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Problems of Astronomical Spectroscopy

By

P. Swings

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(Vorgelegt in der Sitzung vom 11. Juni 1960)

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The teamwork of Bunsen, the chemist, and Kirchhoff, the physicist, one hundred years ago, represents an epoch in the development of astronomy. To be sure, Fraunhofer, in 1824, had already noticed that the spectrum of Sirius differed from that of the Sun, and thus established a basis for stellar spectroscopy. Yet it is the development of the spectroscopic method of chemical analysis by Kirchhoff and Bunsen which opened up the possibility of a determination of the chemical composition of the atmospheres of the sun and stars, as well as of terrestrial substances. Kirchhoff's spectroscopic evidence for the presence of sodium in the sun represents a landmark in astronomy.

For a period of 80 or 90 years after Kirchhoff's and Bunsen's spectacular work spectroscopy remained a glamorous part of physics and astrophysics, a status which it has partly lost in recent years in favor of nuclear science and other new developments. The spectroscopic discovery in Heidelberg, of cesium in 1860 and of rubidium in 1861, was followed by that of thallium by William Crookes in 1861, of indium by R. Reich and T. Richter in 1863, and of gallium, samarium and dysprosium by Lecocq de Boisbaudran a little later. The first new chemical element discovered in a celestial body is helium, which P. J. C. Janssen found by the observation of the D_3 line at the solar eclipse of August 18, 1868. The same year Huggins reported the presence in stellar spectra of lines of H, Na, Mg, Ca and Fe. An era of close and fruitful collaboration between laboratory and astronomical spectroscopy was beginning. All along, for a century, most new investigations in laboratory and theoretical spectroscopy have found applications in astronomy. But this has not been a one-way influence. Astronomers have also led the spectroscopists to new concepts, new mechanisms or new compounds. It is true that the spectacular discovery of helium in the sun has not been followed by other discoveries of unknown atoms in stars. But the assignment of the so-called nebulium lines to forbidden transitions opened important new possibilities to the spectroscopist, and this was followed a few years later by the interpretation of the coronium. The bands of the tricarbon radical C_3 had been observed and studied in comets, long before they were found and identified in the laboratory; the same is true for the SiC_2 molecule. The observations on interstellar lines led HERZBERG to the laboratory spectrum of CH^+. Indeed the investigation of many atomic and molecular spectra was started at the urgent request of astronomical spectroscopists.

It is not strange that astronomical spectra should have inspired important problems to the laboratory spectroscopists. Several million stellar spectra have been obtained, some two hundred thousand of them with slit and comparison spectrum. These concern stars in which conditions of temperature, gravity and even chemical composition vary. In addition other spectra concern interstellar matter, nebulae, comets, planets, etc. The range in physical conditions is extraordinarily wide. No wonder many spectroscopic problems arise which require the cooperation of the laboratory.

For eighty or ninety years spectroscopy was the major source of information on atoms and molecules on the one hand, on celestial bodies on the other. In the last twenty years spectroscopy has lost much of its glamour among the young physicists, most of whom go now into other fields, such as nuclear physics. Similarly many young astrophysicists prefer new fields such as radio-astronomy, nuclear astrophysics, magnetohydrodynamical problems, etc. Yet there are a great number of unsolved problems in astronomical spectroscopy, and the help of the laboratory is required for many of them. It is most gratifying to note that a close cooperation continues to exist between many experimental and astronomical spectroscopists.

Ten years ago at a meeting of the Joint Commission for Spectroscopy I gave a report on "Spectroscopic Problems of Astronomical Interest" in which I covered all types of spectra of celestial bodies and stressed some of the corresponding unsolved problems with emphasis on the identifications. Although considerable progress has been made during this decade quite a few of the most outstanding puzzles which I mentioned in 1950 remain unsolved. Eloquent calls have been made recently, especially to the young scientists, in favor of astronomical spectroscopy because so much of the progress of astronomy depends on continued endeavors in spectroscopy. My present report to this conference is another plea in the same direction.

