.[13] Just two years after the publication of Kirchhoff's and Bunsen's first paper on spectrum analysis, the sixth edition of 1862 already included two full chapters on spectroscopic issues. The first concentrated on the older body of knowledge related to prismatic dispersion; the second contained all the new knowledge about flame and arc spectra and commented on the reversion of emission and absorption spectra, which is the core of spectrum analysis. This edition was supplemented by several woodcut illustrations taken from the recent spectroscopic literature and no less than three chromolithographed plates illustrating different types of spectra (the first is a reprint of Bunsen's characteristic spectra of alkaline and alkaline-earth elements, the second exhibits typical phosphorogenic spectra, and the third depicts various molecular band spectra).[14] In later editions of this textbook, which was continuously updated until the end of the nineteenth century, the amount of information on spectroscopic issues grew steadily.[15] Spectroscopy filled a major portion of the second volume of Adolph Wüllner's (1835–1908) four-tome *Lehrbuch der Experitnenralphysik*, which went through five editions between 1862–65 (1st edition) and 1896–97 (5th edition).[16] In Heinrich Kayser's textbook, on the other hand, spectroscopic issues took up only about 30 of a total of 513 pages (~ 6 %)[17] —this despite Kayser being a specialist in the field and tending to have his doctoral students work on spectroscopic topics for their dissertations in physics.[18] Finally, the field was given only a meagre six pages in Emil Gabriel Warburg's (1846–1931) contemporary textbook on experimental physics,[19] reflecting the fact that Warburg did not do any work at all in spectroscopy.

(p.366) Practical guides to laboratory research give a better insight into the daily routine of education in experimental physics and neighboring disciplines. As Kathryn Olesko has pointed out, with the appearance of its first edition in 1870, the *Leitfaden der praktischen Physik* by Friedrich Wilhelm Georg Kohlrausch (1840–1910) “quickly set the standard for practika across Germany”.[20] There were about 20 editions of it, each considerably fatter than the last (the first of 1870 filled 123 pages with 41 exercises and the eleventh, the last to appear during his lifetime, in 1910, was 736 pages long and included roughly 800 exercises). It was also translated into English, French, Russian, and Japanese.[21] Spectroscopy accounts for a substantial portion of part one, which includes general matters, mass, density, heat, and light. His discussions of the measurement of the prismatic angle of deviation and the angle of refraction soon became a model for other introductory practical guides. In the early editions, Kohlrausch’s discussion of the characteristics of the Fraunhofer lines and of spectrum analysis focused on the skills needed to chart emission spectra in the scale of the maps by Bunsen and Kirchhoff. In editions appearing after the turn of the century, this was supplemented and to some extent replaced by an introduction to more complex measurements, as in interferometry.[22] This tendential shift away from a discussion of spectra *per se*, which is related to a change in research practice and an increasing theoretization of spectroscopy, can also be found in other textbooks after 1900. For instance, Edward L. Nichols and William S. Franklin’s three-volume college textbook *Elements of Physics* devotes a full chapter of its third volume covering light and sound to dispersion and spectrum analysis, but with a strong emphasis on photometry.[23]

Given the importance attributed to spectroscopy in *physics* textbooks and laboratory course manuals in the second half of the nineteenth century, it is quite surprising that contemporary textbooks on general *chemistry* tended to omit the subject altogether. The explanation for this paradox—considering the great importance of spectrum analysis in chemistry since 1860—is that at most universities chemistry students were required to attend the introductory physics lectures as well as some relevant practice sessions. In other words, chemists could rely on their colleagues in physics for training their students in **(p.367)** this field. In some local contexts, however, where the chemistry professors happened to have an unusually strong interest in spectroscopy, another solution was found. Both John Frederic Daniell (1790–1845) and his successor to the chair for chemistry at King’s College, London, William Allen Miller, opted for a special subdisciplinary category called ‘chemical physics’ as one part of their general course in chemistry, the other two parts being devoted to inorganic and organic chemistry.[24] Because Daniell’s research on electric batteries and pyrometry and Miller’s research on flame colors, spectroscopy, and photochemistry, lay at odds with the emerging disciplinary boundaries between chemistry and physics, the usual division of labor and competence practised elsewhere simply did not make sense. The inclusion of subjects like

electrochemistry, thermodynamics, and molecular force makes ‘chemical physics’ seem a virtual forerunner of ‘physical chemistry’, as later inaugurated by Ostwald, Nernst, G.N. Lewis, and others.[25] Yet, it differed considerably from the latter by including subjects like chemical affinity, elasticity, cohesion and adhesion, crystallization, applied optics, electricity and magnetism, as well as photochemistry, and spectroscopy. Miller’s textbook is a particularly interesting test case in this regard, because its first edition appearing at the early date of 1855, with later editions (in 1860, 1863–64, and 1867–68) appeared during the boom in spectrum analysis. Even the first edition includes a full discussion of the prismatic analysis of light, various absorption and emission spectra, as well as Stokes’s phosphorogenic spectrum.[26] Later editions added detailed commentary of the solar spectrum with its Fraunhofer lines, flame spectra with their bright emission bands and lines, spark spectra of the elements and, of course, Kirchhoff ‘s and Bunsen’s spectrum analysis. Miller’s work scarcely differed, in fact, from the standard expositions in physics textbooks of the period with regard to its selection of topics, depth of discussion, and choice of accompanying illustrations.[27] Similar selections were made in Daniell’s and Miller’s regular chemistry textbooks, as well as in the ones by the two Drapers, John William and his son Henry, both professors of chemistry at the University of New York. Likewise for Thomas Ruggles Pynchon, professor of chemistry and the natural sciences at Trinity College, Hartford, and Henry Enfield Roscoe, who taught chemistry at **(p.368)** Owens College, Manchester.[28] Miller’s demonstration of colored flames into which minute quantities of various metal salts had been introduced must have impressed his students. We read in the diary of a medical student who had attended Miller’s lectures: “Professor Miller regaled us with some beautiful experiments, showing the different colours of the various metals during combustion”.[29] These demonstration experiments occurred just months after an English translation of Kirchhoff and Bunsen’s paper had appeared in the *Philosophical Magazine.* The rapid encroachment of spectroscopy upon the broader curriculum must have made it unlikely for any student, say in the 1870s, not to have come across the topic. Thus at Owens College the opening of the academic year in 1879 for the Natural Philosophy Classes was celebrated with a plenary lecture by Balfour Stewart on ‘some points in the history of spectrum analysis’. It included demonstration experiments of some of the key discoveries by Newton, Bunsen and Kirchhoff, and Lockyer and was subsequently also published in *Nature?*[30]

9.2 The case of the Massachusetts Institute of Technology

Most of the textbooks on experimental physics and physical laboratory manuals that I have seen from English-speaking countries, dated 1875–1945,[31] include spectroscopic experiments as part of practical training in physics. The place to start a survey of instruction in spectroscopy in the United States is the Massachusetts Institute of Technology (in the following abbreviated MIT). From its very conception in 1864, the planned scope of this “school of industrial science” and “comprehensive Polytechnic College” was instruction combining lectures, laboratory exercises in manipulation and analysis, and “continued practice in the kinds of drawing appropriate to these studies”.[32] Specifically, practice in physical and chemical manipulations was supposed to familiarize the student with the adjustment and use of the apparatus as well as with the “agents employed in the more important experiments and processes in natural philosophy and chemistry”. Under the guidance of their teacher, small groups of students were expected “to execute with their own hands various experiments in mechanics, pneumatics, sound, optics, electricity, and other branches of experimental physics, and to exhibit chemical re-actions, to set up chemical apparatus, to prepare gases and other products, and to demonstrate their properties by suitable experiments.”[33] The first appointed physics professor there, Edward Charles Pickering **(p.369)** (1846–1919),[34] implemented this program in the late 1860s and established America’s first physical laboratory specifically designed for student instruction.[35] This practical education placed strong emphasis on the “graphical method, or the representation of phenomena by curves”, because Pickering was of the opinion that “from a curve we are able to judge with far more certainty the nature of the errors and the best means of diminishing them, than it is possible to do from the numerical results”.[36] He thus required that his students plot and graphically analyze the data collected in their experiments, determine measurement errors, and find the best fitting curves.[37] Soon thereafter, Sarah Frances Whiting at Wellesley College, Henry Augustus Rowland in Baltimore,[38] and Arthur Schuster at Owens College, Manchester (England), initiated similar courses,[39] even though the teaching method “entailed too much work to be popular at first”.[40] It is notable that both E.C. Pickering and H.A. Rowland had studied civil engineering, as opposed to physics, which suggests a transfer of educational practices from technology into physics, but the late formation of the discipline of physics also played a role.[41] These are the beginnings of a hands-on approach to physics teaching, with a heavy reliance on visual representations, to attract the students’ initial interest, and to direct them toward specific research areas where these visual skills were of vital importance. As we shall see in the following, by the end of this century, this sort of *Anschauungsunterricht* had become quite popular.[42]

(p.370) Among the 50 separate student exercises listed in Pickering's *Plan for the Physical Laboratory* of MIT, experiments 28 to 42 deal with properties of light; no. 37 is entitled: "*Spectroscope* (chemical). Spectrum analysis of unknown mixtures. Mapping spectra", and no. 38: "*Spectroscope* (large physical). Measurement of position of prominent lines, and intensity of light in different parts." After the first year, Pickering described in more detail the students' work with the apparatus, taking as an example the case of a student who specialized in spectroscopic experiments, having already completed the elementary exercises. I quote this passage in full because it offers a unique look at the way in which Pickering gradually introduced his students to increasingly sophisticated experimentation:

> When a student wishes to pursue a special branch of physics, or to study a single instrument, the course is arranged to suit the requirements of each case. For example, a student, wishing to learn to use the spectroscope, would first perform the experiments of the general course bearing on this subject, such as measurement of the angles of prisms, of the power of telescopes, insertion of cross-hairs, determination of the index of refraction of different rays, and the wave-lengths of the more prominent lines of the spectrum. He would also use the spectroscope, as described above, only with a greater variety of substances. After attaining some proficiency with this instrument, in which measurements are made with a photographed scale, a second spectroscope with graduated circle is given him, and with it he measures as before, the principal lines of the solar spectrum. He then constructs a curve, in which vertical distances represent scale-readings and horizontal wave-lengths, and thus has a means of reducing all his measurements to the normal spectrum. This method is then applied to electric spectra, obtained by a Ruhmkorff coil. The lines of gases are obtained by Ge[i]ssler tubes, those of metals by using them as terminals, also by drawing the spark from the surface of solutions of their salts. These measurements are reduced to wave-lengths by the curve, and pl[o]tted as before. In this experiment he learns to prepare a battery, and to use the induction coil. Next, he uses the large spectroscope belonging to the Institute (which produces a dispersion equal to eleven prisms of 60°), and with this he compares parts of the solar spectrum with Ångström's chart, new lines being measured by the spider line micrometer, and interpolated from those on the map. He also reverses spectra and projects images on the slit with this instrument. The projection of the solar and metallic spectra on a screen and the spectrum-microscope will be added hereafter, and eventually the means of observing astronomical spectra, especially those of the solar prominences. This example is selected since it has been performed substantially, as here described, by a student in spectroscopy.[43]

Pickering thus included a hands-on examination of both the chemical and the solar spectrum in his canonical exercises, which were eventually published in 1874 under the title *Elements of Physical Manipulation.* This first American laboratory manual of physics was reprinted several times even after he left to become director of the Harvard College Observatory.[44] The book was dedicated to MIT's founding president William Barton Rogers **(p.371)** (1804–1882), "the first to propose a physical laboratory".[45]

The students' response to this interactive teaching was enthusiastic, once they had adapted to the practical approach, as E.C. Pickering confirms in his report of 1877 to the new president of the polytechnic:

> A student accustomed to learn merely from books acquires a new knowledge of physical phenomena when he himself proves the correctness of theoretical knowledge by actual experiment. Facts thus learned are also far more readily remembered. An interesting feature of this method of teaching is the rapid improvement, especially with classes who have had no previous laboratory practice. Such a class, during their first hour, accomplish almost nothing, and almost discourage both themselves and their instructor; the next hour shows an improvement, and before many weeks, experiments are readily performed without question, which at first were quite unintelligible to them.
>
> A good test of the character of the instruction is the relation of teacher to pupil. My own relations, which have always been of the pleasantest character, I ascribe largely to the interest of the classes in their work. They remain beyond the hour, encroach upon their dinner-hour, and frequently ask, and are allowed, to work at other times which they might devote to amusement.[46]

Although Pickering later turned his attention away from undergraduate teaching towards research,[47] his early interest in improving the standards of university teaching at MIT left a lasting mark.[48] Since the 1890s, MIT had a separate Optical Laboratory devoted to advanced work in optics for third-year students and for research work. It included a separate room for the large Rowland concave-grating mounting along with the various plane diffraction gratings, interferometric equipment such as a Michelson interferometer, a Zeiss focometer, a large Pulfrich refractometer, and a separate dark room for investigating the discharge of electricity through rarefied gases.[49]

Pickering’s *Physical Manipulation* became the model for a rapidly growing number of laboratory manuals published since the 1880s. To stay with MIT in discussing the later laboratory manuals, let us look, for instance, at the one by Silas Whitcomb Holman (1856–1900), one of Pickering’s many students in physics who had graduated with the class of 1876, becoming Pickering’s assistant and, after the latter’s resignation, physics professor at MIT. To supplement his oral directions Holman assigned his *Physical Laboratory Notes*, which emphasize his specialty in thermometry and heat measurements but also include **(p.372)** a brief discussion of absorption spectra. Holman clearly had Pickering’s model in mind even in his version around the turn of the century.[50] Although the focus of Holman’s own research clearly was in the areas of electrical and high-temperature metrology, for which he established separate laboratories, several of his students later entered spectroscopy and acquired key positions: George Ellery Hale (class of 1890) founded the Mt Wilson Observatory, Charles Greeley Abbot (class of 1894) became assistant to Langley and secretary of the Smithsonian Institution, and George K. Burgess (class of 1896) became director of the Washington Bureau of Standards.[51] From Holman’s manual, which is much briefer than Pickering's, it is evident that there was a map of the solar spectrum in the laboratory as the students were performing their experiments. After introducing the basic apparatus and its manipulation, Holman instructs his students: “Locate on the scale as many of the Fraun-hofer lines as can be readily seen, recording their positions and their letters as found from **(p.373)** the *map accompanying the apparatus*[52]. The following photograph (Fig. 9.2) of MIT’s main physics lecture hall, taken around 1890, shows that poster maps of the spectrum also were hanging in this auditorium on the front and flanking walls. Even though these maps were certainly consulted during lectures, in this location they fulfilled a much broader function as well. Not unlike the omnipresent periodic table at chemistry sessions since about 1890, they had come to symbolize the successful application of physical methods within the realms of chemistry, astronomy, metallurgy, etc.—in short, they had become an icon of spectroscopy’s usefulness and inherent beauty.

What about a chemist's training at the Massachusetts Institute of Technology? Compared with Pickering's laboratory manual, corresponding texts by his chemist colleagues Charles William Eliot[53] (1834–1926) and Frank Humphreys Storer (1832–1914). which also started **(p.374)** to appear in the late 1860s,[54] somewhat surprisingly contain no reference whatsoever to spectroscopy or spectrum analysis, despite the enormous importance of both in chemical practice at the time. The reason was that all MIT students had to attend the physics laboratory exercises during their second year, so the chemists could concentrate their laboratory teaching on the more traditional techniques of "chemical analysis and manipulation".[55] Although the chemists thought "the theory and use of these instruments [microscope and spectroscope] constitute a part of the general course in physics", in the same breath they insisted on the importance of spectroscopy as a research tool and confessed, "the need has long been felt for the proper facilities for applying them in other subjects of study".[56]

Fig. 9.1 General physics laboratory, MIT Boston campus, in the 1890s. Students performing exercises, one with a microscope and one with a prism spectroscope and a small heliostat mirror. Reproduced by permission of the MIT Museum, Department Photo Albums, vol. 24, no. 10.

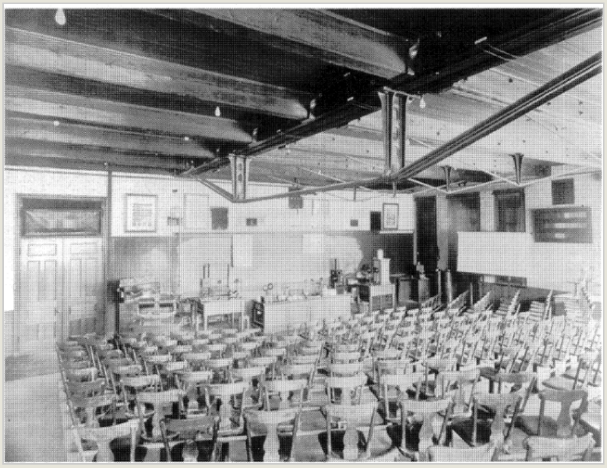


Fig. 9.2 Main physics lecture hall at the Massachusetts Institute of Technology. Walker Building. Boston campus. 1890s, with lour poster maps of the spectrum at the front and one big map to the right. Reproduced by permission of the MIT Museum, Department Photo Albums, vols. 24. no. 4, vol. 26. no. 3. or vol. 27. no. 2.

In 1875 an extension of the chemistry department into a new temporary building included a separate women's chemical laboratory with a joint laboratory for microscopy and spectroscopy and a dark room for photographic work, which was open to students from all faculties.[57] Practical training in scientific photography had been a part of the MIT curriculum since the appointment of John Adams Whipple (1822–1891) as instructor of photography in 1869.[58] His successor, E.C. Pickering's brother William Henry Pickering (1858–1938), expanded the training in scientific photography, which included practical exercises with cameras and photographic plates. In the early 1880s he established a separate photographic laboratory and a dark room (cf. Fig. 9.3), and as many as 100 students a year were enrolled in his courses. He covered the optical principles of the camera as well as practical work with glass negatives, dry-plate photography and development, chemical experiments with emulsion sensitizers, and exercises in photomechanical printing.[59]

(p.375)

After the Great War, the physics curriculum was expanded significantly to accommodate modern physics, that is, relativity and quantum theory. The optics course and the accompanying laboratory exercises on optical measurements were henceforth taught in the first term of the second year. It combined a very brief overview of the basic optical principles with a stronger focus on theoretically relevant issues, such as interference and diffraction, and a quantum theoretical discussion of radiation. In these introductory courses spectroscopy assumed a more minor role; the same is true of the subsequent course on atomic structure with associated laboratory exercises.[60] However, according to George Russell Harrison (1898–1979), professor of physics at MIT from 1930–64, most of the physics students also registered in the courses on 'line spectra' and 'excitation of

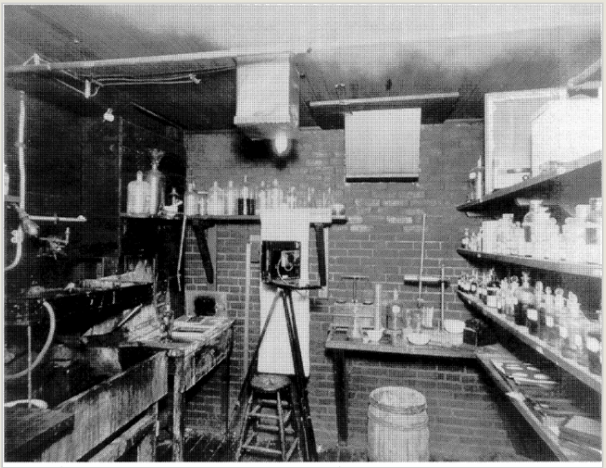


Fig. 9.3 Photographic dark room in the MIT laboratory of general physics (65 × 30 feet), with the necessary chemicals and shelving for drying the photographs (right), small balances and vials for mixing the developers and fixers, as well as a large photographic camera (center) and various containers and sinks for the developing and fixing processes. By permission of the MIT Museum, Department Photo Albums, vol. 24, no. 48.

spectra’ during their senior or early graduate years when spectroscopic issues were dealt with on the theoretical **(p.376)** foundations of Bohr’s quantum model and Heisenberg’s and Schrodinger’s quantum mechanics. Interested students continued with a course on the ‘theory of spectra’ and took part in the ‘spectroscopy seminar’ devoted to “discussion and reports by students on special topics in spectroscopy”.[61] In 1932 MIT opened a separate spectroscopic laboratory as part of the George Eastman Research Laboratories.[62] This thermally and vibrationally isolated laboratory, with its state-of-the-art instrumentation was equipped for high-precision measurements at the research frontier. Its installations included a 35-foot and a 21 -foot concave grating in a Paschen mounting, separate rooms for vacuum spectrographs and various interferometers. Nonetheless, it was open to students enrolled in the advanced courses on ‘spectroscopic analysis of matter’ or ‘special problems in spectroscopy’.[63] During the summer term, students from other departments desiring to learn about spectroscopic techniques, industrial physicists and chemists eager to apply quantitative spectroscopic analysis in their own fields, and qualified researchers from other institutions had access to these resources as well.[64]

9.3 Laboratory training at other universities in the United States

Within the Harvard physics curriculum, spectroscopy found its place even earlier, in the 1880s.[65] There is unfortunately scant documentation on the Physics 3 course taught by John Trowbridge (1843–1923),[66] who was appointed assistant professor of physics at Harvard in 1870 and initiated practical laboratory exercises only two years later. Arguing vigorously for the necessity of a physical laboratory there in the late 1870s, he managed to convince the Friends of Harvard University and other donors to follow the example set a few years previously by The Johns Hopkins University and build a new laboratory, which cost $115 000.[67] In 1884 Trowbridge became director of the then newly built Jefferson **(p.377)** Physical Laboratory.[68] It is fair to assume that he included spectroscopy in the curriculum. Not only was it part of his research agenda (cf. here footnote 67 on p. 376), but spectro-scopic issues are covered in the 40 pages devoted to optics in his discussion of *The New Physics* at the elementary level of preparatory schools.[69] Furthermore, the determination of refractive indices and wavelengths are mentioned in the brief *Syllabus of a Hundred Physical Measurements* summarizing the two-year physics course at the Jefferson Laboratory in 1885, as well as in the later four-volume *Course of Experiments in Physical Measurement*, both published by the physics instructor at Harvard University Harold Whiting (1855–1895).[70] In the early 1890s Whiting retired from Harvard after quarreling with members of the faculty. For a short time thereafter he was associate professor of physics at the University of California at Berkeley, for which he also wrote *A Course of Exercises in Elementary-Physics* that included exercises with the photographic camera, platinotype printing, and the drawing of various emission spectra, as well as a detailed set of examination *Questions on General Physics.*[71] The latter used the analogy between light and sound with a handsome list of 41 points, asking the examinee to name "'some twenty or thirty of them […] which have been thought to be explanable by the corpuscular theory", but added a little twist to it with the instruction: "show that a theory should not be accepted by strength of analogy alone" and "state one or more significant points of difference between sound and light".[72]

A former student of Rowland in Baltimore, Edwin Herbert Hall (1855–1938), was instrumental in the establishment of a curriculum at Harvard incorporating laboratory exercises. Before entering The Johns Hopkins University as a graduate student in physics in the fall of 1877, Hall had also made inquiries at that eminent Massachusetts college but “was advised with engaging candor by John Trowbridge […] to go to the Johns Hopkins because Harvard did not possess adequate facilities”.[73] Soon after being appointed instructor of physics at Harvard in 1881, where he later advanced to assistant professor (1888) and full professor (1891–1921), Hall was commissioned by Harvard’s president Charles **(p.378)** Eliot and his colleague Josiah Cooke, both pioneers in the laboratory teaching method in college chemistry, to devise a series of experiments for the university’s entrance examination.[74] Each student was supposed to record the results of these exercises (selected from the laboratory manuals by Worthington or Trowbridge) in a laboratory notebook and submit it to the examiner.[75] Once again, we see a transfer of laboratory teaching methods from chemistry to physics.[76]

Initially, Hall’s *Descriptive List of Elementary Exercises in Physics*, first issued in 1886, contained at least the basics of spectroscopic experiments, “Refraction-Principle of spectroscope-Angle of deviation”, but no separate mention of the spectroscope or spectra is made in the 1897 expanded list of 61 exercises.[77] But we should keep in mind that this set of experiments merely described the canon of experiments that a Harvard freshman in science was expected to be familiar with. The impact of this list on secondary education was quite considerable: one indicator of this is the rapid adaptation to it by instrument manufacturers. Around 1900 at least five equipment suppliers offered complete sets of apparatus specified in Hall’s *Descriptive List* “at a reasonable price” under the tradename ‘National Physics Course’.[78]

But what about the spectroscopy curriculum at Harvard College? Hall's *College Laboratory Manual of Physics*, which indicates the topics covered in the introductory Physics 1 course for freshmen, does include a description of the determination of the index of refraction as exercise no. 33 (out of a total of 35).[79] And the more advanced Physics C course, also offered in the university's Summer School, included a heavy schedule of optical experiments, most of which directly pertain to spectroscopy. The *Student's Manual* written by Wallace Clement Sabine (1868–1919), Trowbridge's long-time assistant and co-worker who was also responsible for preparing the laboratory courses, described the canonical exercises required of Harvard students between about 1890 and 1913. It discussed photometry, **(p.379)** spectrometers (in particular two methods of measuring the angle of the prism), the determination of wavelength using Newton's rings or a diffraction grating, and finally use of the direct-vision spectroscope to plot the spectra of sodium, lithium, barium, and strontium volatilized in the Bunsen-burner flame. Calibration of the scale readings in the direct-vision spectroscope by measurement of known wavelengths throughout the spectrum, and determination of unknown substances through their spectrum with the aid of the gauge curve thus obtained was left to students "especially interested in the subject".[80] The essence of these exercises as well as most illustrations used in the text can be traced through the many versions of these manuals issued in subsequent decades.[81] Resolving the sodium D line into a doublet (a comfortable 6 A apart) advanced to the status of a standard demonstration for beginning students of physics, and it was even incorporated into the high-school curriculum, because that resolution can be reached with very modest equipment.[82]

At the University of Chicago the laboratory course in physics published by Robert Andrews Millikan and Henry Gordon Gale also built on this tradition. It included a detailed discussion of spectroscopic phenomena in a chapter on prisms and, from the second edition onwards, also devoted separate chapters to color phenomena and invisible radiation. A revised version in 1920 that involved other coauthors expanded these sections and added a separate chapter on the diffraction grating.[83] The later editions of this course on practical physics were widely used at American colleges and universities. In the interwar years, it was supplemented by a *Manual of Experiments* designed to bridge the gap between classroom discussion and the problems that arise with practical manipulation of the instruments. Experiment 49, for instance, thoroughly familiarizes a student with the refractive characteristics of prisms in single and combined arrangements. The follow-up experiment 50 deals with determining the angle of minimum deviation and index of refraction of a glass prism by first introducing the student to two alternative procedures, and then asking him or her to compare the two values obtained. In the final optics experiment 54 (cf. Fig. 9.4), measurement of the wavelength of the yellow sodium D line with the aid of transmission gratings and a Bunsen burner is discussed. Students are subtly trained to develop a sense for internal consistency in their measurements by being made to use several transmission gratings with different line spacings e and then to compare the mean of all the results obtained with the accepted value for the Nan wavelength.[84]

(p.380)

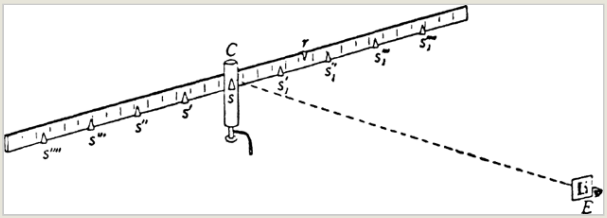


Fig. 9.4 Student exercise: description of the determination of wavelengths in the sodium spectrum. The observer looks through the transmission grating E with a line spacing of E towards the Bunsen-bumer flame at C at distance a from E, and sees the first-order diffraction spectrum at distance $ss' = (\lambda/\epsilon) \cdot a$. Figure from Millikan, Gale, and Edwards [1938*a*] p. 210.

As the variety of transmission gratings in the last example indicates, the availability of fairly cheap diffraction gratings on transparent film made it much easier to broaden the teaching agenda to an examination of all kinds of light sources outside the laboratory. Prior to about 1925, fairly expensive direct-vision spectroscopes consisting of prism trains alternately of flint and crown glass could be used pretty much like a telescope. Diffraction gratings, however, were far too valuable and sensitive to be placed in the hands of inexperienced students outside the controlled environment of the laboratory.[85] But eventually, cheaper transmission gratings made assignments like the following possible: "Take the grating to the Museum and explain the appearance of mercury light when viewed through it."[86] With these kinds of exercises, which are still common today,[87] education in spec-troscopy could become as casually enticing as bird-watching with a pair of binoculars or insect inspection through a magnifying glass for biology class.[88] As will be shown in the subsequent sections, with the progressive inclusion of spectroscopy in the curriculum, the very nature of its optical exercises strengthened the culture of visual representations in such *Anschauungsunterricht.*

(p.381) 9.4 Mapping spectra in classroom exercises

Although visual representations of the solar spectrum were only rarely printed in such brief laboratory manuals—and if so, only in low quality on cheap paper—there is nevertheless strong evidence that such maps were used extensively in practical physics and astronomy education both at the training-college and university levels. But this alone does not suffice. As Rudolf Arnheim has written in 1969, just placing "authentic photographs, drawings, or models in front of the pupils' or students' noses," is not enough. One has to work out the essential features of the picture's subject matter in order to attain an "active understanding" and mastery of the *Gestalt* impressions "in the perceptual realm itself."[89] Quite in accordance with this general insight into the process of learning, science students around 1900 were urged to do more than just observe these spectra passively. They were asked to draw them as well, because there is no better way of learning how to discriminate between the different *Gestalten.* To quote from Holman's instructions for examining the absorption spectra of gelatine films colored with various aniline dyes: "The best way of recording the results in this experiment is by drawing sketches of the spectra, one above another, with a scale beneath, and with the dark bands located as observed upon the scale of the instrument."[90]

One of the most detailed instructions I have seen in print for nonspecialist audiences on how to draw spectral maps is contained in the manual *Demonstrations and Practical Work in Astronomical Physics at the Royal College of Science*.[91] Even before Joseph Norman Lockyer (1836–1920) joined the faculty, spectroscopic issues had been a standard part of the agenda then revolving around electricity and magnetism.[92] The students were asked to construct a spectroscope with a bisulphide-of-carbon prism as its center piece

with which “the spectra of various metallic vapours are examined till some familiarity is acquired with different spectra.”[93] Lockyer had borrowed this idea of student-built scientific instruments. As a regular teacher at South Kensington from 1881 until his retirement in 1901 he expanded the role of spectroscopy in the curriculum there. Three of the 24 chapters of Lockyer’s 1894 course manual deal with spectroscopic issues: no. XI treats ‘spectra of the heavenly bodies’, no. XX spectrum observations, and no. XXI spectrum photography. His course is generally conceived as parallel to Pickering’s introductory courses on ‘Physical Manipulation’ (see above pp. 37If.). However, he also brought in ideas he had developed earlier in his various primers and *Elementary Lessons in Astronomy*, mostly written **(p.382)** for school use.[94] In comparing his manual of 1894 with other contemporary astronomy manuals we can see that Lockyer was much more particular about having his students—for the most part aspiring schoolteachers—make not just approximate drawings, but fairly accurate maps of the spectra under study.[95] He emphasized precise adjustment of the prism spectroscope used in the student exercises, particularly orienting the prism in the position of minimum deviation and setting the lines in sharp focus.[96] Then the emission spectra of several metals held in the flame of a Bunsen burner, as well as the absorption spectra of iodine vapor, didymium glass, chlorophyll, and blood had to be plotted. Each map was drawn on a sheet of graph paper 18 inches wide with 3-inch divisions to represent one degree of deflection. These in turn were subdivided into 30 parts, thus calling for an accuracy of at least two minutes in the determination of the angle. In the next teaching session, he even touched upon spectrum photography, employing specially prepared dry plates to produce prints of the yellow and red ranges of the spectrum and allowing the students to find out the appropriate exposure times by trial and error. Following procedures used in contemporary research (cf. here Chapter 6), photographic recordings of the solar spectrum were made on the same plate with terrestrial comparison spectra, along with spectra from the oxygen blow-pipe flame or an electric arc. Lockyer then asked his students to measure the photographs with a micrometer just like the ones used in his own spectrometric research, reading to a 1/100 000th of an inch with the aid of a vernier. Finally, they had to construct an interpolation curve translating the micrometer readings of the prismatic deflections into wavelengths. This allowed them to draw a normal wavelength map in which “the intensity of each line in the photo, being noted at the moment of reading off, may be represented by making its length in the map proportional thereto.”[97] With this hands-on instruction, borrowing much from current research practice, it is not surprising that Lockyer made a substantial contribution toward the proliferation of qualified spectroscopists at this time. His classes averaged between 70 and 80 students a year.[98] The most prominent of these is probably Alfred Fowler (1868–1940), who became Lockyer’s first assistant upon completing his studies, and from 1885 chief demonstrator for astronomical physics at the Normal School of Science. In 1901 Fowler

succeeded his teacher as instructor in astrophysics, and later became full professor for astronomical physics in the new Imperial College, London.[99]

(p.383) The other influential laboratory course manual in the British context was compiled by two demonstrators at the Cavendish Laboratory in Cambridge: Richard Tetley Glaze-brook (1854–1935) and William Napier Shaw (1854–1945), and was published as *Practical Physics* in 1885.[100] In the introduction they acknowledged using ideas and laboratory instructions from the Physical Laboratory of Berlin and lamented "the absence of any book covering the same ground". Yet their course also borrowed characteristic elements from Pickering's exercises: for instance, measurement of the angle of a prism by two different methods, and spectrometer adjustment.[101] Entirely in the spirit of Cavendish physics in its early years, which fostered precision measurement but carved out areas that were conceived as merely observational, their focus shifted away from mapping spectra, which was the main interest of Lockyer and others outside the Oxbridge' centers, and towards precise determination of the natural constants. They included a very detailed discussion of the determination of the refractive index of a prism by two different methods, and an equally detailed treatment of the measurement of wavelengths by means of a diffraction grating.[102] With the appointment of J.J. Thomson as director of the Cavendish Laboratory in 1894, the research changed its orientation to the physics of gas discharges. Accordingly, the textbooks and laboratory manuals from this later period include much more on electric sparks and arcs, the electricity sources (such as Leyden jars and Rühmkorff induction coils), and the Geissler, Plücker, and Schuster gas tubes used in such experiments.[103]

We have now discussed Lockyer's laboratory manual for aspiring teachers and engineers in South Kensington, England, and various physics curricula, with special emphasis on MIT and Harvard, both in the US. Let us now briefly look at one manual written for students of chemistry in Germany. The most instructive case is a work placing special emphasis on physico-chemical techniques by two professors of physics at the University of Erlangen. Eilhard Wiedemann (1852–1928) and Hermann Ebert's (1861–1913) *Physikalisches Praktikum* was intended to complement the existing laboratory manuals for physics students. Aside from the standard section on the determination of refractive indices, it incorporated a substantial section on spectrum analysis,[104] which discussed the various light sources and types of instruments, the gauging and conversion of prismatic into 'normal' wavelength spectra, and of course emission and absorption spectra of various substances. This text gives far more details about the issues involved in preparing chemical samples, adjustment of the apparatus, and practical hints about the graphical recording of the observations. Different from other manuals for physics students, it discussed changes in these **(p.384)** spectra with varying temperature, absorption density, and solvent concentrations and it treated applications of these types of measurements in quantitative chemical and medical examinations, which at that time were still in the exploratory stage.[105]

Figure 9.5 illustrates the kind of spectral map that the students were supposed to produce upon completing the exercises on absorption spectroscopy. We see eight spectra plotted above a scale ranging from 0 to 180 and indicating scale values proportional to angles of refraction, with the sodium D line designated 50 according to Bunsen's prescription.[106] A gauging curve is drawn across these spectra from the top left (K_α) to the bottom right (K_β), which allows conversion of any line crossing this curve to an approximate wavelength scale that runs from 750 to 400 nm (left). Aside from using parallel lines to indicate spectral lines and bands of varying intensity to convey the fading of the bands at each end, we also see Bunsen's technique of using separate curves to indicate the rough profiles of absorption regions.[107]

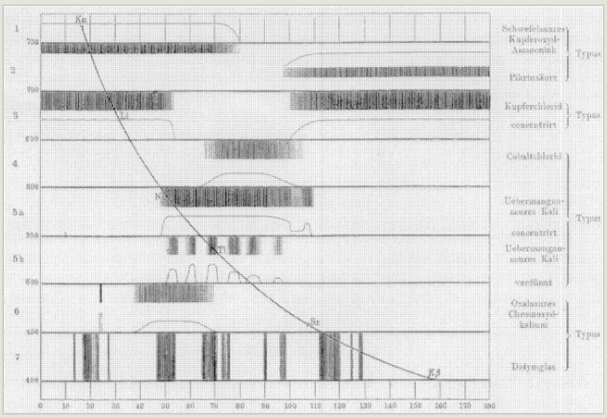


Fig. 9.5 Sample charting of absorption spectra in laboratory exercises for chemistry students (see main text). From Wiedemann and Ebert [18906] p. 295.

This example may appear to be a special case using a broad repertoire of classical (i.e., nonphotographic) types of representation. But even a laboratory manual of physics specifically **(p.385)** written for liberal arts students by two physicists from Ohio State University includes a hefty serving of spectroscopy, presumably because these exercises appealed so much better to the students than experiments relating to such abstract physical principles as energy conservation or electromagnetic fields: "the student should be able to perform the experiment and understand the principle involved whether or not he has had the theory in class".[108] The students were asked to "measure and chart" the spectrum lines of the Sun, of several elements vaporized in the Bunsen flame, as well as of hydrogen and helium in a vacuum tube through which a discharge was sent from an induction coil.[109] A similar shift towards purely observational issues is observed in Glazebrook's elementary textbook on light, written specifically for use in a physics course for medical students. Here the discussion of dispersion is intimately linked with optical applications in the camera, eye-glasses, and simple microscopes, and the spectrum is treated in the context of color perception. A much more schematic discussion of the principles of spectrum analysis and basic emission spectra is followed by an analysis of absorption spectra including the spectrum of blood.[110] As this section has amply demonstrated, mapping of selected spectra was thus a widespread technique for familiarizing students with basic spectroscopic features and aiding their memorization of different spectra.

9.5 **Sarah Whiting's courses at** Wellesley College

This section has a closer look at what happens inside the classroom. It focuses on the teaching of spectroscopy by Sarah Frances Whiting (1847–1927):[111] 'from 1876 to 1912 professor of physics, and from 1900 to 1916 also director of the observatory at Wellesley College, a prestigious women's college in the environs of Boston. The college founder, Henry Fowle Durant (1822–1881), was aware of the recently established laboratory method of physics instruction at MIT and convinced Pickering to relay his new teaching techniques to Wellesley. To this end Whiting attended Pickering's classes as MIT's first female physics student. With this preparation and visits to other college laboratories and institutes at Harvard, Yale, Amherst, Bowdoin, and Pennsylvania to view their instruments, Whiting was able to establish a similar laboratory at Wellesley College in 1878.[112] The *Wellesley College Calendar* advertises: "The lectures are illustrated by lantern-slides, charts, and globes, and are accompanied by frequent observation of the heavens with a four-and-a-half inch telescope. Spectroscopic astronomy is illustrated by laboratory work sufficient to show some of the methods of the new astronomy." The section on light actually was the first and not, as was **(p.386)** common at the time, the last in the series light, electricity, and heat. The more specific topics chosen for discussion were: "Photometry, photography, measurement of angle of prisms, indices of refraction; mapping of spectra of the sun, of metals and gases rendered incandescent by the electric spark, and of absorption spectra; study of the phenomena and theory of color and of polarized light; measurement of wave lengths."[113] Shortly after moving to the Harvard College Observatory, Pickering invited Whiting to see the local instrumentation for stellar spectroscopy, and thus was born Whiting's own course on Practical Astronomy in 1880.[114] In 1893 the department was renamed Department of Physics and Physical Astronomy to reflect the growing importance of astrophysics, and in particular spectroscopy.[115] Figure 9.6 depicts some of Whiting's students at their instruments, including a cathetome-ter, a dividing engine, and a spectroscope by the Société Genevoise, and a large Browning spectroscope.[116]

In 1900, a grant by a Wellesley trustee and personal friend of Whiting made it possible for a small observatory to be built on the college campus from plans drawn up by Whiting herself.[117] Her class then was able to use a 12-inch refracting telescope with attached spectroscope and photometer, a transit instrument, and a fully equipped spectroscopic laboratory including a Rowland concave grating spectroscope of six-foot radius and a double-mirror heliostat made by John A. Brashear's Astronomical & Physical Instrument Works in Allegheny.[118] In 1908 an Evershed protuberance spectroscope was also added.[119]

(p.387)

The alumni collection at Wellesley offers an unusually abundant choice of lecture notes and laboratory records produced by Whiting's students. The sources referred to thus far (i.e., textbooks, laboratory manuals, popular expositions, instrument lists, etc.) give a fairly detailed picture of practical instruction in spectroscopy. An even denser account results if we incorporate the student's perspective. From these notes we can see what was actually done during the laboratory sessions, how the students reacted to the new topic, and what kind of problems they struggled with. This material documents the many different layers of education:

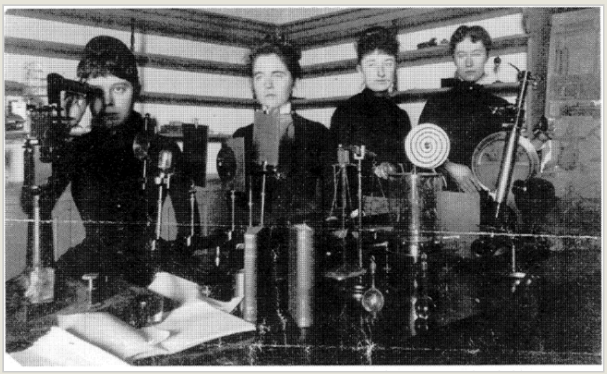


Fig. 9.6 Students in second-year physics at Wellesley College in the early 1890s with instruments from the physical laboratory—at the far left, one student is looking through the eye-piece of a prism spectroscope. Courtesy of Wellesley College Archives, visual collections.

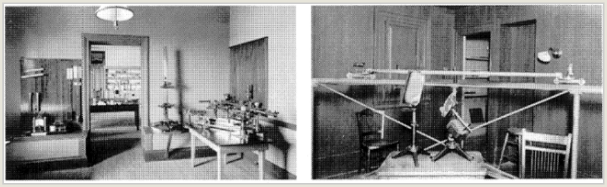


Fig. 9.7 *Left:* Physics Laboratories 4 and 5 at Wellesley College. In the foreground to the right a cathetometer and (on the table) a comparator as well as a big prism spectrometer. *Right:* A Rowland concave grating in a Rowland mounting with a double-mirror heliostat on the small table in the front. Courtesy of Wellesley College Archives.

(p.388)

- the topics covered in Whiting's lectures in physics and astronomy in various years;
- handwritten (or partially typed) mimeographed summaries by the lecturer herself with a series of keywords;
- mimeographed lists of topics and questions for review and
- examination questions;
- preparatory handouts for laboratory work and general directions on how to write a laboratory notebook;
- some representative detailed laboratory notebooks.

A typical Wellesley student first encountered spectroscopic topics at the end of the first part of Whiting's introductory physics lectures which surveyed all the major relevant fields.[120] In the accompanying laboratory sessions, Whiting mostly followed the sequence of elementary exercises suggested in Pickering's *Physical Manipulation*.[121] However, as her correspondence in the 1880s and 1890s shows, she also tried to obtain more recent material on physics education from various instructors and professors of physics at Harvard and elsewhere.[122] Spectrum analysis featured as one of the last exercises of the first semester. Apparently in some years, time did not suffice,[123] but a couple of very neat notebooks do include the pertinent part on spectroscopes. In 1890/91, for instance, Ella Penniman recorded what she saw when looking at clouds on a bright day with a "small spectroscope", presumably a direct-vision spectroscope:

> We see the spectrum with dark lines. Some were faint – the prominent lines were the C in the red – in the orange was the D line, quite distinct and seen in the yellow – the E in the yellow–green, the b in the green, the F in the green–blue – the G in the indigo – Some horizontal lines are seen across the spectrum but these are not in Sun's spectrum but due to dust on the glaze or imperfections in glaze.[124]

(p.389) Note the prominence of the color terms and the student's uncertainty about the cause of the horizontal lines. (The latter are actually due to dust on the slit rather than on the prism faces—a fact mentioned only toward the end of Whiting's course.) The subsequent descriptions of the emission spectra of various metals in the Bunsen flame and of didymium sulphate and chlorophyll absorption spectra are equally dominated by color terms, not unlike the efforts of such early observers as Brewster or Talbot prior to 1830 to describe what they saw (cf. here p. 36). Following Pickering's model, Whiting asked her students to draw these spectra, which they did either together with a solar spectrum, indicating the position of the main Fraunhofer lines, or with an internal numerical reference scale according to Bunsen's convention (cf. here p. 50). In both cases the students also attempted to indicate different line intensities and widths and added color terms, in one case even horizontal braces to indicate color ranges (see Fig. 9.8):

Part II of these physics lectures was devoted more fully to spectroscopy, other optical investigations (including the polarization of light), and electrostatics.[125] According to the most detailed lecture notes extant, Whiting began with a more in-depth discussion of the **(p.390)** refraction of light in prisms, and in particular Newton's experiments with which he established that "white light is not simple, […] the violet ray being most bent".[126] Continuing along historic lines, she discussed Wollaston's discovery of discontinuous spectra and explained his technique of measuring the index of refraction of various glass types. She then briefly returned to a more systematic discussion of other kinds of prisms, the correlation between spectral color and wavelength, and the basic principle of a prism spectroscope.[127] Having set the stage in this way, she could discuss the work of Fraunhofer, Kirchhoff, Thalén, and Ångström in the mapping of the solar spectrum, giving the various line totals that each observer had arrived at (ranging between 576 and 2000) and thus suggesting a direct line of progress. She even linked this topic to contemporary research: "Lockyer is at present mapping the lines in a spectrum which is a mile long", thus challenging her students to extrapolate this immense scale of dispersion from their own experience with spectra a few inches wide. In later years, this part was amended with remarks about Rowland's and Langley's maps of the solar spectrum and a systematic comparison of the wavelength readings for a few characteristic lines taken from these maps to show the improvements and corrections in wavelength measurement over time. Langley's map of the infrared part was commented upon as follows:

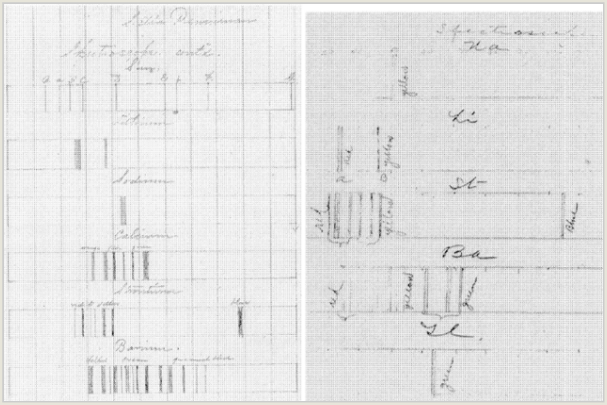


Fig. 9.8 Student drawings of spectra observed with a simple prism spectroscope from S.F. Whiting's laboratory session. *Left:* Li. Na, Ca, Sr, and Ba spectra relative to the solar spectrum drawn by S. Ella Penniman in 1890/91. *Right:* Na, Li, Sr [not St as labeled], Ba, and Tl spectra drawn by Mary Barrows (class of 1890) relative to a micrometric scale superimposed on the spectroscope viewing field and gauged after Bunsen's convention. Both from laboratory notebooks kept at WCA, reproduced by permission.