Let us start with a few remarks on the most spectacular recent spectroscopic progress, and especially on the prospects for progress in the fairly near future, i.e. the extension of astronomical observations into the far ultraviolet region from rockets and satellites. A symposium on this topic will take place in Liège next July; already now over a hundred astronomers have announced their active participation; this gives a clear indication of the interest shown by astronomers in this matter, which might have been considered a fairy tale only a few years ago, but which, owing to the accelerating pace of satellite development, appears now in the realm of possibilities within a few years. Indeed many of our colleagues who are devoting their efforts to rocket- or satellite astronomy are convinced that the launching of complex vehicles, suitable for astronomical observations from above the earth's atmosphere is only a matter of a few years.

Rockets have already given us extremely important information on the far ultraviolet spectrum of the sun. The NRL solar spectrograms taken from a height of about 195 Km show Fraunhofer lines longward of 1750 A, but below 1550 no photospheric continuum is present, only emission lines. About one hundred emissions have been observed by the NRL group; among them fifty are clearly present between L_α (λ 1216) and λ 550; they belong to the Lyman series (at least 8 members; but Lyman γ is missing, which means that the atmosphere at 200 Km is still optically thick to Lyman γ, the absorber being N_2), C I, N II and III, O II—III—IV, Ne I and VIII, Mg X, Si I and II, S I; the Lyman emission continuum is clearly present from λ 910 to about λ 820. Another group, at the University of Colorado, studied the spectrum in the region of shorter wavelength from heights ranging from 140 to 212 Km. Lines were measured down to 83.9 A, the resonance line of He II at λ 304 being very intense. Actually the intensity of this He II line has been measured by another group (H. HINTEREGGER), as well as its absorption in the atmosphere. Using a high resolution instrument (13th order of a grating of 50 cm radius, 1200 lines per inch) the NRL group obtained the profile of Lyman α with a dispersion of 2.6 mm per A. Lyman α has a half-maximum width of the order of 1 A, with wings extending about one A on either side of the center. A broad central depression leaves two maxima separated by about 0.4 A. In the center of the broad weak reversal is a deep narrowcentral absorption core, with a width at half maximum of 0.03 or 0.04 A. This core is probably due to absorption by geocoronal hydrogen. If this hydrogen is located close to the earth the numbers of H-atoms per square centimeter column is about 2×10^{12}.

Other important results have been obtained on the X-ray emission of the sun, but much remains to be done before we have a clear picture of this X-ray spectrum.

Rocket-astronomy will, of course, be continued and developed. Indeed Lyman α-emission has already been observed during night launchings. We may, for example, hope that aurorae will be observed from various heights and "from above". But the next step, satellite-astrophysics, will still be of much greater significance. We may try to foresee what could be expected from the far ultraviolet observation of celestial bodies, remembering however that the unexpected results will probably be of greater importance and impact than the expected. Take, for example, the far ultraviolet spectrum of a comet. Assuming a fluorescence mechanism—which has been proved to be the only excitation process for the molecules of the usual spectral region—each strong solar emission line coinciding with an absorption line of a cometary molecule will give rise to a "resonance series". For example Lyman γ will excite N_2-molecules and give rise to a series of triplets. One may expect a major role to be played by the H_2-molecules. The Doppler shift of the solar emission lines will be very effective: a slight change in radial velocity may suppress or create a resonance series.

Let us consider the stars in general. Are all stars built like the sun, with a corona at a million degrees, or are such non-thermal envelopes exceptional? What shall we actually see of the ultraviolet region of stellar spectra? The interstellar matter will absorb wide regions. Assuming a hydrogen abundance of one atom per cm^3 one finds that the optical thickness at λ 912 (threshold of the Lyman continuum) for 100 parsecs is about 2000! To reduce the optical thickness to 1, λ must be reduced to about 80 A. To this we still have to add the absorption in the continua of He and He^+. At the limit λ 504 of the He I-continuum the absorption is about the same as that of H, but at shorter wavelengths it becomes more important, and it exceeds that of H by a factor of 20 at 10 A. We may thus expect that the stellar ultraviolet spectra will actually consist of two ranges: the optical from λ 2900 to λ 912, and the X-ray, below, say 30 A. The X-ray spectroscopy of stars will become of great importance. From measurements with the 21 cm-line of hydrogen we know that there are about 10^{20} atoms of H per cm^2 column to the Crab nebula: we shall thus be able to detect the X-ray emission from the Crab nebula. Even for nearby stars the profiles of the stellar Lyman lines will be strongly perturbed by the interstellar Lyman lines; there is very little likelihood that we shall ever observe the Lyman lines of gaseous nebulae or of bright line stars.