> This map expands the spectrum to 40,000 ten millionths millimeter. The infra red is [4 crossed out] 9 times the length of the visible spectrum. The spectrum has thus been studied from wavelength 3,722 to 40,000 ten millionth mm. It ranges through 4 octaves. The eye perceives one.[128]

Whiting then turned to a thorough discussion of spectrum analysis, starting with Kirchhoff's discovery in 1859, and Swan's estimate for the extreme sensitivity of the yellow line in flame spectra as an indicator of the presence of sodium. She also discussed suitable physical analogues with acoustical resonance phenomena for this coincidence of emission and absorption spectra, and finally the theoretical underpinnings such as Prevost's law of exchange.[129] To exemplify the widespread applications of spectrum analysis Whiting mentioned Bessemer steel production and H. Bence Jones's reported feeding of lithium to an animal to examine spectroscopically the circulation rate of its blood: "after two minutes [he] found a little in the lens, after three minutes some in the humour of the eye and plenty in other parts of the body."[130] Needless to say, this latter example must have appealed to students with a leaning toward the biosciences.

(p.391) The gist of these remarks conveyed the fascinatingly vast universe of spectra still waiting to be explored by relatively straightforward techniques also practiced in the student laboratory. Minor inaccuracies, in particular in names and dates,[131] are eclipsed by the boost of interest in the new field from such inspiring and well-organized lectures. The suggestion to "use drawings in illustration wherever it is possible" right at the beginning of a checklist of topics for review for the class of 1893, which includes many points directly related to the mapping of spectra, reveals one of the primary goals in Whiting's teaching at Wellesley: forming a distinct mental image of various characteristic flame spectra and of the solar spectrum rather than simple memorization of facts. Some traces of this learning process have survived: For some of these entries in the checklist, the student has entered keywords, probably noting down Whiting's oral explanations. For instance, under point (VI a) we find jotted down: "spectrum analysis–diff[erent] salts always fixed lines of same no., order + color for same salts", and beside each of the four elements mentioned in (VI d) we find color designations for the strongest line in the respective spectrum.[132]

Likewise, Whiting's list of review questions preparatory to the final examinations for the Astronomy I course attended by the class of 1909 also emphasizes the issue of spectral maps with questions like:

> 11. By what apparatus do we obtain a normal spectrum and why is it called normal?
> 12. What was the work of Aèngstrom, Draper, Rowland? […]
> 15. What is the extent in wave length of Rowland's map, and what of Langley's map?[133]

Astrophysical applications of spectroscopy take up a major portion of the examination; the review list includes such topics as Doppler shift, the objective-prism method in gathering stellar spectra, solar rotation and sun spots, the physical nature of the photosphere and its chemical constitution, the “reversing layer”, the chromosphere, protuberances, and the solar corona.[134]

Laboratory exercises also accompanied Whiting’s lectures in astronomy. The lab book by Georgia French, class of 1900 and hence among the first students to have the privilege of working in the newly erected observatory, indicates that the overwhelming majority of the exercises were related to the observational instruments of traditional astronomy. The interesting thing here is the strong emphasis on drawing. The student notes are filled with sketches of the Moon’s surface, solar spots, Mars, Jupiter, Saturn, and stellar nebulae, **(p.392)** sometimes drawn directly during observation, but apparently in some cases also from photographs displayed in the classroom.[135]

Obviously, Whiting assigned great importance to visual material for her students’ practical training in physics and astronomy, arguably more so than anywhere else at the time.[136] She could rely on quite well developed sketching skills, since graphic art was among the obligatory courses at Wellesley. The same pains were taken to render the changes in solar spots or the lunar craters, for instance, as was generally devoted to plant drawings made on botany excursions. The close observation necessary for such sketches fostered the ability to recognize patterns. A set of typewritten laboratory exercises in Physical Astronomy from the year 1902, duplicated in larger numbers, is another example. The students were asked to fill in gaps left on nearly every page containing sketches of the instruments used and the observations made with them (such as a ray diagram for a prism spectroscope or a wiring diagram for an apparatus used to generate electric sparks). With respect to spectra, they had to draw in the main Fraunhofer lines seen with a direct-vision spectroscope and to chart the Bunsen-burner flame spectra of various substances observed with a large prism spectroscope. The printed text either gave directions for the necessary adjustments during observation or served as a template for the students’ laboratory notes:

> (make and record in a notebook observations as follows) Observations of Spectra:
>
> 1. With a pasteboard tube with a slit in the end and a grating held before the eye at the other end the normal spectrum was observed. […]
> 2. With a direct vision spectroscope and slit open wide the prism spectrum of sunlight was observed. It differed from the normal Spectrum in that the blue was more stretched out.

> 3. The slit of the direct vision spectroscope was more nearly closed and the spectrum carefully focussed when the Fraunhofer lines C.D.E.F.G. could be seen. [Space for student's drawing …]
>
> Conclusions from Observations: 1. [etc.][137]

Although this may appear to be channeling the students' observations toward foregone conclusions, Whiting's aim evidently was to focus the students' attention within the broad array of topics covered in the course. This is how she portrayed her teaching method and the prominent place that visual material played in it to an audience of astronomers in 1905:

(p.393)

> the colored maps of Kirchhoff and Bunsen and of Huggins and Miller, found in most laboratories, are of great use in preparing the student for observation, and for identification of lines. They also serve as guides for the simple plots of spectra required. […] The classic maps of the spectrum, those of Fraunhofer, from Schellen's spectrum analysis, of Kirchhoff, Ångström, the Draper photograph, the map of Cornu, of Langley, and finally the Rowland strips are displayed for study, and a table is made of the principle lines, with Kirchhoff's numbers, Ångström's wave length, and finally the standard length in tenth meters. […] The students notebook work consists in careful descriptions of the apparatus employed accompanied by drawings, in detailed record of observations, and spectrum maps finished with colored crayons after the order of the elementary maps on the Kirchhoff charts. They are plotted to a convenient scale from tables furnished upon cards. To show whether the application of all this to the subject in hand is apprehended, notebook answers to a list of questions on the interpretation of photographed spectra of the envelopes of the sun and stars are advised.[138]

The importance of active (re)drawing of visual representations, not only as a mnemonic, but also as a heuristic device, is stressed in her *Daytime and Evening Exercises in Astronomy*, published in 1912. With reference to charting the stars in the sky or mapping of spectra Whiting wrote "In this subject as in botany or zoology, sharpening the pencil sharpens the eye—to draw the object fixes the attention upon details of structure".[139] The parallel she drew between astronomy and natural history is not accidental: The educational methods used in these classificatory disciplines are in fact very similar. Each rely extensively on atlases and plates as well as on observational drawing skills. A similar discussion of their teaching practices, which would enable deeper comparisons, is, however, beyond the scope of this book.

9.6 Teaching the classification of stellar spectra

Few are the fields in which the sharpened eye is as crucial as in stellar spectroscopy. As-trophysical students and researchers alike had to acquire the art of reading and classifying stellar spectra from the low-dispersion photographs taken with a thin prism inserted in front of the objective. Considering that women very often happened to end up specializing in this task, Whiting's methods of teaching this subject at Wellesley give a good idea of the mechanisms at work in the training of such lowly paid data-processors, some of whom later worked as 'computers' for Pickering.[140] The most famous is, of course, Annie Jump Cannon who graduated from Wellesley in 1884 (see above p. 353 about her work on the classification of stellar spectra). But successful researchers of Cannon's or Antonia C. Maury's calibre were more the exception among the all-female members of Pickering's computers and aids in stellar classification in Cambridge.[141]

(p.394) Whiting's exercises in astronomy illustrate an approach to the study of spectroscopic issues emphasizing visual representation and manual reproduction of spectroscopic features. Whiting's own notes for her course on Physical Astronomy for the year 1902/03 unfortunately broke off soon after the sections on solar spectrum maps, discussed above; but one of the student laboratory notebooks does include the topic of stellar spectra, the last section of the course.[142] According to this source, Whiting first showed the students about ten different spectra, illustrating fundamentally different types from Secchi's phenomeno-logical classification. For each example, she pointed out which segment of the spectrum was strongest and then identified the most prominent lines in them, thus giving the students a basic feeling of the richness and complexity of stellar spectra and the main indicators used in classifying them. After presenting this rough classificatory grid she continued with the statement, "nearly all the stars may be arranged in a continuous system so that each spectrum will be identical with one of the types, or intermediate between them". To bring home this point, she next showed examples of spectra that fell between the major classes previously shown.[143]

Whiting's students were also given selected photographic glass plates taken with the Draper telescope at the Harvard College Observatory by the objective-prism method, together with handouts and plates illustrating the classification schemes proposed by Secchi, the Harvard team in 1901, and Lockyer in 1902.[144] After briefly listing the characteristics of each of the five basic types of Secchi's classification and ten main classes of the Harvard classification, Whiting gave the following directions to the students:

> Placing the plate upon the viewing-frame, study it with the eye-piece; note the way in which the spectra are placed as to the violet and red ends. Identify the hydrogen and other lines; place the plate over the Durchmusterung Chart, which is taken to the same scale, and identify the stars. Finally, record in tabular form the class of each star and its *x* and *y*, using the same line of the spectrum for measurement in all cases.[145]

Her subsequent listing of five typical samples from the Harvard collection of plates specially suited for the purpose of training spectral classification leaves little doubt that this exercise had been tailored as solid preparation for participation in the multi-decade-long endeavor underway at the Harvard College Observatory since 1886 to classify hundreds of thousands of stellar spectra. Mary B. Jenkins, whose laboratory notebook we have been **(p.395)** quoting from, described a glass plate of the Pleiades, very likely on loan from the Harvard College Observatory, as follows:

> This plate shows negative of star spectra in this region. Majority seem to be of Type 1. True that stars in nebulous regions are found to be of Type 1. One spectrum seemed to be of Type 2, with K intense.[146]

Granted, the expertise of Cannon or Maury had not yet been reached; the attributions are carefully qualified, but it was one step in the steady accumulation of essential experience from growing numbers of examined plates.

Despite the considerable sophistication reached since that time in this branch of astrophysics (there are now 16 different classes and 10 subdivisions), further amended by six luminosity classes in the MK system (see here pp. 357ff.), educational patterns are still the same. In a teaching package developed by Mary Teresa Brück (born 1925) at the Royal Observatory in Edinburgh,[147] the complex task of stellar spectrum classification is simplified by having the student start with gathering just three stellar spectrum groups of broadly similar appearance:

- spectra showing the Balmer lines of hydrogen (comprising classes B and A),
- spectra showing the H and K lines of doubly ionized calcium (including the spectral classes F and G), and
- spectra showing many broad features (mostly including K stars).

Only later are they subdivided into narrower groups. This approach is justified since not only the very young stars (from O to about B5), but also the very late main sequence stars (type M) are comparatively rare against those between classes A and K. After specifying how to break these groups down into classes and other subcategories, Brück found it necessary to offer the following encouragement:

> A student should not be discouraged if he cannot identify all the spectra he examines. Weak features may be discerned by one person’s eye which are not obvious to another's; the visibility of features is also a function of the density of the image. The subdivisions of some spectral classes, e.g., A type, are more easily recognised than others. The student should at least be able to assess the spectral class of suitably exposed spectra. After intercomparing large numbers of spectra he may find that he can subdivide them into half classes, e.g., A0, A5, F0, F5, etc. A good check is for two students to study the same region of the field independently and compare their results. They will then be able to estimate the accuracy of their classification for the later exercises.[148]

In a manual compiled by three researchers from the University of Iowa, *Activities in Astronomy*, the discussion of the classification of stellar spectra still opens with a reproduction of the famous plate showing Pickering’s original classification scheme (cf. here pp. 35 Iff.), **(p.396)** acknowledged as being “remarkably similar to reference systems used today”. This is followed by a figure with reference spectra of the main classes, presented along with a tabular list of main characteristics and a typical plate with an objective-prism spectrogram. One exercise reads:

> Carefully examine the plate. You should be able to see the diversity of spectra present. The region of the sky chosen for the plate shows examples of nearly every Harvard spectral type. […] Working with a laboratory partner, look at the first five numbered spectra. Compare these spectra with the reference spectra […] Observe not only the spacing on the lines present, but the relative intensity of the lines. Determine what spectra type you believe these five examples are. Record your answers. After a few minutes, share your answers with your instructor. Your instructor will then supply the spectra types agreed upon by professional astronomers. Using this feedback should assist you in classifying the rest of the numbered spectra on the plate.
>
> Examine the remaining numbered spectra […] Using the reference spectra, assign spectra types to each of the stars. Remember to assign decimal subdivisions as needed. Record your answers.[149]

This passage nicely describes the interactive learning process to which the students are exposed. Finding the ‘right’ spectral type for all of these minute spectra is by no means easily accomplished without such ‘feedback’. Initially, many mistakes are made and often the students are simply unable to attribute any of the given classes to the minute spectra. But with the help of their instructor’s mastery of *Gestalt* recognition, the students gradually learn and refine this skill. It is hard to transmit the essence of what goes on during this process, because its most crucial components are nonverbal. It is teaching by ‘showing’ rather than by ‘talking’; it is learning from ‘experiencing’ in a somewhat holistic manner rather than from analytic ‘decomposing’ or mechanical ‘memorizing’.[150] This has been the essence of teaching stellar spectroscopy—at least up to the very recent introduction of interactive computer packages.

9.7 The Harvard Students Astronomical Laboratory

Documents relating to the early history of the Harvard Students Astronomical Laboratory provide further insight into the teaching of spectroscopy within the context of astronomy in general. Its purpose was to fill the need for basic practical training of undergraduate students in observational astronomy, astrophysics, photography, and geodesy, which task the research-oriented Harvard College Observatory understandably shirked.[151] This student laboratory was opened in 1903 and was well stocked with equipment for instruction in both traditional and physical astronomy. It owned a Steinheil spectroscope, several prisms, **(p.397)** a heliometer, a stellar spectroscope, a photometer, and a fully equipped photographic darkroom.[152] The usual maps of prismatic, solar, and chemical spectra were used, of course, and prefabricated slides of all kinds of astronomical photographs could be shown with a lantern projector to larger audiences. As has already been pointed out by the instrument historian Deborah Warner, the use of such projection apparatus for teaching purposes was already quite common in antebellum America and played a central role in American education in the second half of the nineteenth century.[153] The bookkeeping records and other documents among the papers of this teaching institution reveal that several such slides were ordered with spectrographic themes; others could be borrowed from E.C. Pickering’s copious collection at the Harvard Observatory.[154] On one occasion in 1923, the new Mt Wilson solar spectrum map was displayed at the astronomical colloquium during Henry Norris Russell’s talk on “ionization in stellar atmospheres”. It reproduced the full solar spectrum at a dispersion of 1 cm = 1 Å and came to a total length of 30 meters.[155]

Between the years 1891 and 1901, Robert W. Willson (1853–1922),[156] the first director of the Harvard Students Astronomical Laboratory from its foundation until 1919, kept statistics of his students and their professional backgrounds: in 1896/97, for instance, among the eleven students enrolled in the Practical Astronomy course, seven were civil engineers, one was a draughtsman for Penery's Iron Works in Pennsylvania, and one was superintendent of 'Planters Compress Co.' in Paris, with the background of the last two unknown. All in all, the students registered in the Descriptive and Practical Astronomy courses had backgrounds in fields as diverse as civil engineering, archeology, geology, mining, naval architecture, and mathematics, and many were school teachers, professors, and instructors from other colleges in the Boston area.[157] The student body thus differed substantially from a normal class, say in organic chemistry. This was largely because of **(p.398)** the importance of practical and descriptive astronomy in the precise determination of longitude in exploration. Needless to say, astronomy's attraction among laymen was generally strong as well. Given this high level of interest, it is not surprising that the drop-out rate was low—only about 10 % of all enrollees in the Descriptive Astronomy course, for instance, failed the final examination.[158]

From the Students Astronomical Laboratory diary kept since 1920 by its new director Harlan True Stetson (1885–1964), we also learn more about the total number of students inscribed in the various lectures and courses offered at Harvard: in 1920, the introductory lectures on Elementary Astronomy (la), which also included two hours of laboratory work and observations per week, initially attracted no less than 152 men, which number was reduced to 141 by an admissions test. The next most popular course was Practical Astronomy (emphasizing the applications of astronomy for navigation and exploration) whereas the courses on Elementary Astrophysics, which focused on "astronomical spectroscopy", "solar and sidereal physics" and "stellar photometry," attracted only two students each.[159]

If we compare the manuals on *Laboratory Astronomy* written by R.W. Willson and by his former assistant and eventual successor, H.T. Stetson, it becomes evident that Willson's emphasis was much more on the traditional methods of astronomy. This included measuring altitude and azimuth, or equivalently, hour-angle and declination for equatorial instruments in conjunction with the related forms of representation of the celestial sphere in maps and globes. Not a single spectroscopic exercise is included in his manual, which appeared in 1901 and 1905.[160] The same is true of Whiting's *Daytime and Evening Exercises in Astronomy* and the similar manual by Mary Byrd (1849–1934), who directed the observatory and department at Smith College from 1887.[161] This simply reflects the contemporary convention that elementary instruction in spectroscopy be done at the *physics* departments while instruction in practical *astronomy* was usually limited to work with the sextant, transit instruments, zenith telescopes, meridian circles, and perhaps some micrometer work on the equatorial. This

even applies to the astronomy curriculum at Princeton University under Charles Augustus Young (1834–1908), who was an accomplished solar spectroscopist. In response to Whiting's inquiry about Young's experiences in teaching practical and physical astronomy, Young wrote, only "a few of the students have done a little with the spectroscope—visual observations only. I am speaking *of under graduates*—one or two of the *fellows* have done a little at spectrum photography with the 23 inch inst[rument]—but not as yet with much success. The laboratory spectroscopic work has been done in the Physics Dept., under charge of Prof. Magie; but other subjects have been **(p.399)** more prominent."[162] Sarah Whiting was not happy with this kind of compartmentalization. When the situation had still not changed ten years later, she became actively involved in a Committee on Cooperation in Improvement of Teaching Elementary Astronomy.[163] Among the eleven questions in a questionnaire sent to observatories and colleges in 1911, the eighth reads: "Is any spectrum work given to form a basis for intelligent discussion of elementary astrophysical problems?" which more or less presupposes that without such exercises in spectroscopy no such "intelligent" discussion is possible. Of the 80 institutions to reply, only twelve offered "some daytime exercises", ten "some review of the elements of spectrum analysis as a basis for study of stellar classification", and only two (Harvard and Wellesley) two hours of daytime laboratory work by the students.[164] Perhaps reflecting this increased awareness of the need to integrate spectroscopy early on in the astronomy curriculum, the astronomical laboratory handbook issued in 1923 by Stetson together with John Charles Duncan (1882–1967), professor of astronomy at Wellesley College and since Whiting's retirement also director of the local Whitin Observatory, did include a discussion of the "principles of spectroscopy", grating and prism spectroscopes and the classification of stellar spectra. But the scant space devoted to these topics (only a half dozen pages out of a total of 183, in an exposition of the physical principle behind diffraction gratings, a two-prism spectroscope, and an approximate determination of the wavelength of the sodium D line, and a couple of pages on the very basics of stellar spectroscopy) shows that this was a very first glimpse at these topics, to prepare students for the succeeding specialized course no. 7 on "elementary astrophysics" also taught by Stetson every other year.[165] The underlying reason for this shift in the curriculum is the increased theoretization of spectroscopy with the rise of quantum theory and quantum mechanics. Spectra had become mere indicators of electron transitions between states whose energy levels could, in principle at least, be precisely calculated. The corresponding new visual aid to oust the now defunct iconic spectrum map in science teaching is the symbolic term diagram.[166]

9.8 Spectroscopy at high schools and its further dissemination

Spectroscopy also made surprisingly rapid headway in preparatory high schools. The historian Max Lehmann (1845–1929), who received his secondary education at the prestigious **(p.400)** Joachimsthaler Gymnasium in Berlin, reported that, besides being exposed to Schiller's *Wallenstein* and Goethe's *Faust*, a good dose of Latin and French, and some mathematics, he was also introduced—in a "gripping presentation"—to spectrum analysis.[167] That was in 1863, just four years after its discovery by Kirchhoff and Bunsen. The initiative to include such a recent topic and, more broadly, to demonstrate experiments and thus venture away from standard 'chalk-board physics' was left to the individual schoolteacher, however. In Germany, physics was taught approximately two hours per week in the last four years of high-school education. In compliance with a *Reglement* from 1856, Prussian preparatory *Gymnasia* offered two hours a week in *Prima* (the final two years of school) and one hour in *Sekunda* (the preceding two years) but physics was not included in the school leaving examination *(Abitur).* The more technically oriented *Realschulen*, on the other hand, assigned two hours in *Sekunda* and three hours in *Prima.* In October 1859, physics instruction at *Realschulen* was jacked up to two hours per week from the entrance age of ten years on, followed by six hours weekly for *Sekunda* and *Prima* classes, with physics finally being included in the *Abitur* examinations.[168] By 1879, physics teaching at Austrian *Realschulen* was likewise reoriented towards "facts about simple natural phenomena and their laws conveyed by means of experiment, with some attention to their practical applications".[169] The official standard curriculum for Austrian polytechnic schools, which had been masterminded by the famous experimental physicist, physiologist, and philosopher of science Ernst Mach (1838–1916), included spectroscopic demonstration experiments on refraction, prismatic dispersion, and the solar spectrum in the fourth and fifth years (comparable to the German *Sekunda)*, and a discussion of interference as well as the chemical action of light in the final seventh year. The great importance attached to visual skills is evident from the schedule of three hours weekly for free-hand and geometrical drawing for all but the first year.[170] The state curriculum in Germany introduced in 1892 likewise favored *Anschauung*, a concept only approximately translatable as 'intuition' or 'visuality'. This took the form of more demonstration experiments or practical exercises, or a heavier emphasis on practical drawing skills. As Kathryn Olesko has pointed out, this radiated out into other subjects such as mathematics, with preferred subjects including astronomical geometry, geometric projection, and geodesy: "precise observation and drawing cultivated a **(p.401)** certain type of visual acuity, and so helped to create a culture more visually oriented."[171] Spectroscopy fitted well within this newly formed 'visual culture', even contributing substantially to its formation. It was but one more field requiring proficiency in drawing and visual memory, precisely those skills needed for *Gestalt* recognition.

Before the turn of the century, it was still possible for schoolteachers at the classical *Gymnasia* and the polytechnic-type *Realschulen* in Germany, Austria, and Scandinavia to contribute substantially toward the advancement and dissemination of scientific knowledge.[172] The physics teacher and director of the Cologne *Realschule* Heinrich Schellen (1818–1884), for instance, authored a standard textbook on spectrum analysis that was illustrated with 13 plates (six in color), including reproductions of Ångström's and Kirch-hoff's maps. The book originated from a series of talks delivered before the Cologne Association for Scientific Lectures and was explicitly addressed to a general audience of "educated persons not previously acquainted with physical science".[173] Within a year of its publication, avid interest in the "newest and most brilliant discovery of this century" prompted a new edition. At the instigation of William Huggins, who recommended it as the best elementary book on the spectroscope,[174] it was translated into English and quickly became a standard reference work among Anglo-Saxons as well. When Schellen's book first appeared in 1870, teachers still had to devise their own demonstration setups. This popular textbook opened the way for more detailed how-to guides with elaborate experiments for demonstration in front of a class. Elementary experiments dealing with the refraction of light, dispersion, and various spectra were the usual choices by teachers.[175] Friedrich Carl Gustav Müller's (1848–1931) technical manual of demonstration experiments for physics teachers (1st edition 1906) likewise included detailed instructions on how to demonstrate dispersion, spectra, Fraunhofer lines in the solar spectrum, and the coincidence of emission and absorption lines. Müller even recommended exposing different types of photographic plates to the solar spectrum in front of the class in order to demonstrate the unequal sensitivities of the emulsions in the different color ranges.[176] Ernst Grimsehl (1861–1914), who taught physics at the Hamburg Oberrealschule auf der Uhlenhorst, developed a special tube with a slit at one end and a collimator lens at the other, to simplify the spectroscope **(p.402)** mounting when projecting different absorption spectra.[177] In the case of Austria, the school inspector Karl Rosenberg[178] (1861–1936) published a similar teacher's manual which also included tips on projecting various types of spectra in the classroom.[179] He specifically recommended cheap direct-vision spectroscopes that could be passed around the class so that each pupil had a chance to see the various spectra, instead of using one finicky high-resolution spectrograph, which was only appropriate for advanced pupils.[180] This text is also remarkable for its advice about contemporary suppliers of instruments for school use.[181] No agreement was reached on whether a discussion about the rainbow ought to be included in the curriculum. Rosenberg preferred to brush over this sensitive issue. Others like Friedrich Poske (1852–1925) or F.C.G. Müller, on the other hand, pled for inclusion of at least the basic phenomena and their explanations, such as the circular shape and color sequence, while omitting such complications as varying widths, the dominance of blue and inner secondary rainbows with an inverted color sequence.[182]

Prior to the 1890s, pupils were rarely prompted to conduct experiments themselves. Among the 128 British endowed schools that replied to a query by the Royal Commission on Scientific Instruction in 1875, only 63 taught any science at all, and of these only 13 had a laboratory, and 18 often but rudimentary scientific apparatus.[183] When in 1877 the science masters at several larger British public schools were asked for "suggestions as to how far Physical Laboratory work is possible at School having regard to the time at a boy's disposal", only two out of the 18 responses received were favorable.[184] A similar survey made in 1880 for the US Government Bureau of Education covering 607 public and private secondary schools revealed that just 11 of these American schools offered a physics course incorporating some laboratory work, and out of these only four were carried throughout the **(p.403)** academic year. The others relied on the traditional method of textbook and lectures.[185] Between 1890 and 1900, the number of high schools in the US jumped from 2526 to more than 6000, accommodating a total of over 530 000 pupils. By 1910 the number had risen further to 10 213 schools with 915 000 enrolled pupils, amounting to 1 % of the population.[186] This significant expansion of the US educational system seems to have been accompanied by a demotion of the sciences: according to a 1905 report by the Commissioner of Education, only 17.5 % of all pupils attended physics courses and 7.4 % chemistry courses in 1902, against 22.8 % and 10.2 %, respectively, in 1892.[187]

How much spectroscopy was there in actual student exercises? Because E.H. Hall was also chairman of the Committee on Physics of the Science Department of the National Educational Association (NEA), his 'descriptive list of elementary exercises in physics' (see here p. 378) had a major impact on the NEA's recommendations for College Entrance Requirements, first issued in 1899. Consequently its list of exercises outlining laboratory work in physics did not contain any spectroscopy proper, not venturing beyond determinations of the index of refraction of glass and water.[188] Nevertheless, a first-hand encounter with spectra was certainly possible for those who attended physics laboratory sessions. For spec-troscopic exercises frequented various other published exercise selections.[189] Particularly in British 'Organized Science Schools' (approximately equivalent to German *Realschulen*) the curriculum developed by the Committee of the Incorporated Association of Headmasters shortly before the turn of the century included optional spectroscopic exercises.[190]

The introduction of practical exercises for German pupils seems to have come even later. Serious discussion about it arose in the 1890s and related publications attempted to initiate a movement away from textbook physics.[191] Clearly, *Realgymnasia* and *Oberrealschulen* had much more experience with such practical regimes than the philology-dominated *Gymnasia*, but these debates became mired in the general struggle by the former for recognition of their *Abitur* diplomas as equivalent certifications of 'general preparedness **(p.404)**

for university’. That was only achieved by decree, in late 1900.[192] By 1905, practical training of school children through observation and experimentation had become one of the three educational canons sanctioned by the commission of the scientific society Gesellschaft Deutscher Naturforscher und Ärzte, in what is known as the Meran Report.[193] The sample curriculum suggested by the Meran Commission included among its topics for the second to last year *(Unterprima)* emission and absorption of light as well as spectrum analysis, phosphorescence, fluorescence, and heat radiation. Upon instituting practical exercises, the Prussian Education Board allocated an annual budget of 25 000 marks for suitable laboratory facilities. According to a questionnaire prepared by the society in 1906, of all Prussian secondary schools, only 6 *Gymnasia*, 17 *Realgymnasia*, and 7 *Oberrealschulen* offered any practical exercises in their curriculum. Just three years later, however, 141 institutions of higher education in Prussia already offered practical exercises in physics. Yet the contemporary curriculum for Bavarian high schools still listed no pertinent topics among their *practika.*[194] At any rate, participation in such laboratory exercises remained facultative and depended on the gradual introduction of laboratory facilities in schools. Leaving aside the frequently missing physical prerequisites (suitable rooms, simple scientific instruments, and sufficient funds for running expenses and repairs), schoolteachers needed additional training for this new type of hands-on education.[195] After 1900 some German universities, inspired by successful efforts in this direction especially in England,[196] also started to introduce special courses (often held during the summer vacations) on the practical skills necessary for laboratory education at high schools. The University of Göttingen, for instance, offered such training from 1902 with a program on constructing and handling simple scientific instruments suitable for demonstration and student exercises: From an initial donation of 800 marks plus an annual budget of 300 marks, a special workshop was equipped with tools for planing, sawing, joining, soldering, and glass-blowing.[197] In 1905 the University of Greifswald likewise began to offer training in demonstrations of **(p.405)** physical apparatus, explicitly limited to instruments available in school laboratories.[198] By 1914, several other universities had introduced similar courses but World War I hobbled the impact of this advance in teachers’ education.[199] All in all, until the Great War, the best chance a German pupil had of actively conducting experiments was either at *Realgymnasium* or, better still, in institutions of higher learning, that is at university, in a polytechnic, or a special professional training college where the curricula included, at least occasionally, *Practika* in a student laboratory.

Ludwig Külp's[200] (1835–1891) exercises for physics students exemplify one training course offered at the Darmstadt hohere Gewerbeschule. That polytechnical school was later transformed into a technical university. Another example is the introduction to experimental physics by Adolf Ferdinand Weinhold[201] (1841–1917) at the Chemnitz Royal Technical Schools (Technische Staatslehranstalten). It went through several editions and was also translated into English.[202] Weinhold had studied chemistry in Leipzig and Göttingen and in 1861 became assistant at the agricultural experimental station linked to the Chemnitz Royal Technical School. During a staffing shortage in 1864, he was asked to take over the physics classes, which gave him an opportunity to transmit the laboratory didactics so familiar to him as a chemist. In the foreword to the English edition of Weinhold's textbook, George Carey Foster (1835–1919), a former student of William Thomson at the University of Glasgow and professor of physics at the University College, London, defended his outspoken preference for a school physics curriculum that abandoned the top-down approach in the laboratory and allowed the students to conduct experiments themselves, thus emphasizing "the concrete facts from which the abstractions are derived." He continued:

> In any sound system of teaching, particulars must come before generalities: for, unless a student has clear conceptions of individual phenomena, it is impossible for him to understand their mutual relations or the general conclusions that are based upon them. […] The kind of knowledge, however, which is really serviceable for this purpose is not such as can be got by merely reading or hearing descriptions of phenomena, or even by seeing experiments made by the teacher; it needs that the student should observe and experiment for himself. It is not merely that the knowledge we obtain, by seeing and handling an object for ourselves, is more vivid and complete than what can be obtained second-hand through the testimony of others, but that a great part of the mental discipline which the study of physics is capable of affording, depends upon our becoming convinced, through direct personal observation, that the general laws of the science represent conclusions truly derived from an accurate examination and comparison of the impressions which the actual phenomena make upon our senses.[203]

(p.406) This passage points out the change that was taking place in the basic approach to teaching physics at schools. The beginner acquired his practical knowledge, starting from the particulars, moving upwards to more general rules, and finally arriving at the physical laws on a more abstract level. Pedagogical considerations, an inductivist philosophy of science, and disciplinary issues of ranking experimental versus theoretical physics are all part of this mix, which we find in so many introductions to textbooks and laboratory manuals of the final two decades of the nineteenth century when practical training at the preparatory level eventually became feasible.[204] Inductivist programmatics are carried to an extreme in *Elements of Physics* by Alfred Payson Gage (1836–1903), a teacher at the English High School in Boston, with its accompanying laboratory manual entitled *Physical Technics.*[205] Gage started with laboratory exercises and a manual of physical manipulations even *before* giving a very brief 'general review of physics'. The students were thus supposed to rediscover some of the most important natural laws themselves, and even if they did not manage, at least to learn the hard way how difficult it had been for researchers in the past.

But those already convinced that having the students perform at least a few suitable laboratory exercises was desirable still faced a basic problem: funding to build up even a rudimentary physics laboratory for students. Thus replete with arguments for why work in the laboratory was indispensable for the "inculcation of the scientific method",[206] laboratory manuals of the late nineteenth century also bristle with practical tips about how to work on a shoestring budget. For the limited funds usually sickered away into the school's chemistry laboratories. In his manual of experimental study written for high schools and preparatory colleges, John Trowbridge—himself virtually free from such pecuniary constraints at Harvard University—devoted considerable space to arguing that an elementary laboratory of physics "need not cost more than a chemical laboratory such as is now provided in many high-schools."[207] He did not confine his text to describing "simple and inexpensive apparatus", but added the occasional tip on how to built it. In one experiment, for instance, he directed the reader to make a small spectroscope in a tin tube—supplied by the tin-man—into which lenses "which can be obtained from any optician" are inserted.[208] In a similar spirit, Lockyer asked his students to build their own telescopes, and Weinhold even let them first build bisulphide-of-carbon fluid prisms, using parts of a broken lampglass **(p.407)** cylinder glued to two plates of glass for installation in a "very simple spectroscope" basically consisting of a blackened box with a slit and a viewing window.[209]

This make-shift scientific apparatus certainly could not deliver refined observations, not to speak of precision measurements: Weinhold's box spectroscope only revealed the three most prominent Fraunhofer lines in the solar spectrum. Its dispersion was not sufficient to resolve those in the blue and green regions, thus merely exhibiting a strange striped shading. On the other hand, even with this primitive spectroscope Weinhold's students could observe the continuous spectrum emitted by Drummond's lime light, strong emission lines of elements held in the flame, the reversion of lines, and the correlation between the emission and the absorption spectrum based on Kirchhoff's law (cf. Fig. 9.10):

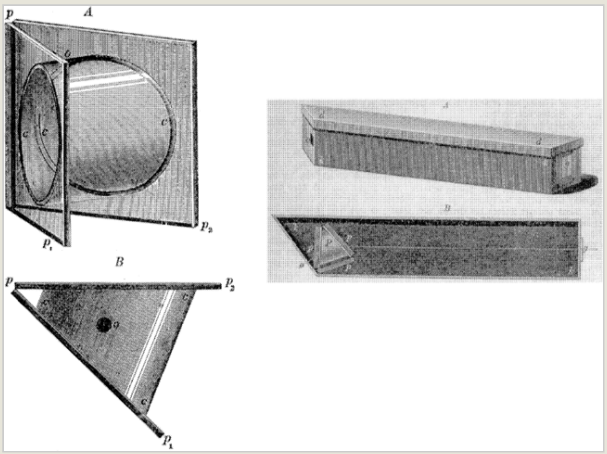
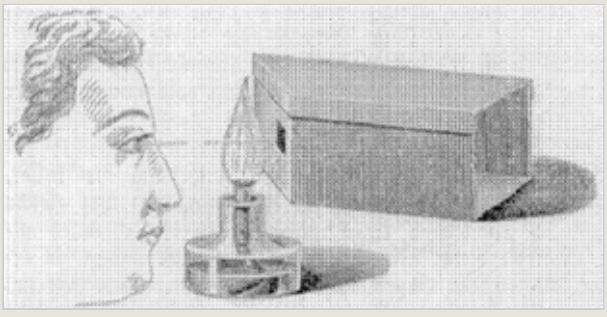


Fig. 9.9 Homemade fluid prism *(left)* consisting of cut and ground section of a lamp-glass cylinder glued onto two flat glass plates about 1 cm larger than the diameter of the cylinder. It is installed in a simple box spectroscope *(right)* for use in student exercises. The box is equipped with a slit at *g* and a viewing window at *o*. Woodcut illustrations from Weinhold [1872*e*] pp. 482, 499 top.

Such a modest introduction by means of homemade apparatus was quite effective in inspiring beginners. George Ellery Hale (1868–1938) is a prominent example. Following the directions in *Cassell's Book of Sports and Pastimes*, which he had received as a Christmas present in 1881, he built a 'luster prism' spectroscope, using old lusters from a candelabrum, and later even a fluid-prism spectroscope quite similar to Weinhold's prototype.

(p.408)



He was so captivated by the spectra he was able to observe through these extraordinary tools that he decided to continue to explore their possibilities. Despite the "odoriferously disastrous" work with the carbon bisulphide prism, George was—as he later remembered— "completely carried off my feet. From that moment my fate was sealed."[210]

Fig. 9.10 Student observing the reversion of the sodium line in the spirit flame with his handmade box spectroscope. From Weinhold [1872*e*] p. 510.

Hermann Hahn (1857-?), a former teacher at the Berlin Dorotheenstädtisches Real-gymnasium,[211] and in the 1920s director of the German Office for Science Education (Hauptstelle für den naturwissenschaftlichen Unterricht) in Berlin, was more extreme. He restricted the recommended apparatus for spectroscopic experiments in school laboratories to a Bunsen burner, simple prisms, and a few handmade accessories such as are needed for this clever substitute for a slit: The physics teacher was to arrange two thin wooden sticks, a pencil, and a polished needle on the window sill as shown in Fig. 9.11. If the pupils oriented the refracting edge of their prisms parallel to the pencil at the height of the window sill and looked at the whole arrangement from a distance of about 120 cm, it served as a good substitute for a narrow slit by reflecting the beam of sunlight only along a sharply defined edge.

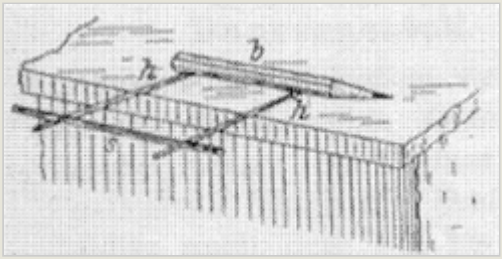


Fig. 9.11 Homemade substitute for a spectroscopic slit to observe Fraunhofer lines. From Hahn [1909*c*] p. 290.

The downside of cheap instrumentation was easily seen in a positive light: “it is considered of greater advantage to show how comparatively accurate results may be obtained by rough apparatus, than to explain the use of instruments of precision, which in the hands of a student are apt to give erroneous results.”[212] Simple apparatus was considered more suitable for drawing a pupil closer to nature, enabling him or her to play an active part in triggering the natural process under study, and hence to imbibe the essence of physical method: **(p.409)**

> For lasting success in physics instruction, it must therefore appear desirable to bring the pupils in closest possible contact with the processes themselves. […] The pupil must use his own hands and thus become virtually a part of the natural process involved in each instance. […] It is more a matter of insight into the essence of the physical methods than technically perfect performance; exact measurements go beyond the scope of school education and belong in practical sessions at university.[213]

In other words, in the eyes of these teachers it was not arriving at correct results of such experiments that counted so much as “cultivating habits of precise expression of ideas and principles”.[214] A similar point is made by the assistant master of Clifton College: “it should not, I think, at first be the aim of the teacher to show his pupils how measures of Physical Constants may be *most accurately* made, so much as to give them a clear idea as to what such measures *mean*,—to give them, in fact, a thoroughly intelligent conception of what is to be aimed at.”[215] Teaching the students how to experiment was conceived, first and foremost, as “cultivating what may be called the scientific instinct.”[216] This instinct entailed accuracy, a systematic working method, and experimental dexterity, as well as such mental qualities as perseverance, good judgment, and logical thinking. Careful execution and self-confidence paired with self-scrutiny and integrity, all these attributes were thought to form what Kathryn Olesko has called the “ethos of exactitude’ in the process of experimentation under the critical supervision of a teacher already imbued with such norms.[217] In the words of one report by the Royal Commission on Scientific Instruction and the Advancement of Science from the mid-1870s: “the true teacher of science consists not merely in imparting the facts of science, but in habituating the pupil to observe for himself, to reason for himself of what he observes, and to check the conclusions at which he arrives by further observation or experiment.”[218] Leaving aside the exhileration felt at coming face-to-face with important phenomena for the first time, the sheer sense of satisfaction from assembling the instruments oneself was often enough to spark a pupil’s enthusiasm: Many of Lockyer’s students kept their homemade telescopes for years afterwards as a souvenir of happy hours and early achievements in the student lab.[219]

(p.410) The *Laboratory Manual of Physics for Use in High Schools* published in 1902 by Henry Crew, a former student of Rowland’s who taught physics at Northwestern University, already includes exercises to be performed by the class. The last and most detailed exercise is a study of ‘fundamental phenomena in spectrum analysis’.[220] In line with the earlier remarks by his European colleagues about the modest essentials for fitting out a basic physics laboratory, Crew emphasized that the experimental setup for spectroscopy comprised only one 60° prism “costing somewhere between twenty-five cents and three dollars, according to the grade of it”, a Bunsen burner, an opaque screen with a slit, 0.1 inch wide, as a crude substitute for an adjustable slit, and a few substance samples like table salt and a “small bit of thallium sulphate, size of a bird shot”. His students were asked to compare the flame of an ordinary gas lamp (or candle) with the burner flame, and to observe the Bunsen flame when table salt, thallium sulphate, and chloride of lithium were held in it on a strip of thick moistened blotting paper. Crew and his assistant Robert Richardson Tatnall (1870-?) continued as follows:

> You have now examined the incandescent vapor of three different elements,—sodium, lithium, and thallium. Next let your assistant place in the flame any one or two (or even all) of these, without your knowing which, and see if you can tell which substance he is using. This method of detecting the presence of a substance is known as spectrum analysis.[221]

Having thus been conveyed the gist of spectrum analysis, the students are deemed ready to analyze the solar spectrum as the climax of the exercise. This is the limit of what is achievable with the primitive instrumentation for Crew's physics course: "When sufficiently powerful instruments are used, many thousands of these [Fraunhofer] lines can be seen in the solar spectrum, but a more minute study of these must be left for the advanced student."[222] In order to get an idea of how popular spectroscopic education had become in the US around the turn of the century, it is instructive to quote a letter by a physics teacher at the High School in Chelsea, Massachusetts:

> some of my pupils in adv. physics (Phys. C), I might say almost all of them, became crazy over the trifle of spectrum analysis in that course + insisted I would do that work of themselves, and hankered for more. They read a little bit in Lockyer or whoever it is. Now I am of the impression that much can be done with a cheaper form of apparatus] than has been hitherto used. But it had took me 10 years to feel I had Physics B in the palm of my hand. Now about astronomy?[223]

In this case, the students apparently outstripped their teacher in enthusiasm over the study of spectra. This letter is important insofar as it captures pedagogical reality and not just the programmatic level of commission reports, and lists of recommended exercises on which we often have to rely in our reconstruction of past methods of teaching. Hints of substantial **(p.411)** differences between the paper world of curricula and the daily practice of school teaching abound in the literature. Hans Hahn, for instance, cautioned his readers:

> New curricula are always elevating reading material […] And yet, the most eloquent words, even in the best curricula, remain but words that have been impressed upon the white page in printers black. More important than wording is the structure of curricula, and more still their implementation. But as experience tells us, turning curricula into a reality usually causes some disappointment.[224]

Nonetheless, as a physics teacher in a *Gymnasium* near Braunschweig has just recently confirmed to me, spectra have not lost any of their fascinating appeal in our day: pupils still let out the same 'oohs' and 'aahs' as their fellows in Chelsea from a hundred years ago, when they observe a line spectrum for the first time.[225]

Popular science books and pamphlets on spectroscopy disseminated the basic ideas and visual repertoire of spectrum analysis to broad segments of society. Bunsen's pupil and colleague Henry Enfield Roscoe did much in this respect. He not only translated most of Kirchhoff's and Bunsen's research papers, but also lectured widely on their new methods, for instance, as early as 1861 at the Chemical Society and the Royal Institution.[226] His later *Lectures on Spectrum Analysis*, originally comprising six lectures delivered before the London-based Society of Apothecaries, were a notable vehicle for promoting the new analytic technique and its many applications.[227] Along the same vein, William Allen Miller's lecture on spectrum analysis, first delivered in mid-1861 at the Manchester meeting of the British Association for the Advancement of Science, was welcomed with so much interest that he delivered it again half a year later in an evening lecture for the Pharmaceutical Society of London.[228] Similar texts and lectures, addressed to such diverse professional audiences as chemists, astronomers, photographers, physicians, engineers, industrialists, and physiologists, were also authored by William Crookes, the founding editor of the widely read *Chemical News*, by Huggins, Proctor, Secchi, Tyndall, and Young, and the schoolteacher Schellen, among many others in the late 1860s and 1870s.[229] Joseph N. Lockyer, whom we have encountered in his capacity as a physics teacher in South Kensington, also contributed to this flood of texts, both as founding editor of the semi-popular journal *Nature* (1869), and as the author of several books on astronomy and spectroscopy **(p.412)** catering to different specializations and degrees of technicality.[230] When the Astronomer Royal for Scotland Charles Piazzi Smyth started the weather-forecasting fad by means of a simple 'rain-band spectroscope' in the 1880s, a whole array of publications appeared targeted at meteorologists, farmers, seamen, and other professional groups particularly interested in weather conditions (cf. here pp. 107ff.). Following a quite different vein, physicians and physiologists also became interested in spectra as soon as they were made aware of the possibilities of spectroscopic examination of bodily fluids.[231]

As noted above, visual representations of the spectrum played a central role in all these stages of transmission and dispersal of knowledge. Aside from a recurrence of familiar plates and maps also used at preparatory school and university, we encounter another characteristic: the inflationary use of analogies and metaphors. To demonstrate how far-fetched these could sometimes be, let me quote from a popular exposition in *The New Physics* where the prismatic dispersion of light is explained as follows:

> To form a conception of the effect of the prism in separating the beam of white light into light of different colors, let us suppose that a flock of birds, all advancing with the same velocity—red birds moving with long, flapping wings and yellow birds with somewhat less powerful wings, and therefore flapping their wings oftener to keep up with the red birds, blue birds, green birds, violet birds, and so on—should fly toward us. All together, their colors, properly mingled as in the case of a beam of white light, would be indistinguishable. On meeting a dense, wedge-shaped medium, the more powerful birds would be less diverted from their path than the small birds, whose wings move much faster than those of the larger or red birds. In the effort to maintain their advance with the red birds, the birds whose wings move more rapidly are crowded away from the slower and more powerful birds and are dispersed, so that a gunner on the other side of this wedge-shaped medium would see the birds advancing in the order of the colors of the spectrum.[232]

Obviously, the author was trying his best to use appealing practical images. This one works because his assumption about the relation between flapping frequency and wing length agrees with common knowledge that the frequency of a swinging pendulum increases as its length is shortened. By employing such an iterative analogy (first, light as a mechanical system, the pendulum, and thence birds' wings), Trowbridge successfully assimilated wavelength and frequency to wing length and flapping frequency, making plausible to the layman the different behaviors of colored light rays refracted by a 'denser' medium (this, in turn, elucidating 'a medium of higher refractive index'). Such popular introductions typically skirted mathematics as much as possible, using only the occasional trigonometric function and simple fraction. Qualitative phenomena were discussed in the main, so numerical values or calculations are rare. Spectroscopy is a topic ideally suited for such constraints, because so much of its essentials—I should say, so much of what were its **(p.413)** essentials before the emergence of quantum theory in the twentieth century—could be conveyed without touching quantitative issues. Even the area that relied heavily on numerical values for wavelengths, namely the search for series relations, could be conveyed to broad audiences with the familiar analogy between light and sound, whereby absorption becomes a kind of resonance, and spectral series and homologies a 'kind of harmonics'.[233]

9.9 The case of France: the École Polytechnique

Thus far I have been discussing the aspect of teaching and dissemination mostly in English and German-speaking countries. The case of France invites closer study, however, because its strictly centralistic political and educational systems produced a remarkably homogeneous and transparent situation regarding what was taught, when changes were introduced, and even which instruments were used. The recently republished collection of official decrees and programs concerning science teaching in France between 1789 and 1914 offers a unique opportunity to trace the development of practical education systematically in French secondary schools.[234] I have to confine myself here, of course, to the field of optics and specifically to spectroscopy and spectrum analysis, and I will focus on one teaching institution of special importance in this field, the École Polytechnique.

Spectroscopic tasks found their way into the impressively broad curriculum of French secondary high schools astonishingly early, in 1819. The seventh and last part of the contemporary physics course covered optics, ranging from the properties of light (reflection, refraction, diffraction, and polarization) to optical instruments like lenses and the microscope. As part of its chromatic explorations, the program examined the varying refrangibilities of rays of light of different colors and demonstrated the diverse physical and chemical properties of different regions of the solar spectrum.[235] The text does not specify *how* these topics were to be demonstrated to the pupils but we can fill in this gap by looking at the list of required physics instruments at Royal colleges.[236] This scientific apparatus of about 100 items includes the following optical instruments: a goniometer, two plane and two concave mirrors, three lenses of 4 inches, ten small lenses without mounting, three [crown]-glass and two flint-glass prisms, achromatic and high-dispersion fluid prisms, a camera lucida and a dark chamber. They are listed with their prices, which ranged between 300 francs for the goniometer manufactured by Gambey, and 3 francs for the small lenses manufactured, **(p.414)** as all the other optical equipment was, by the Parisian optician Jean-Baptiste-François Soleil[237] (1798–1878). Twenty years later, this list was amended to include an achromatic lens “for the spectrum lines, [an] apparatus of Newton's for mixing the colors”, and the supplies needed for daguerreotype (which had been made public just a few years before, in 1839).[238] From a list of canonical topics on the final examination for the *baccalauréat ès sciences* in 1837, we learn that point 36 (among a total of 42 in physics) was related to Newton's *experimentum crucis* of prismatically decomposing light, and then reuniting the rays to obtain white light.[239] Students attending an intensive course on “special” (i.e., applied) mathematics and physics during their secondary education were familiarized with the “calorific, chemical, and phosphorescent properties of the various regions of the solar spectrum” along with the newly invented photographic recording technique of daguerreotype.[240] Another decree issued in 1840 had an even more detailed prescription, actually phrasing the questions to be posed to the examinees:

"Which phenomena result from transmitting a ray of light through a prism? Concerning the solar spectrum. What are the spectral colors, and in what order do they appear? How is one able to recompose white light?"[241] The program seems not to have been altered substantially for the next four decades.[242] Comparisons of the emission spectra of several articifial light sources seem to have entered the curriculum only in 1885, the term 'analyse spectrale' in mid-1891, and specific segments of the spectrum such as the infrared and the ultraviolet only in 1902.[243] Interestingly, at no time does there seem to be any mention in the chemistry curricula of the new possibilities of spectrum analysis for chemical analysis. This suggests a stronger and more rigid division between these two fields than in contemporaneous university systems. The basic curriculum prescribed in 1866 is important for another reason as well, since it reveals one of the basic themata of physics education of the time, namely, the analogy between acoustics and optics. As in all previous decrees, optics was the last in the order of **(p.415)** subjects taught, with acoustics immediately preceding it. This decree thus makes explicit the reason for this ordering: the wave processes encountered in the study of sound ought to be translated into optics; hence a subtle transfer of physical models took place. Oscillatory behavior in general, resonance, but also tonal relations and harmonics, which were already familiar concepts to pupils from acoustics, were supposed to be applied by analogy to the less intuitive field of optics:

> Whatever the nature of light may be, its undulatory motions act upon the organ of sight like the vibrations of air on that of hearing. One thus passes imperceptibly from the study of acoustics to that of light, which fittingly brings the course of physics to a close.
>
> Propagation, reflection, refraction of light;- luminous spectrum, spectrum lines;-phosphorescence;- plane or curved mirrors, lenses, the eye, vision;- telescopes;- eye glasses.
>
> In this second part, as in the first, accurate experiments always precede or follow the teacher's explanations.[244]

So, unlike the previous examples from the US and Germany of the turn of the century, in France of the 1860s pupils were not supposed to perform any experiments themselves, but to watch their teacher demonstrate them capably in front of the class. The analogy between optics and acoustics, on the other hand, was a key component of physics education in these countries as well and thus deeply implanted in the minds of physics students prior to 1900.[245] Even after the modernization of French curricula in 1902, which introduced a choice between classes with a heavier emphasis on languages (called A and B) and those stressing mathematics and science (C and D), the analogy between light and sound still had its place.[246]

In outlining the stages of education upon completion of basic schooling in France, we may rely on the textbooks published by professors at the *grandes écoles* in Paris, who led the way in determining university curricula in the provinces. One of the most prestigious institutions was founded in 1794 with the specific aim of providing engineers with a modern education. The École Polytechnique initially emphasized descriptive geometry and chemistry, but soon gradually shifted its sights towards modern mathematics, like calculus and algebra.[247] This elite school, mostly catering to aspiring military engineers, is an appropriate topic for a case study because the published sources in its archives are supplemented by a good selection of hectographed notes used in actual lectures given there at the time.

Between 1858 and 1866, just when the boom in spectrum analysis had begun, a new three-volume *Cours de Physique* appeared, authored by Jules Célestin Jamin (1818–1886). Jamin held the chair in physics at the Polytechnique from 1852 to 1880 and also taught **(p.416)** at the Sorbonne between 1863 and 1885.[248] Famed for his experiments in optics and interferometry, Jamin not surprisingly gave these two subjects extensive treatment, taking up roughly 35 % of his 1329-page textbook.[249] After addressing the more conventional topics of the propagation of light, reflection, and refraction, Jamin added a full chapter on the "analysis of solar radiation", including not only the optical spectrum with Fraunhofer lines, but also the "caloric and chemical spectra".[250] For the chemical rays (today's ultraviolet spectrum) he cited Edmond Becquerel's studies on actinometry and his efforts to photograph the spectrum dating back to the 1840s and 1850s (see here p. 195). But he also specifically referred to Mascart's recent experiments (cf. here p. 95). Jamin reproduced Mascart's table from 1864 and a simplified lithographed drawing of the solar spectrum from the lines A to T.[251] His emphasis on these recent extensions of the spectrum maps beyond the red and violet ends of the visible spectra led him to address the associated problem of how to extend the dispersion formulas of Cauchy and others into these realms, and how to measure indices of refraction for gases at different pressures.[252] The next chapter was wholly devoted to issues of absorption and emission including, of course, a thorough exposition of spectrum analysis and its recent victories with the discovery of caesium and rubidium. It also discussed molecular spectra and the continuous spectra emitted by glowing solids.[253] What strikes me as a more unusual feature of Jamin's text is the specific approach taken when discussing the processes of emission and absorption, in obvious adherence to Kirchhoff's 1861 theorem about the relation between absorption and emission coefficients which closes the chapter. At variance with Kirchhoff, however, who always tried to present this theorem in an abstract fashion without resorting to any specific models of matter, Jamin firmly linked his discussion to an atomistic framework and he also pled for a unified conception of the different forms of solar radiation as manifestations of a single kind differing merely by period of oscillation.[254] Considering Jamin's general abhorrence **(p.417)** of "spéculation" and hypothetical deductive reasoning,[255] this firm stance in interpreting all types of radiation as vibrations in the aether is quite remarkable.

In the next chapter, Jamin took up another research tradition that was particularly strong in France and that is missing in many other textbooks of the time, namely phosphorescence. Antoine Becquerel and his son Edmond had contributed much to this field since the early 1840s (see here § 2.8). Jamin added a novelty by entitling this chapter “De la transformation des radiations”. Hence he concentrated less on the phosphorogenic spectra and techniques of recording them as such, as on the process of transforming one (invisible) type of radiation into another (visible) one. Jamin thus happened to emphasize the one aspect of this research strand that later became important in quantum theory: According to Stokes's rule, the wavelengths of reemitted types of radiation are always larger than the initially absorbed wavelengths.[256] This chapter as well as the succeeding one on photochemistry (i.e., photography), place Jamin's textbook most obviously in line with an earlier tradition, starting in 1844 with Antoine Becquerel's *Traité de Physique*, and continuing with Adolphe Ganot's *Cours de Physique* (1856), Pierre Adolphe Daguin's *Traité élémentaire de physique théorique et expérimentale* (from 1855), Edmond Becquerel's *La Lumiére* (1867/68), Aimé Witz's *Cours de Manipulations de Physique*, as well as his *Exercises de Physique et Applications* (1883, 1889).[257] Ganot's textbook, written for pupils at the secondary level in preparation for academic study at one of the French state universities,[258] illustrates the growing coverage of spectroscopic issues between the first edition in the 1850s and the many later ones (in 1905 it appeared in its 23rd edition!). Up to the late 1850s, the discussion of spectra in the section on dispersion filled only eight pages and treated Newton's basic experiments with just a brief mention of the Fraunhofer lines. In later editions another ten pages were appended discussing spectrum analysis, different types of spectroscopes, and astrophysical applications such as measurements of Doppler shifts. They included, furthermore, a fairly detailed 24-page treatment of the photographic techniques using silver-bromide dry emulsions and later orthochromatic emulsions.[259]

The main successor to Jamin's textbook during the last decade of the nineteenth century was Eleuthère Mascart's three-volume *Traité d'Optique.* More detailed and complete than any other pertinent textbook of the time, it remained the reference text for researchers and advanced students in need of full details, whether about instrumentation, or theoretical derivations. Quite in line with Mascart's own research area of ultraviolet spectroscopy, the pertinent sections of volume 3 emphasize the determination of wavelengths and everything connected with it. Dispersion formulas for the index of refraction of gases and solids, interference **(p.418)** effects, and the gauging of spectrometers were given extensive treatment at a considerable level of mathematical sophistication. In his teaching at the Collège de France, Mascart could also afford to specialize much more than his colleagues at the École Polytechnique: the experiments he demonstrated to his small but select audience were drawn from his own research.[260]

By contrast, spectroscopy at the École Polytechnique was much more empirically based on experimentation and scientific instruments throughout the remaining decades of the nineteenth century. Both Marie Alfred Cornu, who taught physics there from 1867 to 1902,[261] and Alfred Potier (1840–1905), who was elected Jamin's successor in 1880 and also taught at the École des Mines, continued to focus on optics, each devoting over a third of their treatises to that field.[262] Potier's stronger theoretical inclinations, however, shifted the focus of his lectures substantially towards issues relevant to the wave theory of light and electromagnetism and away from the practical concerns of spectroscopists.[263] But Potier's increased emphasis on theoretical issues was complemented by Cornu's *Cours de physique*, which continued the tradition of experimentally oriented introduction. His course was still based on experimental ‘demonstrations’ of fundamental optical facts, such as the law of reflection, Newton's *experimentum crucis*, or Kirchhoff and Bunsen's experiment on the inversion of emission and absorption spectra. Janssen's method of observing protuberances, or Edmond Becquerel's phosphoroscope too were not only discussed but practically demonstrated. The students had to memorize the labels of the major dark lines observed on a projection of the Fraunhofer spectrum, and spectrum photographs on collodion and gelatino-bromide plates were made. Only after a similar discussion of the velocity of light (another area of Cornu's expertise) did a brief section discuss ‘the nature of light and the motion it constitutes’, but even this remained thoroughly embedded in experimental discourse on Newtonian fringes, refraction experiments, and other ‘vérifications experiméntales’ of the wave theory of light.[264] The associated practice sessions dealt with angular measurements with a Babinet goniometer, spectroscopic analysis of various emission spectra (hydrogen series lines, magnesium spark spectrum, and calcium-chloride band spectrum), observation of the reversion of the sodium D line, and actual registration of the Fraunhofer lines in the solar spectrum.[265] Cornu's style in general was well-known for a preference of geometric demonstrations, and thus very visual.[266]

(p.419) This tendency was prolonged into the early twentieth century by Auguste Pérot and Charles Fabry, both of whom taught at the Polytechnique, 1909–25, and 1926–36, respectively. Pérot's course in 1920–21 quite clearly placed more weight on interference, but the spectroscopic parts still followed the rough outlines of Cornu's from twenty years earlier. It updated some sections just slightly with such more recent topics as Gramont's ‘raies ultimes’ (cf. here § 8.7, p. 327) or Hale's and Deslandres's spectroheliograph.[267] Fabry's course at the École Polytechnique, as well as his other textbooks, which were based in part on his lectures at the Sorbonne from 1925 on, also followed the typical pattern of French textbooks in placing the strongest emphasis on electricity and optics, while downplaying mechanics as well as the most modern branches of theoretical physics, relativity theory, and quantum mechanics.[268] This, of course, only mirrored the importance of applied optics, and spectroscopy in particular, in the research profile of French experimentalists.[269]

From this survey, we may thus conclude that between the birth of spectrum analysis and the advent of quantum theory, visual representation played a central role at all stages of practical education in spectroscopy in the United States, Germany, Britain, and France alike.

Notes:

(1) See, in particular, Moyer [1976], [1982] on the emergence of the physics teaching laboratory in the US context. Olesko [1991] investigates the origins of student laboratories in Königsberg under F. Neumann in the early nineteenth century, Warwick (forthcoming) treats the Cambridge Mathematical Tripos in Cambridge, England, and the acquisition of theoretical technologies in the late nineteenth century, and Warner [1988] discusses instruments produced specifically for the classroom.

(2) Pyenson [1978] p. 94. For surveys of science teaching in different local and national contexts around 1900 see, e.g., Pyenson and Skepp [1977] for Germany, or Perry [1880], Koizumi [1975], Bartholomew [1989] for Japan; Stichweh [1984] provides a sociological perspective on the rise of physics in Germany.

(3) On this process see, e.g., Anon. [1875*a*], [1884*a*], and further sources cited by Phillips [1983], and James (ed.) [1989] on the development of the laboratory. On the genesis of individual physics teaching laboratories see also, e.g., Bottomley [1872], W. Thomson [1885], Beare [1894], Gray [1897], Lodge [1908], Perry [1880], [1908], James (ed.) [1989] part II, and Widmalm [1993]. For a survey of Victorian Britain, see Sviedrys [1976] and Gooday [1990]. For the German context, see Cahan [1985] and Jungnickel and McCormmach [1986] vol. I, pp. 107ff.; on Gustav Magnus in particular, Hoffmann (ed.) [1995]; on France, Smeaton [1954] and here § 9.9.

(4) Histories of chemical teaching laboratories include Wurtz [1870], Remsen [1894], Alexander Smith in Smith and Hall [1902] pp. 18ff., Smeaton [1954], Morrell [1972], and F.L. Holmes in Olesko (ed.) [1989] pp. 121–64. Cf. also Belhoste in Belhoste *et al.* (ed.) [1994] pp. 13 and 19 for early and not very successful attempts to introduce laboratory education in chemistry at the École Polytechnique around 1800.

(5) See Morison (ed.) [1930] pp. 260, 278, and 285. The same precedent of chemistry labs over physics labs is found in Uppsala: see here p. 434.

(6) Roscoe described his chemical education and early experiences as Williamson's assistant at the Birkbeck Laboratory of the University College in London, and his later emulation of these student laboratory facilities at Owens College in Manchester: see Roscoe [1906] chaps. 2 and 5.

(7) Foster *et al.* [1894] p. 281; cf. p. 286 for floor plans and pp. 299–301 for Foster's description of the new physical department.

(8) Anon. [1884*a*] p. 172. The same author estimated the total number of research laboratories internationally at 400 to 500. Sviedrys [1976] p. 405 counts more than 25 academic physics laboratories in Britain by the end of the nineteenth century. See also the interesting survey of scientific apparatus at various American institutions, published in Gibbs *et al.* [1879] and partly reprinted in the *Harvard University Bulletin* 11–12 [1879] pp. 302–4, 350–4, as far as Harvard and Johns Hopkins University are concerned.

(9) See Weinberg [1902] for a thorough survey of 200 teaching institutions in Europe, the US, and Australia: on p. 125 he asserts: "above all in laboratories in England and the United States […] one gives special attention to manipulations connected with mechanics", but among the 910 different exercises he listed, about 30 concern spectroscopy or spectrophotometry, several of which were practised at many institutions (e.g., nos. 322, 342f., 475, 494, 497).

(10) For interesting comparisons of the resources available at various physics institutes, see the study by Forman, Heilbron, and Weart [1975] on physics circa 1900, as well as the estimates given in Webster [1899] pp. 89f. on the expenses incurred by student laboratories in the US (between $1000 and $200 000), to which a sum between $20 000–50 000 must be added for equipment and apparatus. According to the same source, the Zurich Polytechnic cost a quarter of a million dollars. The secondary school system in the US around 1880 is documented in the appendices to Clarke [1880] and Wead [1884]. On Europe see Wead [1884] pp. 74–105, Smith and Hall [1902] pp. 356ff.

(11) On the importance of textbooks in a reconstruction of teaching at universities see, e.g., Jungnickel and McCormmach [1986] vol. 1, pp. 23ff., and here footnote 20 on p. 366. Physics textbooks in the German context between 1700 and 1850 are treated in particular by Lind [1992] and Clark [1997]; on chemistry textbooks see Paul [1906], Schwarz [1940], Harvey [1957] pp. 212ff., Haupt [1987].

(12) See, e.g., Ostwald [1911] pp. 572–7 on the outdatedness of standard chemistry textbooks, and here p. 428 on the many editions of Müller-Pouillet or Kohlrausch's textbooks.

(13) See, e.g., the forewords to the first, second, and third German editions in Müller [1847*a*] pp. v–xi. and pp. 419–39 and 633–6 on spectroscopic and photographic issues. Lind [1992] p. 319 describes the general impact of Müller's textbook. For Müller's background see here footnote 159 on p. 211, and footnote 31 on p. 428.

(14) See Müller [1847*d*] vol. 1, pp. 632f. for small segments of Kirchhoff's [1861/62] solar spectrum map, and pl. II—III, IIIa; altogether, spectroscopic issues filled approx. 80 pages, that is approx. 10% of vol. 1 of this two-volume textbook.

(15) The 7th edition appeared in 1868, the 8th edition in 1876; from the 9th edition on, the revision was done by Leopold Pfaundler, the 10th edition in 1906 together with O. Lommer; this textbook was also available in English translation from 1847.

(16) For instance, in the 3rd edition of 1875: pp. 120–45. 227–61, and other mentionings.

(17) See H. Kayser's *Lehrbuch der Physik*, [1890*a*] pp. 412–37, 453–6.

(18) Among Kayser's 170 doctoral advisees in Bonn between 1895 and 1926, 125 (or 73 %) pursued spectroscopic research—see the list of dissertations appended to Kayser's autobiography [1936], pp. lxxiv–xcv.

(19) See Warburg [1893*b*] pp. 244–50.

(20) On the history of practice sessions in German university education, see Olesko [1991], especially pp. 166, 403, 410–12 as well as Cahan [1985] on Kohlrausch's textbook. Kohlrausch and his work on electrolytic conductivity in particular is also discussed by Cahan in Olesko (ed.) [1989], cf. further references there. Arrhenius disappointedly reported that in 1886 Kohlrausch's laboratory in Würzburg was bureaucratically run with restricted opening hours and dull research projects; see Crawford [1996] pp. 65ff.

(21) According to Thomson [1885] p. 412, the English translation of Kohlrausch's treatise on physical measurement, Kohlrausch [1870*d*], was "a most serviceable manual" until it was superseded by Glazebrook and Shaw [1885] and others mentioned further below. The French translation appeared in 1886, the Russian translation was done by his former student Sergei Lamansky (cf. here p. 73), and Japanese translations were published as late as 1957.

(22) See Kohlrausch [1870*a*] section on light and the English translation by Thomas Hutchinson Waller and Henry Richardson Proctor: Kohlrausch [1870], pp. 94–101. Cf. the reprint of the 19th German edition from 1951, vol. 1, pp. 351–26 (Spektrum und Interferenz), 417–64 (Spektroskopie der Atome und Moleküle), that is, 113 of a total of 534 pages (ca. 20 %)! Besides such direct translations, in 1917 Ralph Smith Minor, a doctoral graduate of Göttingen University from 1902, published a four-volume laboratory manual for use in general physics courses at college: see part IV, § 94 on the spectrometer.

(23) See Nichols and Franklin [1903], vol. 3, p. 96 on the 'spectrophotometer' and chap. IX there on photometry. Cf. also Watson [1913] which assigns a chapter each to refractive index measurement (15 pages), dispersion and wavelength measurements (10 pages), and interference (31 pages), the latter including such issues as the resolution of a prism spectroscope, which earlier had been covered under spectroscopy proper.

(24) See Miller [1855], advertisement for the first edition, also reprinted in the 4th edition (1867), p. vii. Sutton [1976] discusses Miller's early research on emission spectra. See also here § 2.3, footnote 72 on p. 42, for further biographical information on Miller. According to Wolfenden [1973], "'chemical physics' was the name often given to a rather emasculated exposition of the sort of physics that chemists ought to understand."

(25) On the history of physical chemistry see Dolby [1976] and Girnus in Girnus (ed.) [1987]; on the American context in the early twentieth century, see Servos [1990]. Compare the contemporary definition of physics, chemistry and the changing demarcation between them in Berzelius [1829] vol. 1 (which still included light, heat, electricity, and magnetism within the framework of imponderables), for instance, with Cooke [1860] pp. 4–6 (which discussed none of the above). Hiebert [1996] provides further references pertinent to this shift in definition and subject matter in chemistry.

(26) See Miller [1855*a*] pp. 136–41; cf. also pp. 199f. for Miller's discussion of Prevost's and Leslie's experiments on the direct proportionality of absorption and emission, soon generalized by both Stewart [1858], [1860], and Kirchhoff [1860]; cf. also Stewart [1861/62], [1863], Kirchhoff [1863], and Siegel [1976] about the priority controversy.

(27) The 3rd edition of 1864, pp. 140–55, for instance, has woodcuts of the different dispersions of fluid and flint-glass prisms, various emission and absorption spectra, Kirchhoff's single-prism spectroscope with a Bunsen burner, the famous Kirchhoff and Bunsen [1860/61] chart of characteristic alkaline and alkaline-earth emission spectra, and a segment of Kirchhoff's [1861/62*a*] solar spectrum map. The 4th edition of 1867 added a separate section on photography, including detailed recipes of Talbot's calotype, daguerreotype, and wet collodion photography, with woodcut reproductions of photographed spark spectra.

(28) See J.F. Daniell [1839*b*] pp. 178–86, 453–61, W.A. Miller [1855*b*] p. 146. J.W. Draper [1846] pp. 71–97 underwent as many as 40 editions and was later revised by his son: see H. Draper [1866] p. v. Pynchon [1870] pp. 243–75 devoted a whole chapter on light as the "second chemical agent". Roscoe [1868*b*] included a section on spectrum analysis right between the major sections on metals and organic chemistry; see also Roscoe [1872]. Roscoe's other semipopular expositions of spectroscopy are mentioned here on p. 411. W. Gibbs too was ambiguously placed between physics and chemistry at Harvard; see here footnote 65 on p. 376.

(29) See Taylor [1927], entry for 1 December 1860. I was led to this subsequently published diary by Becker [1994] p. 91. Cf. also Miller [1855*b*] p. 146, or [1862] for more specifically spectroscopic passages.

(30) See Stewart [1879].

(31) Good selections are found in the 'Retrospective Collection' of the MIT Library, the Harvard Science Library, the Harvard Widener Library, the Gutman Education Library, and the Niels Bohr Library at the AIR.

(32) See Rogers [1864], p. 4. Cf. also pp. 23–6 on the specifications of the four laboratories on (i) physics and mechanics, (ii) chemical analysis and manipulation, (iii) metallurgy and mining, and (iv) industrial chemistry as conceived by its founding president, who himself taught chemistry, geology, and natural philosophy.

(33) *Ibid.*, p. 23.

(34) The son of an old and distinguished colonial family graduated *summa cum laude* at the Lawrence Scientific School at the age of 19 and was at once appointed instructor of mathematics. Two years later, he became assistant in physics at the MIT, and in the following year he became Thayer professor of physics. Elected to the American Academy of Arts and Sciences in 1867 as the youngest member ever chosen, he later also became member, among numerous other scientific organizations, of the National Academy of Sciences, which awarded him the Henry Draper Gold Medal. In 1898 he founded the American Astronomical Society. On Pickering's life and work see. e.g., Bailey [1919], Metcalf [1921/22], Jones and Boyd [1971] chap. 4ff., and Plotkin [1974], [1978].

(35) See Pickering [1869], where he also mentions chemistry as his model; as well as his 'Report of the Physical Department of the Mass. Institute of Technology, from 1867–1877' in Pickering [1876] pp. 26–38.

(36) Both quotes are from E.C. Pickering [1871] pp. 272, 278. Cf. also Pickering's textbook [1874/76*a*] vol. I, pp. 11–15, and the emphasis on drawing as an "essential feature in the daily duties of the school throughout most of the regular course of four years" in Rogers [1864] pp. 26–7. Some American texts dating back to the 1830s stress the 'utility of visible illustrations': see Warner [1988] p. 391.

(37) *Ibid.* On Pickering's work in stellar spectroscopy, see here § 8.8. pp. 351f.

(38) On S.F. Whiting, see below p. 385. For the physics canon for freshmen in Baltimore, see Rowland [1886*d*], his unpublished notes on 'Laboratory work' (JHUA, ms. 6, ser. 5, box 39) and his lists of apparatus (ser. 2, box 15, and ms. 1, ser. 1) as well as Ames [1897] esp. pp. 455–67 on spectra. Rowland and Ames [1899] included a continuous spectrum and the emission spectra of various gases as pertinent lecture demonstrations, and the mapping of the spectra of some gases as the only relevant exercise (*idem*, p. 253) and was to be used in conjunction with the laboratory manual by Ames and Bliss [1898] esp. § 87–9.

(39) On Owens College see Schuster [1881*b*], [1898], [1932], the textbooks by Stewart and Gee [1871], [1885], Stewart [1888], as well as Anon. (ed.) [1906], and Kargon [1977] chap. 6. See also the description and maps of the physical laboratory at Owens College in Fischer [1901] pl. II and pp. 31ff., where it is mentioned that 100 among the circa 1000 auditors actually worked in the physics laboratory.

(40) S.F. Whiting [1917] p. 4: "one eminent professor of physics in a New England college voiced the general sentiment when he said *he could not have students bothering around*."

(41) See on this issue Kevles [1977] for the US, Sviedrys [1976] pp. 430ff. for Britain, and Cahan [1985] for Germany. For comparative surveys of engineering education mainly in the US. Britain, France, and Germany see Emmerson [1973] and Belhoste (in preparation). Cf. also here p. 432.

(42) Cf., e.g., the literature mentioned in footnote 46, p. 14.

(43) E.C. Pickering [1870]. On the use of such projection apparatus in research see here § 4.5, in teaching see below, p. 397.

(44) See E.C. Pickering [1869] as well as [1874/76*d*] pp. 148ff. An advance issue of the first 70 pages of vol. I had already appeared in 1872 (without the optics part), and according to the MIT *President's Report for the Year Ending Sept. 30, 1873*, p. 68, prior to that date the students had to copy their instructions from the blackboard.

(45) This refers to Rogers [1864] pp. 4, 23f. (see above footnote 32 on p. 368). In the same spirit, the Physical Laboratory was renamed Rogers Laboratory in 1872: see 'Records of corporation meetings', book II (MITA, AC 278), pp. 242f., suggestion by Atkinson, pp. 257f., approval, and 268ff., Rogers's reaction.

(46) Pickering [1876] p. 31. Considering that this was Pickering's last report before leaving, his remarks about his teaching experiences have added weight.

(47) See *ibid*., esp. the section on advanced physics and the long list of scientific papers that arose from work at the MIT Physical Laboratory, pp. 33ff.; during his Harvard years, Pickering stopped giving lectures or courses.

(48) On the practical education by Pickering's successor Charles Robert Cross (1848–1921), himself a pupil of Pickering but with a greater interest in physiological optics, see. e.g., his 'Notes to lecture on light in its relations to color,' Collection of Leaves, MIT, c. 1876; Cross [1893], and Pickering's report (in footnote 35 above) pp. 58–60; cf. also MIT [1933] pp. 27f.

(49) According to a description included in a photo album of the MIT Department of Physics, made for the 1893 Chicago World Exhibition (MITA, album no. 25, photo nos. 27f.).

(50) See Holman [1885] and the 8th edition of 1901. In both versions he also explicitly cross-references Pickering's *Physical Manipulation*, such as in his discussion of the gauging of absorption spectra by calibration with strong Fraunhofer lines in Holman [1885*a*] p. 35.

(51) See MIT [1933] p. 28; on Abbot see p. 272 below.

(52) Holman [1885*a*] p. 35, emphasis added.

(53) Eliot later became president of Harvard University; in 1862 when he was still assistant professor of mathematics and chemistry, he had advised the young E.C. Pickering to transfer from the Boston Latin School to the Lawrence Scientific School: see Plotkin [1974] p. 599.

(54) See Eliot and Storer's *Compendious Manual of Qualitative Chemical Analysis* [1872], first used in the class of 1868 in the form of mimeographs and revised by W.R. Nichols in 1876 and by W.B. Lindsay in 1891; its 20th edition appeared in 1900. See also Eliot and Storer's *Manual of Inorganic Chemistry* [1868] first distributed as proof sheets, and published in several revised editions until the end of the nineteenth century. It was replaced by Arthur A. Noyes's *Course of Instruction in the Qualitative Analysis* (first published in 1897) and his *Detailed Course in Qualitative Chemical Analysis with Explanatory Notes* [1894], both of which in turn were reprinted about 10 times by the 1930s. Cf. also Nichols and Norton [1888] for MIT laboratory experiments in general chemistry, and Crafts [1869] for the course in qualitative analysis at Cornell University.

(55) See, e.g., MIT [1933] on the early history of the departments of chemistry and physics, the annual reports of the MIT President and Treasurer, and Rogers [1864] pp. 10ff., 23f. According to E.C. Pickering in the MIT *President's Reports* for 1871/72, p. 28, the physics students entered the physical laboratory only in their third year after a thorough preparation with mathematical and experimental lectures. With the establishment of physics as an independent academic department, several special courses, including photography, lantern projections, and spectroscopy, were added to the curriculum (cf. the *President's Report* for 1874, p. 69).

(56) See Pickering [1876] p. xiii, as well as the *President's Report* for 1871/72, pp. 30 and 32, mentioning a newly acquired Steinheil spectroscope in the context of instruction in quantitative analysis in chemistry and complaining about limited installation space.

(57) See Pickering [1876] p. xi and the floor plan on p. xii; the initiative for this expansion apparently came from Prof John Morse Ordway (1823–1909), who taught metallurgy and industrial chemistry, leaving MIT in 1884.

(58) On the hiring of Whipple (without salary in the first term), see book II (MITA, AC 278), 17 November 1870 on p. 206, and ‘Records of Committee on Instruction’, book I (AC 272), 8 July 1869, p. 61. In the MIT *President’s Report* for 1871/72, p. 13, E.C. Pickering mentioned a collection of photographs taken by students and submitted to the president as “specimens of their handiwork”, and in the *President’s Report for the Year Ending Sept. 30, 1873*, p. 73, C.R. Cross outlined a more systematic treatment of photography in a lecture course that also included its history and photomechanical processes of reproduction. On Whipple, who experimented with daguerreotypes since 1840 and established a Boston studio in 1850, see also Johnson [1990] pp. 685–9.

(59) W.H. Pickering’s later course in photography, for which he also used the photographic laboratory manuals by Abney [1882*b*] and Hardwich [1855], is best documented in Holman [1885*a*] pp. 85ff. (appendix, pp. 1–8, written by W.H. Pickering). On attendance in these courses by students from all fields, see Jones and Boyd [1971] p. 206.

(60) See, e.g., the courses for use at MIT by Drisko [1929] and Sears [1933] as well as the *MIT Catalogue 1932/33* p. 204 for the courses on optics (8.161) and atomic structure (8.311) and the lab courses on optical measurements (8.162) and atomic structure (8.312). Cf. also Sommerfeld [1919] and Johnson [1928] for similar textbooks on spectroscopy written from the point of view of quantum theory.

(61) See Harrison [1933*b*] p. 110 as well as the *MIT Catalogue Issue Including the Graduate School* **69** (1934), p. 277 on courses 8.32, 8.35. 8.341–2, and 8.343.

(62) For a description see, e.g., Compton [1932], Harrison [1933*a*] pp. 111f., and *the MIT Catalogue Issue Including the Graduate School* **69** (1934), p. 207.

(63) See again the MIT *Catalogue* for 1934, pp. 208, 277f. on courses 8.38 and 8.343.

(64) For a description of these summer courses which were combined with summer spectroscopic conferences in the years 1933–4, see the Harrison Papers (MITA, MC 60, box 2, folder conferences). The MIT summer conferences are mentioned here on pp. 339f.

(65) The course, ‘The spectroscope and its application’ regularly offered by Prof Gibbs is listed, e.g., in the *Harvard University Catalogue* for 1884/85, p. 98. Before 1871, Wolcott Gibbs (1822–1908) taught chemistry at the Lawrence Scientific School, then teaching physics at Harvard College; his research mostly concerned inorganic chemistry, thermodynamics, and what we today would conceive as physical chemistry, including spectroscopy; cf. Morison (ed.) [1930] pp. 259f., 263, 281.

(66) It is described in the *Harvard University Catalogue* for 1874/75 somewhat vaguely as “practical exercises in the laboratory, including the use of instruments of precision in testing the laws of Mechanics, Acoustics, Optics, Magnetism, and Electricity, and an extended course in Electrical Measurements”.

(67) See the *Harvard Catalogue of 1872/73*, pp. 56–60, the newspaper clippings on Trowbridge’s Lowell Institute Lectures of 1879 in S.F. Whiting’s scrapbook no. 1 (WCA, pp. 55–6), one of them entitled ‘The Need of a Physical Laboratory at Harvard Shown by Professor Trowbridge’ with interesting details about impressive demonstration experiments on spectroscopy at this lecture). Cf. also Hall [1932] and Lyman [1925] on Trowbridge’s life and work, in particular p. 653 on his work in spectroscopy, and Lyman [1932], Aronovitch [1989] on the new laboratory.

(68) See the *Harvard Catalogue of 1889/90.* p. 342, Morison (ed.) [1930] pp. 278ff., 289f., Lyman [1932] pp. 5–15 and Holton [1984] on the history of the Jefferson Lab.

(69) See Trowbridge [1884] chap. XIV. Trowbridge acknowledged using the manuals by Pickering [1874/76] and Thresh [1880], and the laboratory manuals for Clifton College omitting optics by Worthington [1881], [1886].

(70) Sec Whiting [1885] § 71–3, although the determination of wavelengths with diffraction gratings seems not to have been required in the end “on account of insufficient apparatus” (p. 2. note); and Whiting [1890/91] vol. 1. pp. 257–69, as well as vol. 4, pp. 1048, 1085, and 917f. where a number of spectroscopic instruments such as prisms, spectrometers, and diffraction gratings are listed under the heading ‘goniometry’. Whiting conceded more than once that this course had been “elaborated from one previously given by Professor Trowbridge”. Cf., e.g, Whiting [1885] p. 1. [1890/91] vol. 1, p. viii. He also mentioned having consulted particularly the standard works by Pickering [1874/76] and Kohlrausch [1870*d*], as well as Glazebrook and Shaw [1885] and later editions of Stewart and Gee [1871]. For the contemporary examination questions at Harvard, see also Whiting [1891]. On H. Whiting’s impact on the modern laboratory method of teaching in physics, see Trowbridge [1896].

(71) See Whiting [1894*a*] pp. 55–60, and [1894*b*], in particular pp. 207–9. Whiting died in a storm at sea on a return voyage from the West Coast via Panama. He played an important role in the canonization of the Harvard physics curriculum; see also Morison (ed.) [1930] pp. 281–5.

(72) Whiting [1894*b*] p. 209. On this analogy see also p. 415 below.

(73) According to the biographical memoir on Hall by Bridgman [1941] p. 75. After discovering in 1879 the effect later to be named after him and taking his doctorate in 1880, Hall received a fellowship to work for one year in Helmholtz's laboratory in Berlin. Hall's research mostly centered around electromagnetic and thermoelectric phenomena; see, e.g. Hall [1938], Bridgman [1939], [1941], Buchwald [1985]. On Hall's influence on the curriculum in secondary-school physics, see also Webster [1938] and Mover [1976].

(74) According to the *Harvard Course Catalogue 18S6/87*, p. 195, the prerequisite for admission were the successful completion of "A course of experiments in the subjects of mechanics, sound, light, heat and electricity, not less than forty in number, actually performed at school by the pupil". Alternatively the student could still choose to be examined in textbook knowledge based on introductions by Lockyer [1870] (chap. XV on the spectrum), Avery [1885] (pp. 409–22 on 'chromatics and spectra'), and Gage [1882], On the gradual establishment of examinations for admission in the US since 1860, see also Eliot [1869] p. 209.

(75) Worthington [1886], Trowbridge [1884]. For contemporary guidelines on how such a student notebook was to be organized, see, e.g., Cooke [1887] pp. 6–8, Smith and Hall [1902] pp. 123ff., 296ff. just as the introductory sections to most laboratory manuals from that time.

(76) Fischer [1901] p. 70 confirmed that chemistry was a role model; on p. 76 Fischer reported that in 1897 the setting up of a simple spectroscope and tracing the sodium D line was one of the four experimental tasks in student examinations at the Natural Science Tripos examinations of Trinity College, Cambridge.

(77) See Hall [1886], Anon. [1887*a*], and Hall [1897]. See also Hall [1887] p. 129 for his letter to the editor of *Science* on the alternative to textbook physics, mentioning a "pamphlet giving a list of forty laboratory exercises", and the important precursor in Charles Wead's [1884] p. 146: 'List of Fundamental Experiments in Physics', which includes refraction of light, dispersion, and the spectrum. The later absence of spectroscopic experiments is also iterated in Hall and Bergen's *Textbook of Physics, Largely Experimental* [1891] and is based to a great extent on the Harvard College descriptive list.

(78) See S.F. Whiting's 'History of the Physics Department at Wellesley College from 1878 to 1912' (referenced in footnote 111 on p. 385 below), p. 20, Bridgman [1941] p. 78, and Moyer [1976] pp. 101f. for the "spread of the Harvard plan" to high schools and *idem*, p. 102, or Hahn [1907] p. 194 on the rising criticism of what some educators like Mann [1912] chaps. 3 and 11 perceived as the "tyranny of the university over the high-school".

(79) See Hall [1904*b*].

(80) See Sabine [1893*b*] p. 53. According to Lyman [1925] p. 653, Trowbridge "inspired the late W.C. Sabine, then a graduate student, to enter this same field, thereby initiating a course of research in the Jefferson Laboratory which has continued to bear fruit to the present day". From 1895 on Sabine specialized in acoustics; see also Hall [1925], [1926].

(81) See the various editions of E.L. Chaffee's *Physical Laboratory Manual* (used at Harvard University) [1914*a*] pp. 73–85, later revised with Saunders in 1920, as well as with Crawford in the 1930s; see also I.B. Cohen *el al.* [1947] pp. 139–48.

(82) See, e.g. Abbot [1958] p. 88: "In our high schools students of physics are shown the yellow line of sodium called 'D'. Sometimes they use a spectroscope that can even show 'D' as a double line. The spectrum of the sun as seen at the 150-foot tower [at the Mt Wilson Solar Observatory] shows these two sodium lines several inches apart!"

(83) See Millikan and Gale [1906*a*] § 50; 2nd edition, 1913, or the revised edition of 1920 coauthored with Williard R. Pyle retitled *Practical Physics* [1906*c*] chaps. XX-XXI, and Millikan. Gale, and Edwards [1938] chaps. XXXII, XXXIV-XXXV.

(84) See Millikan, Gale, and Edwards [1938*a*] pp. 189–95; a very similar exercise was practiced at the Copenhagen Agricultural Polytechnic since 1900 with gratings ruled on a glass surface of 1 cm width: see Ellinger [1903].

(85) Warnings not to touch the grating's ruled surface are frequent in the laboratory manuals mentioned above.

(86) Ingersoll [1925] p. 195 which was used primarily at the University of Wisconsin in Madison. The museum must have had mercury lamps—at that time still a rarity—on open display.

(87) See, e.g., Holzinger and Seeds [1976] pp. 164–5 and 283, 285 or Tattersfield [1979] pp. 161–3 on directions for a homemade cut-out box spectroscope with a small plastic transmission grating (provided by the teacher), and the section on 'educational optics' in *ES Edmund Scientific Industrial Optics Division 1996/97 Optics and Optical Instruments Catalog*, pp. 88 and 239 on cheap card-mounted diffraction grating film (less than $1 a piece), and several versions of direct-vision spectroscopes (the cheapest cardboard tube spectroscope costing only $2.65).

(88) See, e.g., *West's Great Ideas for Teaching Astronomy*, St Paul, 1989, p. 53 on the "pleasant sound" of "ooh's and aah's heard when students view the spectrum for the first time" after inexpensive plastic diffraction gratings had been passed out to the class.

(89) See Arnheim [1969*b*] p. 290 in the section on ‘Erzieherisches Schauen’: “Simply using visual means in class does not immediately produce visual thinking [*anschauliches Denken*].”

(90) Holman [1885*b*] p. 35. Likewise, John Browning [1878*a*] pp. 47f. also recommended that his customers draw important reference spectra, such as the solar spectrum, on a piece of cardboard; so did Kohlrausch [1870*d*] (see p. 366 above), pp. 98f. and Sabine [1893*b*] p. 52.