But this unpleasant fogging effect of interstellar hydrogen and helium will be partially compensated by the important information which the interstellar absorption will give us longward of the Lyman limit. Our present data on the physics of interstellar matter are still scanty because we can use the observations on only two interstellar elements: neutral Na and singly ionized Ca, and we know that interstellar Na and Ca are mainly in the form of Na^+ and Ca^{++}; moreover the corrections for ionization are very uncertain. We shall be able to observe many interstellar lines above λ 912: H, H_2, C I to IV, N I to V, O I and IV, Mg I and II, Si I to IV, S I to IV, A I and II, Fe II and III. Many of these lines will be found with intensities as great as or greater than the *D*-doublet of Na. Even in the near ultraviolet, interesting information will be found in a comparison of the neighboring lines of Mg I 2852 and Mg II 2795 to 2805. Actually unexpected events may take place which may hinder the observation of the numerous lines indicated above: there may be absorption by molecules or by small interstellar grains, but this would again be of utmost interest! Our total ignorance of the abundance of H_2-molecules is very serious. Quite a few astronomers believe now that H_2 molecules are abundant in interstellar space. Who knows? One may even find HD-lines, giving some clue on the abundance of deuterium. Comparison of the H I and H II regions will be most profitable. The possibility, sometimes raised, that there may be hot interstellar regions, say at temperatures of the order of 10^6 K, would be studied: one would find there absorptions from highly ionized C, N and O.

I shall interrupt here these considerations on satellite-astrophysics; such considerations if they involved the other spectral regions: infrared, radio, X- and γ-ray, would indeed require much more time than is at my disposal.

I want instead to speak now of present astronomical spectroscopy, and I shall even restrict myself to the photographic region, say from λ 3000 to λ 9000, with a possible short incursion into the near infrared. Hence I shall not speak on 21 cm-astronomy, a wide field in itself.

Instrumental developments of tremendous importance have been made in the field of astronomical spectroscopy, and others may be expected soon. To start with the expected developments let me express the hope that we shall soon apply in astronomy, especially for the long wavelengths, the recent laboratory work on SISAM and on the application of the Fabry-Perot interferometer. The most spectacular recent progress is the electron camera; this technique is opening extraordinary possibilities because its sensitivity and resolution are so much greater than those of photographic emulsions. The spectral photoelectric scanning is also very important, and it is progressing satisfactorily. Scans with low resolution are already possible at many installations, down to the 10th magnitude, thus giving the absolute energy distributions in standard or variable stars. This technique fills a gap between the multi-color photoelectric photometry and the difficult high resolution scan: the latter is only in a beginning stage. The progress in the receivers for the various spectral regions is eagerly awaited by stellar spectroscopists.

From the considerations which will follow it will be abundantly clear that the present emphasis is on quantitative intensity determinations of radiation. Hence the installation of the Happel-Laboratorium für Strahlungsmessung at the Heidelberg-Königstuhl Observatory was sincerely welcomed by all astrophysicsts, and its Director, Professor KIENLE, must be congratulated for his endeavors and his competence. Precise spectrophotometric data are, for example, needed for the determination of interstellar extinction, hence of absolute magnitudes.

One cannot overemphasize the need of detailed accurate studies of the distribution of the magnetic field of the sun, including the active zones. The development by H. D. and H. W. BABCOCK of the solar magnetograph, based on the Zeeman effect, represents a great instrumental advance. Fine details in intensities higher than 0.3 gauss can be observed. The general field is a dipole whose mean intensity is 1 gauss. The emphasis is now on the study of the magnetic field of active regions.

Large spectrographs have been installed, especially for solar spectroscopy. Let us mention especially the vacuum instruments at the University of Michigan and the Jungfraujoch; the spectrographs at Göttingen (Prof. TEN BRUGGENCATE), Oxford (Prof. H. H. PLASKETT) and Crimea (Prof. SEVERNY).