(91) See [Lockyer] [1894] and the masters thesis by Kevin Johnson [1996] to whom I am indebted for pointing out the existence of the printed version of Lockyer’s anonymously published course manual. On Lockyer’s activities as secretary of the Devonshire commission on scientific education between 1870 and 1875, see also Lockyer *et al.* [1875], Meadows [1972], and Wead [1884] pp. 91f. as well as here footnote 218 on p. 409. On Lockyer’s research in spectroscopy see here § 5.3 and 6.8.

(92) Anon. [1875*a*] provides a brief description of the education in practical physics around that time.

(93) [Lockyer][1894], pp. 246f. This idea of letting the students construct their own fluid prisms originates from Weinhold [1875*a*] pp. 482ff. Cf. here Fig. 9.9, p. 407.

(94) See Guillemin [1866] (in Lockyer’s English translation), Lockyer [1870], the associated list of questions by Forbes-Robertson [1870], Lockyer [1875*b*], and Lockyer (ed.) [1868].

(95) See, e.g., Satterly [1921] and T.M. and W.L. Lockyer [1928] pp. 122–5 with reminiscences by the later professor of mathematics and physics in Toronto John Satterly (1879–1963) about Lockyer’s astrophysical courses in particular p. 124: “Stress was laid in all cases on accurate draughtsmanship”. The obituary on Satterly by Watson [1963] also points out Satterly’s success in teaching experimental physics.

(96) See [Lockyer] [1894] pp. 52f. For similar descriptions of adjustment procedures see also Glazebrook and Shaw [1885] pp. 297f., 306f., and Ames and Bliss [1898] pp. 460–3 with constant reminders of possible sources of error: cf. pp. 460, 465, 474.

(97) [Lockyer] [1894] p. 56.

(98) According to Johnson [1996]. The parallel drawn in footnote 96 on p. 382 to the research centers in Baltimore in Maryland and Cambridge, England, which focused on similar issues in their student training (such as adjustment and gauging of apparatus, sources of error, and accuracy in the readings, which are conspicuously lacking at other places) also applies with respect to the fairly large numbers of students going into research.

(99) See Fowler [1923], Fowler's reminiscences about Lockyer in T.M. and W.L. Lockyer [1928], and Johnson [1996] pp. 7f., 19f., 24.

(100) Their instructions had been distributed to the students prior to that date in the form of mimeographs and proof sheets—see Glazebrook and Shaw [1885] pp. vii and x. For a description of the student laboratories at the Cavendish, see Fischer [1901] p. 32: by 1900 circa 200–300 of the 3000 students at the Cavendish took laboratory courses.

(101) *Ibid.*, pp. xii, 308ff.

(102) *Ibid.*, pp. 309–17; there was no change in the chapter on spectra, refractive indices, and wavelengths until the 4th edition of 1893. This selection is also very similar to Thresh [1880] chaps. 24–8 written for students preparing for the science examinations at London University.

(103) See, e.g., the 6th edition (1914) of Glazebrook's textbook on *Physical Optics* [1883*e*] pp. 260–3. Cf. also Glazebrook [1926], J.A. Crowther [1926], Sviedrys [1976] PP. 427ff., Falconer in James (ed.) [1989], Robotti [1995], and J.G. Crowther [1974] on the Cavendish in a more general sense.

(104) See Wiedemann and Ebert [1890*b*], pp. 272–303, with more than 30 pages, indeed the largest section of the second edition filling 432 pages.

(105) *Ibid.*, pp. 298ff.

(106) See *ibid.*, p. 281 and their plate II. On Bunsen's convention cf. here p. 50.

(107) See in particular spectrum no. 5b. Cf. here p. 52 on this type of representation and its use in particular in the context of explorative chemical investigations.

(108) See Woodbury and Jarvis [1926] p. 3.

(109) *ibid.*, p. 142. The discussion of the other experiments, including adjustment of a prism spectrometer, determination of the index of refraction of a prism, and use of a diffraction grating to measure wavelengths, resembles the one given in the Harvard Laboratory Manuals *(idem*, pp. 140–58; cf. footnote 81 above).

(110) See Glazebrook [1894c] pp. I95ff., 206f., examination questions II–8 and III–8.

(111) On Whiting see, e.g., *Science* **36** (1912), p. 271. S.F. Whiting [1913], as well as Cannon [1927], Anslow [1971], Rossiter [1982] pp. 18f. Cf. also Whiting's typescript 'History of the Physics Department at Wellesley College from 1878 to 1912', dated 1926 (WCA, sec. physics dept.).

(112) On this second undergraduate teaching laboratory of physics in America see, e.g., S.F. Whiting's history from 1926 (referenced in the previous footnote), pp. 3–7, 20–2; McDowell [1936], Converse [1939] p. 197, Hackett [1949] p. 45, Anslow [1971] p. 594. Cf. Whiting [1913] pp. 3–5. G.F. Barker to S.F. Whiting, 8 May 1888 (WCA, S.F. Whiting papers, folder; 'Letters from noted scientists'), and Whiting's later letters on European laboratories, 1883–1890 (AIP, collection MP 205). On Wellesley College in general see also Palmieri [1995].

(113) Quotes from the *Calendar of 1886/87*, category 'physics and astronomy', pp. 44f. A 1924 inventory of the Whitin Observatory at Wellesley College lists 830 lantern slides; by 1934 their number had risen to roughly 1200; in 1902, a set of 40 such "lantern slides of astronomical objects, telescopes, observatories, spectra, etc." were bought for $20 (WCA, observatory inventories).

(114) Initially this course was entitled 'applied physics'; after 1900 the elementary courses in general physics, heat, light, and electricity were partly given by other instructors, but Whiting continued to teach the courses in 'advanced laboratory work', 'advanced optics', 'physical astronomy', and 'advanced astronomy work': see, e.g., the *Wellesley College Annual Reports President and Treasurer 1903*, Boston: F. Wood, 1904, p. 30, *Wellesley College Calendar of 1904/05*, pp. 91–4. Cf. S.F. Whiting [1912] p. viii: "Professor Pickering […] inspired the writer to attempt students' daytime work in astronomy"; cf. also her 'Tribute' to Pickering of 1917.

(115) A promotional prospectus of Wellesley College, prepared for the Chicago 1893 World Exhibition, comments as follows on the semester course on Physical Astronomy: "Lectures illustrated with lantern slides, charts, and photographs. While the elements of general astronomy are covered, special attention is given to astro-physics. Laboratory work with the sun spectrum and the spark spectra is given and frequent observations are made with a 4.5 inch telescope" (WCA, transcript from fragile original, p. 39).

(116) In the mentioned prospectus, the value of the apparatus is estimated at $17 000 (*ibid.*, p. 40).

(117) See the reports on the Whitin Observatory in *Our Town* **3** (1900) issue no. 10 as well as other newspaper clippings collected by Whiting (WCA, sec. dept. of astronomy, folder clippings and magazine articles, 1875–1940) on the opening ceremonies. Cf. also S.F. Whiting's history from 1926 (referenced in footnote 111 above), pp. 26f.; on its financier Mrs John C. Whitin (note the slightly different spelling), see Whiting [1918*a*],

(118) See S.F. Whiting's correspondence with Brashear in the years 1898 and 1899 including price lists and detailed specifications of the various spectroscopes offered by Brashear along with mounting and operating instructions. Cf. an undated sketch on the development of the observatory in Whiting's handwriting (probably written in late 1901), and an undated list of purchase prices for the spectroscopic instruments, totaling $519 (both WCA, sec. dept. of astronomy, folder 'Correspondence, general'), and a typewritten inventory of astronomical apparatus, dated c. 1902 (folder 'Observatory inventories').

(119) Ordered at Albert B. Porter's Scientific Shop on 13 June 1908: see their letter in reply to Whiting, 15 June (WCA, sec. dept. of astronomy, folder 'Correspondence: spectroscopes'); it was exported from London by Hans Heele, with whom Whiting had already been corresponding in April 1906 (*idem*).

(120) The sequence followed in the course in 1879 was: an introductory lecture with a definition of physical science, a brief history since antiquity, remarks on the inductive and deductive method, then lectures on physical units, mechanics, general properties of matter, composition and resolution of motion and forces. This was followed by a preparatory to laboratory work, lectures combined with student experiments on balances, energy conservation, dynamics, gravitation and pendulum, mechanics of liquids, the kinetic theory of gases, pneumatics, and finally light. See the class notes by Flora Mussey Metcalf (graduating class of 1881), Physics, vol. I, late 1879; cf. also the class notes taken in 1879 by Katherine Bacon (class of 1880)—Like all other student materials quoted in the following, these form a part of the holdings of the college archives (WCA).

(121) This orientation is also clear from the emphasis given to the graphical method of discussing experiments in the 'Directions for Laboratory Books' and the 'Preparatory to Laboratory Work', both of which were mimeographs for her students, preserved, for instance, as loose sheets in Metcalf's Physics Notebook vol. I, and Mary Barrows's class notes and outlines for physics and psychology (class of 1890).

(122) See, e.g., letters to S.F. Whiting by Harold Whiting (unrelated), 18 September 1886, promising to send her a printed copy of his lab manual; by C. Cross at MIT, 9 October 1886 about his notes on mechanics for physics students; by J. Trowbridge, 22 May 1893, about a visit by about 15 Wellesley students to Trowbridge's lab to see the "Rowland grating + Hertz phenomena" [electromagnetic waves]; by E.H. Hall, 12 May 1895, sending her copies of examination papers, and by N. Lockyer, 1 February 1897, sending her a syllabus of the Practical Demonstrations given in the Astrophysical Laboratory of the Royal College of Science in London (all filed among the S.F. Whiting Papers, folder 'Letters from noted scientists.')

(123) See, for instance, the physics laboratory notebook by Anna Fuller (class of 1884) with only 15 mimeographic handouts on mechanical, thermodynamic, and electrostatic experiments, as well as similar notebooks by Helen Kitchell Lake, of November 1880, or Mary Barrows, from c. 1889.

(124) Physics laboratory notebook by S. Ella Penniman from 1890/91, bound sheets of paper with vertical rulings at 1 cm intervals, § 'Spectroscope', p. 1.

(125) See again the class notes by Flora Musscy Metcalf. Physics, vol. II (beginning date January 1879), or by Mary Barrows.

(126) Handwritten lecture notes by Flora Mussey Metcalf, dated January 1880, and interspersed with mimeographic handouts by S.F. Whiting, vol. II, unpaginated (pp. 1–2 of section 'prisms').

(127) *Ibid.*, p. 2. In one handout Whiting added the bracketed term 'light sifter' to explain the function of a spectroscope: see the collection of six handouts under the heading spectroscope (WCA, sec. physics dept. folder general).

(128) S.F. Whiting's handwritten draft on physical astronomy, dated 1902–03, entitled 'Preliminary to Printed Book' (WCA), § 'Sun Spectrum Maps' and 'Designations of Lines of Spectrum on Various Maps'. Cf. here p. 74 about Langley's work on the infrared spectrum—from the wavelength range given, the map used is probably an unpublished one, since Langley [1900] pl. 20, 24–5 near p. 200, already reaches 53 000 Å.

(129) Lecture notes by Flora Mussey Metcalf, dated January 1880, vol. II, § prisms, pp. 7–8. For more examples of this analogy in other introductions to spectroscopy, see here footnote 233 on p. 413.

(130) *Ibid.*, p. 7. The contemporary application of spectrum analysis in Bessemer steel production is the subject of footnote 4 here on p. 291. See also Turner [1994]. On the other episode, see Jones [1865].

(131) For instance, we often read the date 1812 for Wollaston's discovery, or the name Nicholson instead of Michelson in Metcalf's lecture notes (vol. II, p. 5), evidently the student's mistake. Likewise, a mimeographed checklist entitled 'Topics for Review in Light' (WCA, sec. physics dept., folder 'General') from Alice Campbell Wilson (class of 1893) also contains several misspellings of names.

(132) *Ibid.*

(133) Printed list of Review Questions for the Examination in Astronomy I, Wellesley College, from E. Louise (Smith) Elliott (class of 1909, WCA), 20 pages, with pages 14–17 dealing with matters directly pertaining to spectrum analysis and solar physics, quote from pp. 14–15.

(134) *Ibid.*, pp. 15f. Compared with a later sheet used in the 'General Examination in Astronomy' at Wellesley College in 29 May 1936, there are fewer astrophysical topics than astronomical ones. One model for Whiting may have been John Forbes-Robertson's *Questions on Lockyer's Elementary Lessons in Astronomy* [1870], esp. questions no. 487–507 on spectroscopy. Stellar spectroscopy, which Whiting's Physical Astronomy course also covered, was discussed above in § 8.8.

(135) See, for instance, the lab notebook by Mary B. Jenkins (class of 1903), dated 1902–03, with "drawings from photographs of the Moon (Lick Observatory), comparisons of the Mars drawings by Proctor and Schiaparelli, and a "Study of Photographs of Milky Way" and of the Southern Cross region (WCA, § 16, 33f.).

(136) In Weinberg's [1902] survey, Whiting was the only respondent to list specific exercises such as no. 323: "Comparative study of the famous drawings of spectra (Kirchhoff, Ångström, Rowland) and wavelengths" or no. 324: "Drawing of a portion of a spectrum using a spectroscope with a micrometer hairline". By contrast, no. 322, "Photographing of a spectrum", was practised at 17 universities and polytechnics, and "A study of the spectra of metals, salts or gases" (nos. 317–19) was commonly done at nearly 100 institutions among the 206 laboratories that submitted detailed lists of their curriculum in response to Weinberg's circular.

(137) Template for lab exercises, according to the title page printed by the First National Bank Building in New Haven, Connecticut, in 1902 (WCA, sec. dept. of astronomy). The text is virtually identical to a handwritten set by Whiting and entitled 'Preliminary to Printed Book', dated 1902–03, and was apparently used in her courses at that time, and also very similar to the handwritten astronomy lab notebook by Georgia French, a member of the class of 1900 (WCA).

(138) S.F. Whiting [1905] pp. 389f. Cf. also Whiting [1912] pp. 46f. on ‘charting spectra’ with crayons in notebooks with millimeter-scale strips, and here fig. 9.8 for two examples.

(139) Whiting [1912] p. vi. The parallel between spectroscopy and botany is elaborated here on p. 357.

(140) As mentioned earlier, Wellesley College astronomers at the local Whitin Observatory enjoyed close ties with their colleagues at the Harvard College Observatory: Whiting had even been trained by Pickering before resuming her office as the first professor of physics and instructor in astronomy. On the later impact of Whiting’s classes see also footnote 165.

(141) See the statistics on Pickering’s ‘harem’—as the fairly large group of female computers was also referred to—in Rossiter [1982] pp. 10, 26, 53ft’.; cf. also Fleming [1893], Lankford [1994], Lankford and Slavings [1996], and Charlotte Bigg’s contribution in Hentschel and Wittmann (ed.) [2000].

(142) On the following see the Astronomy laboratory notebook by Mary B. Jenkins, § 36.

(143) *Ibid.*, 2nd and 3rd page of § 36: “α Coronae (X81114 isochrom[atic film], 82 m[inutes exposure time]) p. 156. Spectrum lines mediate between Secchi’s first and second type. Hydrogen lines intense and calcium bands wider than in Sirius. Plate shows H calcium band merged with Hydrogen$_{\varepsilon}$, the K line and Hydrogen. 16 polar lines counted between K and H. […] K is as intense as H_2 and H calcium combined and more intense than H_1.”

(144) See S.F. Whiting [1912] p. 92. and the undated six-page handwritten mimeographs entitled ‘Spectroscope (light sifter)’ (WCA, sec. dept. of physics pp. 5–6) under letter III for Whiting’s brief characterization of Secchi’s types of fixed stars in which she also mentioned the relative frequency of each type. On Secchi’s classification, see here pp. 346ff. For the Harvard classification see the *Annals of the Harvard College Observatory*, vol. 28, part II, pl. I, and the *Annals of the Tulse Hill Observatory*, vol. I, as well as, e.g., Hoff *et al.* [1978] p. 105 for a copy of a handwritten version of this often reproduced plate, which in many respects fulfilled a similar function to the Bunsen chart of chemical spectra from 1860.

(145) S.F. Whiting [1912] p. 93; a very similar approach is taken in Stetson and Duncan [1923*a*] exercise no. 630.

(146) Astronomy laboratory notebook by Mary B. Jenkins (class of 1903), 4th page of § 36.

(147) On the following see Brück and Tritton [1988], esp. pp. 1.7–1.14. I am grateful to Mary Brück and Sue Tritton for having provided me with a complimentary copy of these educational materials, which are designed to prepare students for working with real research data obtained with the UK Schmidt telescope objective prism. The latter are compiled for educational purposes by Savage *et al.* [1985].

(148) Brück and Tritton [1988] p. 1.14.

(149) Kelsey *et al.* [1978] p. 107. To standardize these student estimates, the manual also contains a ‘spectral classification-data sheet’ right next to a reproduction of the selected objective-prism spectrogram *(idem*, p. 109); cf. also Holzinger and Seeds [1976] exercise 29, pp. 187–92.

(150) Cf. Garrison [1995] p. 511 about W.W. Morgan’s teaching style exemplifying this technique of learning by sample inspection, and Mihalas in Garrison (ed.) [1984] p. 13 on the contrast between showing and talking, and its relation to Wittgenstein’s *Philosophical Investigations* (1953).

(151) See Pickering’s clause in the annual *Harvard University Catalogue*, e.g., 1909/10, p. 409: “opportunities for working at the Harvard College Observatory may sometimes be obtained by advance students specially devoting themselves to the study of astronomy, though the constant employment of the principal instruments greatly limits the use that may be made of them for this purpose.” One of these privileged students was George Ellery Hale.

(152) See the list of instrumentation (HUA, UAV 168.10 box 1) and the correspondence between R.W. Willson and Newton & Co., London, about the Zöllner star spectroscope (UAV 168.12. file correspondence K-R). Cf. also Anon. [1911], Kidwell [1986] p. 158, Morison (ed.) [1930] pp. 288, 303–6. and the course description in the annual *Harvard University Catalogue*, Cambridge: Harvard University Press, e.g., 1909/10, pp. 408–9, 775–6.

(153) Scc Warner [1988] p. 392. [1992]. Cf. also the pre-1900 photograph of MIT’s large collection of lantern projection apparatus (MITM, Dept. photo albums vol. 11, no. 26, vol. 25, no. 9. vol. 26, no. 11. and vol. 27, no. 12). one of which is also visible at the podium in Fig. 9.2. On the use of these instruments in spectrum mapping see here p. 94.

(154) See the ledgers for the years 1916–33, and 1934–38, 2 vols. (HUA, UAV 168.249). in particular, p. 194; 5 May 1926: spectrum chart for $9.50, p. 205; 11 August 1928: 1 Spectra demonstrator. $50, and p. 171: several lantern slides from the University of California at a rate of $0.75 each. Furthermore, a sales catalogue with 295 items of *Astronomical Photographs from Negatives Taken at the Yerkes Observatory*. Chicago University Press. 1904, as well as a separate leaflet list of *Lantern Slides and Prints* from the same supplier, undated, c. 1910. have been preserved, on which ordered items were marked—see also a handwritten list of the slides eventually obtained from the Yerkes Observatory (UAV 168.12, folder misc.).

(155) See the Diary or Notebook of the Students' Astronomical Laboratory. 1920–23, entry Friday, 30 March 1923: according to the *Harvard University Calendar*, e.g., 1920/21. p. 65. the purpose of the astronomical colloquium was to discuss research in progress and to review current periodicals in astronomy and astrophysics.

(156) Willson was appointed instructor in physics and astronomy at Harvard in 1891 and promoted to assistant professor of astronomy in 1903 and full professor in 1903. See Stetson [1923].

(157) Sec the correspondence and papers of Robert W. Willson (HUA, UAV 168.10, folder 'students in astronomy. 1891–1901'), list of science students in the Practical Astronomy course. Cf. also Edwin B. Frost to E.C. Pickering, 12 February 1898, according to which Frost taught 110 students in General Astronomy in the Shattuck Observatory at Dartmouth College.

(158) *Ibid.*, list 'College, Graduate, and Scientific Students in Descriptive Astronomy'.

(159) See the Diary or Notebook of the Students Astronomical Laboratory, 1920–23 (HUA, UAV 168.218), entries under September 1920 and the *Harvard University Calendar*, 1920/21, pp. 64f. The enrollments for 1921 were not very different, e.g., 160 men registered in Astronomy la.

(160) See Willson [1901a,fo]. However, in Whiting [1912] pp. 47–9, a so-called 'Willson's apparatus' to demonstrate the reversal of the sodium lines is discussed, indicating that Willson must have devoted some time to developing this demonstration instrument.

(161) See Whiting [1905] and Byrd [1899], On Byrd and teaching at Smith College, which emphasized celestial mechanics and astrometry, see also Byrd [1902] and Lankford [1997] pp. 318f., which also provides other case studies, see *idem*, pp. 110ff.

(162) C.A. Young to S.F. Whiting. 24 June 1899 (WCA, sec. dept. of astronomy, folder correspondence: initial observatory building), original emphasis. His *Manual of Astronomy*, Young [1902], devotes chaps. VIII–IX to spectroscopic issues.

(163) Organized by the Astronomical and Astrophysical Society of America, founded in 1899 and renamed American Astronomical Society in 1914. The chairman was Charles L. Doolittle (University of Pennsylvania), other members were C.A. Chant (University of Toronto), John A. Miller (Swarthmore Observatory), and Philip Fox (Northwestern University). Cf. also the *Publications of the American Astronomical Society* **3** (1918), p. 354. Rothenberg [1981] pp. 309ff., and Lankford [1997] pp. 5ff., 294f., 374f.

(164) Figures according to the Report of the Committee, undated but based on Whiting's correspondence with Chant c. 1911/12 (WCA, sec. dept. of astronomy, correspondence folder Committee on Cooperation in Improvement of Teaching Elementary Astronomy).

(165) See Stetson and Duncan [1923]. Their title page to the 3rd edition, as well as the preface to the first, p. iv, read: "the accompanying manual of laboratory astronomy is largely the outgrowth of the development of laboratory classes in astronomy at Harvard, Radcliff, and Wellesley Colleges during the past twenty years."

(166) Some examples of this more theoretical perspective on spectroscopy in textbooks are Pohl [1948] pp. 238–47. Herzberg [1937], Candler [1937].

(167) See *Universitcitsbund Güttingen, Mitteilungen*, **4** (1922) p. 28. My thanks to Klaus Sommer for pointing out this source.

(168) See Sievert [1967] pp. 82f. and Manthei [1996] p. 383. On physics instruction at Prussian secondary schools before 1859, see Olesko in Olesko (ed.) [1989], and Lind [1992] chap. 7. Jungnickel and McCormmach [1986] vol. 1, pp. 246–52 discuss the high status of Berlin *Gymnasia*, and Pyenson and Skepp [1977], Young [1906], Strong [1907] discuss the reorganization of the Prussian curricula after 1905. A broad general introduction is provided by Sievert [1967] chap. 3 on physics education in German states after 1850. None of these historical surveys of physics education single out teaching of optics or spectroscopy.

(169) See the 'Verordnung des Ministers für Cultus und Unterricht vom 15. April 1879 … betreffend einen Normal-Lehrplan für Realschulen', printed in the Viennese *Zeitschrift für das Realschulwesen*, **4** (1879), pp. 351–62, esp. pp. 359f. on physics, to be taught a total of 13 hours per week among the different classes: three hours in the third, fourth, and sixth years, and four hours in the seventh year.

(170) *Ibid.* Mach's authorship of the Austrian *Realschul-Verordnung* was first documented by A. Hohenester: cf., e.g., Hohenester [1988] or Hoffmann and Manthei [1991] p. 280 and footnotes 2 and 68 there. Mach also co-edited the *Zeitschrifi für den physikalischen und chemischen Unterricht* since its foundation in 1887—see, e.g., Mach [1892] on diffraction spectra, just one of his published suggestions for school experiments in physics.

(171) Quote from Olesko [1998], draft p. 8; cf. W. Kemp [1979] pp. 188ff. and pp. 2l8ff. on the inclusion of drawing lessons in Prussian and Württembergian reforms of school curricula after 1800, and *idem*. pp. 288ff. for the practical teaching methods inspired by Pestalozzi and his school.

(172) For a survey of the curricula in Prussia revised in 1882, and on the differences between the various types of schools in Germany, see Wead [1884] pp. 76–9, which also provides a comparison between French and British schools, pp. 74f., 83ff. A comparison of German and American high-school physics instruction is made by Olesko [1995]. The best survey of German high-school teaching is obtained from the annual *Schulprogramme* which often contain scientific papers: see the bibliographic listing by Schubring [1986].

(173) See Schellen [1870/72*b*] p. ix. The Verein fur wissenschaftliche Vorlesungen must be seen as a precursor of the later *Volksliochschulbewegung.*

(174) See *ibid.*, p. vii as well as Huggins's preface to the English translation, pp. v–vi.

(175) This is exemplified by Weinhold [1875*b*], which devoted roughly 40 pages of an 862-page text to spectro-scopic issues. Cf. *idem*, p. iii on the purpose of demonstration experiments. The list of fundamental experiments in physics printed in Wead [1884] p. 146 likewise includes the refraction of light (singled out as one of the few experiments considered suitable for student laboratory work), dispersion, and the spectrum. Schellbach [1888] presents a demonstration experiment on the correlation between emission and absorption spectra.

(176) See F.C.G. Müller [1906*a*] pp. 196ff. or [1906*b*] pp. 203ff., 213ff.

(177) See Grimsehl [1907*b*]; cf. also Volkmann [1907].

(178) Rosenberg studied physics and mathematics at the University of Graz and in 1887 became a teacher at the kaiserlich-königliche Offizierstochtererziehungsinstitut in Hernals, Vienna. In 1898 he was engaged at the Viennese Staatsrealschule, in 1903 took a professorship, a year later also the directorship of the teachers training institution Pädagogikum in the Austrian capital, and from 1913 was professor for methodology of physics teaching at the University of Graz. Additionally, between 1906 and 1925 he was *Landesschulinspektor* for Steiermark and Kärnten.

(179) See Rosenberg [1908/10*b*] vol. 2, pp. 447ff.

(180) Earlier direct-vision spectroscopes contained several prisms mounted sequentially. The availability of cheap diffraction gratings substantially reduced the cost of such simple instruments: cf., e.g., Kleinpeter [1912] p. 40 on the instrument manufacturer Leybold in Cologne providing such grating copies “in excellent quality for a cheap price”.

(181) For instance, a universal spectroscope modeled after Hermann Wilhelm Vogel’s prototype, with which he had performed his important experiments on the sensitization of photographic plates with dyes in 1873, was obtainable from the Berlin instrument makers Schmidt & Haensch for 80 marks (including mounting and prism), and wall-hanging posters of various spectra were distributed by E. Leybolds Nachfolger in Cologne and by Max Kohl in Chemnitz.

(182) See Rosenberg [1908/10*b*] vol. 2, pp. 437ff.; F.C.G. Müller [1906*a*] p. 191, Poske [1915] pp. 318f. Poske succeeded Bernhard Schwalbe (1841–1901) at the Askanische Gymnasium in Dahlem, Berlin.

(183) See Lockyer *et al.* [1875] p. 1. A circular had been sent to 202 British schools with annual endowments of over £200.

(184) According to Arthur Mason Worthington (1852–1916), at the time assistant master at Clifton College, who quoted some of the answers. They were published as an appendix to the ‘Report of the Head Masters Conference’ for 1877, a source unavailable to me; see Worthington [1881] p. 1.

(185) See Clarke [1880] and Wead [1884] appendices, for tabular surveys of the type and amount of instruction in chemistry and physics in US secondary and normal schools, colleges, polytechnics, and universities around 1880.

(186) Data according to Mann [1912] pp. 4f.; for further statistics on physics laboratories in American public high schools see also Rosen [1954]. According to Crew [1904] p. 485, the number of student laboratories at American colleges and universities rose from just four in 1871 to about 400 by 1900.

(187) See Bush [1905] p. 431.

(188) See the commented reprint of this list and the general recommendations of the NEA in Smith and Hall [1902], pp. 327ff., as well as variants of it in Hall and Bergen [1891] and Brooks [1901/02].

(189) See, for instance, Charles Wead's 'List of Fundamental Experiments in Physics' in Wead [1884] p. 146 (see footnote 175 above), C.R. Mann's article in *School Science and Mathematics.* **6** (1906), pp. 422f., reprinted in Hahn [1907] p. 260: "no. 23: Spektralerscheinungen".

(190) See Fischer [1901] p. 24: "III. Optics … (f) [can be omitted] dispersion of light; light path inside prisms, continuous and line spectra, line inversion, the solar spectrum, mapping of spectra and measurement of refractive indices, achromatism, light absorption, body colours, fluorescence, the spectrometer."

(191) For surveys see Fischer [1901] pp. 80–4, Schüfer [1970] pp. 240ff., and Sievert [1967] pp. 95ff., 116f. Noack [1892] was one of the first German pamphlets containing concrete suggestions for practical exercises. Schwalbe [1893] p. 164 cites Hall's [1886] Harvard *Descriptive List*, Trowbridge, Worthington, Mayer, and Barnard as paradigms. Cf. also Schwalbe [1891] and Poske [1891] p. 57 for a plea to move physics teaching away from a theatrical performance without any active participation by the pupils.

(192) This "Allerhöchste Erlaß vom 26. 11. 1900", was signed by Wilhelm II, totally fed up with the endless bickering between philological and science-oriented schoolmasters; see Manthei [1996] p. 387: "With reference to qualifications, it is to be assumed that Gymnasium, Realgymnasium and Oberrealschule are equivalent educative forms of preparation for academia."

(193) See Gutzmer (ed.) [1908] pp. 93–146, and the abstract in Grimsehl [1911] p. 109, Grundsatz III. The strong impact of the Meran report is also discussed by Schäfer [1970] pp. 248–52.

(194) See Gutzmer (ed.) [1908], pp. 122ff, Gscheidlen [1909] p. 17, Grimsehl [1911] pp. 109ff., Leick [1910] p. 7, and Sievert [1967] p. 117; cf. *idem*, part I, for an interesting historical survey with further German references.

(195) This point is raised, for instance, by Bose [1904], Fischer [1907] pp. 67ff., Grimsehl [1907*a*], and Noack [1907].

(196) See in particular the book *On Laboratory Art* by the Sidney Professor of Physics, Richard Threlfall (1898), which became a model of its kind; on its impact in England and Germany see esp. Fischer [1901] p. 55.

(197) See Walter Kaufmann's undated petition 'Vorschläge betr. Einrichtung von Handfertigkeitskursen für Lehramtskandidaten der Physik und Mathematik', supported by the institute directors E. Riecke and W. Voigt in late January 1902, and granted by the education doyen Althoff in the Prussian Ministry on 3 March 1902 (all in HUA, UAG, 4. V.h.33, vol. 1, sheets 204–10, 214). Cf. also *Verzeichnis der Vorlezmngen auf der Georg-August-Universität zu Göttingen wdhrend des Sommerhalbjahrs 1902*, p. 17: *Übungen in der Handhabung und Herstellung einfacher Demonstrationsapparate* (Dr Kaufmann), 1904 (Dr Bose) and 1907 (Dr Krüger); cf. also Bose [1904], Riecke [1906] pp. 67f., and Fischer [1907] pp. 69f.

(198) See, e.g., Schrcber [1906]; cf. also Sievcrt [1967] pp. 235f. on the *Übimgen im Demonstrieren physikulischer Apparate* in Greifswald.

(199) See, e.g., Gscheidlen [1909]. Wehnelt [1920].

(200) Külp had been teacher of physics at the Darmstadt *Realsclutle* since 1861; he additionally held an assistant position at the physics institute of the Darmstadt polytechnical school 1858–72.

(201) On Weinhold sec Feige and Szöllösi in Stolz and Wittig (ed.) [1993] p. 255. and Fcige and Söllosi [1990].

(202) See Külp [1874] (its examples are partly based on laboratory notes by students), and Weinhold [1872*a*,*c*] translated into English in 1875 by Benjamin Loewy (1831-?), pure science master at the International College. Spring Grove, and examiner in physics at the College of Preceptors, both in London.

(203) G.C. Foster in the preface to Weinhold [1872*e*] pp. vii-viii; cf. also Foster [1872] for his general conception of physics instruction. Foster's role as a vociferous protagonist of teaching laboratories is sketched by Gooday [1990] pp. 28f., 40f.

(204) For other examples of this fairly naive inductivist stance see, e.g., Wead [1884] pp. 117ff., Trowbridge [1884] pp. vi-ix, Alexander Smith in Smith and Hall [1902] pp. 87f. and further citations in Woodhull [1910] pp. 6ff. For some German examples, see Weinhold [1872], [1875], Frick [1895], Stark [1904] pp. 129, 137, Rosenberg [1908/10], and further references in Lind [1992] p. 332, [1996]. However, we also find some counterexamples to this inductivist trend: Holman [1899] p. 16, for instance, explicitly rejects this "vicious feature of too much of elementary laboratory literature", and so does E.H. Hall in Smith and Hall [1902] pp. 274ff. Rowland and Ames [1899] p. iv state that "the experiments shown the student in the lecture room or performed by himself in the laboratory are to be considered as illustrations of the laws, not as attempts at verification".

(205) Gage [1882*b*], [1890]. The textbook (bearing the motto ‘Read Nature in the Language of Experiment’) was followed by a laboratory manual in 1890. Other examples of such ‘heuristic teaching’ are critically discussed in Smith and Hall [1902] pp. 105ff., 269ff.

(206) Holman [1899] p. 19.

(207) Trowbridge [1884] p. xi; cf. also the detailed lists of apparatus and estimated expenses for elementary courses in physical measurement in Worthington [1881] pp. 5–10, [1886*a*] pp. 6–9, Whiting [1891] vol. 4, pp. 929–38, and Frick [1895*b*].

(208) See Trowbridge [1884] pp. 331f., experiment 198.

(209) See [Lockyerl [1894] pp. 49–51, Weinhold [1872*e*] pp. 482ff, on the fluid prism and pp. 497–501 as well as pp. 313–16 on the construction of the primitive spectroscope. The most parsimonious series of optical experiments relying almost completely on homemade instruments “for the use of students of every age” is prescribed in Mayer and Barnard [1877].

(210) Hale (1928) as quoted by Wright [1966] pp. 40–2; on Hale’s later role in astrophysics cf. Hentschel [1998*a*].

(211) This school was in fact one of the pioneer institutions for practical exercises in physics conducted by pupils: see, e.g., Schwalbe [1893], Bohn [1894], and Leick [1910] p. 7.

(212) Whiting [1890/91] vol. 4, p. vi; on instrument-making courses at normal schools “giving familiarity with the making of apparatus as well as its use”, see also Wead [1884] p. 122, which particularly recommended Mayer and Barnard [1877] and Weinhold [1875] as “among the best books for this work”.

(213) Poske [1891] pp. 57. 61.

(214) Chute [1894*c*] p. iv; cf. also Hunt [1854b] p. 76: “trained into habits of observation”. Foster [1872], Foster *et al.* [1874] p. 71: “mental training and discipline”, the various quotes in Wead [1884] pp. 54 (by Gibbs). 92–5. 122ff., as well as Smith and Hall [1902] pp. 114ff. on the “degree of exactness required”, and pp. 87ff., 142ff., 337ff. on the educational value of practical science education, including “teaching caution and mental rectitude” (p. 90), and instilling a “habit of observation” (pp. 243f.).

(215) Worthington [1886*a*] p. 3. original emphasis; cf. *idem* p. 4 on “instructive rather than accurate methods of measurement”.

(216) See the newspaper abstract of Trowbridge’s Lowell lecture 1879 (WCA, S.F. Whiting papers, scrapbook no. 1, 1877–84). p. 55.

(217) See Olesko [1991] § 10 for the German context. Cf. also Olesko [1995], pp. 137–40 on the work ethic as perceived by American physics teachers, and Daston [1991], esp. p. 433 on this mix of the “character trails of diligence, fastidiousness, thoroughness, and caution.”

(218) See Lockyer *et al.* [1875] app. 2 to this sixth report by what was known as the Devonshire commission, chaired by the Duke of Devonshire, with J. Norman Lockyer as its secretary.

(219) See Johnson [1996] pp. 23, and pl. XVI showing students making their own achromatic telescopes. Again. I am most grateful to Kevin Johnson for a copy of his M.Sc. thesis, which covers in detail Lockyer’s teaching in the South Kensington Department of Arts and Sciences.

(220) Crew and Tatnall [1902] p. 211. On Crew’s photographic mapping of metallic spectra, see here p. 245.

(221) *Ibid.*, p. 212, part 7 of exercise no. 94.

(222) *Ibid.*, p. 213; similarly in Crew’s textbook [1900*a*], p. 341, the diffraction spectroscope is merely mentioned as “an instrument of marvellous power [that] must be left for the more advanced student”. For these latter, Crew and Tatnall [1902] pp. xii and 210, include references to some of the previously mentioned manuals and textbooks by Crew [1900], Rowland and Ames [1899], and others.

(223) Frank M. Gilley to Robert W. Willson, 28 May 1897 (HUA, UAV 168.10, folder summer school). The book read by the students was most likely Lockyer [1870] or [1878*d*].

(224) Hahnf [1906]pp. 7f.

(225) Michael Barth to the author, email dated 11 September 1998.

(226) See Roscoe [1861], [1862]. On the impact of these lectures compare also Becker [1994] pp. 81 f., 96f.

(227) See Roscoe [1869]; see also Roscoe’s essays on ‘light’ [1865*a*] and ‘spectrum analysis’ [1868*a*] for Henry Watt’s *Dictionary of Chemistry*, as well as his autobiography Roscoe [1906].

(228) See W.A. Miller [1861] and [1862*a*]. William Fairbank's presidential address at the same Manchester meeting in 1861 reveals slight reservations still: "the remarkable discoveries of Kirchhoff and Bunsen require us to believe that a solid or liquid photosphere is seen through an atmosphere containing iron, sodium, lithium, and other metals in a vaporous condition" (*idem*, p. liii). Cf. also Becker [1994] pp. 87ff., and C.T. [1871] p. xxii for anecdotal details about these lectures, and for evidence that the later standard account of the discovery of spectrum analysis as the confluence of four research strands, namely (1) "cosmical lines" [i.e., stellar spectra], (2) absorption bands. (3) bright lines produced by sparks, and (4) colored flames, originated with Miller in 1861.

(229) See W. A. Miller [1867], [1869], Crookes [1861], Huggins [1866]. [1868*b*–*c*], [1868*c*], Proctor [1870] chap. 2. [1877], Secchi [1870], Tyndall [1873], Young [1872/831], [1881]. Schellen [1870/72], Grandeau [1863*a*], Abney [1877/7], [1881/82]. Cf. also further references in the 6th English edition of Ganot's textbook [1856*c*] p. 462. On the genre of popular expositions that emerged around the middle of the nineteenth century see Paul [1906] pp. 46f.

(230) See in particular Lockyer's various textbooks on astronomy [1870], [1875*b*] at the high-school level: [1873], [1874*c*], and finally his more technical [1878*d*]. Later publications such as, e.g., Newall's booklet [1910] borrowed a number of plates and other material from Lockyer's books and articles.

(231) See, e.g., Valentin [1863], Stokes [1864*a*], Sorby [1865]-[1876], Roscoe [1868b], Schellen [1870/72*b*] pp. 196f., Stein [1877] pp. 279f. Cf. further literature mentioned here in footnote 5, p. 291.

(232) Trowbridge [1884] p. 328 Cf. p. 340 for his use of this same analogy to explain diffraction of light by a slit.

(233) As we have seen in Chapter 8, not in the straightforward sense. For examples see, e.g, Trowbridge [1884] p. 330, Hopkins [1889] p. iii, Lommel [1890] p. v on the avoidance of mathematics, and *idem.* p. 252, Miller [1855*c*] pp. 123–7. Schellen [1870/72] § 13–14, Tyndall [1873*a*] p. 157. Stokes [1884*b*] pp. 1311'.. and O. Stewart [1924*b*] p. 710 on the analogy of acoustic resonance.

(234) For the following see Belhoste (ed.) [1995]. I am grateful to Bruno Belhoste for having pointed out to me the existence of this very useful anthology of official decrees. For curricula after 1882, see also Wead [1884] p. 74–6, 158, Poske [1900], and Smith and Hall [1902] pp. 365–71. The special topic of drawing lessons in French curricula is covered in W. Kemp [1979] pp. 161 ff. (with respect to Gaspard Monge's *geomeétrie descriptive*), pp. 201ff. with regard to the post-revolutionary reforms, and pp. 31 Off. on Nicolas-Toussaint Charlet and his successors Léon Cogniet and others, who taught free drawing to approximately 6000 students at the École Polytechnique from his nomination in 1839 into the 1880s.

(235) See Belhoste (ed.) [1995] ‘Programmes de cours de sciences physiques dans les collèges royaux’, issued on 30 November 1819, p. 96.

(236) Fully specified in a decree of 18 January 1821, *ibid.*, pp. 98f'f.

(237) *Ibid.*, p. 100. According to Silbermann [1843] p. 585, Soleil resided at 35, rue de l'Odéon in Paris. According to Payen in DeClerq (ed.) [1985] p. 176, Soleil’s firm was founded in 1819. After 1849 his former apprentice and son-in-law Jules Duboscq continued the business which later split into Henri Soleil (taken over by Laurent in 1872) and Duboscq (renamed Duboscq Pellin in 1883 and Pellin in 1886). See also Turner [1975] about the close ties between Soleil and Fresnel, and Syndicat [1901] pp. 188–97 for a listing of the instruments sold by Ph. Pellin (Maison Jules Duboscq) around 1900.

(238) *Ibid.*, ‘Instruments de physique pour les collèges royaux’, issued 27 December 1842, p. 185.

(239) See Belhoste (ed.) [1995] ‘Programme les baccalauréats ès sciences mathématiques et ès sciences physiques’, issued 3 February 1837, p. 142.

(240) *Ibid.*, ‘Programme de physique dans la classe de mathématique spéciale’, issued 23 September 1842, p. 180.

(241) *Ibid.*, ‘Questions de mathématique et de physique au baccalauréat ès lettres’, issued 14 July 1840, p. 159.

(242) See, for instance, *ibid.*, ‘Programmes modifiés de l'enseignement scientifique des lycées’, issued 24/25 March 1865, p. 407, ‘Nouveaux programmes des sciences dans les lycées’, issued 23 July 1874, p. 450, ‘Nouveaux programmes des sciences de l'enseignement secondaire classique’, issued 2 August 1880, pp. 456, 463, ‘Programme des sciences de l'enseignement secondaire de jeunes filles’, ‘Programme des sciences de l'enseignement secondaire special’, both issued on 28 July 1882, pp. 472 and 485, respectively, modifications of the latter issued on 22 January 1885, p. 506, and on 28 January/ 12 August 1890, p. 522.

(243) See *ibid.*, pp. 506 and 522: “spectre des diverses sources lumineuses”. See also the ‘Programme des sciences de la classe des mathématiques élémentaires’, issued on 24 January 1891, p. 533; the ‘Programme des sciences de l'enseignement secondaire moderne’ issued on 15 June 1891, pp. 544 and 547, and the ‘Programme des sciences et de compatibilité des classes secondaires dans les lycées et colleges de garçons’ issued on 31 May 1902 and revised on 4 May 1912, pp. 613 and 695, respectively.

(244) *Ibid.*, ‘Plan d'études et programmes des sciences de l'enseignement spécial’, issued 6 April 1866, p. 434.

(245) This is supported, for instance, by the importance of Rayleigh's theory of sound within the British context; cf. also p. 377 above.

(246) For instance, in the final 'classe de philosophie (A and B), according to the survey of Hahn [1906] p. 25; cf. also *idem*, pp. 18, 23, and 27 for spectroscopic topics in the curriculum.

(247) See, e.g., Emmerson [1973] pp. 41f., 77ff., Bruno Belhoste's essay in Belhoste *et al.* (ed.) [1994], and further references there. The earlier teaching of optics by the chemist Hassenfratzis discussed by Silliman [1974] pp. 144f. as well as Shapiro [1993] chap. 8.

(248) Jamin had studied at the École Normale Supérieure, and subsequently taught at various lycées before being called to the École Polytechnique in 1852 and to the Faculté des sciences de Paris in 1863. He was a member of the Académie des Sciences since 1868, and elected as its *secrétaire perpétuel* in 1884. See, e.g., Thooris *et al.* [1997] pp. 87–9 as well as Michel Atten's essay in Belhoste *et al.* (ed.) [1994] pp. 221ff., on vol. 1 of Jamin's textbook designed for the "classe préparatoire". and vols. 2–3 for his courses at the Polytechnique (1858–74), in the later period (1878–87) reworked by Bouty.

(249) See *ibid.* p. 222 for a comparison of the various versions of this textbook between 1859 and 1878 and the relative amounts of space taken by the four areas: heat and elasticity (~ 30 %), electricity (25–30 %), acoustics (7–13 %), and optics (33–37 %).

(250) See Jamin [1858–66*a*] vol. 3, pp. 403–42. Cf. here pp. 68f. on the contemporary interpretation of the spectrum in terms of three (or more) separate coexisting spectra.

(251) That is, from the red extreme all the way to what we now call the ultraviolet: see *ibid.* vol. 3, p. 433 and pl. V following p. 448 for the "dessin simplifié, que je dois à l'obligeance de M. Mascart".

(252) *ibid.*, pp. 433–41. Cf. also his unpublished *Cours de Physique, 1 ère Division*, 1879–80. pp. 96–102 (AEP).

(253) See Jamin [1858–66a] vol. 3, pp. 458f. for a simple woodcut reproduction of Bunsen's famous chart of the characteristic spectra of some alkaline elements. His hectographed lecture notes do not include such spectrum maps, of course, but detailed verbal descriptions of the various chemical emission spectra: see his *Cours de Physique* (previous footnote), pp. 103–5.

(254) *Ibid.*, pp. 444f.; likewise also in his unpublished *Cours de Physique. 1 ére Division*, 1873–74 (AEP), premiére leçon and pp. 76–7, 89–93. Jamin thus supports Edmond Becquerel's earlier claims against Draper, Hunt, and other defenders of the conception of three separate kinds of solar spectra. We also find plotted side by side in Jamin [1870] pp. v-vi, 572ff., an abbreviated version designed for use in secondary schools.

(255) See, e.g, Jamin [1858–66a] vol. 1, p. 2 and Atten in Belhoste *et al.* (ed.) [1994] pp. 221–5.

(256) See Jamin [1858–66a] vol. 3, pp. 479ff., cf. Stokes [1852] § 80, 102.

(257) See A. Becquerel [1842/44] vol. 2, esp. books iv and viii; E. Becquerel [1867/68] vol. I, books 1 and 6, vol. II, books 2–3; the 4th vol. from 1878–79 of Daguin [1855–79]. Ganot [1856] carries the subtitle 'purement experimentale à l' usage des gens de monde'. indicating its fairly popular level. In the English translation of 1863 (the 5th edition of which came out in 1872, its 10th edition in 1881, and its 17th edition in 1907) this was rendered as *Experimental and Applied, for the Use of Colleges and Schools.* Witz [1883], [1889] both of which carry the subtitle 'préparatoires à la licence'. Cf. also the interesting survey of textbook accounts of luminescence by Harvey [1957] pp. 213–19.

(258) See the subtitle of the 7th edition (1878) of Ganot's [1856] textbook: 'à l'usage des Établissements d'instruction, des aspirants aux grades des Facultés et des candidats aux diverses écoles du Gouvernement'.

(259) Compare, for instance, the 7th edition in 1857, pp. 413–22 with the 23rd in 1905, pp. 348–65, 426–49.

(260) See, e.g., Janet [1909] p. 501: "his experiments, which the small number of auditors rendered feasible, were true laboratory experiments and the rarest and most delicate phenomena in Optics were presented there with perfect precision: his assistants recall the hard work they had setting them up and adjusting them; many weeks' labor was often necessary to prepare one of them."

(261) "Cornu and his research in ultraviolet spectroscopy are discussed here on p. 132. Cf. also Atten in Belhoste *et al.* (ed.) [1994] p. 225 for short excerpts from his handwritten course notes of 1879/80.

(262) Cf. Atten in Belhoste *et al.* (ed.) [1994] p. 234 for the relative share of optics in the physics curriculum.

(263) Although Potier's courses have never been published, his approach towards optics is evident in Potier [1912], in the introductions by Henri Poincaré and A. Blondel to this anthology of his papers on electricity and optics, and in Lapparent [1906].

(264) On the foregoing, see Alfred Cornu, *Cours de Physique. Deuxième Annee* lère Division, 1894–95 (AEP), 10th-15th lessons, pp. 87–161.

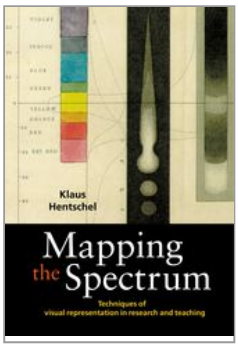
(265) See the hectographed ‘Programme de la 2è Manipulation de Physique’, 1894–95, *ibid.*

(266) See S.P.T.f [1905] p. 187; cf. Burgess [1902] p. 239 on Cornu’s graphic representation of Fresnel’s integrals by ‘Cornu spirals’.

(267) On the foregoing, see Auguste Pérot, *Cours tie Physique. Deuxiéme Division*, 1920–21 (AEP), nos. 267–77. esp. pp. 464, 471f. On Fabry’s and Pérot’s work in interferometry see Hentschel [1998] § 5.4–5.5 and references given there.

(268) For a closer analysis of Fabry’s textbooks, and a comparison with Bruhat’s and others, see Pestre [1992] chap. 2, esp. pp. 34f., 59ff.

(269) According to Pestre [1992] pp. 80ff., esp. p. 86, which covers the period 1918 to 1940 in this regard, in 1922 the output of French physicists in atomic and molecular spectroscopy (most notably Fabry, Pérot, Cotton, and Cabannes) was twice as high as that of Americans, and it was still of the same magnitude in 1934, in contrast to most other fields, by which time it was far inferior.



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
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Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

Epilogue

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DOI:10.1093/acprof:oso/9780198509530.003.0010

Abstract and Keywords

Despite its broad application in various disciplines, such as chemistry, physics, astrophysics, and the materials sciences, spectroscopy never became a discipline of its own, remaining a research technology practised in all these other disciplines (scopic regimes vs. spectro-scopic domains). This chapter considers some possible reasons for this as well as the implications on spectroscopy as a visual science culture. It analyses the making of a spectroscopist based on a detailed prosopography of several dozen important early practitioners of spectroscopy and spectrum analysis, e.g. a surprisingly high percentage of the early spectroscopists had artisanal and polytechnical backgrounds (where drawing skills were encouraged more than at universities). The omnipresence of aesthetic criteria and motives during the production of spectroscopic images is also documented.

Keywords: scopic regime, spectro-scopic domain, research technology, aesthetic criteria, spectroscopist, aesthetics

10.1 Spectroscopy: not a discipline

It is hard to over-estimate the importance of spectroscopy for the sciences in the last third of the nineteenth and first third of the twentieth century. Despite its great utility for a plethora of applications ranging from chemical analysis to meteorology, astronomical observations and steel analysis, I would like to argue that spectroscopy never made the transition to a scientific discipline in the proper sense. According to standard historiography,[1] a fully-fledged scientific discipline incorporates most if not all of the following defining elements:

1. strong and stable communications between its practitioners,
2. an intellectual core, in the sense of a broadly accepted methodology and/or a set of
agreed central problems and paradigms,
3. dedicated professional organizations,
4. discipline-specific journals,
5. professorial chairs and stabilized recruiting mechanisms,
6. institutes devoted specifically to this area, and finally,
7. a socially construed boundary between insiders and outsiders of the discipline.

The Società degli Spettroscopisti Italiani with its international membership and associated journal[2] might qualify as meeting the third and fourth of these criteria. But many others were left wanting or had to wait a long time still for fulfillment. Most of the influential practitioners of spectroscopy throughout the nineteenth and early twentieth centuries either occupied chairs in experimental physics (e.g., Heinrich Kayser in Bonn, Edward Charles Pickering at MIT, or Friedrich Paschen in Tübingen), or in chemistry (e.g., Josiah Cooke at Harvard), or in general astronomy (e.g., Charles Piazzi Smyth in Edinburgh, or Pickering later at the HCO). I am not aware of any professorial chair devoted specifically to spectroscopy during that time. The earliest case—that I have come across—of a professional title indicating full-time devotion to spectroscopy is the appointment of Thomas Ralph Merton (1888–1969) as lecturer in spectroscopy at King's College, London in 1916, followed by his nomination as Reader (1919) and Professor (1923) of spectroscopy at Oxford **(p.421)** University.[3] At roughly the same time, William F. Meggers joined the National Bureau of Standards (1914) as a laboratory assistant; in 1920 he became chief of the Spectroscopy section and held this influential post until his retirement in 1958.[4] By 1930, George Russell Harrison (1898–1979) was nominated professor of experimental physics and director of MIT new Spectroscopy Laboratory, built in conjunction with new physics and chemistry research laboratories at the Massachusetts Institute of Technology with funds contributed by George Eastman. Together with NBS's Spectroscopy section, these were the first research institutions to appreciate spectroscopy as more than a mere technique, adopting it as a name-tag and as a cognitively integrating element. After the breakthrough of quantitative spectrochemistry in the late 1930s and 1940s, other countries also followed this path, one example being the Institut für Spektrochemie und angewandte Spektroskopie, founded in Dortmund at the instigation of Heinrich Kaiser in 1951.[5] Prior to these events, spectroscopy definitely does *not* constitute a discipline.

This is in striking contrast to astrophysics. Its institutionalization as a subdiscipline, clearly demarcated from its parent disciplines astronomy and physics, has often been studied. Depending on national context and on specific preference for the institutional or cognitive components of the disciplinary matrix, this transition has been located to somewhere between the coining of the term ‘Astrophysik’ in Karl Friedrich Züllner's (1834–1871) habilitation thesis at Leipzig from 1865,[6] the establishment of the first permanent chair for astrophysics at the University of Berlin, first occupied by Julius Scheiner (1858–1913) in 1894,[7] and the foundation of the *Astrophysical Journal* with its international board in 1895.[8]

The *Astronomische Nachrichten*, the *Journal of the Optical Society of America*, or the *Chemical News* each published numerous spectroscopic papers, of course, but they constituted organs of *other* disciplines (astronomy, physical optics, and chemistry) and were not dedicated to a separate field of spectroscopy. The same applies to some of the central institutions for spectroscopic research: The Astrophysical Observatory in Potsdam (founded **(p.422)** in 1874), the Harvard College Observatory, the Mt Wilson Solar Observatory (founded in 1906) and a few others[9]—although undoubtedly crucial sites of knowledge production in spectroscopy—had their heart elsewhere. They were the core institutions of the newly emerging field of astrophysics. At all these institutions spectroscopy was one of the central techniques used by such key actors as Hermann Carl Vogel, Edward Charles Pickering, or George Ellery Hale. But that alone did not suffice for its institutionalization, either as a separate discipline or as a well-circumscribed subdiscipline within, say, physics or chemistry.[10] Whether at the Universities of Bonn, Tübingen, or Uppsala, in the chemistry departments of Heidelberg or Harvard; at the École Polytechnique, the National Bureau of Standards, or the American Brass Co.: spectroscopy was practiced in disguise, that is, it operated in the context of other disciplinary frames ranging from metrology to materials science.

Not that this—in and of itself—was automatically a disadvantage. Quite the contrary. ‘Spectroscopists’—as we may label this mottley assortment of researchers—were on the editorial boards of journals throughout the disciplinary landscape and, as ostensible members of respected scientific communities, enjoyed access to the resources spread throughout the sciences. But the undisputable usefulness of their technique and, consequently, the wide distribution of their members in quite different areas of expertise, came at a price: a lack of disciplinary coherence. Spread over the huge fields of astronomy, optics, and photography, accruing more scientists in the US than many other research areas in the sciences around 1910,[11] spectroscopic research was split into many specialties, widely differing in approach, techniques, instrumentation, and agendas. Considerable tension existed between the main camps from which spectroscopists were recruited, as is shown in the following quote. Victor Schumann explains to a close friend why he preferred to publish his latest article on ultraviolet spectrography in the *Photographische Rundschau* rather than in a scientific journal:

> The reason why I chose the *Rundschau* for the publication was that the members of the club may perhaps be more receptive to a communication like mine than many a professional spectroscopist. For we surely agree, dear friend, that far too much is still being perpetrated in spectrophotography, precisely by the persons in command, simply because the gentlemen haven't the faintest inkling of what photography is about. The fact that we, on the contrary, have the best versed of photographers among our amateurs, who also have a thorough knowledge of physics besides, surely needs no particular comment.[12]

(p.423) No doubt, similar suspicions were likewise raised by the ‘leading spectroscopists’ mentioned here, i.e., people like Kayser or Pickering, with a background in physics, who were equally skeptical when confronted with the latest claims of some photographer, a field infamous for its many quacks and fortune-seekers.

It did not help that in the long period between the emergence of spectrum analysis around 1860 and Bohr's quantum theory of 1913, spectroscopy lacked an accepted explanatory theory. As we have seen in § 8.3, by 1880 the efforts to explain spectrum lines as harmonic overtones had utterly failed because Arthur Schuster was able to demonstrate that all earlier efforts in this direction were statistically flawed. Even though there was thus no theoretical ‘paradigm’ in the sense of an uncontroversial theoretical framework, on the purely experimental and instrument side there was considerable stability. Spectroscopy thus exhibited many of the characteristics of Kuhnian ‘puzzle solving’. There were standardized experimental methods, heuristically powerful phenomenological rules governing expectations, anomalies disappointing these expectations, and the transmission of highly specialized skills. Long-standing research programs like H.A. Rowland's inventory of about 20 000 Fraunhofer lines in the solar spectrum strengthened the emphasis on skillful observation, precision, and extensiveness—both as to the spectral recording of growing numbers of elements, compounds, stars, etc., and as to the exploration of ever wider ranges of the electromagnetic spectrum. Concurrently, we find repeated efforts to expand the same basic techniques of analysis into new areas of application (such as steel production, blood analysis, etc.). Consequently, more persons skilled in the basic spectroscopic techniques were sought. In an age of growing specialization and major investment in scientific instrumentation—leaving little room for the scientific amateur after 1900[13]—only the self-replicating system of college and university education could provide these collaborators. But these were trained (and had a B.S. and/or Ph.D.) in physics, chemistry, or electrotechnology, and they usually remained in these fields throughout their careers, irrespective of how much spectroscopic research they were doing. As I have shown, someone like Kayser in Bonn advised about 170 doctoral students throughout his 30-odd years as professor of experimental physics there. Thus we have the paradox that despite stable and “strong teaching programs” there nevertheless was nothing close to a “launching of a scientific discipline.”[14]

So we have here a good example of a thriving experimental culture, with an overwhelming predominance of descriptive and phenomenological methods not bogged down by the longstanding theoretical impasse in interpreting the basic objects of spectroscopic research. As we have seen (towards the end of § 8.8), in such research areas as stellar spectral classification, this preponderance of phenomenology and data-gathering persisted well into the twentieth century.[15] Terry Shinn's concept of a ‘research technology’ comes to mind, because spectroscopy, too, is situated between disciplinary borders and is strongly dependent **(p.424)** on the developments in scientific instrumentation. Until recently, Shinn's own examples of research technologies (vacuum technology, high magnetic fields, or ultracentrifuges) were drawn exclusively from the twentieth century, but in his most recent anthology on instrumentation, science, and the state, he and others pursue traces of research technology also into the

nineteenth century, particularly in Germany.[16] His indicators, including the founding of the Deutsche Gesellschaft fur Mechanik und Optik in 1879, or heavy sponsorship of contemporary instrument exhibitions, are of relevance to our story, because spec-troscopy played a substantial role in these contexts.[17] Besides Jackson's example of Fraunhofer's Optisch-Mechanisches Institut in Benedictbeuren (see here pp. 36f.), pioneers of diffraction-grating production, such as Nobert, Rutherfurd, or Rowland's instrument maker Brashear, also seem feasible candidates for such ‘research technologists’, as they pursued “hybrid careers” with an agenda centered around instruments. Their goal, too, lay in the design, construction, and diffusion of “high-performance devices for the purposes of detection, measurement and control”, and in elaborating “general instrument systems that could subsequently be tailored by specific industries to suit their particular needs.”[18] Indeed, I would argue that the production and handling of diffraction gratings, and likewise the manufacture and sensitizing of photographic plates, constitute perfect nineteenth-century examples of such multi-purpose and multi-audience research technologies. Another ‘generic’ research technology that found wide-ranging use is Albert A. Michelson's interferometer. Its applications include high-precision measurement of spectral wavelengths, fine structure examinations of multiplet lines, and metrological definition of the meter in terms of multiples of spectral wavelengths.[19] Ignoring for a moment earlier candidate research technologists (such as Fraunhofer), Shinn argues that a realignment of the intellectual and material resources of academia, industry, and the state shortly before 1900 led to the formation of a new stratum of highly specialized technologists. These developers of multi-purpose devices focused on design and optimization and felt no particular loyalty to any scientific discipline. He dates the origins of the ‘research-technology matrix’ in Germany to after 1860, particularly after the *Reichsgründung* and the events leading up to the founding of the German institution of weights and measures, the Physikalisch-Technische Reichsanstalt.[20] But there were similar realignments at the time between universities, industry, and national research establishments in Great Britain and the United States. These sociological roots aside, the increasing complexity of scientific experimentation and the emergence of big science since World War II undoubtedly favored the growth of such research technologies. Yet the exact **(p.425)** time of their emergence does not alter that spectroscopy as such is still far too broad. If anything, it is a bundle of research technologies.

So the problem remains: How might we structure this huge range of spectroscopic applications and research techniques within a plethora of disciplinary contexts? The classical approach has been either *Problemgeschichte*, institutional history, or biography: J.B. Hearnshaw, Frank James, Michel Saillard, and others have emphasized the different research agendas (for instance, physicists and electrical engineers, who explored the phenomenon of the electric arc, versus chemists, who searched for sensitive analytic techniques). Donald Osterbrock, Dieter B. Herrmann, and a few others, on the other hand, have focused on the history of various key institutions. A.J. Meadows, H.A. and M.T. Brück, or Helen Wright—to pick just three examples—preferred to follow the trajectories of key figures (such as Lockyer, Smyth, or Hale) through this maze. We might also decide to look at the different instruments employed. Indeed, the various clusters of ‘spectroscopists’ could be grouped around their respective favorite instruments: a simple Bunsen-style spectroscope for the qualitative chemists, a thin objective prism for a large proportion of stellar spectroscopists, a spectrohelioscope for the examination of solar protuberances, a quartz-prism UV spectrograph for materials scientists, a large Rowland concave grating in an Abney or Runge mounting for the photographic spectrum mappers, a Fabry-Pérot interferometer for the metrologists and fine-structure specialists, and the hand-held direct-vision spectroscope for a few others, such as the Victorian rain-band seekers or Bessemer steel engineers. For this study, however, I choose to take a different tack.

10.2 Implications of spectroscopy as a visual culture

The guiding idea behind this book has been to portray spectroscopy as a prime example of a ‘visual culture’. This term, which I first came across in Svetlana Alpers's magnificent study. *The Art of Describing*, has become somewhat of a buzzword in postmodern discourse. A sorry example is Nicholas Mirzoeff's *Visual Culture Reader*, where visual culture is misdefined as a “tactic with which to study the genealogy, definition and functions of postmodern everyday life” and contrasted against a supposedly textbound nineteenth century “classically represented in the newspaper and the novel”.[21] How far this is off the mark! Lisa Cartwright's tracing of the visual culture in medicine in *Screening the Body* also focuses on the broader cultural meaning of popular images such as X-ray photographs or TB Public Health Films. Although interesting on their own, these studies of ‘public cultures’ are far removed from the uses of visual representations in scientific research and teaching treated here. We have to make sure that the term remains specific enough to single out certain scientific practices as visual, and to understand why they developed in this direction in contrast to others. Therefore, I would like to return here to the original meaning of the term ‘visual culture’, which Alpers exemplified so convincingly (albeit without actually defining it formally) in her study of Dutch art in the seventeenth century. Interestingly, her case is situated in the early modern period, well before the rise of modern “mass visual culture embodied in the new pictorial magazines, spectacles, and entertaining toys based on scientific **(p.426)** gadgets”.[22] Some authors have taken these visual resources to be emblematic not only of a reorganization of vision (which they certainly were), but also as the defining characteristics of the term ‘visual culture’ (which they definitely are not). For the purposes of historiography, a scientific practice should be called a ‘visual culture’ only if it incorporates most—if not all—of the following features:

- proficiency in a specialized visual, nonverbal skill (such as pattern recognition);
- inculcation of such skills in rigorous hands-on training;
- high ranking of visual, i.e., nonverbal resources (e.g., plates, atlases, photographs, or CCD images) within the taxonomy of publications;
- continual improvements in techniques of detection (e.g., color sensitization in scientific photography) and in the published renditions of these images;
- a highly developed infrastructure for duplication (printing, or other technologies for converting and proliferating visual representations, e.g., photocopiers or scanners);
- a true connoisseurship concerning aesthetic aspects of science (cf., e.g., § 10.9 on the attribution of beauty to various spectroscopic features), and often, albeit not always,
- a reflexive stance towards issues of visual perception in general.[23]

I have taken considerable care not to define visual culture too closely and thereby obstruct potential comparisons with other periods or contexts. Thus, Leonardo da Vinci's fascinating visual analogies and his overall approach to nature are to be understood in the context of a visual culture as much as Ferguson's visually trained engineers do. It would be another project to demonstrate the wide applicability of this notion of ‘visual culture’, from which I must refrain here. But the following section should be read as an exemplification of an intentionally broad historiographic concept by means of the individual case of spectroscopy (with a focus on the late nineteenth century, but reaching back into the early part of that century and extending forward into the early twentieth century).

Members of such a visual culture will often transgress the professional boundary to indulge their obsession with visual records at home as well. The Astronomer Royal for Scotland, Charles Piazzi Smyth, is an obvious example. His extraordinary aesthetic sense might already be surmised from the sheer volume of the visual material he produced throughout his life, a large part of which is still preserved among his papers. The Piazzi Smyth collection of drawings, photographs, and manuscripts at the Royal Observatory in Edinburgh contains reams of sketches, watercolors, and calotypes made during his extensive travels to South Africa, Tenerife, Portugal, Italy, Egypt, Russia, and elsewhere,[24] documenting **(p.427)** his strong orientation toward the visual. For this ‘astronomerartist’, as he has been aptly described, it was a natural attraction toward the “wonderfully novel panorama field of spectrum analysis”, a mere extension of his wider search for visual patterns in cloud formations, lunar craters, cylixes of ferns, or cultural relics of Ancient Egypt.[25] Recording the treasures of the pharaohs, the fauna and flora of the Canary Islands, or the ever-changing British skies was a life-long passion that he shared with his wife Jessica. Photography came in handy too, even though Piazzi Smyth was far from wanting in drawing skills. One obituary attributes to this scientist “a gift of great artistic skill in committing to paper, canvas, and even to frescoes, beautiful drawings, photographs, and colored paintings of the scenes of travel which he witnessed, and of sights which clouds, the heavens, or his beautiful experiments disclosed to him”. This accomplishment, it goes on to say, “led him to leave to others the study of the actinic spectrum-regions with the aid of photography, and to restrict his spectrum-measurements entirely to all that could be seen and measured by the eye alone, of the solar spectrum, or of the characteristic features of gaseous bright-line spectra, in the whole visible portion of the spectrum only.[26]

Early photo-albums like David Brewster's reveal the obsession of these “Disciples of Light” with fixing the moment on the photographic plate. They took shots of everything conceivable, long before the omnipresent snap-shot.[27] But the pastime with light predated the invention of photography and its subsequent improvements by several of our main actors (e.g., William Henry Fox Talbot and John Herschel, Hermann Wilhelm Vogel, William Abney, and Victor Schumann). Other gadgets designed to produce entertaining visual effects already existed. It is significant that William Hyde Wollaston, the first to notice the dark lines in the solar spectrum (see here p. 33), was much better known to his contemporaries for his invention of the *camera lucida.* This simple instrument projected an image of a given object onto a flat drawing plane for easy retracing along its contours.[28] The much older *camera obscura* and microscopes likewise engaged these same protagonists, who were just as much swept up by the great Victorian craze for stereoscopes.[29]

10.3 The making of a spectroscopist

One might think that with such a passion for visual documentation, a figure like Charles Piazzi Smyth was a rather atypical case. In certain respects he was. Piazzi was looked upon **(p.428)** as an outsider by the Oxbridge guard of his time. With regard to formative factors, however, such as family background and scientific training, I have come across many other nineteenth-century spectroscopists sharing more in common than might initially be surmised. What inspired a young student to choose spectroscopy as his or her speciality? What made the some dozen leading researchers remain loyal to this field? There were plenty of equally exciting alternatives. In case after case, similar circumstances emerged that seem to have engendered such preferences:

- A family background in the fine arts or artisanal crafts such as engraving, lithography, or printing, and/or
- studies at a polytechnical school or a Gewerbeakademie, in both of which drawing was very much emphasized in the curriculum (particularly for subjects such as civil engineering or architecture), and/or
- teaching at such polytechnics, often prior to receiving a call to a university,
- teaching of classes in perspectival drawing, descriptive geometry, or geometry, and
- application of their skill in drawing, engraving, lithography, and photography not only to spectrum maps, but also during their leisure, to other sujets.

From among our prosopographical sampling, take Johann H.J. Müller,[30] for instance. His father was a painter at the court of the prince of Waldeck, who later became director of the Darmstadt art gallery and the founding head of a graphic arts academy. Three brothers of our physicist received their initial training in the graphic arts there and later became renowned engravers or painters. This extraordinary enculturation within such a visually oriented environment might well illuminate the path leading to Johann's cooperation with court photographers to achieve his scientific goal of recording the ultraviolet spectrum by means of photography. His skill in drawing likewise underpins his motivation to transform a rather dry textbook by Pouillet into a richly illustrated ‘free adaptation’ that underwent eight editions during Müller's lifetime, each one adding more wood engravings based on Müller's own drawings.[31] Müller's affinity to visual aids for teaching was so great that in his lectures he regularly used ‘demonstration drawings’ *(Demonstrationszeichnungen*, manufactured by the university's drawing teacher Lerch)[32] and in research his visual style led to the invention of a graphic method of converting a prismatic spectrum into a normal (wavelength-proportionate) spectrum map (see here pp. 78f. for Langley's variant of it).

An intense lifelong appreciation for the visual arts is also documentable for various other spectroscopists, not by any means restricted to the nineteenth century. We might even be seeing just the tip of the iceberg, because of the tendency of traditional biographers and archivists to eschew the nonscientific aspects of scientists’ lives as purportedly irrelevant **(p.429)** for an understanding of their science. I would argue quite the opposite: in order to grasp the personal styles and modes of thinking of our actors, their preferences for or abhorrences against visuality have to be taken into account, without arbitrary exclusion of their pastimes and general predilections. To take another example: The mastermind of the MK stellar classification scheme (see here p. 357), William W. Morgan, went beyond the usual hobby of art collecting and photography. As is mentioned in one of his obituaries,

> In the local primary school, during his later years, he thoroughly enjoyed serving as ‘Picture Lady’, which involved taking a work of great art to one of the classrooms, showing the children how to ‘see’ its patterns, and helping them to understand its greatness.[33]

Various other spectroscopists were noted for their outstanding drawing or printing skills. Let us begin our brief recapitulation of such cases with Johann B. Listing (see above p. 32). This mathematical physicist is best known today for his topological studies which contain striking visual analogies. He illustrated the rather arcane subject of linear complexions in space with various types of knots found in “ordinary daily life” and spiral structures found in botanical and zoological specimens.[34] Such a pronounced visual thinking may be linked with an early training in architecture, which certainly included a hefty serving of drawing and other graphic arts.[35] Thus Listing was able to prepare and lithograph his own plates for his textbook on physiological optics.[36] His choice of iris print to illustrate his study of the color ranges in the spectrum (see here p. 124) also reflects his fastidiousness in printing matters. The astronomer Hermann Carl Vogel and his assistant Oswald Lohse did not have to rely entirely on lithographers either. So they were able to draft the plates for their atlas of the solar spectrum from 1879 themselves.[37] An inquiry into the background of these two Potsdam astronomers revealed that both Vogel, son of a Leipzig school director, and Lohse, son of a master tailor, had attended the Royal Polytechnic Highschool in Dresden before embarking on a study of the natural sciences at the University of Leipzig.[38]

A beautiful drawing of a sunspot by Lohse is hanging on the workroom wall at the Einstein Tower in Potsdam. The technique of heightening with white for pictorial effect requires much skill. Other drawings published in 1883 had been executed in a technique he had devised for himself, graphite stumping. After making a rough sketch in charcoal at the telescope, Lohse transferred the outlines in graphite pencil onto sturdy bristol board. The finer details of the sunspots were made by stumping with leather, cork, paper, or sponge, and finally the superposed filigree bright parts were rendered by erasing with a rubber, **(p.430)** using a few transparent gelatine templates cut in frequently recurring shapes. In his article on astronomical drawings of that year, Lohse emphasized that he had taught himself this method also known as *dessin à l' estompe?*[39] he was clearly a perfectionist obsessed with visual representations. During his 40 years of working at the Bothkamp and Potsdam Observatories, Lohse also experimented with photographic emulsions, comparing different kinds of commercially available ones, as well as testing developers and fixers. He was among the first to use the new method of gelatine dry-plate photography for astronomical purposes.[40] Speaking of solar-spot drawings, another name springs to mind: S.P. Langley (whose work on infrared spectroscopy was discussed in § 2.9 and 7.4.2). Among astronomers, he was probably better known for his meticulous drawings of sunspots dating from 1873, which showed minute details in the penumbra that became visible during moments of exceptionally good seeing but were not photographically recordable for another hundred years.[41] It will not come as a surprise that this son of a wholesale merchant also had undergone unusual training for a researcher, having studied, not science, but engineering and architecture.[42] Incidentally, the same is true of Kirchhoff's student assistant Karl Hofmann, who had studied at the polytechnics in Vienna and Carlsruhe as well as at the Freiberg Mining Academy in Saxony before including mineralogy, chemistry, and physics among his courses at the Ruperto-Carolina University in Heidelberg.[43] The Swiss spectro-scopist Walther Ritz, whom we have met (on p. 304) in the context of the search for series formulae, was doubly preconditioned, being the son of a landscape painter *and* having enrolled at the Zurich Polytechnic. Both Frank McClean and Victor Schumann (introduced on pp. 238 and 71, respectively, as innovative spectrographers) had only concentrated on this specialty after long-time employment as chief engineers: Schumann had previously worked for a number of machine factories and McClean held a position in his father's engineering firm, McClean & Stileman. In Schumann's letters, these commercial jobs only feature as a source of irritation; nevertheless his engineering skills explain why it was Schumann as opposed to someone else who successfully constructed complex vacuum spectrographs and **(p.431)** devised appropriate gelatine-free emulsions for photography further in the ultraviolet.[44]

By way of association, let me add that our spectroscopists shared this exposure to engineering culture and technical drawing during their training with various

other scientists who became famous for breakthroughs linked to visual thinking or a visual *Gestalt* switch. Famous examples are August Kekule, who envisioned the structure of the benzene ring; or John A. Wheeler, who worked out the liquid-drop model of the nucleus together with Niels Bohr and later became the originator of geometrodynamics, a strikingly visual way of presenting and thinking about the general theory of relativity.[45] That training in civil engineering or architecture almost inevitably elicits a pronounced visual acuity is already well documented by Antoine Picon's case study on the training of French architects and engineers in the age of Enlightenment. With respect to engineers, Eugene S. Ferguson has advanced similar claims about “thinking with pictures” as “an essential strand in the intellectual history of technological development.”[46] What has escaped serious discussion so far, though, is the special constellation of individuals initially trained in drawing and other graphic techniques as part of an education in engineering, architecture, or the applied arts, who later changed fields. My thesis is that these people were especially suited to transfer specific visual skills into the natural sciences and hence were instrumental in creating visual science-cultures.[47] Indeed, the astonishing regularity of so many prominent spectrum mappers having undergone some kind of technical training invites this tentative generalization linking such training in descriptive geometry, perspectival drawing, architecture, graphic arts, etc., with a propensity for visual cultures within the sciences. Their rapid rise during the nineteenth century may thus also be closely linked with the institutionalization **(p.432)** of drawing lessons in the curricula of French, German, and Austrian schools after 1800.[48] Besides the examples of Piazzi Smyth and Robert Hunt, H.C. Vogel and O. Lohse, J.H.J. Müller and S.P. Langley, I could also have referred to J. Listing, H. Kayser, F. Paschen, W. de W. Abney, E.C. Pickering, V. Schumann, and H.A. Rowland. All of them deviated from the standard science education by having obtained a thorough—mainly prior—training in programs emphasizing visual skills. Several of them not only had been *educated* in the applied graphic arts during their youth, but also actually *taught* at institutions where this visual style was disseminated. Henry A. Rowland, for instance, initially taught physics at the Rensselaer Polytechnic Institute in Troy, New York, whence he himself had graduated in civil engineering in 1870.[49] Hermann Wilhelm Vogel, whom we have met in the discussion about sensitization experiments of photographic emulsions, taught photochemistry, spectrum analysis, and applied optics at the Royal Prussian Commercial Academy (königliche Gewerbeakademie), which merged with the Architectural Academy (Bauakademie) into the Charlottenburg Polytechnic in 1879. Likewise, the doyen of spectroscopy in Germany, Heinrich Kayser, taught at Hannover Polytechnic before accepting a call to the physics professorship at Bonn University in 1894. And Friedrich Paschen was Kayser's assistant at the Hannover Polytechnic before he later received a call to Tübingen University, where he became known for his experiments on the Zeeman effect and other spectroscopic precision measurements. Johann Listing taught mechanical engineering at the Höhere Gewerbeschule, the local precursor

institution to the Hannover Polytechnic, where Kayser later taught, and Robert Wilhelm Bunsen, co-discoverer of spectrum analysis, taught at the Kassel Höhere Gewerbeschule from 1836 to 1839. The French spectroscopist Pierre Jules César Janssen, a grandson of the famous architect Paul-Guillaume Le Moine, taught at the École spéciale d'architecture in the 1860s before being appointed the prestigious post as director of the Meudon Astrophysical Observatory.[50]

The cases mentioned thus far exemplify personal links to civil engineering; we also have such links to its military counterpart, foremost, of course, teachers at the École Poly-technique, founded as a training institution for French military officers. Aside from Cornu, Mascart, and Fabry (whose teaching was discussed in § 9.9), we also have a few British examples: the pioneer of infrared spectrum photography, William de Wiveleslie Abney, taught photography at the Chatham School of Military Engineering.[51] From 1883 on, Abney **(p.433)** also offered occasional lectures in photography at the South Kensington Science and Art Department where Joseph Lockyer, too, was a member of the teaching staff.[52] But the best example of the strong emphasis on visual techniques of recording, data analysis, and representation in this book undoubtedly is the American one: MIT, then still located in Boston and institutionally linked to a Society of Arts. At MIT, technical and perspec-tival drawing, along with exercises in descriptive geometry, were compulsory for all first and second-year students.[53] Some members of the physics faculty also held appointments as instructors in technical drawing. One of these, John Trowbridge, advanced to “superintendent of drawing” before becoming assistant professor in physics and transferring to Harvard.[54] Johann H.J. Müller too offered courses in ‘geometrical drawing’ several times during his long tenure as professor of experimental physics at Freiburg University.[55] Furthermore, like J.J. Balmer in Basel, Müller even wrote a successful textbook on technical and perspectival drawing.[56] Countless other scientists may well have been similarly engaged. But such side activities were rarely taken seriously enough by biographers and so it is hard—but not necessarily impossible—to document nowadays. Scientific and technical education have rarely been analysed together, having rather been relegated into totally different corners of the history of science. What we see here are intertwined educational strands that enabled easy transfer of skills, representational techniques, and attitudes. This surprising finding of such a strong correlation, on the one hand, between training, or at least temporary teaching practice in architecture, engineering, or other artisanal trades, and on the other hand, a subsequent preference for a visual science culture, deserves closer examination on a prosopographic basis broader than this book can encompass.

This leads us to another layer in the multifacetted visual culture of spectroscopy. I would venture to say that researchers heavily involved in spectroscopic research were often the ones to initiate curricular reforms towards encouraging practical exercises as opposed to mere demonstration experiments or conventional chalk-board physics. This is, of course, but a tentative generalization from various cases discussed in Chapter 9, but the impressive array of names, including R.W. Bunsen, J.P. Cooke, E.C. Pickering, H. A. Rowland, S. Whiting, J. Lockyer, H. Crew, among many others, suggests a special incentive towards implementing a hands-on—and eyes-open!—approach in this field. Another name that might be added to this list is Anders Jonas Ångström in Uppsala, who instituted student use of the instruments in the physics cabinet, hitherto exclusively reserved for faculty members, for teaching purposes. Ångström's direct successor. Robert Thalén, was apparently less inclined to follow this new trend and carefully guarded the precious apparatus **(p.434)** against such abuse. But it regained new momentum particularly under the directorship of Knut Ångström.[57]

10.4 Scopic regimes and spectro-scopic domains

The rather all-inclusive lumping together of such diverse factors as personal background, teaching experience, and research preferences, under the descriptive category of visual culture might obscure various more specific components: scientific practices, each of them coherent and fully absorbing, but more or less mutually exclusive. Mastery of a complex term diagram in Walter Grotrian's classic *Graphische Darstellung der Spektren von Atomen undlonen* (1928) does not, by any means, imply an ability to ‘read’ the gold content from, say, a wedge spectrogram of an iron-gold alloy—Nor could we usually find these two skills in one and the same person, historically speaking.

In search of an appropriate term, I came across Martin Jay's ‘scopic regimes’. Jay was the first to raise doubts about the traditional notion of a single modern mode of vision, traditionally conceived as starting with Kepler and Descartes. His pathbreaking essay from 1988 on the ‘scopic regimes of modernity’ argued for a reconceptualization of visuality “as a contested terrain, rather than as a harmoniously integrated complex of visual theories and practices.”[58] The essay then focused on the distinguishing features of three main visual cultures in the modern era, namely Cartesian perspectivalism, seventeenth-century Dutch art with its narrational ‘art of describing’ (Alpers), and baroque art with its strongly haptic qualities. Jay thus debunked the oft-heard opinion that Cartesian perspectivalism was the sole reigning visual model of modernity. I find his claims very inspiring but don't think his term can be easily transferred to a specialized field like ours because it is nonscalable—to use physics jargon. ‘Scopic regimes’ aim at visuality *tout court*, at broad cultural strata extending beyond national and local contexts. It is a macroscopic concept on a very coarsegrained scale to describe visual practices persisting over many decades, indeed, centuries.

What we need is a related concept on a much finer scale, one that captures the more subtle distinctions between, say, a gauging photograph for quantitative spectrochemistry, and a plate with various types of stellar spectra. Rather than 'regimes' *tout court* with its imperial connotations,[59] what we have been exploring throughout this study are 'domains' on a much smaller scale, both in the social as well as the cognitive sense. Therefore I suggest the term **spectroscopic domains** to denote the various representational cues within the subdiscipline. Two of the various definitions of the word 'domain' in the OED come **(p.435)** quite close to what I have in mind: "(3b) A district or region under rule, control, or influence, or contained within certain limits; realm; sphere of activity, influence, or dominion. […] (4a) A sphere of thought or action; field, province, scope of a department of knowledge, etc."[60] As the first of these definitions shows, the shades of meaning range from strict rule to weaker control and influence; a 'sphere of activity' neatly connotes the radius of action of certain specific practices within spectroscopy which are itemized further below. They are identifiable 'departments of knowledge' without sharp demarcations, sharing certain overlap zones characterized less by 'local coordination' (in the sense of Peter Galison's 'trading zones' between different subcultures of physics), than by common root knowledge needed in each area of specialization. Even a quite specific definition of 'domain' in the context of ferromagnetic materials could easily be metaphorically extended in the direction of my concept: "a region which behaves as an elementary magnet, all the atoms or ions in a region having the axes of their permanent magnetic moments aligned in the same direction."[61] Like ferromagnetic atoms oriented in parallel, all practitioners of one spectroscopic domain are 'oriented' towards a common goal, all sharing predispositions towards certain *Gestalt* patterns that they are versed in recognizing immediately, and preferences for certain types of visual representations useless to other domains.

Let me clarify my approach with a historiographic parallel to Jonathan Crary's study on *Techniques of the Observer.* Taking examples mainly from the nineteenth century, Crary presented a plethora of modes of vision, created by means of various optical devices ranging from the *camera obscura* (known since the seventeenth century) to the stereoscope, kaleidoscope, and phenakistoscope.[62] Xiang Chen recently contrasted a visual tradition of optical measurements in the nineteenth century against a geometric tradition in his analysis of instrumental traditions and theories of light during that century. In the former tradition, man-made optical instruments were regarded as “aids to the eye, and evaluated according to how well they produced images suitable for the perception of the eye” as the ultimate “goal of the optical system”. The geometric tradition strove to “reduce and eventually eliminate the role of the eye in optical experiments”.[63] Following a similar vein, Thomas Schlich distinguished between the cultures of microscopic and photographic vision in the early history of bacteriology. To belong to the latter meant “to know how to ‘read a photograph’ and […] to share certain presuppositions as to which interventions by the photographer were to be tolerated and which ones constituted forgery.”[64] We likewise may regard the various types of spectroscopes, spectrographs, and spectrometers encountered thus far as ‘visual technologies’, in the sense of “any form of apparatus designed either to be looked at or to enhance natural vision, from oil painting to television and the Internet.”[65] I argue that the visual culture of spectroscopy is another “contested terrain” with competing instrumentation linked to specific observing and measuring practices. If we look at our case from this **(p.436)** angle, various **spectro-scopic domains** emerge. Each of these domains is characterized by specific visual practices, preferences for certain recording and printing techniques, pattern recognition skills, manipulations of specialized scientific instruments, and other tacit knowledge, none easily transferable from one domain to the next. In the visual culture of spectroscopy these domains include:

- dark lines in the solar spectrum used as convenient markers for diffraction index measurements in glass production (Wollaston, Fraunhofer, Brewster);
- emission spectrum lines treated as fingerprints of the chemical elements (Bunsen, Kirchhoff, Roscoe, and various other chemists);
- spectrum portraiture sought to produce a refined, highly aesthetic likeness (Kirchhoff and Hofmann 1861/62, Lecoq de Boisbaudran, Thollon);
- photographic mapping of spectra, emphasizing extension, enormous numbers of lines, and an alleged ‘mechanical objectivity’ in recording (H. Draper, Abney, Rowland);
- channeled spectra interpreted as evidence for quasi-acoustical harmonics (Lecoq de Boisbaudran, Stoney, Schuster before 1880);

• homologies sought between series spectra of various elements (Mitscherlich, Lecoq de Boisbaudran, Ciamician, Hartley);
• patterns, such as, phenomenological formulas for line distances, discerned to decipher series and band spectra (Smyth, Balmer, Rydberg, Deslandres, Kayser, Runge, Paschen, Ritz, Lyman, Bjerrum);
• line spectra interpreted as indicators of electron quantum jumps (Bohr, Sommerfeld, Landé, Grotrian, Hund, and many others);
• spectrum-line displacements used as indicators of stellar radial velocity (Doppler, Maxwell, Huggins, H.C. Vogel, Christie, Pickering, etc.);
• spectral similarities sought within a finite set of chosen types, for star classification (Secchi, Lockyer, Pickering, Fleming, Maury, Cannon, etc.);
• continuous line profiles from thermopiles, bolometers combined with galvanometers, photoelectric photometers, etc. (Melloni, Lamanski, Langley, Abbot, Moll, Houtgast, Minnaert);
• line splittings into doublets, triplets, etc., as indicators of electric and magnetic fields (Zeeman, Stark, Paschen, Back, Bohr, Sommerfeld, Landé, Schrödinger, Takamine);
• interference techniques used for high-precision measurement of wavelengths or line profiles (Michelson, Fabry, Buisson, Perot, etc.);
• ‘sensitive’ or ‘residual’ lines used as aids in quantitative spectrochemistry (de Gramont, Löowe, Twyman, Gerlach, and many others).

Keeping these different spectro-scopic domains apart signifies more than just distinguishing various research specialties, however. Each of these practices had its own focus on specific aspects of spectra—along with its corresponding blind spot toward others. Each of them had its own paradigmatic examples, its own training cycles, and its own tacit knowledge acquired only through an intense period of enculturation under the supervision of someone who already mastered these skills (see here Chapter 9 for examples). How different these spectro-scopic domains could be, even during the same period, can easily be seen by comparing the tradition of spectrum portraiture (see here § 4.5), starting with Kirchhoff's **(p.437)** and Hofmann's 1861/62 highly detailed atlas of the solar spectrum, and ending with Thollon's high-dispersion lithographic map of 1890, with the roughly contemporary tradition of photographic mapping of spectra (see § 6.7–6.9).

Unlike Jay's three scopic regimes, these spectroscopic practices were not totally “disheveled”, but shared common knowledge in many areas of expertise and skill. For instance, a practitioner of any one of these domains would have no problem recognizing the Balmer series, identifying the Na_D doublet, or discriminating between a series and a band spectrum. But the existence of such common ground between the different spectroscopic practices does not imply that one could easily switch between their everyday routines. The drastically different *Gestalt* quality of their resulting spectrum representations made symbolic aids in “translations” between them indispensable: whether labeling of certain features according to standardized spectrum-line ‘names’ or numbers, tabular correspondence rules, or dual plotting of the spectrum according to both conventions.[66] Switching between them meant more than a seemingly innocuous change of research orientation. It required new training in the specific visual skills involved, and to some extend unlearning those that had been intuited before. For instance, not infrequently, practitioners complained about the difficulty of recognizing a certain spectrum in, say, a high-dispersion wavelength plot customary in the mapping tradition, while being thoroughly at home with it in a lower-dispersion representation of the prismatic decomposition.[67] And even the most ardent advocates of scientific photography had to grant that “excellent as is the work that may be done by photography, there must always remain a large field for astronomical drawing” because of the latter's advantages in bringing out the significant details.[68] Listing all these spectro-scopic domains one after another does not imply that they all enjoyed equal weight and prestige. It is significant, for instance, that Langley did not simply publish his continuous recordings of the solar infrared, but tried everything to find a way of transforming his bolometric traces into something looking remarkably similar to standard photographic prints of spectra (see here Fig. 7.9 on p. 271). Large-scale photographic maps had gained high prestige with the publication of Rowland's and Higgs's atlases, whereas continuous line profiles were still much less common. When photometric work came into fashion—approximately since the publication of the Utrecht atlas in 1940—the graphic conversion rather went the other way and older photographic records were scanned to extract more precise information about the various line profiles from them. Thus there were clear hierarchies of preference and degree of familiarity, but they were highly dynamic and could change rapidly with research practice. Perhaps what distinguished the most well-versed practitioners of the art of spectroscopy from the ‘normal scientists’ whose practice was confined to just one or two of these domains was their ability to move freely between several of these domains: only a few *virtuosi*, such as Fraunhofer, Rowland, and Michelson worked in more than two or three of them, and they were widely hailed as ‘masters of light’ for their ability to do so.

(p.438) Not all of the above-listed practices could be explored here in the same depth, and none of them exhaustively. I hope, however, to have shown the stark differences between visual representations drafted according to different spectro-scopic domains and the need for translating between them. The following diagram, taken from a textbook entitled *Atomic Spectra* from the 1930s, is another clear illustration of this.

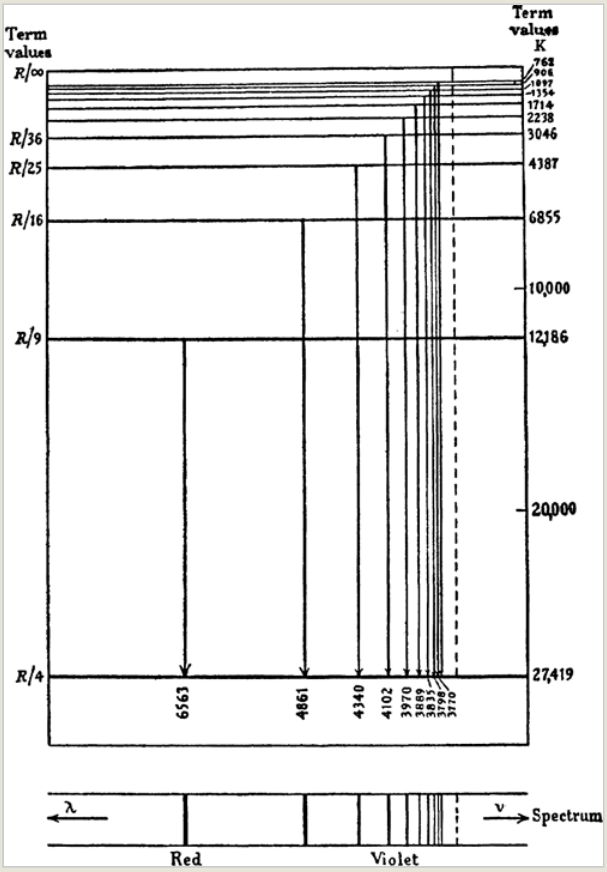


Fig. 10.1 Level diagram and frequency plot of the Balmer series. From Candler [1937] p. 8.

The lower part of Fig. 10.1 is easily identifiable as a simplified depiction of a series spectrum. The spectrum lines are set against a uniform scale of frequency ν, as was common among practitioners from the 1870s onwards in their search for series formulas (see here § 8.2). The upper part represents the ‘same’ Balmer series of hydrogen, this time depicted **(p.439)** according to Bohr's quantum theory. The horizontal lines symbolize different energy levels, corresponding to different values for n in the relation R/n^2, written algebraically on the left-hand margin, and numerically on the right. The parameter R is the so-called Rydberg constant, with the value 109 678.72 cm^{-1}. The vertical arrows symbolize the different possible electron jumps from higher to lower levels. In a normal term diagram, these arrows would be equidistantly spaced. Here, the translation between the two modes of representation has been achieved by placing each arrow directly above its corresponding spectrum line. The correctness of this ‘translation’ can be checked by connecting the points of origin of the various arrows. They then form a straight line proportional to the frequency variable ν. The lower representation is still iconic (albeit somewhat schematic compared to photographs or hydrogen spectrum maps of the nineteenth century). The upper one, by contrast, is purely symbolic: differences in potential energy of various electron orbits are symbolized by the different heights of the horizontal lines to indicate energy levels—which term itself is a metaphor—and transitions between them are symbolized as arrows.

As has been argued (in § 2.3, esp. p. 45), a diachronic analysis of the semiotic types of spectrum representations reveals a vacillation in the predominance of icons versus symbols. *Grosso modo*, in earlier sources we saw a predominance of **verbal** descriptions of flame or line colors (such as Wheatstone's), followed by **symbolic,** vertical arrangements (such as Alter's), succeeded by **iconic** horizontal charts (such as Masson's or Bunsen's), and ultimately by spectrum maps at ever better dispersions. Of course, these shifts are closely associated with the various spectro-scopic domains listed above. What might be more surprising is that they are also related to “basic patterns of progression” found by the historian of cartography Paul Harvey. In his cross-cultural examination of the development of topographical mapping he identified “three evolutionary stages” in portraying landscapes: first symbols, then pictures, and ultimately surveys.[69] Even though, strictly speaking, these qualitative transitions cannot be quantified, the following graph may nevertheless roughly retrace their approximate relative weights as a function of time.

Figure 10.2 shows some relatively stable plateaus among the jagged troughs and peaks. What it does not—and cannot—show are the competing ‘spectro-scopic domains’. For instance, lithographic portraiture and spectrum photography both aimed at mechanical portraiture during the 1870s, but inclusion of these various subcultures would only clutter the graph. Some of these domains are also closely linked by social ties like masterpupil relations, or bonds of collegiality (e.g., Bunsen and Kirchhoff in Heidelberg). For the most part, though, the various groups of names in the itemization on p. 436 do not form such socially coherent sets within the ‘scientific community’. Let us just take as an example the researchers involved in the search for homologies among the spectra of different elements: we move from Berlin (Mitscherlich) to Cognac (Lecoq) to Vienna, Padua, and Bologna (Ciamician) to Dublin (Hartley), with none of these people closely connected to any other member of this domain. And yet they pursued very similar strategies in searching for visual analogies, in most cases fully aware that they were following in the footsteps of others in the same category. The visual practice and associated skills could travel without any personal interaction necessary, because well-illustrated publications allowed initiation into these techniques, quite independently of where one was situated.

(p.440)

10.5 Persistent modes of visual representations

The existence of such plateaus for preferred types of visual representations did not by any means imply that the conceptual underpinnings prevailing during those periods were equally stable. On the contrary, throughout this study, we have repeatedly encountered astonishingly resilient visual models of how to perceive or represent the spectrum, despite profound changes to their underlying theory. The most prominent example is the nearly 200-year-long career of Newton's set of seven primary colors (first published in 1675, and still used by Listing in the 1860s: see here pp. 30–32). Newton's graphic reduction of the continuous spectrum to a finite string of circular images of the pinhole in his window shutter (see Fig. 2.8, p. 30 for this paradigmatic example) actually conflicted with his claim of the existence of an infinitude of light rays of differing refrangibility, and thence color. But this seems not to have disturbed any of his contemporaries much. By Hassenfratz's

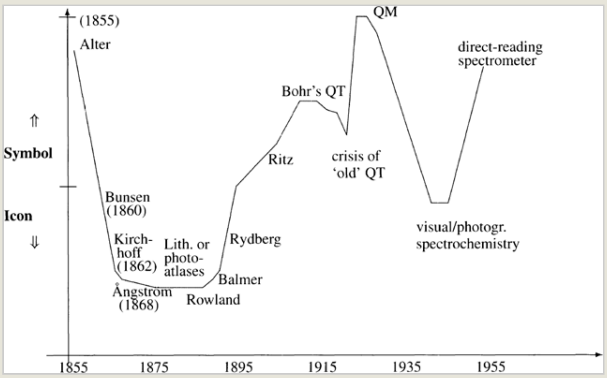


Fig. 10.2 Graph of the relative weights of symbolic and iconic signs in visual representations of emission spectra 1855–1955: the line connects what I would consider typical representatives.

day, this contradiction between the visual baggage and theoretical underpinnings had become apparent and the *polytechnicien* himself pointed it out explicitly in his papers of 1807 and 1808. Nonetheless, even he continued to use the Newtonian convention of representing his absorption spectra as a superposition of seven distinct spectral-color spots (see Fig. 2.10). This persistence of certain visual schemes shows that visual representations too have a life of their own—to take up and slightly modify the famous slogan on experimentation coined two decades ago by the Canadian philosopher Ian Hacking. This finding agrees well with David Kaiser's recent analysis of the tenacity of the Feynman diagrams in the 1950s and 1960s, despite trenchant changes in the conceptual and theoretical frameworks into which these symbolic representations of certain scattering processes and elementary particle **(p.441)** transformations were embedded.[70] In Kaiser's case, the stability of this representational style could be explained by a “high degree of overlap between the visual representational schemata of the Feynman diagrams with those of Minkowski diagrams and of the bubble chamber reconstructions”.[71] In my case, however, I do not see any older pictorial tradition to which the Newtonian images of the primary colors could be subscribed. The debate over how many primary colors there are in the rainbow has a centuries-long history, but never had the color spectrum been represented as a superposition of pinhole images before Newton. Thus the astonishing tenacity of this pictorial convention may be traced to the authoritative status that Newton's *Opticks* rapidly acquired since its appearance in 1704, and its inculcation in succeeding generations of opticians. The art historian Ernst Gombrich has emphasized the importance of the teaching practice for understanding the stability of certain visual models. In his path-breaking study on the psychology of pictorial representation, he wrote, “all representations are grounded on schemata which the artist learns to use”.[72] The same holds for scientific iconography and (in Chapter 9) we have viewed manifold stages of this training.

Student notes and laboratory handbooks provide an invaluable source for reconstructing this learning process: the mapping of spectra in the classroom (as described in § 9.4) was an essential exercise in schooling the eye. It taught students to discriminate, recognize, and memorize the various spectroscopic *Gestalten*, such as, for instance, Bunsen's characteristic emission lines or the various basic types of stellar spectra (§ 9.6). E.C. Pickering's courses at MIT (§ 9.2), and S.F. Whiting at Wellesley College (§ 9.5) show that in the US as well, instructive use of such visual aids as posters, slides, and illustrations in textbooks and laboratory manuals followed a visual culture strongly emphazising such nonverbal skills as proper observation, drawing, and photography. This culture reverberated in a broader tendency away from dry text-bound instruction in the physical sciences and towards a vivid *Anschauungsunterricht* that became increasingly popular at the secondary-school level as well (cf. here footnote 46 on p. 14). This pedagogy raised the science practitioners in the various visually oriented subcultures, which continued to rely on these skills in research up to World War I. With Bohr's quantum hypothesis of 1913, spectra—formerly the domain of phenomenology—became consistently interpretable on a theoretical basis. As we have seen (in § 9.3), this also had its repercussions on the teaching of spectroscopy, such as the choice of new types of experiments (e.g., interferometry), and to some extent a replacement of visual skills by calculational proficiency. But even then simple observations and retracings of the spectrum remained a standard component in the physics curriculum.

There are two perspectives from which this visual training can be viewed. Firstly, it is the major mechanism for creating and then stabilizing a specific spectro-scopic domain, instituted by an adherent, who preferentially uses in the classroom the visual devices linked to his or her way of seeing and representing. Through much repetition, quasi-automatic couplings are generated in the students' minds and, in the end, a *Gestalt-Kollektiv* emerges as a perfect analogue of what Ludwik Fleck called a thought collective:[73] a group of persons **(p.442)** with similar training who all inadvertently identify a given ambiguous visual stimulus in a certain way as a specific *Gestalt*, in accordance with the patterns emphasized during their intense training.

Secondly, under realistic conditions no training will be as monothetic as Fleck would have it. Elements of other scopic regimes (or domains) will creep into the curriculum even under the strictest regimentation, and besides, the trainees will be exposed to them anyway outside the laboratory and practice session. Far from detrimental, this unintentional broadening of the horizons makes transitions, translations, mixtures, and convergences among the different visual domains much smoother.[74]

10.6 Visual analogy

In Barbara Stafford's book *Visual Analogy*, the point of this procedure is scarcely enunciated. She loosely defines the term as the propensity “to discover the relevant likeness in unlike things”. For her, analogy is fundamentally determined by optical, i.e., visual characteristics, so she also calls it “the vision of ordered relationships articulated as similarity-indifference”, but few of her ninety examples really show the persuasive force of a perceptive visual analogy.[75] What is—or rather what should be—implied by the term is a strategy of connecting two phenomena normally not considered to be interrelated, solely on the basis of a (usually striking) similarity in their outward appearance. Or more sharply defined, in an effort to circumvent its postmodern deflation: a visual analogy is a link between two patterns normally occurring in different contexts and without any prior cognitive connection, solely on the basis of their similarity in *Gestalt.* Good examples of such visual analogies are Leonardo's comparisons between anatomical structures and mechanical machines or musical instruments, van't Hoff's visualization of the valencies of the carbon atom as the vertices of a tetrahedron, or John Augustus Roebling's application of the design of a sailing ship's backstays to construction details of nineteenth-century suspension bridges like the Brooklyn Bridge.[76]

The highly developed skill of pattern recognition among versed spectroscopists of the late nineteenth century exercised, for instance, in their analyses of spectral series (cf. § 8.2) also led to a variety of examples of such visual analogies. Balmer's transferral of the visual pattern of perspectival shortening to the regularly decreasing interstices between series lines is a particularly striking example. From his technical drawing lessons at the Basel preparatory school for girls, and his lectures on similar topics at the University of Basel, Balmer was fully immersed in the techniques used in architectural drawings of perspectivally shortened flights of stairs, rows of columns, and similar motifs. Thus it comes as no surprise that he saw a visual analogy between the regularly decreasing distances of series lines and the pattern formed by the railway ties of a train track collapsing into the distance, or the apparent compression of the vertical ribbing on a column when seen from the side.[77]

(p.443)

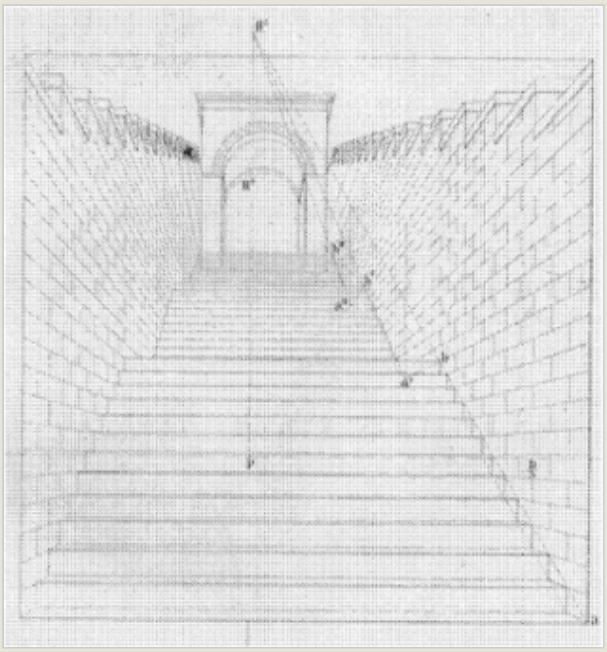
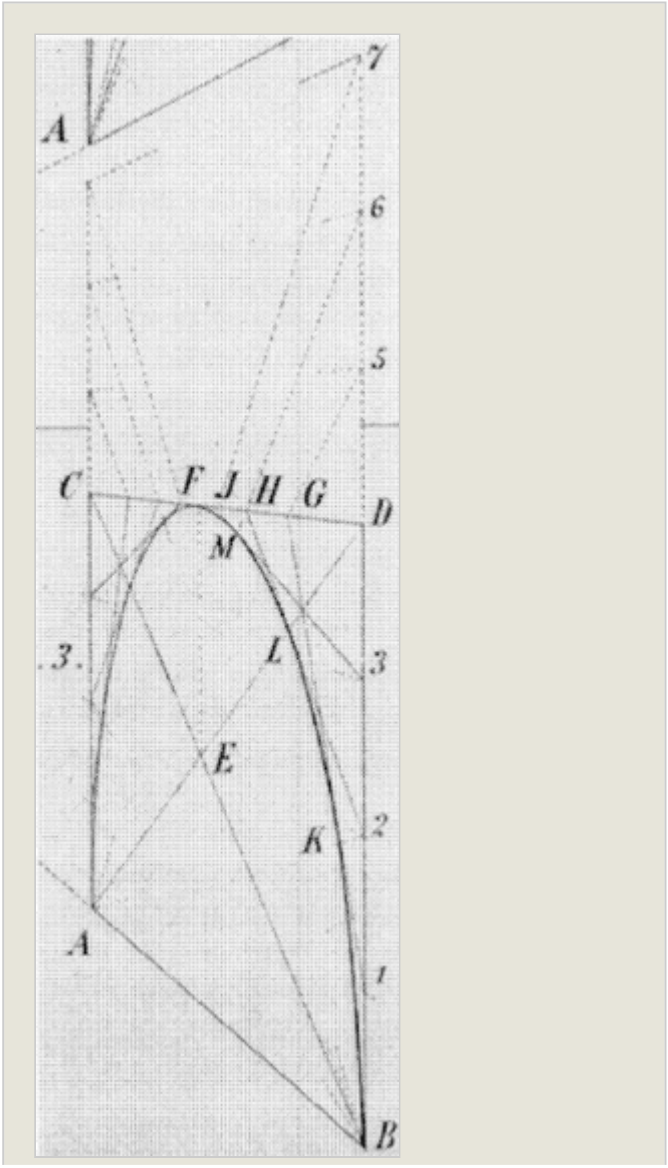


Fig. 10.3 Balmer's drawing of a perspectivally shortened stairway. The middle part, turned 90 degrees, looks remarkably similar to the pattern formed by the hydrogen series, as it was then observed in the visible and near-ultraviolet part of the spectrum. The ‘series limit’ of all the sequences of steps is at the vanishing point H^{I} of the drawing, but the landings introduce changes in the intervals for each new set of steps. From Balmer [1887] pl. IX.

Given his training and continual practice in perspectival drawing, there is something inevitable in Balmer's visual analogy. For others not sharing this formative background, however, it is a strange and unexpected mental leap. In fact, it is tempting to modify Ludwik Fleck's concept of compulsory modes of thinking (*Denkzwang*) in order to describe such a quasi-automatic link between two phenomenologically similar patterns. But to speak of *Gestaltzwang* might overshadow the creativity and persistence involved in not only noticing such a vague similarity, but following it up as Balmer did. The experimental psychologist Rudolf Arnheim preferred to use the term ‘preperception’, coined by William James, for describing such cases where a perception (here of the first few hydrogen series lines) is quasi-automatically treated as similar to something else that has been seen often enough already to be part of a mental set, a sort of inventory of standard visual patterns. James was so radical as to presuppose that only stimuli similar enough to such a preperception have any chance of being consciously noticed.[78]

Even if this might be too strong a claim, our Balmer case certainly exhibits a quite strong coupling between the two visual domains. Significantly, the same year that Balmer must have started to write his famous study on the hydrogen series, he also published a commentary on Jean Thomas Thibault's (1757–1826) method of circle projection, and three years later, he expanded on this theme in his textbook on perspectival drawing.[79] As Balmer explained to his readers in 1884, Thibault's method is based on the idea of enclosing a circle within a foreshortened square and then defining points on the circumference of the circle by constructing right triangles (whose sides satisfy the Pythagorean relation 3:4:5) **(p.444)** inside the circle. But because this method is limited to constructing only one or two points of the circle at a time, Balmer went on to develop another procedure, what he called the tangent method. The perspectivally shortened circle is obtained by constructing an arbitrary number of its tangents (cf. here Fig. 10.4).



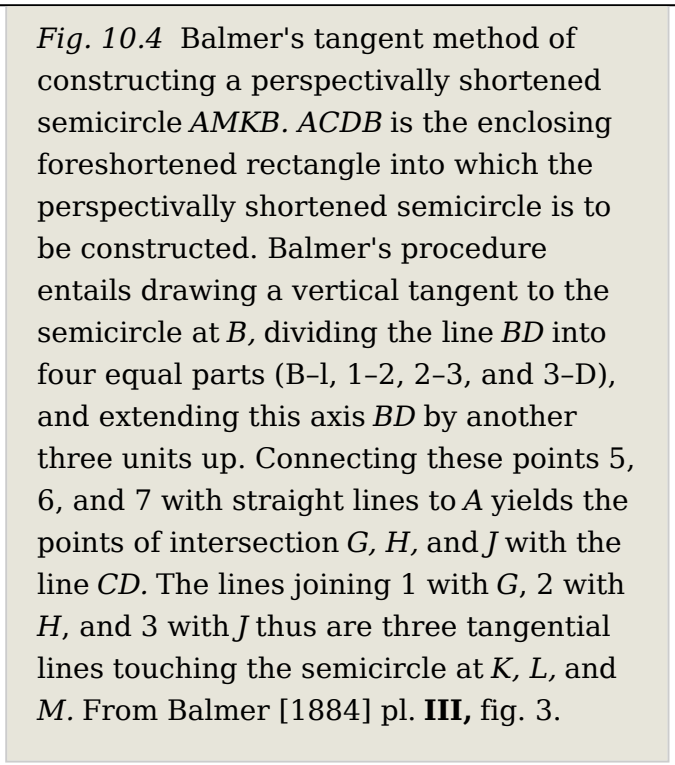


Fig. 10.4 Balmer's tangent method of constructing a perspectivally shortened semicircle *AMKB. ACDB* is the enclosing foreshortened rectangle into which the perspectivally shortened semicircle is to be constructed. Balmer's procedure entails drawing a vertical tangent to the semicircle at *B,* dividing the line *BD* into four equal parts (B–l, 1–2, 2–3, and 3–D), and extending this axis *BD* by another three units up. Connecting these points 5, 6, and 7 with straight lines to *A* yields the points of intersection *G, H,* and *J* with the line *CD.* The lines joining 1 with *G*, 2 with *H*, and 3 with *J* thus are three tangential lines touching the semicircle at *K, L,* and *M.* From Balmer [1884] pl. **III,** fig. 3.

The similarity between this tangent method with Balmer's geometric construction of his series (as illustrated in Fig. 8.3 on p. 300) is striking. The line *BD* divided into seven equal units (in Fig. 10.4) corresponds to the *X* axis (of Fig. 8.3), there divided into 10 equal units. In both cases, the circle is tangential to this axis, and in both cases the circle is circumscribed by a whole set of tangents meeting the vertical axis at regularly increasing intervals. Balmer's sequence of regularly diminishing intervals l_3, l_4, l_5 (measured along the *Y* axis from point *O* on Fig. 8.3) corresponds to the decrease in distances *DG, GH*, and *H J* (of Fig. 10.4), with *F* as the series limit for choosing an arbitrary number of divisions of line *BD.* Of course, when Balmer drew this figure (presumably in 1883) for an annual publication by his school, this visual analogy had not yet occurred to him. That explains why the rough labeling fails to emphasize this regular shortening, quite in contrast to Fig. 8.3. The exciting feature about Fig. 10.4 is that it brings us right to the doorstep of Balmer's discovery. Just one short step remained to be taken. His focus until 1884 had **(p.445)** been the construction of a foreshortened circle. The crucial *Gestalt* switch towards considering the geometrical relationship of the resulting line intervals in the horizontal axis *CD* almost automatically led Balmer to his formula for the series relations. His approach also yields a determination of the series limit, or in Balmer's own terminology, the fundamental number *h* of hydrogen.[80] This by no means diminishes Balmer's extraordinary creativity in effecting such a *Gestalt* restructuration. I would argue that this line of reasoning, guided by visual imagery and leading to such an extraordinarily good match between observations and calculated values, provided something like a visual proof.[81]

Regardless of whether Balmer's geometric argument constitutes rigorous proof or not, heuristically his visual model of the phenomenon of series lines yielded decisive clues, which he then felt compelled to follow up. And it is plausible that such a consistent solution would be most feasible for a person totally immersed in the techniques associated with perspectival drawing. At the time, few would have outdone Balmer as an exemplary member of a visual culture. As with all satisfactory historical explanations, this reconstruction also goes a long way towards helping us understand *why* the discovery of the series formula for hydrogen was made in this particular context of perspectival drawing, and not by scientists who had opted for purely algebraic search strategies (such as Carl Runge and Heinrich Kayser). It also gives us certain clues about the specific form in which Balmer's suggestion was cast, such as the strange parameter n^2 in eqn 8.1, despite the fact that from his limited empirical basis, n could not take any value other than 2.[82] Balmer acted under a *Gestaltzwang*, just as did Stoney and other adherents of the interpretation of spectral lines as harmonic overtones, who were fixated on finding numerical relations between spectral lines as multiples of one fundamental line of low frequency. But complementarily to the earlier efforts, Balmer's fundamental h was the shortest wavelength. That was an impossible step for anyone in the other camp to take (for whom the fundamental was always the longest wavelength), but a most natural starting point for the geometry teacher in Basel.

Balmer's use of a visual analogy, the key activity of any visual culture, is hence a constituent feature of this central episode in the deciphering of the spectral code. Paradoxically speaking: it was Balmer's unusual upbringing that enabled him to bypass the standard analogy between acoustics and optics so deeply engraved in the minds of contemporary physicists. His quite different background makes him into another case in support of my argument of a link between a preference for visual strategies and previous training in architecture and technical drawing. Having learnt the basic drawing skills from his artistic mother, Balmer had attended courses on architecture, practical geometry, and technical drawing at the Karlsruhe Polytechnic and the Berlin Bauakademie.[83] His Ph.D. thesis **(p.446)** treated cycloids, and his habilitation thesis discussed reconstructing an antique temple on the basis of biblical sources. Occasionally, Balmer also gave lectures on descriptive geometry at the University of Basel, aside from teaching calligraphic writing, perspectival drawing, and arithmetic at a secondary school for girls in Basel.[84] Architecture continued to attract his attention later in life as well: in 1876, for instance, he designed a bridge across the Rhine River in Basel (where the Wettstein Bridge now stands),[85] and half a dozen years later, in 1882, he rescued the medieval Barfusser church in the old city core from demolition by launching a newspaper campaign arguing its historical value and divine proportions. He also designed various smaller churches and simple but carefully thought-out housing for workers, under the asgis of the Basler Bauverein, of which he was an active member.[86]

Beside this professional training, his family background also provided strong links to a variety of visual cultures: One of the mathematician's brothers, Josef Balmer (1828–1918), was a historical painter, another, Fritz, was a talented draughtsman. Balmer's son Wilhelm (1865–1922) became a painter and maître de dessin, and one of his grandsons, Wilhelm Knapp, was a sculptor.[87] The sister of his wife, Pauline Rinck, was married to the Basel publisher Ferdinand Riehm, who published religious treatises and artisanal books under the company name of Balmer & Riehm,[88] and his best friend's sister was married to the famous art historian Jacob Burckhardt (1818–1897). Balmer's environment was thus teeming with a variety of visual cultures, ranging from the printing trade and architecture to art history and stereoscopic or perspectival drawing.

Balmer's training in a polytechnical school fits him perfectly into the mould created by Ferguson in his perceptive studies on the ‘inner eye’ of creative engineers. Ferguson provided many compelling examples of such visual problem solving, ranging from designs of fortifications, bridges, and machines, to fundamental inventions. He even boldly inverted the argument, deploring the recent demise of mechanical drawing or design courses in engineering curricula, foretelling negative consequences in the form of a loss of nonverbal **(p.447)** imagination and creativity.[89] Several experimental studies by cognitive psychologists have also confirmed the existence of these two types of ‘strong visualizers’ versus ‘non-visualizers’.[90] In his survey of the various theories of problem-solving, the experimental psychologist Geir Kaufmann came to the conclusion that human problem-solving and creative thinking cannot be understood as merely conceptual activities. His thesis is that visual imagery is closely dependent on the type of task at hand. Basing himself on experimental tests he concluded that visual representations are particularly important for novel, demanding problem situations, whereas linguistic strategies have more significance for sequentially organized tasks. Visual imagery in general, and visual analogies in particular, lead to faster multiple solutions to highly complex, novel problems requiring synchronous, parallel organization of the given information and background knowledge.

> In face of a novel task, imagery is particularly appropriate as a representational medium. Being ‘holistic’ and ‘crude’, imagery leaves the problem-solver with several alternatives which are all necessary when knowledge is scarce. With increasing familarity, some alternatives may be dispensed with and a more exact and swifter linguistic representation may be used in tackling the problem. The price to be paid for greater swiftness and economy is the following: Since language forces standardization and constraint on the problem-solver, he will be at a loss to tackle a *novel* task deviating from the principle implemented in the linguistic representation. *With increasing complexity and novelty of the task, the utility of a pure linguistic representation decreases systematically.*[91]

The tasks ahead of Balmer, Rydberg, and the other pattern-seeking spectroscopists of the late nineteenth century were of precisely this type: there was a high degree of novelty, and a highly complex information basis requiring parallel processing. Not caught in the mathematical ‘language’ of harmonic overtones of a different training, Balmer could creatively explore other avenues suggested by visual analogies afforded by a rich store of imagery guaranteeing more freedom of association. Just as is sketched in the above quote, these analogies were most useful as an initial heuristic guide, allowing him quite some leeway in implementing the basic idea of perspectival shortening. Once he had settled on a definitive model, it could be retranslated into the exact language of simple geometry, which pointed the way to his formula for the hydrogen series.

Thus, visual analogies such as Balmer's are particularly risky but rewarding examples of what Ferguson, Arnheim, and many psychologists have called ‘visual thinking’. Various other **types of visual thinking** are brushed upon in the literature but it is still sadly unsystematic in this regard, as far as examples from the history of science are concerned. They comprise, besides visual analogy:[92]

(p.448)

- analytic decomposition into constituents,
- spatial thinking,
- gap-stopping or reconstruction of missing (or obscured) parts of visual patterns,
- phenomenological distinction of types and morphological classification,
- schematization of processes (in flow-charts, etc.),
- (imaginary or real) cinematographic serialization, and finally,
- deceleration of rapid processes into an imaginary succession in slow motion.

Some of these types of visual thinking (such as spatial thinking and gap-stopping) are incorporated into modern standardized intelligence tests; others (such as the last two) have gained considerably in importance since the advent of cinematography. Thus Janssen's ‘revolver photographique’ is often mentioned as a precursor of Marey's and Muybridge's serial photographs which in turn then led to the invention of cinematography.[93] Yet others (such as visual analogy) are still marginalized or misunderstood as unfounded associations. It would be a worthwhile endeavor—although clearly beyond the scope of this book—to seek out further types of visual thinking to add to this list and select examples from various scientific disciplines.

10.7 Interdependence of representation and research strategy

There are several good examples of visual thinking interspersed in Chapter 8. With respect to the search for series and band patterns, I can also substantiate a claim advanced earlier (see here § 8.1, pp. 290ff.) about the interdependency of representational technique and research strategy. In summary, Chapter 8 yields the following theses:

1. The search for series relations was clearly based on spectral maps drawn at the highest available dispersion. The inevitable result was hypotheses about line groupings that did not necessarily agree with the line intervals indicated on these maps. Nor were they always in accordance with the wavelengths entered in the accompanying tables. So this search naturally led to demands for greater precision and magnified representations of the same spectra. We thus have a typical cycle in the research practice that goes from the mapping of a certain spectrum to a search for series relations, back to mapping the same spectrum on a larger scale. The internal dynamics of progressive enlargement of spectral maps (as described in § 3.1) is augmented further by the demand for amplified survey maps and zoomed cutouts of special interest (§ 3.2).
2. Beyond fostering such demands for increased precision within already well-studied parts, the series relations suggested by known lines often invited extrapolations into regions not yet accessible, such as the farther infrared and ultraviolet, which were just being explored during the nineteenth century. That is, we also have a cycle departing from a map of a known segment of the spectrum, to hypothetical series relations, to a demand for a map of an, as yet, unexplored region. The most famous example is Theodore Lyman's discovery of the fundamental series of hydrogen in the ultraviolet in 1914.[94] Other examples we have encountered in this book are Victor Schumann's **(p.449)** research in the ultraviolet (based on vacuum spectrographs and gelatine-free photographic emulsions), and Samuel P. Langley's exploration of the infrared with his holographs (see pp. 71 and 267ff., respectively).
3. At least until the publications by Ciamician and Hartley in the early 1880s on ho mologous spectra, and arguably even until the discovery of the Balmer series of hydrogen, it was fundamentally unclear which scale was best suited heuristically to finding the mathematical relationships between the adjacent members of a spectral series. Those favoring analogies between optics and acoustics pled for the frequency (or wave-number) scale, while others preferred to rely on their photographic plates or visual recordings of normal (i.e., wavelength-scaled) spectra. Because the overall *Gestalt* of the corresponding plots of spectra differed so drastically, it was hard to recognize a given line group in one type of map if one was accustomed to working with another. So here we have another instance of two mutually exclusive spectro-scopic domains competing with each other.

4. Bohr's atomic theory provided a first clue to why the Balmer, Paschen, and later the Lyman series reflected a significant relationship between certain lines. Hitherto, the physical reasons for the existence of series relations in certain spectra had remained a mystery, and all speculations about their possible cause in terms of acoustical analogies or mechanical resonances proved to be unsound, if not completely wrong. The most blatant failure of early theories on series relations was Schuster's no-go theorem, which ruled out *any* mechanical analogy as a possible explanation for observed series patterns.[95] Similarly, before Bjerrum's theory of rotational degrees of freedom, the physical origin of band spectra was basically unknown. As in point 2 above, speculations in the right direction were put forward quite early on, but speculation is quite a different matter from knowing for sure. Thus prior to 1914 the search for series relations is a phenomena-driven, not a theory-guided research program.[96]

5. As the discussion about Balmer should have shown, I think it is fair to say that, in general, scientists who worked with graphic or geometric strategies for identifying and fitting spectral series were more successful than those who worked with algebraic or arithmetical strategies. Thus despite Runge's great talent in applied mathematics and his meticulous collaborative work with Kayser on the calculation machine, which helped them to fit their data to a Taylor-like series expansion with three adaptable parameters, it was the outsider Balmer who hit upon the right formula for the hydrogen series from within the visual culture of perspectival drawing. And a few years later, Rydberg's educated guess of a fitting formula for other spectral series, likewise based on geometric reasoning, was the generally accepted one preferred over the purely algebraic suggestions by Kayser and Runge. Note that it is not hindsight, knowing who ultimately happened to be ‘right’, but the verdict of the contemporaries that I rely on in claiming that geometric strategies, intimately coupled to graphical representations **(p.450)** of spectroscopic data, were more fruitful in the search for series relations at least until the turn of the century, possibly even until 1913.[97]

10.8 Periodization

Given such diversity in illustrations of a single object of study, here the spectrum, how does one best organize the publications? In other words: how do we periodize our topic? The most straightforward strategy is according to the available **recording** techniques. This would set the first major turning point at the year 1800 when visual observation combined with drawing, thus far the only way to record spectra, was supplanted by thermometric and chemical techniques of tracing ‘invisible light’ (see here p. 61). The next rupture is then caused by the invention of photographic techniques, most notably with the publicizing of Daguerre's discovery in 1839, followed by the development of wet collodion plates in 1851, dry gelatine plates 1871, and their sensitization two years later; panchromatic plates in 1906, and commercially successful color films in the mid-1930s. Another revolution comparable in impact with the one constituting the invention of photography finally occurs with the replacement of photographic plates and films by charge-coupled devices (CCDs), which are based on sensitive photocells that emit an electric signal upon being hit by a photon. The effect of these developments (discussed in some detail in § 6.1 and Chapter 7) on spectrography (see § 6.2, 6.4, and 6.6) shows that one should not overrate the importance of photography for our field prior to, say 1880. Photography was welcomed as a new tool to record the regions of the spectrum not observable directly by eye. But it also had the stigma of a ‘trial-and-error environment’. Stability and reproducibility of results could not be guaranteed, and very faint lines long evaded the photographer's wet collodion plates, because the emulsion solvents (alcohol or ether) would evaporate away within a matter of five minutes.[98] Moreover, as a technique of reproduction, photography could not compete for many decades with the refined art of lithographed or steel-engraved spectrum maps. Direct transfer of photographs into print only became viable with the invention of efficient techniques of photomechanical reproduction.[99] According to Ann Blum, photomechanical processes actually induced a change in the depiction norms of zoological illustrations, away from continuous tone images, towards line drawings and other types of highly schematized images.[100] But I cannot corroborate these claims within my area. Louis Thollon's lithographic high-resolution map of the visual spectrum, an outstanding contribution towards spectroscopic portraiture, appeared in 1890 (see here pp. 135ff.), that was *after* the release of Rowland's *Photographic Map of the Normal Solar Spectrum* in 1886 (cf. here pp. 56ff.).

(p.451) Taking these findings into account, an alternative periodization suggests itself, namely, according to the available **printing** techniques.[101] Then the first breakthrough would again be set around 1800, with the recent invention of lithography, justifiably hailed as the first real alternative to the various types of copper engraving then in use. The next major advances would be the invention of various procedures to convert a photograph into a printable plate (most notably Albertype, heliotype, and Woodburytype) in the 1870s and early 1880s, and the final stride forward would be the rapid proliferation of half-tone and offset-printing around the turn of the century. Leaving the time frame of this study for a moment, we might even be able to situate very recent representations of spectra in the internet, as a modern-day continuation of conventional paper prints, hitherto the sole effective means of publication and distribution. One of the webpages of the Departamento de Astronomia do Instituto de Fisica da Universidade Federal do Rio Grande do Sul on ‘espectroscopia’—presumably designed foremost for students—offers displays of the characteristic lines of the spectra of most of the chemical elements upon selection of the appropriate field on a periodic table. Another mouse-click toggles between emission and absorption spectra.[102] This example shows that new representational techniques—here the internet with its ability to integrate hypertext with visual representations—lead almost automatically to new forms of representation. But despite the many associated innovations in image technology, the original Bunsen representation still shines through in the relative orientation, size, labeling, and overall schematization.

This periodization according to the available printing techniques, although capturing the basic changes in the creation and multiplication of the primary material, unfortunately also has its hitches. One is rooted in the tendency of many newly invented printing technologies to imitate their predecessors. Lithographers, for instance, were proud to succeed in disguising their products as engravings, and daguerreotypists framed their portraits in such a way as to make them resemble paintings. The effect of this camouflage strategy is obfuscation of the breaks between the various printing traditions. In addition, *de facto* there is often a considerable delay between the development of a new technique and its application to scientific illustration.[103] The oldest lithographic representation of a spectrum that I have come across is W.A. Miller's chromolithograph from 1845, i.e., roughly five decades after Senefelder's invention (cf. here § 4.2, pp. 119ff.), and the first successful photomechanical reproduction of a spectrum photograph was achieved in 1873 (cf. here p. 213), roughly 35 years after the announcement of daguerreotype and 30 years after John William Draper's first photograph of a spectrum (see here Fig. 6.3, p. 197). This considerable time-lag may appear to be somewhat exceptional for the realm of spectral analysis, related to the **(p.452)** particular challenge posed by generating a spectrum of proper resolution and representing it sharply as well. However, as late as 1926 we still find spectroscopists explicitly preferring lithographed drawings over photographic maps because of their ability to bring out significant features at the very limit of photographic contrast and resolution. One of these practitioners asserts:

> My personal experience has led me to prefer the sketch to the photographic reproduction. […] enlargements […] change the image of the spectrum and make the resolution of certain particularly complicated groups difficult. The readings made by a trained observer are certainly more precise than those that would be made on an enlargement.[104]

Seeing such astonishingly long-lived preferences for a particular technique makes one wonder whether there wasn't something else behind this tenacity. Aren't there other, deeper cultural trends that determine the choice of one medium over another, and one technique of representation over another? This question leads us directly to the research agenda followed by Lorraine Daston and Peter Galison, who have traversed their terrain of visual representations in a manner designed to extract a periodization valid for a number of disciplines at once.[105] They chose their sample atlases from botany and radiology, anatomy, and bubble chamber physics, with the aim of tracing major changes in their intended functions. To summarize a lengthy and well-illustrated line of argumentation, Galison and Daston distinguish between three different types of atlases:

• Type I, predominant in the eighteenth century, attempts to invoke a kind of **metaphysical image.** It aims at the ideal of a “truth to nature” through a process of subjective mastery in the selection and idealization of given phenotypes.
• Type II, emerging since 1830, aims at a **mechanical image** gained wholly without, or at least, with as little human intervention as possible. In accordance with this conception, we find various different techniques, such as photography, heliogravure, or other types of automated recording methods, as were used, for instance, in physiology. All were praised for purportedly allowing “Nature to leave her own imprints” in a quasi-automatic mode unmarred by human error.
• Type **III,** the **atlas of typical patterns,** which according to Galison occurs mostly after 1920 and explicitly rejects the former downplaying of the human observer. In modern publications,[106] the authors rely heavily on human interpretation and judgment, intent on developing their readers’ skills in recognizing essential features of the depicted objects (cf. here § 9.6 on the pedagogical strategies effective in training these visual skills).

Within the first type, Galison and Daston distinguish between (Ia) atlases depicting ideal types (such as Goethe's *Urpflanze*) construed as a kind of synthesis of many different samples, versus (Ib) an atlas presenting specific samples selected as characteristic, or typical, **(p.453)** and (Ic) atlases that merely exhibit representatives, construed synthetically from a whole class of phenotypes. One of the spectroscopists, who featured prominently in our study, captured the gist of classes (la) and (Ic) of idealized illustrations in an early letter:

> The object of painting as well as of literature, is to present something more perfect than that which is commonly seen; to give a local name and habitation to those abstract images of ideal & perfect beauty; which though derived from nature herself, are never to be seen entire[ly] in any one of her forms. Nevertheless, the excellency of painting has been by many, much too frequently looked upon as consisting in closeness of imitation: in the same mistaken point of view that the beauty of fictitious writing (the drama, romances, & novels) has been said to be owing to their holding a mirror up to nature.[107]

While Romanticism in the late eighteenth and early nineteenth century still subscribed to this ideal of mental images being superior to any naturally obtainable ones, the following generations gradually moved away from this view —partly in conscious reaction to such sentimentality, partly in sharpened awareness of the need to record natural processes as faithfully as possible, with as little human intervention as possible. The transition from type I to type II, from “truth-to-nature to mechanical objectivity”, is thus not determined by the innovations of photography. The latter is rather just an epiphenomenon of a much broader trend that started earlier, with the invention of various self-recording instruments, and went much deeper. The essential features of such systems of graphic registration include: (i) long scrolls of paper or other surfaces on which the record is inscribed, and (ii) a rotating disk, moving grid, or some other transport mechanism run by clockwork. Even though these components had been developed in the eighteenth century already, it took until the next century for instruments with these key features to be introduced on a larger scale, roughly synchronously in many fields. From 1830 on, they began to appear, for instance, in ballistics (recording of the trajectory of a bullet), chronometry (time registration), dynamometry (force and work measurement), communication (Morse telegraphy), geophysics (seismometry), botany (Julius Sachs's auxanometer for recording somnolent movements of plants), and most famous perhaps, physiology (Matteucci's and von Helmholtz's traces of muscle contractions or Carl Ludwig's recording of the variations in blood pressure in the artery of a dog).[108] According to Daston and Galison, it was not just the prospect of attaining temporal dimensions and variables normally inaccessible to direct human observations (such as the speedy flight of a bullet or the barely quantifiable changes in blood pressure) that led to rapid acceptance of these recording techniques. They point in addition to the practitioners’ emphasis on the automaticity of the recording procedure.

Turning back to our case: did we find evidence of such a belief in ‘mechanical objectivity"? Certainly in our discussion of early photography. The motive of ‘Nature registering herself, a claim of pristine records, untouched by the human hand recurs repeatedly in **(p.454)** interpretations by the actors themselves about their craft (see here § 6.3, p. 189). Photographic plates were interpreted as the incorruptible “retina of the scientist”,[109] who unlike amateurs and laymen did not have to rely entirely on such a fallible sensory organ as the naked eye. Any closer look at scientific practice in this period will readily show, however, that while engravers or lithographers were no longer indispensable for the production of these records, rampant human meddling remained. From adjustable exposure-time setting, choice of plate and filter before the shot is actually taken, enhancement methods of the photographic image during development and fixing, and inevitable retouching of the finished negatives (cf. here Fig. 6.13 on p. 222), human intervention was everywhere—not to forget final selection from among the resulting positive prints for publication. Nevertheless, this periodization has the advantage of tidily linking photography to other fields of scientific practice, in which representations were differently acquired, yet all under the same banner of ‘mechanical objectivity’.

The transition from type II to type III, from “mechanical objectivity to skilled judgment” was not triggered by some loss of confidence in photographs. Quite to the contrary, the photochemical industry harvested its greatest successes after 1920, with increasingly systematic sensitization of photographic emulsions (see here pp. 248ff.). It was rather the growing complexity of the research objects under study—an increasingly refined taxonomy of various types and subtypes of stellar spectra, for instance—that forced this change in attitude towards personal skill and careful judgment. There is an ironic twist to this periodization, though, if we take the case of stellar spectra and the multiple efforts to classify them since the days of Secchi, H.C. Vogel, E.C. Pickering, and A.J. Cannon (see here p. 353). In a way, the many different versions of spectrum charts, in which the basic types of stellar spectra were depicted one above the other, are prime examples of the earliest type I in Daston and Galison's periodization. These comparative plates aimed at more than simply depicting individual idiosyncratic spectra. They tried to capture the most typical representative of a whole class, in order to facilitate recognition of other samples belonging to the same class. True, this classification according to the finite raster of spectral classes required judgment—indeed judgment and skill of the highest calibre, as Annie Jump Cannon's work exemplifies (see pp. 353ff.)—but so does recognition of any ideal type (class Ia) or representative sample (class Ib in Daston's scheme). What we would thus have is a recurrence of the earliest type of spectrum atlas towards the end of our time span—surely a strange result.

Daston and Galison concede that the time frames subsumed under this rough classification of three atlas types does not completely match the historical record, in which several types often co-exist at once. They thus conceive these categories as predispositions more than obligatory standards. These concessions already pretty much water down their claim and make the periodization somewhat toothless.

What I find disturbing is that this scheme is based on the meta-level of what the actors *thought* they were doing, rather than on their actual *practice.* The American pioneers in the photographic mapping of spectra Lewis M. Rutherfurd or H.A. Rowland, are good **(p.455)** examples of this dogmatic belief in ‘nature registering herself’ Henry Draper too (quoted on p. 218) makes statements going precisely up this alley. However, as was also conclusively shown, these statements were gross misrepresentations of what actually happened in Draper's photolab and at Bierstadt's Albertype printing agency. And because it is the level of practice rather than self-conceptualization—or deeds rather than words—which stood at the center of this study, I would prefer to base a periodization of the various maps and atlases discussed in the foregoing pages on a synthetic consideration of the various intrinsic qualities of spectrum depictions. A good place to start is Fig. 10.2 (on p. 440) which summarizes the prevalence of iconic or symbolic types of representations. Several clear breaks and plateaus are obvious from this graph:

(i) a preference for symbolic spectrum representations around 1855;
(ii) a sharp slope towards a relatively stable type of iconic spectrum map towards the end of the nineteenth century;
(iii) a waning of this tradition in the early twentieth century, as the symbolic term diagrams gain headway after 1913 to dominate quantum theory and its 1925 sequel, quantum mechanics;
(iv) another reversion to iconic types of spectrum representations in the traditions of quantitative spectroscopy (after 1925).

As I have argued (in § 10.4 above), the various spectro-scopic domains resulting from such temporarily stabilized practices were clearly discriminable, both in terms of social composition and in terms of research practice—their common ground being teaching, which usually incorporated all of these different practices to some extent. Because of the interdependence of research practice and representational form (see here Fig. 3.1 on p. 88), these spectro-scopic domains also provide a clear, straightforward, and unambiguous way of periodizing our field.

10.9 The resplendent band: the aesthetic appeal of spectra

Newly published spectral plates and atlases, whether in the form of photographic or lithographic prints, invariably caused a stir. In the debate over the virtues and pitfalls of these visual representations, expressions of aesthetic appreciation are conspicuously intermingled with scientific arguments, and it is to this dimension of spectroscopy that I now turn.

When Heinrich Hertz asked his colleague Heinrich Kayser for suitable material for a talk on spectroscopy, Kayser sent him not only Rowland's *Photographic Map of the Normal Solar Spectrum*, but also an enlarged photograph he had made of the cyanogen band near 3883 Å (cf. Fig. 10.5). He did so with a special purpose in mind:

> [The magnification] shows very clearly the wonderful structure of this figure. The beginnings of the individual series are marked underneath. I specifically draw your attention to the beautiful spot near 3836.5 [...], where all the series coincide.[110]

Kayser pointed out a particularly beautiful spot (*schöne Stelle*) on the photograph, much like a musician would appreciate a harmonious chord in a complex canon, or recall a few melodious bars from a larger composition. The photograph of the cyanogen band is combined with a schematic drawing of the three consecutive band heads. The diagram serves **(p.456)** as a pointer, providing additional emphasis for the superposition of these three remarkably regular patterns, starting at 3883.5, 3871.5, and 3861.9 Å.

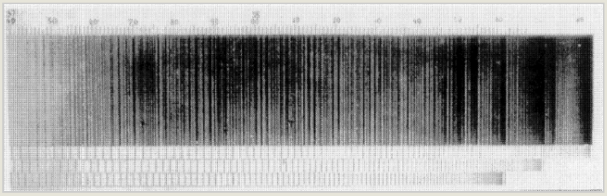


Fig. 10.5 Kayser's composite photograph of the cyanogen band spectrum near 3883 Å, taken with a Rowland grating in fourth order on plates by the company J. Gaedicke in Berlin, on eosine plates by M. Perutz in Munich, and on custom-made azalin plates. From Kayser and Runge [1888–93], part II, plate.

Others would praise the “most glorious butterfly-dance of tridents and sextents of needle-like lines that can be imagined”,[111] the “ ‘Carbon-B’ *suite* of bands”, or the “strong *pharos-like* ultra-violet Outing's delicate train of bright lines and linelets”.[112] Charles Piazzi Smyth went so far as to declare “the awfully colossal proportions” of the Fraunhofer line A as “something for an intelligent man to have seen once before he dies”. This statement obviously predated the age of political correctness. But more captivating even than the intricate band structure of ‘great A’ were the amazing changes that both this band and its neighbor, ‘little a’ exhibited at sunset off the coast of Spain on 18 June 1877:

> In the high sun, ‘little a’ is little a indeed, as to its small visibility in any shape; but at set of sun what have we got here? At first I could not believe my eyes, and made quite sure that the huge black bar almost at the red end of the spectrum was ‘great A’. But no; though I have not seen attention called to the circumstance elsewhere, great A was then a comparatively unimportant line in the further red and almost outer darkness; while ‘little a’ had swelled up from the frog size to that of the bull, and had at last become positively elephantine in thickness and ponderosity; or it was even a case of a shrimp that had grown to be bigger than a whale.[113]

These live metaphors of weight and dimension, spiced with fantastical biological transmutations, illustrate well the impressiveness of these observations, at least for the spectroscopic connoisseur. In the classic *Atombau und Spektrallinien* of 1919, Arnold Sommerfeld alluded to “the mysterious organon, on which nature plays its spectral music”.[114] This odd assortment of metaphors reveals how inadequate verbal comparisons really are in capturing **(p.457)** the spell of the observations themselves, or their visual representations, their splendor albeit reduced to the partly symbolic syntax of black-and-white spectrum drawings (compare the previous band spectrum photograph with the engraved drawing in Fig. 10.6).

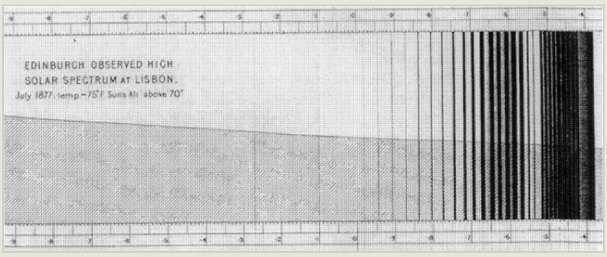


Fig. 10.6 Piazzi Smyth's drawings of the Fraunhofer great A line together with its associated band (left) and the Fraunhofer little a band (right) in the solar spectrum, Lisbon, 1877. Engraved by W. & A.K. Johnston. From Smyth [1877*d*] (iii) pl. iv. All shadings of the background intensity and between the vertical spectrum lines are rendered as diagonal or horizontal lines to avoid ambiguities.

Expressions of aesthetic appreciation abound in the spectroscopic literature and even more so in the private correspondence. The optical spectrum itself could be admired directly, of course. But its various representations, whether neat drawings or well-made reproductions, also attracted compliments. It was usually understood, though, that these renditions never could do full justice to the charm of the original.[115] Apparently aware of the metaphorical extension of his judgment, William Huggins spoke of the “great technical beauty” of George Higgs's photographs of the solar spectrum, thus setting it apart from the ‘natural beauty’ of the spectra themselves.[116] John Herschel chose a different strategy in attempting to convince the readers of *Good Words* that a pocket spectroscope could provide an “inexhaustible source of amusement and interest”. Hoping to kindle their imaginations, he appealed to their experience with colors in painting:

> To the water-color painter, the study of the prismatic composition of his (so fancied) simple washes of colour and the effects of their mixture and superposition:– to the oil painter, that of the various brilliantly coloured powders which mixed with oil form the material of his artistic creations, all are replete with interest and instruction.[117]

(p.458) As suggested at the beginning of this chapter, I would venture to say that particularly visually oriented minds were attracted to the subject of spectroscopy, a field so rich in nonverbal, pictorial resources, but throughout the nineteenth century, so relatively wanting in any deeper explanation of the filigree patterns. Langley, for instance, took great pleasure not only in scrupulously plotting the solar infrared spectrum, but also in carefully drawing sunspots, which latter were valued for their extraordinary “beauty and accuracy” and “reproduced repeatedly in astronomical works ever since”.[118] The pioneers of spectrum photography are other instances. Their boundless enthusiasm for (photo)graphic documentation led to their snapping shots of all sorts of things besides, ranging from houses to still lifes and microscopic objects.[119] Rowland's pupil William Jackson Humphreys (1862–1949) became most famous for a collection of photographs of snow crystals, and Robert Williams Wood (1868–1955) for a series of woodcut-pairs that transform a bird on the left to a flower on the right by just a few alterations in the placement of the lines.[120] Wood and Michelson also appear in Root-Bernstein's list of ‘scientist-artists’, which he had compiled on the basis of some 150 case studies in order to show that there is a “correlation between the sort of science produced by a scientist and whether or not he [or she] demonstrated nonscientific forms of creativity”.[121]

At any rate, whatever aesthetic pleasure they may have found outside their professional field, our actors always reserved a prominent place for the spectrum and its beauty. In a lecture before the Photographical Society, Captain Abney even chose the superlative in describing the spectral colors:

> Now I never feel as if any lecture is complete when dealing with light unless we introduce the spectrum. Of all beautiful things—including a beautiful face—the spectrum is the most beautiful; it has no form, and is void of artistic properties in many ways, but the colouring is to me an endless source of enjoyment.[122]

Given Charles Piazzi Smyth's universal fascination with visual patterns, it is not surprising that the Fraunhofer B line in the high-sun spectrum would elicit his high praise. But, as he reports, he was not alone in appreciating this segment of the solar spectrum:

> it is more the *beauty* of the B line which has been of late dwelt on by observers possessing very powerful spectroscopes. “The most beautiful line in the whole solar spectrum” is a remark in one of his many optical papers by the accomplished Mr. Rutherfurd, of New York, probably the greatest master of line drawing and most consummate judge of geometrical symmetry and mechanical perfection in the whole world.
>
> **(p.459)**
> In what, then, does the alleged beauty of the said B line consist? I presume the answer will greatly depend on the degree of telluric development under which the line may have been viewed by each observer […]. Generally, however, and to all inhabitants of northern countries at least, where the Sun can never be observed very near the zenith, and therefore not through a zenithal *minimum* thickness of the Earth's atmosphere, the almost proverbial *beauty* of the great B line must consist in the rhythmical arrangement of the powerful lines forming the preliminary band to B and its attached band of finer, closer-set lines, or even linelets. Forcible, dark lines the former are, clean edged, well defined, no one of them exactly like another, either in thickness, or depth of colour, or distance from its neighbour on either side: and yet the whole forming a harmonious group, from which not one element could be taken away, and to which not one could be added, without introducing a discord and spoiling the entire system.[123]

Nor was such refined taste for this region confined to discerning men of science, as Smyth assures us in the following report about his observations with his high-resolution solar spectroscope of the famed B line during a summer stay in Lisbon:

> And pray what formed the beauty of the B line, then and there, do you ask? Unwilling to trust my own eyes alone, I asked my wife to look into the telescope, and immediately came the exclamation: ‘Oh! the beautiful double lines!’ Exactly so! each of the usually seen thick lines was now a double line, or rather showed two lines; so perfectly free from any filling up, even with the faintest haze, was the space between the components of any and every pair; while every line was so almost infinitely fine, but at the same time infinitely sharp, clear, and well defined on either side, and such perfect order and symmetry pervaded the whole arrangement, that it was a case *par excellence* of science and art combined.[124]

It is hard to say what precisely makes this beauty, but it seems the band spectra combine the following elements:

- an overall symmetry and harmony among the line groups;
- a pleasing balance between the “clumsy and coarse lines” and the “feeblest, closest and most uniform lines";
- clear regularities in the line intervals; and
- a curious dependence on the time, location, and altitude at which they are taken which causes the same line group to change its *Gestalt* in a striking manner.

These exquisite cannellated spectra evidently stimulated interest in exploring the relevant spectral regions.

> Seeing that the group—constellation almost—had such a decided and well marked physiognomy, and as the harmony and symmetry pervading all its lines of construction—except perhaps a few single lines seen in, or projected upon, the attached band—show it to be dependent on one element, or elementary combination, and not to be the result of a chance coming together of stray lines from all sorts of alien elements scattered through the rest of the spectrum, I append both a record of my micrometer measures, though far from positively accurate, and a graphical representation; fervently hoping that by aid of it, notwithstanding its manifold imperfections, the chemists may **(p.460)** one day succeed in finding a substance which, under *some* temperature or pressure, may present just such a picture, but in bright lines.[125]

It is true that such open exclamations are more often found in nineteenth-century publications, having become relatively rare in modern scientific literature. Nevertheless, this does not necessarily mean that the aesthetic component in scientific observation has gone, but that twentieth-century spectroscopists have become more reticent about expressing such aesthetic judgments in public. With the advent of photoelectric registration methods and CCDs, spectral observations admittedly have become less direct, but I would think that, in principle, the same qualities could be seen, say, in the symmetrical peaks of a photoelectric registration. An inquiry into whether aesthetic considerations play a part in contemporary scientific work would lead us too far astray, of course. But recent sociological studies of representational craft in contemporary astronomy has shown that astronomers at two image processing laboratories “orient explicitly to the ‘aesthetic’ judgments of their audiences when preparing images to promote and popularize their research”. Moreover, they use more subtle forms of “crafting natural resemblances” in the earlier cleaning-up stages, “bootstrapping” around “cosmetic defects”, and image sharpening.[126] In our days of electronic imaging, the old craft of retouching is attaining new heights.

10.10 Taking the mapping metaphor seriously

In Chapter 5 (esp. pp. 168ff.), we saw how many ties there were between spectroscopy and the geosciences, both *socially* in terms of the engravers and lithographers employed for the mapping, and *technically* in terms of the reproduction procedures and skills used. Quite a few spectroscopists even had hands-on experience in the mapping of terrain, such as Lieutenant John Bobanau Nickerlieu Hennessey, who worked for the Great Trigonometrical Survey of India, Robert Hunt, who between 1845 and 1883 was Keeper of the Mining Record Office and also lectured at the newly formed School of Mines, or Charles Piazzi Smyth, who assisted in the surveyal of colonial South Africa during his first employment at the Cape. The Italian pioneer of ‘physical astronomy’, Angelo Secchi, also worked in geophysics and in meteorology, and as the Pope's scientific advisor was also involved in the construction and proper equipping of lighthouses along the coast, and in a geodetic survey of the Papal States. Among the American physicist-engineer hybrids, both Henry A. Rowland and Samuel P. Langley worked as civil engineers for railroad companies in early stages of their careers.[127] But there is more to this link than mere practicality or sheer coincidence.

In the geographic, topographic, or astronomical sense of the word, ‘map’ means “a representation of the earth's surface or a part of it, its physical and political features, etc., or of the heavens, delineated on a flat surface of paper or other material, each point in the drawing corresponding to a geographical or celestial position according to a definite scale **(p.461)** or projection.”[128] But the defining characteristics of such a map, a conventional representation of the spatial distribution or the relative positions of components, normally to scale and usually on a flat medium, can easily be generalized to comprehend objects as diverse as spectra, wave forms, weather fronts, mathematical sets, or even the human genome.[129] Geographic mapping of *terra incognita* and spectroscopic mapping of unidentified spectra have a basic quality in common: a surprising malleability of their objects. Strange, you may initially think, as there is nothing malleable about solid rock in a mountain range. But there are many different ways of depicting the latter, even if we disregard nonscientific ways of representing mountains, as on souvenir postcards, oil landscapes, etc., and confine ourselves to the modes of representation practiced by professional cartographers. As the following Fig. 10.7 illustrates, a mountainous region can be topographically mapped (i) by means of contour lines, (ii) in vertical profile, or (iii) following other conventions, rendering the steepness of a slope proportional to the density of short parallel lines.

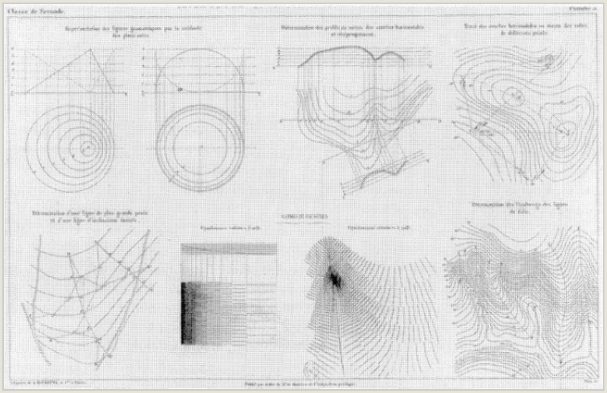


Fig. 10.7 Instruction sheet on various techniques of drawing topographic maps, and translating between various projections, such as profile and aerial views. Engraved by Dulos for the Ministère de l‘ Instruction publiqué. undated, but based on the BNE inventory stamp, before 1854. By permission of BNE: cliché Bibliothèque natioriale de France-Paris.

(p.462) It is particularly fitting to note that this instruction sheet of some techniques of translation between various projections was made by one of our master spectrum engravers, Pierre Dulos.[130] There is no single ‘right’ way of depicting a mountain, but various equally ‘correct’ ones, some of them highlighting various different surface features while others construing imaginary contour lines.[131] The point I would like to make here is that, in principle, spectra share this malleability. Their overall appearance as well as individual line distances are both strongly dependent on the experimenter's dispersive medium and registering device. But malleability does not mean total amorphousness. Each of the various spectro-scopic domains listed earlier in this chapter has its own expectations and norms to be met for a given spectrum representation to be classified as ‘good’ or ‘adequate for the intended purpose’. In case of doubt, or during the exploration of new regions of the spectrum, it was common practice to compare different types of visual representations of the spectroscopic feature under study in order to calibrate the output of new instruments (such as, for instance, the tracings of Melloni's thermopile, Langley's bolometer, or Coblentz's radiometer in infrared spectroscopy) against records obtained with other instruments (such as Abney's photographs).[132]

Like topographic or cartographic maps, spectrum maps too can be classified according to three dichotomies:

- spatial fidelity vs. recognizability
- high vs. low resolution, and
- completeness vs. typicality.

The abstract ideal of a “visually isomorphic representation” has sometimes been identified with a combination of spatial fidelity, maximum resolution, and completeness.[133] Alas, real registering instruments have their limitations in resolution and sensitivity. Thus true comprehensiveness, as was indeed sought, for instance, within the tradition of photographic mapping of spectra prior to 1900 (cf. here § 6.9), is not achievable. For many traditions it necessarily had to remain a chimera, because in spectrum analysis, for instance, typicality was what was sought. The first of the three norms is not irrevocable either (as we saw in § 4.5). With their spectroscopic portraiture, Lecoq de Boisbaudran and Cornu aimed at ease of recognition. Their purpose was to imprint the skeletal *Gestalten* of their spectra on the memory, even if that entailed suppressing some of the more confusing lines, or slightly shifting a few others, and thus betraying the ideal of spatial fidelity.

As we have seen in Chapter 3, recognizability in itself is not a lasting goal once reached. With each new order of magnification and dispersion attainable by the latest spectroscope or spectrograph model, even familiar features became barely recognizeable at the new resolution. Hence ‘old’ representations were successively rendered more or less useless for **(p.463)** work with these state-of-the-art instruments, and the demand for new spectrum atlases returned: whether ones showing selected interesting sections (see here § 3.2 on zooming), or ones expanding the full spectrum range at the new scale (see §3.1 on enlarging). But regular practitioners did not work with the latest technology, generally relying on the tried and true standard instruments like the Bunsen spectroscope, whose basic design did not change for nearly a century within the context of qualitative emission spectroscopy as practiced by chemists. So they had no use for such high-resolution maps. They kept alive the demand for condensed, low-resolution maps displaying the full spectrum range relevant for their specific purposes. These research strands thus opted for the condensed types of representation (discussed in § 3.3).

This back and forth between zooming and enlarging is a familiar pattern in the history of cartography. From each map of a specific area, say the British Isles, another map of the same territory was born at still higher resolution:[134] A 1 inch-to-1 mile map of Kent (published in 1801) was suceeded by a 6 inch map (initiated in Ireland around 1825, and then expanded to other areas), eventually to be followed by a largescale 1 : 2500 map in 1853. Independently of this cartographic progress, various town maps were printed at scales between 1 : 1056 and 1 : 500 since c. 1850, and certain hill ranges like the Cuillins on Skye at even larger magnifications. Needless to say, the British Empire kept its cartographers very busy as well. Each extension of its colonizing tentacles, in turn, prompted revisions or additions to existing maps into often still uncharted terrain.

As I hope to have shown, this same process reappears in the small world of spectrum lines, in perfectly analogous representational trends: (i) stepwise enlargement in the scale of maps, (ii) detailed examination of areas of special interest in zoomed cutouts, and (iii) groping expansion into totally new bordering zones, with occasional technological leaps leading to new conquests. The two appendices, with which I close this book, list chronologically the major maps of the solar spectrum (Appendix 1) and of terrestrial spectra (Appendix 2), outlining the spectrometric progress alluded to above by means of the range-to-length factor R/L, with R the extent of the spectral range covered, and L the corresponding length of the spectrum map (in units of Å = 10^{-8}cm per unit length L = 1 cm). The ratio thus serves as an indicator of the overall scale of representation: a high R/L is indicative of a condensed map, and a low R/L, a high resolution. From it we see that the overall scale of resolution in representations of the visible solar spectrum, for instance, burgeoned by a factor of 500, from a compact 1100 Å/cm in Wollaston's sketch of 1802, to a rarefied 2 Å/cm in Thollon's high-resolution map of 1886/90. And the maps grew correspondingly in length, from a mere 2.7 cm to 11 m, with several pertinent segments mapped at even higher resolutions.

However valid these remarks may be, they should not be construed as implying a one-dimensional progressive history of spectroscopic maps. In fact, for a long time the history of cartography itself was caught up in a similar mistake by focusing on the development of maps only from the perspective of an “increase in the accuracy with which […] elements of distance and direction are determined and [… in the] comprehensiveness of the map **(p.464)** content”.[135] The distortions of this ‘progressive paradigm’ were as fatal as Whiggish accounts in the history of science supposing a strictly cumulative growth of knowledge. We saw (on pp. 84f.) that many of these steps in spectrum resolution were accompanied by serious problems in translating the ‘old’ lines into the new. Aside from these ‘Kuhnian losses’, we also discussed the drastically different *Gestalt* in which the spectrum appeared say, in a prismatic or a normal map, which placed a sort of ‘incommensurability’ on these different modes of representation. You could not have it both ways. You just had to decide in favor of one of them, with various actors championing one or the other camp, as exemplified by the conflict between photographic ‘mappers’, who usually preferred the wavelength-proportional mode close to the photographs obtained with their Rowland circles, against the harmonious overtone seekers, who preferred the frequency-proportional plot more convenient for their acoustic analogies (cf. here pp. 307, 323, and 295f.). But venturing beyond this simplistic, progressive historiography should not risk throwing out the baby with the bath-water. Scale remains an important formal characteristic of any map, but we have to realize that successive enlargement is just *one* of several strands of our story. Highly accurate spectrum line positions in as large a magnification as possible is fine but of no help to a user who wants to recognize a certain line group in a low-dispersion spectroscope. Accuracy and efficiency may thus be conflicting goals, leading to totally different types of visual representations. Thus, in Chapter 3 we saw that, aside from repeated enlarging of spectrum maps, there were at least three other modes of representation: zooming of interesting segments, condensing into low-resolution survey maps, and distilling out the quintessential. We encountered a good dozen different ‘spectro-scopic domains’ (in § 10.4). It would not make sense to evaluate a spectrum map from any one of these domains as ‘better’ than those stemming from others, because each domain has its own aims and criteria for what counts as ‘good’ or ‘useful’. Historically, many of these different modes of representing the spectrum are related, while others co-evolved. Thus the overall pattern of development is highly complex and nonlinear.

Beyond these dynamic intricacies in the various modes of representation, I hope my book has shown how to make sense of looking at ‘mapping as a process’. As David Woodward has spelled out particularly clearly within the framework of cartography, we have to take into account not only surveying, compilation, engraving, printing, and (perhaps) coloring, but also selling and distribution, acquisitioning, cataloguing, and—actually foremost—use and interpretation by various groups wielding different skills.[136] Most of these levels have been touched upon in this book—wherever the density of sources permitted it. The result is, I hope, a balanced and integrative portrait of the practice, both in research and teaching, implementing the many different kinds of spectrum representations in use until about 1960. At its climax between 1860 and 1913, before being transformed by changes in its theoretical underpinnings and instrumentation, spectroscopy was an exemplary visual science-culture. **(p.465)** **(p.466)**

Notes:

(1) See, e.g., Lemaine *et al.* (ed.) [1976]; special issue no. 1 of the *Berichte zur Wissenschaftsgeschichte* (1978), or the studies on discipline formation in Guntau (ed.) [1978].

(2) As detailed on p. 217, the initial print-run of the *Memorie*, which appeared from 1872 to 1919, was 300; it was co-edited by Secchi and Pietro Tacchini (1838–1905) at Palermo university's modestly equipped observatory.

(3) See Hartley and Gabor [1970] esp. pp. 423f. As detailed there, from about 1930 on. Merlon's interest shitted to instrument design and inventions—thus fitting Shinn's description of a research-technologist even more. Edward Charles Cyril Baly's (1871–1948) short lectureship in spectroscopy at University College, London, from 1908 to 1910 was too brief to count. This author of a widely read textbook on spectroscopy soon became professor of inorganic chemistry at the University of Liverpool (1910–37).

(4) See, e.g., the obituary in the *Washington Post,* Monday, Nov. 21, 1966 and here Chapter 8, p. 261 on his role as ‘spectroscopy pioneer’ esp. in metrology and quantitative analytics.

(5) See Compton [1932], Harrison [1933], [1939*c*]. and his unpubl. memo on ‘The founding and early days of the MIT spectroscopy lab.’, MIT Museum, Harrison files; Kaiser [1952], [1966]. Cf. here pp. 339f. and 342ff.

(6) See Zöllner [1865] p. 315 where the task of the new discipline is circumscribed as explaining all differences and changes of celestial objects on the basis of general properties of matter. Cf. also Hufbauer [1991], and Hentschcl [1998] p. 63 for further context on astrophysics, and Hermann [1981*a*]. [1982], Sterken and Staubermann (ed.) [2000] on Zöllner.

(7) On Scheincr's chair and earlier lectures on astrophysical topics by Zöllner, Vogel, and others see Herrmann [1977]. Apparently. Zöllner's name was registered at the Leipzig University as a professor of physical astronomy, but this did not become widely known, nor was Zollner's position rcappointed after his death.

(8) For a summary of the many interdependent stands of discipline formation in astrophysics specifically in the US see Lankford [1997]. For a comparison with Germany see also Herrmann [1973], [1975], and on the impact of amateurs as ‘risk-takers’ Lankford [1891], Hufbauer [1984]. and Becker [1994] pp. 73f. Osterbrock [1995] discusses the founding of the journal.

(9) See the overview in Hentschel [1998] p. 66.

(10) The thought crossed my mind whether one could not construe astrophysics as a subdiscipline of astronomy using spectroscopic techniques, but even this is misleading, because other physical techniques were used in astrophysics as well: measurement of the Zeeman and Stark effects, comparisons with emission spectra obtained under varying temperatures in an electric oven, interferometric measurements, etc. On the institutionalization and demarcation of physics and chemistry see, e.g., Hiebert [1996] and Stichweh [1984],

(11) According to Forman, Heilbron, and Weart [1975] p. 35, with data from the *Adressbuch der lebenden Physiker* (1909): astronomy 111, mechanics 18, electrotechnology 32, other engineering 11, photography and optics 11. All other fields lower; the grand total of 440 physicists (in the widest sense) comes mostly from 155 college teachers, and many smaller entries.

(12) V. Schumann to N. von Konkoly, 3 July 1892 (HUBL, Nachlass 208), carbon copy in Schumann's correspondence booklet, original emphasis.

(13) On the social changes in the groups active in spectroscopy between 1859 and 1940 see, in particular, Lankford [1997] and Hufbauer [1986].

(14) Quotes from Pyenson [1978] p. 94. On Kayser's doctoral students see the appendix in Dörres and Hentschcl (ed.) [1997]pp. XLIII and lxxxiv-xcv.

(15) Cf. here pp. 357f. for a parallel to other classificatory sciences, and Sccord [1986] pp. 31–5 on Whewell's evaluation, in his *History of the Inductive Sciences* (1837), of almost all geological work as descriptive and phenomenological, with maps as their primary goal.

(16) See, e.g., Shinn [1993] on the birth of a research-technology community in France after 1900, and Shinn's as well as Jackson's contributions in Joerges and Shinn (ed.) [2001].

(17) See Shinn in Joerges and Shinn (ed.) [2001] p. 32, and H.W. Vogel [1880*b*] on the spectroscopic apparatus shown at the *Gewerbeausstellung* of 1879 in Berlin.

(18) Quotes from Shinn [1998] pp. 102 and 107; cf. there pp. 107f. for the contrast between a research technologist and an experimentalist or ‘measurement physicist’. On Rowland as an engineer-physicist hybrid see Kevles [1977] and Hentschel [1999*c*]. Shinn's example of Hermann Carl Vogel (*idem*, p. 38) does not hold because Vogel's steady career within astronomy does not exhibit the interstitiality so characteristic of research technologists. George Higgs, Victor Schumann, Fritz Lowe, or Frank Twyman are more appropriate examples.

(19) E.g., Johnston in Joerges and Shinn (ed.) [2001] p. 122 styles Michelson as a “prototypical research technologist” and discusses Fourier spectroscopy. Cf. also Hentschel [1998] § 5.4 on interferometric metrology.

(20) See Shinn in Joerges and Shinn (ed.) [2001] and Cahan [1985], [1989].

(21) Mirzoeff (ed.) [1998] p. 5. Alpers [1983] p. xxv acknowledges Michael Baxandall as the originator of the term, although it is apparently not actually used in *Painting and Experience in Fifteenth Century Italy* (1972). Even if its author only alludes to ‘cognitive style’ or ‘painting style’, his book certainly is *de facto* an encompassing analysis of the visual culture in the Italian Renaissance.

(22) Quotes from Lightman [2000] p. 651.

(23) Gerhard Wiesenfeld pointed out to me the relevancy of this last dimension. Examples include Thomas Young's, David Brewster's, and Hermann von Helmholtz's work on color perception, the sensory studies of Zöllner and many of von Helmholtz's students, Janssen's and Listing's physiological work on the eye, or Fraunhofer's study of spectral color sensitivity.

(24) See M.T. Brück [1983] pp. 382ff. for a useful finding aid. Cf. also Evans [1989] and H.A. and M.T. Brück [1988] for a biography of Piazzi Smyth. According to Copeland [1901] p. 194, he had gone on the excursions to Portugal in 1877, Madeira in 1880, and Winchester in 1884 because it was “practically impossible to study the solar spectrum in the smoky atmosphere of Edinburgh”. Cf. also a letter by Lecoq de Boisbaudran to C.P. Smyth, 5 March 1880 (ROE, 14.64, folder D): “I easily understand how your scotch climate would have rendered almost impossible the successful accomplishment of your great task. You certainly have done the right thing in going over to Portugal where the sky is so much clearer.”

(25) This attribution originates with Warner [1983]. On Smyth's interest in recording meteorological data and his photographic album concerning ‘Clouds that have been at Clova, Ripon’ (ROE, 20.154), see Ann Thomas (ed.) [1997] pp. 88–91, note 20 on p. 229, as well as pp. 94–6 there about his photograph of the Great Dragon Tree at Tenerife. His egyptological studies are described by H.A. and M.T. Brück [1988] chaps. 6–7 and Schaffer in Lightman (ed.) [1987] pp. 450ff.

(26) A. Herschel [1900] p. 161; cf. also Copeland [1901] pp. 191ff.

(27) For Brewster's album see Smith (ed.) [1990].

(28) See Wollaston [1809] and Schaaf [1989] for John Herschel's ‘tracings of light’ made with the *camera lucida*.

(29) Cf., e.g., Roth [1976*a*] p. 80 on Fraunhofer's construction of a *camera obscura* in the summer house at Benediktbeuren for local entertainment, and *ibid*. pp. 7If. for his work on microscopes and other optical instruments like heliometers. Henry Draper wrote his Ph.D. thesis in medicine on microphotography; Piazzi Smyth, John Herschel, and several other spectroscopists indulged in the art of stereoscopy, taking most of their photographs from two slightly different angles in order to enjoy an apparently three-dimensional view of their motifs. According to Crary [1995] p. 116, stereoscopes were “the most significant form of visual imagery in the nineteenth century, with the exception of photographs.”

(30) Cf. here p. 212 for his pioneering contribution to ultraviolet photography, and footnote 159 there for secondary literature about him.

(31) ‘On his father's tutoring in drawing and other graphic techniques and its importance in Müller's later versatility with respect to the illustrations in his textbook, which is also commented upon here on pp. 365f. see, e.g., Anon. [1875*b*], Warburg [1877*b*] pp. 114, 116. Cf. also Thieme-Becker [1907]ff., vol. 25 (1931) pp. 220, 223, 226, 240, and Kirschmer [1997] p. 330 on Muller, his father Franz Hubert (1784–1835) and his brothers, the engravers Andreas (1811–1890) and Constantin (1815–1850), and the church and portrait painter Carl (1818–1893).

(32) About this pioneering classroom use of posters, also including the solar spectrum several years before Bunsen and Kirchhoff's breakthrough in spectrum analysis, which led to the proliferation of their spectrum charts in poster format (cf. here pp. 14f.), see Muller [1858*a*] p. 10.

(33) Garrison [1995] p. 507.

(34) Listing's work on topology (his term) and the theory of knots is discussed in Epple [1999] pp. 80–7.

(35) See in particular Breitenberger [1993] pp. 6f. about Listing's artistic talent and his study grant in architecture and mathematics, provided by the Städelsche Stiftung in Frankfurt, which normally supported students of the graphic arts and architecture rather than of science. Incidentally, before accepting a call to a chair in experimental physics at Göttingen University in 1839, Listing lectured at the Höhere Gewerbeschule in Hannover.

(36) See Listing [1845] with two oversize lithographic plates depicting the human eye in various positions. On the color plate submitted to the Göttingen Academy of Sciences, sec here p. 32.

(37) See H.C. Vogel [1879*a*] pp. 143, 168; on the drawing technique he used for this atlas see here pp. 123f.

(38) G. Müller [1907] p. 324 reports that H.C. Vogel attended the Dresden Polytechnic 1860–62. and received private drawing lessons while still a schoolboy. According to Kempf [1915] p. 160. Lohse attended the Dresden Polytechnic 1859–62 and graduated with high honors.

(39) See Kempf [1915] p. 165 and Lohse [1883] on his sunspot drawings. Some of the figures accompanying this paper were printed by a special “autographic” procedure of zinc etching by the Photochemigraphische Kunstanstalt C. Angerer & Göschl in Vienna.

(40) See, e.g., Konkoly [1887] 151–4, 197ff. 275ff., Kempf [1915] p. 162, Tsvetkov *et al.* [1999] for a description of the extant remainder of Lohse's historical plate archive, including plates obtained between 1885 and 1889, bearing commercial emulsions by the companies Gaedicke, Beernaert, Schleussner, and Obernetter, as well as home-made emulsions based on iodo-eosine. See also here p. 188 on Lohse's failed attempts to photograph spectra in the infrared.

(41) See Langley [1874] and Axel Wittmann in Hentschel and Wittmann (ed.) [2000] fig. 20 on p. 86 and frontispiece for a comparison of Langley's drawing with a modern CCD photograph obtained in 1998 by Helmold Schleicher with the 70-cm vacuum tower telescope at Tenerife.

(42) On Langley's training and subsequent practical experience in civil engineering and architecture see, e.g., Abbot [1906] cols. 91f., Adler [1906/13] p. 2: he acquired “a mercantile training and skill as a draftsman which were of high importance in his later scientific and administrative career”.

(43) According to his file in the Heidelberg University Archive (H-IV-102/61), Hofmann had attended lectures by the mathematician Hartner in Vienna, the engineer Jacob Ferdinand Redtenbacher in Carlsruhe, and the geologists and mineralogists Johann Friedrich August Breithaupt (1791–1873), Bernhard von Cotta (1808–1879), and Karl Johann August Theodor Scheerer (1813–1875). See also Böckh [1892], Roth von Telegh [1892].

(44) McClean worked also as resident engineer at Barrow docks and for the Furness and Midland railway before retiring: see H.P.H. [1939] p. 505. Schumann—like H.C. Vogel and Lohse—had also been trained at a Royal Technical School (kgl. höhere Gewerbeschule), in his ease the one in Chemnitz, where he probably attended Weinhold's physics classes (see here p. 405). 1865–70 he was chief engineer at the machine factory of August Fomm in Leipzig-Reudnitz, and 1872–93 at A. Hogenforst's machine factory in Leipzig. Cf. also the carbon copy of Schumann's letter to Brashear, 5 July 1892 (HUBL, Nachlass 208) on his resigning directorship of the Leipzig machine factory in order to be able to devote his time fully to his spectrographic research.

(45) On Kekulé” s studies in architecture under Hugo von Ritgen (including descriptive geometry, perspective drawing, lithographic printing) prior to taking up chemistry under Liebig. see Kekulé [1890] p. 1307. On Wheeler's geometrodynamics see, for instance, his famous textbook on *Gravitation* (1973), coauthored with Charles W. Misner and Kip Thorne. It is replete with ingenious devices for visualizing Einstein's rather formal theory. Wheeler's training started with a freshman's course in engineering in 1927 and included a course in mechanical drawing; a summer job at the NBS in 1930 involved his working with W.M.F. Meggers on various band spectra. See Wheeler and Ford [1998] pp. 86, 97 and 31: “Ever since my mechanical drawing course as an undergraduate at Johns Hopkins University, 1 have enjoyed being my own artist and draftsman”; cf. *idem*, p. 73: “I love to illustrate ideas with sketches and diagrams”, and pp. 117, 235, 240, 300, 313, 342 as well as pl. Ill after p. 192 for nice examples.

(46) See Picon [1992], Ferguson [1977], [1992], and below pp. 447f. on visual thinking.

(47) For some hints along these lines see, e.g., Lenoir [1997] pp. 153–61 on possible connections between Guido Hauck's teaching of descriptive geometry at the Technische Hochschule Berlin and von Helmholtz's work on eye movements, or between the founding of Vienna's Museum fur Kunst und Industrie in 1863, the concurrent introduction of drawing class as a requirement in Austrian *Gymnasia*, and Ernst Brücke's researches into the physiology of colors for which he also experimented with prisms. Olcsko [2000] pp. 5f. argues for a broad connection between the popularity of perspectival drawing in the German states from about 1770 to 1850 and “cultural notions of precision and accuracy, linking refined measurement to visual perception.”

(48) On this shift away from regarding drawing as an educational component reserved for the nobility and the specially gifted to one broadly practiced by the bourgeoisie in everyday culture, see W. Kemp [1979], esp. chaps. VII and X on its institutionalization in the nineteenth century and the methods used, for instance, in drawing lessons since 1800 by Johann Heinrich Pestalozzi and his followers in Burgdorf, those by Nicolas-Toussaint Charlet at the Paris École Polytechnique, or by Horace Lecoq de Boisbaudran (1802–1897) and his pupils at the École de dessin des Arts decoratifs. On the history of technical drawing see also Feldhaus [1959].

(49) On Rowland's education at the Rensselaer, which included practical instruction in a teaching laboratory and courses in ‘graphics’ every semester (elementary drawing, topographical, geometrical, architectural, and machine drawing), see, e.g., Sweetnam [2000] pp. 4 and 35f. Cf. also Emmerson [1973] pp. 144–55, Ferguson [1992] end of chap. 3 on the emulation by the Rensselaer of the École Polytechnique (cf., e.g., here pp. 418–418 on Cornu's visual style).

(50) See Bigourdan [1908] pp. 49f. about Janssen's origins “d'une famille bien connue dans les Arts”, about his drawing talent since age 5, and about his frequent visits to ‘ateliers de peinture’ between ages 14 and 16; cf. Levy [1973] p. 77 about Janssen's lectures on effective illumination and sound-proofing of apartment buildings.

(51) On H.W. Vogel, see here pp. 188ff. and 248ff. Listing's Hannover period is mentioned in Breitenberger [1985] p. 701, [1993] pp. 12f.: Listing had to teach three hours of applied mathematics, five of mechanical engineering, and a hefty ten hours a week of technieal drawing of machines. Kayser is treated here on pp. 6, 244. and 365. See also Kayser [1936] pp. 142–70 on his Hanoverian period. Abney's work in infrared spectrography is discussed here on pp. 255ff.

(52) See Meadows [1972] p. 116; cf. also *idem*, p. 85 on Lockyer's cooperation at South Kensington with the Royal Engineers.

(53) See Rogers [1864] p. 11, and the MIT *President's Report for the Year Ending Sept. 30, 1875*, pp. 36–48 on the courses in ‘Free hand drawing’. ‘Mechanical drawing’, and ‘Descriptive geometry, stereotomy and drawing’.

(54) On this little known fact of Trowbridge's early career, see ‘Records of corporation meetings’, book II (MITA, AC 278), entries for 21 August 1868 on p. 129, January 1870, p. 169, ‘Records of committee on instruction’, book I (MITA, AC 272), 29 July 1868 on p. 54, and 10 December 1868 on p. 57. On Trowbridge sec here p. 376.

(55) In the winter terms of 1873/74, 1874/75, and in the summer term of 1875. according to Kangro [1954] p. 79.

(56) See Müller [1865/74], consisting of two volumes each of text and plates; Balmer [1887].

(57) The physics cabinet had been assembled by A.J. Ångström's teacher Fredric Rudberg, and the first student exercises took place in 1862, albeit initially for a maximum of 12 students. In the 1880s, a budgeted position for a ‘laborator’ was introduced, filled first by Claes Albert Mebius and from 1891 to 1896 by Knut Ångström. On this gradual emergence of an “övningslaboratorium”, aside from labs for the assistant and director and further rooms for instrument storage on the second floor of the new laboratory building for physics and chemistry (“Kemikum”), and later permanently built into the new physics institute (“Nya fysikum”) erected between 1906 and 1908, see Beckman and Ohlin [1965] pp. 23f., Sandström [1987], Haglöf [1987], and Widmalm [1993] pp. 55ff. According to Crawford [1996] pp. 13f., 42f., 83, despite a curncular reform in 1877 that made laboratory exercises obligatory for lower as well as for higher degrees, the physics cabinet was open for only a few hours a week.

(58) See Jay [1988*a*] p. 4 or [1988*b*] p. 66; cf. also Lynch [1991*b*] and Brain [1996] pp. 11ff. on ‘regimes of visuality’.

(59) See the *Oxford English Dictionary*, 2nd edition, vol. 13 (1989) p. 508.

(60) *Ibid.*, vol. 4 (1989) pp. 942f.

(61) *Ibid.*, definition (4h). For more about ‘trading zones’ and associated claims about the ‘disunity of science’ which—incidentally—I do not share, see Galison [1997] pp. 781–844.

(62) See Crary [1995]; cf. also Lenoir [1997] p. 164 for von Helmholtz's ‘spectrascope’ for determining complementary colors, and Brücke's variant of it, the ‘schistoscope’.

(63) See Chen [2000] pp. 121–8, esp. pp. 124f. for the quotes.

(64) See Schlich [2000] p. 50.

(65) See the editor's introduction to Mirzoeff (ed.) [1998].

(66) On ‘translations’ between different practices and the question of whether they are ‘disheveled’ or not, see also the discussion between Elkins [1999] pp. 152f. and Galison [1999] pp. 257f.

(67) See, e.g., here p. 452 about the difficulty of recognizing certain spectral features on an enlarged photograph, or here pp. 60, 84, and 85 about other such translation problems between spectral maps in different scales or modes of representation.

(68) Quote from M. Huggins [1882] p. 361. Cf. also interesting examples of retouched anatomical photographs in order to bring out details outside the focal plane in Hentze [2000] pp. 310ff.

(69) See Harvey [1980] pp. 13–26. Cf. also Blakemore and Harlcy [1980] p. 10.

(70) See Kaiser [2000] p. 51.

(71) *Ibid*., p. 75.

(72) See Gombrich [1960*b*] pp. 86, 89, and 298.

(73) On Fleck's concept of *Denkkollektiv* with its respective *Denkzwang*, see Fleck [1935].

(74) In the same way, Kent Staley [1999] reinterprets the oversimplified contrast between the image and logic traditions in Galison [1997] as a clash of ideals rather than a practical incommensurability.

(75) See Stafford [1999] pp. 3, 9.

(76) See, for instance, Winternitz [1967], van't Hoff [1878], and Hindle [1984] pp. 143f., respectively.

(77) On these connections see, e.g., the detailed obituary on Balmer by Riggenbach [1898], who already pointed out that “the arrangement of spectral lines reminded Balmer of the arrangement of columns in perspective”. Balmer himself suppressed the geometrical background of his reasoning, presumably not wanting to clutter his claim with such particulars about his heuristics.

(78) See Arnheim [1969], end of chap. 5. The art publisher DuMont has taken this insight as its motto: ‘One sees only what one knows’ (“Man sieht nur, was man weiß”).

(79) See Thibault [1827] chaps. 6–7, and pl. 21–7, and Balmer [1884], [1887]. Cf. also the introduction to Thibault [1827*b*] pp. 10–12 on Thibault's life and work as an architect, a member of the Institut de France, and *professeur* at the Royal School of Fine Arts.

(80) Even well-informed secondary sources lead one astray in this regard hy suggesting other graphical methods that would have been available to him for obtaining this series limit, such as H. Balmer [1961] p. 58.

(81) On the controversial issue of whether one can prove anything solely with pictures, see Arnheim [1969], end of chap. 12, or J. Robert Brown and Ronald N. Giere in Baigrie (ed.) [1996]. Both Arnheim and Brown claim that one can prove with pictures (p. 253), whereas Giere merely speaks of “the persuasive power of images” (p. 295).

(82) Cf. here p. 298 and eqns 8.2f. on p. 297. The only secondary text aware of Balmer's most crucial advantage is Banet [1970] p. 825, who points out that “Balmer's construction with the circumscribed circle was superior, since it enabled Balmer to visualize a series limit, and additional wavelengths as projections of this circle.”

(83) See H. Balmer [1961] pp. 51f. on his studies in Karlsruhe 1844/45, and on his later lectures (1865–88). Most biographical texts on Balmer incorrectly claim that he studied at the University of Berlin, but according to Imbritt Wiese at the Humboldt University Archive, Balmer's name does not appear in that university's records, *Amtliches Verzeichnis des Personals und der Studierenden der Friedrich-Wilhelms-Universität*, between the summer terms of 1844 and 1850. By 1849 Balmer had already submitted his Ph.D. thesis to the University of Basel. Among his papers (BÖB, Nachlass 133, folder nos. 19–20) we find various notes about the education of an architect and on civil engineering (‘bürgerliche Baukunst’), as well as a set of neat pencil sketches of architectonic elements, presumably stemming from his days as a student at the Bauakademie, one of the precursors of the later polytechnic in Berlin-Charlottenburg. Unfortunately, student records of the Bauakademie are only preserved from 1868 on.

(84) On Balmer's teaching activities see Riggenbach [1898] col. 2, Hagenbach [1921] p. 452, the appendix to Balmer [1884], and his papers (BÖB, Nachlass 133, folder no. 22), and the last page of a small blue booklet in folder 12, mostly containing his notes of a lecture on spectrum analysis by Hagenbach in the winter term 1890/91.

(85) See the separately bound clippings of Balmer's newspaper article ‘Basels obere Rheinbrücke’ (BÖB, call no. Techn. Conv. 28, no. 5), which appends a lithograph of his blue print. Balmer argued the feasibility of constructing such a bridge at that location whose opposing banks were of very different heights.

(86) See his papers (BÖB, Nachlass 133, folder no. 14, part 16, and folders no. 16–17). Balmer's pamphlet *Ueber Arbeiter-Wohnungen in und um Basel. Im Auftrage der Commission for Fabrikarbeiter-Verháltnisse* was published under the initials J.B. in Basel in 1853.

(87) See Wilhelm Balmer's memoirs [1924] and the unpublished reminiscences of Lydia Knapp-Balmer among the Balmer papers for elaborate portraits of Balmer's family life and *Lebenswelt.*

(88) See, e.g., the company's bound set of print samples of intricate pattern elements, typeface styles, and poster or sign lettering (BÖB, call no. BE I 40), dated c. 1865, and a pencil sketch of nested tetrahedra drawn on the back of an advertisement by the Verlagsbuchhandlung und Buchdruckerei Balmer & Riehm (BÖB, Nachlass 133, folder no. 15).

(89) Ferguson [1977] pp. 834f. and [1992] chap. 6.

(90) See, e.g., the contributions by Rosemary Gordon and David F. Marks in Sheehan (ed.) [1972], esp. pp. 65f., 99, and 326f. on correlations with other personality traits.

(91) Kaufmann [1980] pp. 138f., original emphasis; cf. *idem*., pp. 118f., 123, 142ff., 161, 167. For useful distinctions between various types of imagery see also Sheenan (ed.) [1972] pp. 20, 36f.

(92) Aside from Ferguson [1992], there are examples in Arnheim [1969], Kaufmann [1980] pp. 123, 126–8, Baigrie (ed.) [1996], Miller [1996], and Machamer *et al.* [2000].

(93) See, e.g., Bigourdan [1908] p. 56. Brain [1996] chap. 3 and app., and Thomas (ed) [1997] pp. 150ff. and 192f.

(94) See Lyman [1914*a*-*b*]; cf. also Sweetnam [2000] pp. 119–27.

(95) See Schuster [1881*a*] and here p. 307.

(96) See also Brand [1995] p. 177: “series were a sorting device, a means which coordinated lines with one another but did not, or did not yet, amount to anything resembling rotational analysis. Molecular spectroscopy was unable to break out of this pattern for more than a quarter of a century, until advances in quantum theory provided an avenue of escape.”

(97) See, e.g., Ritz [1903] p. 272, who found “a much better agreement of Rydberg's formulas with experiments” than Kayser and Runge's and Paschen and Runge's algebraically found fitting formulas. Cf. also Sweetnam [2000] p. 119 about the “relative absence of goals defined by formulas in Theodore Lyman's notebooks up to 1914”.

(98) Various crucial tests of photography's utility for astronomical purposes conducted in the 1870s failed miserably, with negative repercussions for photography's reputation among the professionals well into the 1880s. See Lankford [1987]. The expression ‘trial-and-error environment’ is taken from Thomas (ed.) [1997] p. 188.

(99) For good surveys see Waterhouse [1890] or Ostroff [1969]; cf. also here p. 155 and further references there.

(100) See Blum [1993] p. 291; cf. also Hammond [1989].

(101) For brief descriptions of the processes mentioned below, see here § 5.2. esp. Table 5.4, p. 156, for a loose parallel with a suggestion from the historiography of cartography to distinguish the eras of (i) chirographic or manuscript maps, (ii) typographic or printed maps, and (iii) photographic and telegraphic maps, see Blakemore andHarley [1980]p. 89.

(102) See http://astro.if.ufrgs.br/rad/elements/Elements.html, last modified on 19 April 2000; cf. also their ex position on spectroscopy and its history at …/rad/ espec/espec.html, or Neckel [1999] and http://www.hs.uni-hamburg.de/german/ forsch int/sonnspec.html for an online version of an absolute disk-averaged and disk-center solar spectral atlas.

(103) On the camouflaging of new printing techniques as old ones see, e.g., Taylor and Blum [1991] p. 131, Soulier [1997] pp. 162f., whose earliest examples of lithographic illustrations for scientific texts date from 1810 and 1811, and further quotes here on p. 120.

(104) Bardet [1926] pp. 28–9.

(105) See Daston and Galison [1992]; cf. also Galison [1998].

(106) Galison quotes the example of Morgan, Keenan, and Kellman's *Atlas of Stellar Spectra* (1943), discussed here on pp. 357ff., but he could also have referred to Nancy Houk's statement in McCarthy *et al.* (ed.) [1979] p. 55: “I hope that the principles outlined by Morgan and Keenan will continue to be followed and that a trained and experienced eye—and brain—will be around and ready to take a look.”

(107) C.P. Smyth to Mary Maclear, c. 1840 (Cape Archives, Maclear–Mann papers), quoted by Warner [1983] p. 111.

(108) For summaries of the history of these devices for graphic recording, see Hoff and Geddes [1959], [1962], and Brain [1996]; cf. also Chadarevian in Mazzolini (ed.) [1993] on botany, and Holmes and Olesko in Wise (ed.) [1995] on Helmholtz and Ludwig's kymograph in physiology. At the Goettingen Institute for Geophysics, a seismometer of Wiechert's design with a self-registering mechanism inscribing on carbon-dusted paper rolls has been in continuous operation now for nearly a century.

(109) This metaphor *la véritable rétine du savant”)* was coined by Janssen [1883] p. 128 in the context of his successful photographic recording of the rapidly changing solar granulation: see also Bartholomew [1976] and Thomas (ed.) [1997] p. 192. On the overlying issue of the professionalization of astrophysics and the widening gap between professionals and amateurs, see Hermann [1973], Lankford [1981].

(110) Kayser to H. Hertz, 1 December 1890 (DMM, autograph no. 2954).

(111) See A.S. Herschel to C.P. Smyth, 1 November 1880 (ROE, 14.64).

(112) A. Herschel [1900] p. 163, original emphasis.

(113) Smyth [1877*d*] (i) p. 218. For the significance of these observations in rainband spectroscopy, see here pp. 104ff.

(114) Sommerfeld [1919*a*] p. viii. As Paul Forman has pointed out in 1970, Sommerfeld retained this passage in the later editions of his canonical textbook of the old quantum theory.

(115) See, e.g., A.J. Ångström to Henry Draper, 21 February 1874: “Accept my most hearty thanks for the memoir and the spectrum. It is extraordinarily beautiful and the most perfect I have ever seen”, and again on 16 May 1874: “The negative is extraordinarily beautiful” (quoted in Reingold (ed.) [1964] pp. 258 and 260). M.C. Campbell to C.P. Smyth. 25 June 1880 (ROE, 14.64, folder C): “Take the lines of what is usually called the carbon band close to the hydrogen, […] only I have not put half the number [of lines into my drawing] nor can I put before you anything like the beauty of those line lines and such sharp divisions black as your hat.”

(116) See Huggins [1891*b*] p. 71, referring to Higgs [1888–1909].

(117) J. Herschel [1865] p. 363; on this religious journal and its impact, cf. here p. 290.

(118) See Langley [1874], and quotes from Jones [1965] pp. 106f. See footnote 41 on p. 430 above.

(119) See, e.g., Talbot's *Pencil of Nature* [1844-46], or David Brewster's *Album*, published in 1990 by Graham Smith under the fitting title *Disciples of Light.*

(120) See Wilson Alwyn Bentley and W.J. Humphreys, *Snow Crystals*, New York/ London: McGraw-Hill, 1931, and R.W. Wood: *How to Tell the Birds from the Flowers: A Manual of Flornithologv for Beginners, with Verses and Illustrations by Robert Williams Wood*, San Francisco/New York: P. Elder and Company, c. 1907; revised edn London: Constable, 1959.

(121) See Root-Bernstein (1985) p. 51. He also refers back to the inaugural lecture by the physical chemist Jacobus Henricus van't Hoff [1878], who advanced the even stronger argument—too strong in my opinion—that, on the basis of more than 200 case studies, “the most scientifically imaginative scientists […] were almost always artists, poets, musicians, and/or writers as well”.

(122) Abney *et al*. f 1896] p. 258.

(123) Smyth [1878*] pp. 38f., original emphasis.

(124) Ibid., p. 39, original emphasis.

(125) Smyth [1878*b*] p. 40.

(126) See Edgerton and Lynch [1988], esp. p. 184 for the quote, and pp. 205ff. for the various stages of image processing.

(127) On Hennessey see here p. 100, on Piazzi Smyth's early cartographic and geodetic work see, e.g., Warner [1983] chaps. 3–4, H.A. and M.T. Brück [1988] pp. 5ff., and on Secchi's little known side activities see Brück [1979*b*] p. 18. On Rowland's training in geodesy and surveying at the Rensselaer Polytechnic Institute see Sweetnam [2000] p. 36, and Emmerson [1973] pp. 154f.

(128) See the *Oxford English Dictionary*, 2nd edition, vol. 9 (1989) p. 348; cf. also Blakemore and Harley [1980] p. 9 for other definitions.

(129) See again the OED (previous footnote), definitions (1f) and (1g) of ‘map’, and definitions (1e) and (1f) of ‘to map’.

(130) On the numerous commissions for official topographic maps of this self-described ‘graveur en architecture’, see here footnote 126, p. 169 above.

(131) For a good survey and some interesting thesis on their ‘evolutionary’ succession, see Blakemore and Harley [1980] pp. 20f., citing a study by Denis Wood (1977).

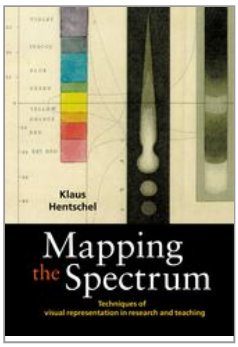
(132) See here § 2.9 and 7; cf., e.g., Lynch [1991*a*] pp. 209ff. or Schlich [2000] p. 45 on the superposition of different modes of visualization of the same object as a control technique.

(133) See, e.g., Staley [1999] pp. 198f.

(134) For the following see Owen and Pilbeam [1992], esp. pp. 180–6 for a survey of the various maps of Great Britain and its various regions issued by the Ordnance Survey between c. 1800 and 1990.

(135) Crone [1953*c*] p. xi, quoted here as an example of similar tendencies in many standard accounts of the history of cartography. For a critique see Edney [1993] p. 56; cf. also Blakemore and Harley [1980] pp. 17–23 about the ‘progressive paradigm’ of traditional cartographic history.

(136) See Woodward [1974]; cf. also Blakemore and Harley [1980] pp. 12f., 89f.



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
Prof. Dr. Klaus Hentschel

Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

(p.467) Appendix 1

Appendix 1: Survey of maps of the solar spectrum 1802–1900. Abbreviations in col. 3: C copper engraving, *E* metal relief engraving, *Se* steel engraving, *Le* stone engraving. *Lg* lithograph, *H* heliogravure, *A* autotype, *Ht* heliotype, *P* photograph. *At* Albertype, *dCIP* dry collodion photograph, *wClP* wet collodion photograph, *Gbe* gelatino-bromide silver emulsion, *D* daguerreotype; *cLg[V]* means color lithograph based on visual observations, *o* in col. 5 means without overlap, that is, the total spectrum length, e means length of each, t total length; col. 6 with the average density *R/L* refers to the ratio ‘wavelength region [in Å)/length of representation [in cm]’; minimal overlap of adjacent maps were counted twice; *R/L* thus gives an approximate measure of the scale of representation. Wavelength measurements prior to 1868 have been converted to Å-units for comparison.

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Wollaston	1802	*1×Lg[V]*	(B−H)	*c2.7*	1110	simple flint glass prism	J. Basire	First drawing indicating dark lines interpreted as color boundaries (‘’ primary divisions‘‘)
Fraunhofer	1814/15	*1×E[V]*	(7610–3900)	36	c.103	prism spectroscope mounted on theodolite, vernier protractor, achromatic telescope 40 x	Fraunhofer	354 dark lines, used as color markers for measurements of refractive index
Brewster (Gladstone)	1833–41 (1860)	*2×C[V]*	(7610–3900)	2x74 = 148	c.25	prism spectroscope mounted on theodolite	J. Basire	More than 2000 dark lines on 4x Fraunhofer's scale. details in 12 x

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
B. Powell	1839	*E[V]*	A-I-(7610–3900)	c.14	c.265	prism spectroscope, achromatic telescope 10 x	B. Powell	Only main lines together with a scale indicating angle of deviation
J. Herschel	1840	*Lg*	*ε-G* (1.4µ-4200)	13	c.250	Fraunhofer glass prism	J. Basire	Thermograph of solar spectrum registered on smoked wet paper incl. heat spots of lines *a* — *s* in IF
E. Becquerel	1842	*1×lg[P]*	X-A-P-(8860–3360)	26.8	c.19	quartz prism, silver bromide emulsion	Dulos	First permanent spectrum photography
J.W. Draper	1843/44	1 *E[D]*	-γ-P-(9800–3300)	16.8	c.387	silver iodide emulsion	J. Basire	‘Tithonograph’ incl. near IF and UV with *α*, *β*, *γ*

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
G.G. Stokes	1852	1 *E[V]*	H-P (4000–3360)	17.5	c.36.5	quartz optics, phosphoro-genic screen	J. Basire	New line groups in the UV
Kirchhoff K.Hofmann	1861/62 (1866)	4x2Lg[V]on 6lith stones	D-F-; A-D;-G-(7600–4300)	8x33 = 264	12.5	Steinheil 4 flint-glass prism spectrograph	C. Laue (F. Barth)	Arbitrary Kirchhoff scale; first map containing chemical identification of many lines, incl. 70 iron lines
J. Müller	1862	1 *P[D]*	G-R (4350–3100)	15	c.83	quartz optics, various photosensitive surfaces	J. Muller & v.Babo	Photography of composite drawing based on several UV photographs, varying exposure times

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Rutherfurd	1862/63 (1872)	*15wCIP* (At)	-b-H-5200–3900	210 t	c.6	3 bisulphide of carbon prisms, photographic camera without objective lens	Rutherfurd (Lith. Inst. A.Schiitze)	UV photography that claims 20x resolution compared to Kirchhoff (lithograph in Secchi [1874]), Kirchhoff scale
Mascart	1864	*2xLg [wCIP]*	G-T. c. 4315–3321	2 x 31.4 = 62.8	c.20	Babinet goniometer, quartz optics, quartz and spar prism. Nobert grating	Dulos	First detailed study of the UV part of the spectrum with c.700 lines

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Ångstrom/ Thalén	1861/62 (1866)	2 x 2*Lg (V + wCIP)*	G-H-. c. 4315–3321	4x28 = 112	8.8	single bisulphide of carbon prism of 60°, Steinheil condensor of c. 90 mm aperture and 3 m focal length, electric-arc between iron poles. Bunsen battery of 50 cells	Schlachter & Seedorff (Stockholm)	Violet and near-UV extension of Kirchhoff [1861/62] with Kirchhoff s numerical scale: comparison with c.460 iron arc spectrum lines

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
v.d.Willigen	1866	*2E[V]*	-A-H- 7610–3960	29.3	c.22	3 Nobert gratings. Steinheil prism of 45°. Meyerstein spectrometer	E.Molenaar	Precise wavelength determination of 51 dark lines and comparison of Nobert gratings, map with enumerated main lines, based on prismatic spectrum
Ångstrọm	1868	6 x *Lg[V]*	-a-H 7320–3933	11 x 32.8 ≃ 348 t	9.4	Pistor & Martins theodolite spectrometer and Nobert grating with 1331 lines/mm	Gen. Stab. Lith. Inr.	First ‘normal’ spectrum with numerical scale 10^{-10}m [=later |Å|; standard until 1886

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Janssen	1870/71	1 *E[V]*	-C-D-6595–5890	32.4	c.28	5 flint-glass prisms	E. Pérot	Comparison of high and low sun for C and D group
Cornu	1871/74	2 x *Se [CIP]*	-h-0 4125–3435	33.2+35 = 68.2	10	Nobert grating of 1801 ruled lines, ε = 0.0037mm, flint-glass prisms and Iceland spar	Dulos & C. Legros	Near-UV extension of Ångstrom (in same manner and scale) up to the absorption limit of crown or flint glass
Lamansky	1872	*Lg*	IF-G-??-4200	c.17.5	c.200	flint-glass and fluorite prisms, thermo-multiplier	A. Schiitze Lith. Anstalt	Rediscovery of Draper's lines α, β, γ in the IF region

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
H. Draper	1873	2 x *At [CIP]*	G-O/-H-4350–3440; 4205–3766	28.4 33.8	32 13	Rutherfurd diffraction grating	E.Bierstadt	’’absolutely unretouched … represents the work of the sun itself‘‘
H.C.Russell	1877	1 *Lg[V]*	-D_1-D_2-5896–5889	3.5	2	Hilger prism spectroscope	-	Zoomed comparison of D region in London, Oxford, and Sydney
H.C.Vogel & G. Müller	1879	2 × 8 *Lg Lg(V + wCIP)*	-E-H_2-5405–3895	16 × 30.6 = 489.6	3.1	Schröder spectroscope with 4 Rutherfurd prisms, Hilger micrometer	Gebrüder Burchard	High dispersion map, in the -F-H region based on wet collodion photographs

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Abney	1880	3 × *Lg [CIP]*	A-9830–7600	2 × 41.7+ 37.7 + 34 = 155.6	14.4	Rutherfurd diffraction grating	West Newman & Co.	Near-IF extension of Ångstrom 1868; dyed collodionfilms containing silver bromide
Winlock	1880	*l* × *Lg[V]*	b group 5192–5161	12.3	2.5	Rutherfurd diffraction grating	?	Detailed “chart” of b group as a good test group for spectroscopes
Cornu	1880	4 × *Lg[P]*	-h-U 4125–2948	33.2,35, 31.19.5 118.6t	9.9	Iceland spar prism, Nobert grating and Brunner grating	C. Legros	Further UV extension of Cornu [1874] up to the limit of atmospheric absorption

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
G.Müller	1881	3 + 1 *Lg[V]*	-B-H-6950–3900 6600–3900	3 × 33.5 100.5 t 25	30.4 108	Schröder spectrometer, flint-glass prism	Grohmann (Berlin)	Medium and small dispersion for orientation purposes
Lockyer	1881	*Ht + LglCIP]*	-H-K-4005–3895	43.5	2.5	Rutherfurd diffraction grating	Lith.enl.by Corp.Murray, Ewings	Begun in 1875, resumed around 1880 with Rutherfurd-grating; enlargement done at School of Military Engineering, Chatham

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
C.P. Smyth (Madeira)	1881/82	17 x 7*C*	-A-G-	c.7–20		Rutherfurd grating, Hilger optics	W. & A.K. Johnston	Revision of 21 parts in the red half of the visible solar spectrum; ‘symbolic’ drawing
Fievez	1882/83	*7 × 3Le[V] on 1 lith. stone*	-C-F-6600–4500	7 × 3 × 28.3 = 594.3	3.5	two high-dispersion half prisms. Rutherfurd grating	Gheselle, Lith. de G. Severeyns	High resolution map that resolves bands into distinct lines, but true haze by dotted surface shading

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Langley	1883	*Lg*	-H-Ω-28000–3000	44	568	Hilger flint-glass prism, Rowland concave grating of very short focus, bolometer	A. Schanz	Survey of far-IF region in two different plots (prismatic and normal)

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
C.P. Smyth Winchester spectra	1884/87	60 *Lg*	-A-h-7697–4032	60 × 24.2 = 1452	2.5	Rowland grating of 3.5 × 5′ with 14438 lines/in	W. & A.K. Johnston Edinburgh	Comparative map of Ångström [1868], Cornu (1880), Fievez [1883], and 3 series of Smyth's own ⊙ obs. June-July 1884; printed with 12 different monochromatic backgrounds for different spectrum regions
Abney	1886	*A[CIP]*	-Z- × X_{IV} 9870–7145	ll × 29.6 + 2.8 328t	8.3	Rowland concave grating in Abney mounting	-	IF extension of Ångstrom

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Thollon	1886/90	33 *Se[V]*	-A-b-7690–5160	33 × 33.5 1107.5 t 1023*o*	2.25	Laurent spectroscope with high-dispersion fluid prisms, Gauthier micrometer	C. Legros	Each segment in 4 × representation: sun at 10°, at 30° in normal and dry atmosphere, and without atmospheric lines

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Rowland	1886	7 × 2.3)*P*	5795–3200	89 e c.1000	c.2.8 c.2.2	Large Rowland concave grating, various color filters-	-	scrolled photograph of the sun's normal spectrum mounted on linen, overlapping orders below 3200 Å and large overlaps in other intervals
Rowland	1888	10 × 2*P*	6953–2967	91 e c.l200t	3–4	ditto	Jewell, photogr.	2nd series; improved photographic quality, served as international standard, nearly 20 000 lines altogether

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Higgs	1888	4 × *P*	4405–3860	3 × 30 + 1 × 19	c.10	high-dispersion prism, cylindrical lens	-	Good photographic quality, sharply defined lines
Lommel	1888/90	3 *Gbe*	Z-B-9500–6870	16e	c.6.6	photography of phosphorescent screen	Lommel L. Fomm	Phosphoro-photography, i.e., photo of screen e × posed to the spectrum (in particular infrared)

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
C.P. Smyth	1889	2 × 13*Gbe*	4450–4020 4030–3650	25 e 4m t	2.2	plane Rowland grating	unpubl.	2 enlarged photos of each section for comparison, 13 plates of part 1 replicate pis. 49–61 of C.P. Smyth (1884); pi. 62–74 cover near-UV
McClean	1890	13 × *A[P]*	7820–2985	35.5 e 461.5 t	c.10.4	Rowland plane grating, absorption screens	Direct Photo Engr.Co.	Comparative photographic spectra of the high and low sun, enlarged 8.5 × from negative

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Higgs	1894	c.32 × *P*	8345–2985	30.5 e, overlap	c.7	concave Rowland grating with 14 438 lines/inch	Higgs	Normal solar spectrum with comparison spectra of superposed order and under different conditions; 1894 full spectrum; 1896 in a ‘consecutive wavelength ed.’
Spée	1899	17 × 2*Lg*	b-f 5166–4383	c.33e	c.l	same as Thollon	Neirynck, Pepermans & Henrijean	Continuation of Thollon's atlas up to line f

Appendix 1

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Langley	1900	*Lg*	-Y-A-53400–7500	8 × 50 400t	115	rock-salt prism, Rowland concave grating, bolometer	A. Hoen & Co. Lith., Baltimore	Normal map of lower IF region in spectral region inaccessible to contemporary photography

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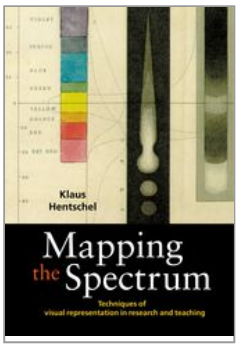

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Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

(p.470) Appendix 2

Survey of maps of terrestrial spectra 1835–1949. Abbreviations in col. 3: *C* copper engraving. *E* metal relief engraving. *Lg* lithograph. *cLg[V]* color lithograph based on visual observations; *A* autotype. *P* photograph. *wCIP* wet collodion photograph. *Gbe* gelatino-bromide silver emulsion. *H* heliogravure. *Ht* heliotype. *Pt* phototype. *PMR* photomechanical reprint. Col. 6 with the average density *R/L* refers to the ratio “wavelength region 1 in A]/length of representation [in cm]'; regions of minimal overlap of adjacent maps were counted twice; e in col. 5 means length of each, t total length. Wavelength measurements prior to 1868 have been converted to Å-units for comparison.

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Wheatstone	1835/61	*Lg*	“red-violet”	9.8 in 1861	c.300	normal prism with micrometer eye-piece	not given	“Table of bright lines” in 6 spark spectra (Hg, Zn, Cd, Bi, Sn. Pb) and in soda flame, only publ. in 1861
W.A.Miller	1845	*cLg*	B-G-. c.7000–4000	15	c.200		J. Basire	“sketches of spectra of colored flames” for 6 substances such as $CuCl_2$, H_3BO_3 $SrNO_3$, $CaCl_2$. $BaCl_2$, and 6 gaseous absorption spectra

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Masson	1851	9 *E*	“rouge-violet”	c.7e		spark inductor, Babinet goniometer. Guinand flint prism	E. Wormser N.Rémond imprim.	“tableau” of 9 spark spectra (Fe, Cu. Sn, Pb. An, C. Bi.Zn, Cd)
Bunsen/ Kirchhoff	1860	7 *cLg*	″	16.6 e	c.l 80	Steinheil prism spectrograph. Bunsen burner	Creuzbauer (Carlsruhe)	Spectral map showing characteristic lines of 6 different elements (Ka, Na, Li, Sr, Ca, Ba) and Fraunhofer lines in the solar spectrum

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Kirchhoff/ Bunsen	1862	9 *cLg*	″	16.7 e	c.l80	″. Steinheil 4-prism spectrograph	Lith.Anst. E.A. Funke	Characteristic lines of 8 different elements (including Rb and Cs discovered by Bunsen)

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Bunsen	1861	8 *cLg*	″	41.5 e	c.72	ditto	Typogr.lith. art.Anstalt Zamarski & Dittmarsch	Color spectrum map for posting on laboratory and classroom walls (total size 63.5 × 93 cm), showing spectra of 7 elements and solar spectrum with the dark Fraunhofer lines extended as orientational markers

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
W.A.Miller	1862	*c* 40 *E[P]*	c.4300–3000	9.4 e	c.144	quartz and high-dispersion carbon bisulphide fluid prisms, induction coil	J. Basire	UV spark spectra for 48 different metals and alloys
Dibbits	1863	4 × *Lg*	-a-H-	c.28e	c.100	small prism spectroscope	v.d.Weyer	Band spectra of CH flame, CN flame in 0_2, ammonia flame in C_2

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Huggins	1864	25 *E*	7285–3975	2 × 37.5 = 75 e	44	Browning 6-prism spectroscope, Dollond micrometer, induction coil. Grove battery	J.Basire	24 metallic spark spectra (Na, K, Ca, Ba, Sr, Mn, Tl, Ag, Te, Sn, Fe, Cd, Sb, Au, Bi, Hg, Co, As, Pb, Zn, Cr, Os, Pd, Pd) and air spectrum as reference standard, Kirchhoff scale
Brasack	1864/66	14*cLg*	c.6300–3900	12.7 e	c.189	Standard spectroscope, Rühmkorff inductor	Lith. Anst. A. Schenck	14 metallic spark spectra printed as in Bunsen 1860

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Diacon	1865	4 *E[V]*	c.6300–3900	16.4 e	c.140	gas burner, chloride flames, standard prism	Dulos	Flame spectra for 4 metallic compounds (CuCI, CuBr, BiI_3,CaFl)
Thalén	1866	46 *Lg*	6970–3960	59.8 e	50.3	Nobert grating	Schlachter & Seedorff	Comparison of 46 metallic spectra
G. Salet	1873	2 *E[V]*	7000–4000	12e	250	single prism	Dulos	Comparison of 25 metalloid spectra: Br, 1, S, Se, Te. N. P. and compounds of Si and Pb.

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Lecoq de Boisbaudran	1874	29 × (2–3) *C[CIP]*	c.6750–3900	17.7	161	Duboscq flint-glass prism spectroscope, Bunsen burner, and small spark inductor	Dulos	Several metallic spark spectra with emphasis on interesting details
Lockyer	1874/75	2 × 3 *Ht*	c.4500–3900	18.2–19.2	c.31			Ca, Sr, Ba spectra
Ångstrom Thalén	1875	5 *Lg*	6970–3960	59.8 e	50.3	6-prism high-disp. spectro-scope, induction sparks created by Holtz induction machine, Ruhmkorff coil, Bunsen battery with 50 cells	Schlachter/ Seedorff (Stockholm)	Band spectra of CH, CO, NO2, and C in gas tubes

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
″	1875	3 *Lg*	5650–5395 4945–5180	25 23	10	ditto	″	Details in band spectra of CH and CO
Capron	1877	4 × 36,4 *[wCIP]*	-b-H-5200–3950	11.4 e	c.110	Browning spectroscope, large Ruḥmkorff coil, sparks 2 in long	G.H.Murray (Surrey Photo.Co.)	Spark and electric arc metallic and gaseous spectra, exp. timed5 min
Schuster	1879	*E*	6200–4200 5330–5160	80 16.3	c.25 c.10	carbon-free tubes both Plụcker and end-on, Sprengel air pump, flint-glass prisms	West Newman & Co.	Elementary and compound oxygen spectrum, zoomed band spectrum resolved into lines
Abney & Festing	1881	54*Lg [CIP]*	12000–7000	13.3 e	c.330	Rutherfurd diffraction grating	West Newman & Co.	Absorption spectra of various liquids

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
C.P. Smyth	1880/82 (1883)	2 × *Lg*	8400–4230	17.7	235	1-prism spectroscope, telescope 10 ×	A. Ritchie & Son (Photolith.)	Gaseous spectra in end-on tubes under small dispersion
Liveing/ Dewar	1882	*Lg*	4100–2160	17 × (3 × 33) = 99 t	19.6	improved goniometer, Rutherfurd grating	West New-man & Co.	Comparative survey of UV spectra of 17 elements, measured by modification of Mascart's method
″	1882	*Lg*	2950–2167	4 × 34.5 + 16.3 = 154	5	″		Detailed map of UV spectrum of Fe and Cu in arc andspark
Liveing	1883	7 × *P* 9 × *Lg* 2 × *L*	varying 4000–2000	11 19	var. 20	ditto		UV spectra of several metals (see preceeding entries)

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Cornu	1883	*2 × L*	6030–5875	2 × 32 = 64	2.4			Detailed map of terrestrial lines in the D region
C.P.Smyth	1884 (1887)	*29 × Lg*	8943–3872	63.1 e	80.3	Hilger bisulphide of carbon prisms, telescope 36 ×, end-on vac.tubes	Th. Heath (A. Ritchie & Son)	Micrometric measures of gaseous spectra of CH, CO. H, O, and N in vacuum tubes under high dispersion
A.Herschel	1884/86	*Lg*	5198–5165	73.3	0.86	ditto	ditto (Photolith.)	Search for recurrent pattern in CO band spectrum as explored by Piazzi Smyth

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Hartley/ Adeney	1884	16*Lg [CIP]*	4600–2000	20.5 e	126.8	small Rutherfurd grating and Browning spectroscope mounting, quartz lenses	West Newman & Co.	Near-UV spectra of 16 elements (Mg, Zn, Cd, Al. In, Th. Cu. Ag. Hg, C, Sn. Pb. Te, As, An, Bi)
″	1884	10 × *Lg*	4700–2000	10 × 29.5 295 t	9.15	ditto	″	Violet and near-UV spectrum of air
Kayser/Runge	1888	20 *P*	6604–2240	20 × 19.9 398 t	10.9	flat Rowland grating	Kayser	Detailed study of Fe arc spectrum used for interpolation of other lines

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
″	1889	6 *P*	5165–4990 3740–3884 etc.	6 × 19.5	c.8	ditto with 568 lines/mm	″	Detailed study of cyanogen band spectra in selected regions; discussion of series formulas
Kayser/Runge	1890–94	*Lg*	c.6700–2250	35.8 e	c.124	ditto	E.Laue (Berlin)	Maps of metallic spectra plotted against wave number for identification of spectral series

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
McClean	1891	*A[P]*	c.4130–3760	36.5 e	c.10	Rowland plane grating with 14438 lines/inch. absorption screens	Direct Photo Engr. Co.	comparative photographic of metallic spark spectra (Fe. Mn. Co. Ni, Cr, Al. Cu, Ru. Ro. Pd, Ag. Au. Pt.
Demarçay	1895	2 × 10 *Gbe*	c.7100–3400	27.1 e	c.136	Flint-glass prism, quart/ optics		20 metallic spark spectra. 6-fold enlarged
Crew	1895	8 × *P*	5900–2400	28.5 e	c.125	Rowland concave grating. 10 ft radius. 14438 lines/in	-	Arc spectra of magnesium compared with iron arc. Ag-print on Li-paper, mounted on thick cardboard

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Crew	1896	8 × *P*	6500–2100	28.5 e	c.125	ditto	-	Arc spectra of Zn and Fe. mounted on thick cardboard
Eder/Valenta	1904	60 × (3–5)*H[P]*	c.5600–3625 5600–3050 2280–2000	c 22 81 22	c.90 32 12.7	glass and quart/ spectrograph	heliographic copies	Normal spectra of many elements in flame, arc and spark, and under special conditions
Hagenbach/ Konen	1905	28 × 10 *H[P]*	5000–2500 5500–3000 6700–4200 7000–4500	14.7 e	170	Rowland concave grating with 1m radius of curv., 20000 lines/in	celluloid. orthochromatic films	Photogravures of emission spectra of 68 elements in arc. spark, and flame on small scale for element identification

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Coblentz	1905–08	≥ 1000	1 ≤ 15/μm	≤ 10cm	1000	mirror spectrometer, rock-salt prism. Nichols radiometer, and Nernst heater	Carnegie Inst.	IR absorption, transmission, and reflection spectra for misc. mostly organic substances
Uhler & Wood	1907	26 *Ht*	6200–2000	16.5	c.25	Nernst lamp, small concave grating, wedge shaped abs. cell	Heliotype Co. (Boston)	Atlas of absorption spectra for misc. mostly organic absorbing media, chiefly aniline dyes
Buisson/ Fabry	1908	7 × 4 *Pt*	6680–2320	22 e	c.13	big concave Row land grating	Imp. de Sémaphore (Marseilles)	Improved photograph of Fe arc spectrum, replacing Kayser & Runge (1888)

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Mees	1909	many	7500–3500	c.9e	c.136	small prism spectroscope. Nernst lamp	Wratten & Wainwright emulsion	Absorption spectra of dyes and filters, complementing Uhler & Wood in the red and near IF
Gissing	1910	*A*	8000–3800	15.3	c.258	large Hilger prism, Cox induction coil, interrupter, accumulators		Spark spectra of 50 metals, Wratten& Wainwright panchrom. plates

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Eder/Valenta	1911	53 × (12–15) *H[P]*	7000–3300 6900–4200 5200–2500	c.25e	148 108	glass and quartz spectrograph	helio-gravures	Atlas of "typical" spectra of many elements and some molecules in flame, arc and spark, made at the Imperial Institute of Military Geography and at the k.k.graph. Lehr- und Versuchsanstalt (Vienna)

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Lecoq de Boisbau-dran & de Gramont	1923	19 × (2–3) *PMR*	c.5000–2200	c.20	c. 150	low disp. prism spectrograph		Flame and spark spectra of various salts, metals, and minerals; ultimate lines for Pb, Ag, Ph, Te, Ti.
Bardet	1926	54*Lg[P]*	3500–2500 various	12? × c.20	c.9	Féry spectrograph with Cornu prism, carbon electrode arc	Imp. Catala Frères (Paris)	Arc spectra of c.40 metals and compounds, grouped together in 6 chemical groups

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Löwe	1928	16 *PMR*	various	4 × c.l0	c.50	Zeiss spectrograph, de Gra-mont's type of spark obtained in acidic solutions of resp. element	Steinkopff, Dresden	Atlas of the characteristic lines in the spectra of low dispersion (between 50 and 150 Å/cm) of 48 chemical elements, photographed at 1, 0.1, 0.01, and 0.001 % concentrations of the solution

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Crook	1935	20+4	5671–2294	35.5	2	concave grating spectrograph, Pfund arc	special emulsions	Atlas for metallurgical spectrum analysis with 20 high-dispersion plates displaying the ultimate arc lines of 31 metals, and 4 plates only the iron spectrum
Gatterer & Junkes	1935	21 13	8388–2242 4650–2242	26	c.4	spectrograph of the Vatican astrophysical lab.		High dispersion arc spectrum of iron from 8388 Å, and spark spectrum of iron from 4650 to 2242 Å

Appendix 2

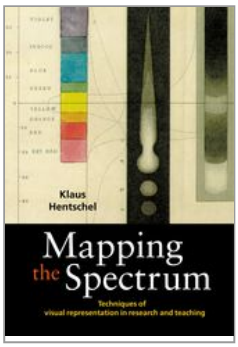
Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Gatterer	1937	28 × 6	5900–2200	38	17	Steinheil prism spectrograph GH	on Lupex paper	Ultimate lines in arc and spark spectra of 30 elements, glossy prints
Gößler	1942	2 × 7	4555–2227	23	12	quartz spectrograph Q24	contact prints	Arc and spark spectrum of iron, combined with labeled ultimate lines of most important elements

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Gatterer & Junkes	1945	45	7600–2265 4530–2265	38	38 20	mainly Q24	ditto	Atlas of the ultimate lines of the rare earths; spark spectra from 4530 Å, arc spectra from 7600 Å on; glossy prints on Lupex paper

Appendix 2

Name	Year	Type	λ region R[Å]	Length L [cm]	R/L (Å/cm)	Noteworthy instrumentation	Illustrator or printer	Remarks
Gatterer & Junkes	1949	42	6340–2100 6340–2265 6340–2039	30 × 40	65 10	see above	ditto	Atlas of the ultimate lines of rare metals and some metalloids in arc, spark, and high-frequency spark; pi. 40–42: hafnium arc and spark spectrum 6340–2260Å at *R/L* ≈50



Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
Prof. Dr. Klaus Hentschel

Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

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Entries here are listed chronologically under author's name, followed by coauthored works. Coauthored works are listed in the name sequence given in the original publication. Authors' full names are indicated only once, with first initials for coauthors. Diacritical marks are generally ignored, with the exception of German *Umlaute*, which are treated as if the relevant vowel were followed by the letter e: *Ä* →*Æ,ö* → *œ; B* → *ss* ss.

Bibliographic Abbreviations

AaA: Astronomy and Astrophysics, Northfield, Minnesota

AAOHC: Annals of the Astronomical Observatory of Harvard College, Cambridge, Mass.

ABRSI: Annual Report of the Board of Regents of the Smithsonian Institution, Washington DC

AJP: American Journal of Physics, Lancaster

AJS: American Journal of Science, New Haven

AMT: Archives du Musée Teyler, Haarlem

AN: Astronomische Nachrichten, Kiel and Berlin

Ann.Chem.Pharm.: Annalen derChemie und Pharmazie, Heidelberg

Ann.chim.: Annales de chimie et de physique, Paris

Ann.Phys.: Annalen der Physik, Leipzig

Ann.Sci.: Annals of Science, London

AON: Annales de l’Observatoire de Nice, Paris

AOROE: Astronomical Observations made at the Royal Observatory, Edinburgh

AP.J.: Astrophysical Journal, Chicago

App.Opt.: Applied Optics, Washington

APT: American Physics Teacher, Lancaster, Penn.

ASENS: Annales Scientifique de l’École Normale Supérieure, Paris

AU: Art Union (later renamed Art Journal), London

BDCG: Berichte der Deutschen Chemischen Gesellschaft, Berlin

BJHS: British Journal for the History of Science, London

BJP: British Journal of Photography. London

BMFRS: Biographical Memoirs of Fellows of the Royal Society, London

BMNAS: Biographical Memoirs of the National Academy of Sciences, Washington

BSCF: Bulletin de la Société Chimique de France, Paris

CN: Chemical News, London

CRAS: Comptes Rendus hebdomadaires des Séances de l’Académie des Sciences, Paris

DAB: Dictionary of American Biography, New York

DNB: Dictionary of National Biography, Oxford

DSB: Dictionary of Scientific Biography, New York

Enc.Brit.: Encyclopædia Britannica, New York and London

Hist.Phot.: History of Photography, London

Hist.Sci.: History of Science, Cambridge

HSPS: Historical Studies in the Physical (and Biological) Sciences, Berkeley

JCP: Journal für Chemie und Physik, Halle

JCSL: Journal of the Chemical Society, London

JFI: Journal of the Franklin Institute Devoted to Science and the Mechanical Art, Philadelphia

JHA: Journal for the History of Astronomy, Cambridge

JHUC: Johns Hopkins University Circulars, Baltimore

JISI: Journal of the Iron and Steel Institute, London

JOSA: Journal of the Optical Society of America and Review of Scientific Instruments, New York

JPC: Journal für praktische Chemie, Leipzig

(p.472) J.Phys.: Journal de Physique et le Radium, Paris

JPR: Jahrbuch für Photographie und Reproductionstechnik. Vienna

JPS: Journal of Photographic Science, London

JPSL: Journal of the Photographic Society of London

KSVAH: Kongliga Svenska Vetenskaps-Akademiens Handlingar, Stockholm

M.Berlin: Monatsberichte der königlich-Preussischen Akademie der Wissenschaften, Berlin

MNRAS: Monthly Notices of the Royal Astronomical Society, Oxford

MSSI: Memorie della Societa degli Spettroscopisti Italians, Pavia

Nature: Nature, a Weekly Journal of Science, London

Natw.: Die Naturwissenschaften. Wochenschrift für die Fortschritte der Naturwissenschaften, der Medizin und der Technik, Berlin

NDB: Neue Deutsche Biographic, Munich

Obs.: The Observatory, Hailsham, Sussex

PAAAS: Proceedings of the American Academy of Arts and Sciences, Boston

PAOP: Publikationen des Astrophysikalischen Observatoriums, Potsdam

PAPS: Proceedings of the American Philosophical Society, Philadelphia

PASP: Publications of the Astronomical Society of the Pacific, San Francisco

Phil.Mag.: Philosophical Magazine, London

Phot.J.: The Photographic Journal, London

Phot.M.: Photographische Mitt[h]eilungen, Halle

Phot.N.: Photographic News, a Weekly Record of the Progress of Photography, London

Phys.Rev.: The Physical Review. A Journal of Experimental and Theoretical Physics, Lancaster

Phys.Z.: Physikalische Zeitschrift, Leipzig/Berlin

Pop.Ast.: Popular Astronomy, Northfield, Minnesota

PRI: Proceedings of the Royal Institution of Great Britain, London

PRSL: Proceedings of the Royal Society, London

PTRSL: Philosophical Transactions of the Royal Society, London

QJRAS: Quarterly Journal of the Royal Astronomical Society, London

QJRMS: Quarterly Journal of the Royal Meteorological Society, Reading and London

QJS: Quarterly Journal of Science, Edinburgh

RBAAS: Report of the Meetings of the British Association for the Advancement of Science, London

SA: Scientific American, New York

SB.W.: Sitzungsberichte der kaiserlich-königlichen Akademie der Wissenschaften, math.-physik. Klasse, Vienna

SHPS: Studies in the History and Philosophy of Science, Cambridge

SM: The Scientific Monthly, New York

SPNBS: Scientific Papers of the National Bureau of Standards, Washington, DC

SPRSD: Scientific Proceedings of the Royal Society, Dublin

SSS: Social Studies of Science, London

Techn.Rev.: Technology Review [M.I.T.], Cambridge, Mass.

TRSE: Transactions of the Royal Society of Edinburgh

VAG: Vierteljahresschrift der Astronomischen Gesellschaft, Leipzig

VKAWA: Verslagen van de gewone Vergaderingen der wis- en natuurkundige Afdeeling van de Koninklijke Akademie van Wetenschappen te Amsterdam

ZAAC: Zeitschrift für anorganische und allgemeine Chemie, Leipzig

ZAP: Zeitschrift für Astrophysik, Berlin

Zfl: Zeitschrift für Instrumentenkunde: Organ für das wissenschaftliche und technische Gerätewesen, Braunschweig

ZPCU: Zeitschrift für den physikalischen und chemischen Unterricht, Berlin

Z.Phys.: Zeitschrift für Physik, Braunschweig and Berlin

ZtP: Zeitschrift für technische Physik, Leipzig

ZwPh: Zeitschrift für wissenschaftliche Photographie, Photophysik und Photochemie, Leipzig

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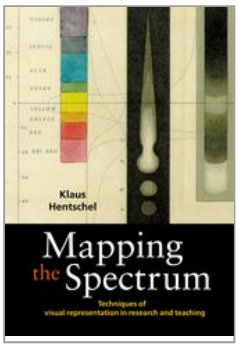
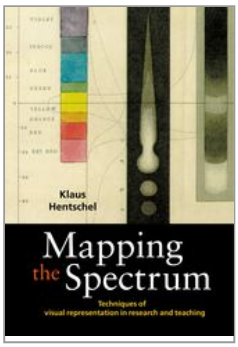


Mapping the Spectrum: Techniques of Visual Representation in Research and Teaching
Prof. Dr. Klaus Hentschel

Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

(p.551) Name Index

The historical actors are listed here followed by company names. Authors of secondary literature are included when mentioned in the main text. First initials are indicated to avoid ambiguities and diacritical marks are generally ignored, with the exception of German *Umlaute,* which are treated as if the relevant vowel were followed by the letter e: Ä → Æ, ö → œ; β → ss. Italics signal biographical information on that page.



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Print publication date: 2002
Print ISBN-13: 9780198509530
Published to Oxford Scholarship Online: January 2010
DOI: 10.1093/acprof:oso/9780198509530.001.0001

(p.562) Company Index