In the following I shall not consider the problems on radial velocities. For lack of time I shall also avoid the discussions on spectral classification, and on stellar structure and evolution. Yet these fields require renewed efforts in low resolution, as well as high resolution stellar spectroscopy. In recent years spectral classification has become indispensible in studies of galactic structure and stellar evolution. I have especially in mind the spectroscopic investigations on associations, galactic clusters and other objects associated with spiral structure on the one hand, those on the amorphous disk and halo population on the other. More and more it will be necessary to differentiate the spectra according to age or evolutionary state of the star. Sometimes, objective prism-or slitless spectrograms suffice. In this connection I wish to stress particularly the usefulness and success of the new objective prism at the Hamburger Sternwarte in Bergedorf. Often a higher resolution is required. The new coudé-spectrograph at Palomar is especially successful. Take the example of stars in globular clusters; they are an entirely different breed from the familiar stars around us, since they have different chemical abundances and follow different evolutionary patterns. But it is not easy to secure their spectra; hardly any of them are brighter than the 14th magnitude in the blue region. At Palomar spectra are now being taken with a dispersion of 38 A/mm, and sometimes even 18 A/mm. The stars in globular clusters reveal very striking peculiarities, especially an extreme weakness of the metallic lines. There are clear abundance phenomena.

By spectroscopy we may pick the oldest stars, and, by accurate comparison of these spectra to those of young stars, we may determine what was the composition of our galaxy in its early history, and also find clues as to nucleogenesis. The youngest stars are especially revealed in stellar associations and in galactic clusters; they offer a variety of samples formed simultaneously and at the same location in the interstellar medium, under common circumstances; while the age is the same, the masses and angular momenta are different. For this type of study a high spectral resolution is required.

The spectroscopic results may have an immediate bearing, sometimes in a spectacular fashion, on stellar evolution, on perturbations in double star orbits, etc. . . In other cases the results will require persistent efforts. Certain results will be obtained, by our successors, in decades or centuries, from the precise spectroscopic data assembled by us now.

Let us now consider in succession most of the classes of celestial bodies of our galaxy, beginning with the gaseous nebulae. Great progress in the field of identifications has been made since my report of 1950, especially by I. S. BOWEN; using quartz optics in long exposures Bowen obtained better data, especially in the ultraviolet. New forbidden lines of N I, Ne III, Na IV, Cl III, A III, Fe III and Fe V were found; the behavior of the nebular emissions is now better understood. Actually the galactic nebulae with emission spectrum are of two distinct types: the diffuse nebulae (usually irregular, extended and of low density) associated with population I exciting stars, and the planetary nebulae (less extended, and more or less symmetric) associated with nuclei of population II. We have gained a clearer picture of the densities and temperatures of the radiating gases, although the interstellar obscuration remains a source of difficulty which we try to solve by using the Balmer decrement. The most accurate quantitative estimates of the density are now based on the intensity ratio of the components of the [O II] doublet for which the target areas for collisional excitation are now well known; the method is sensitive for electron densities of the order of 10^3 per cm^3. If we do understand in a general way all the main features of the discrete emission fairly well this is not true for the continuum; probably the latter is due to a recombination of ions and electrons, and to a double-photon emission, but the latter process is still somewhat uncertain For the detailed understanding we are still in need of certain transition probabilities and of target areas for the collisional excitation of metastable levels; however considerable progress has been made in the last decade.

The nuclei of planetary nebulae are still poorly known, as well as their relation to the surrounding nebulosities. Actually a great deal of spectroscopic observations are still needed. Recently a few stellar nuclei of planetary nebulae of very low surface brightness have been studied spectroscopically; they show characteristics of low luminosity (very broad and shallow lines of H and He II).

Incidentally the nucleus of the planetary Abell 78 has an Of-spectrum, characterized by the queer presence of a strong O VI emission at λ 3810—λ 3835.

The Crab nebula reveals a very strong polarization which has been mapped in great detail. The continuous radiation is most probably due to the synchrotron mechanism. A number of theoretical investigations have tried to establish the physical processes involved (nature of the magnetic field, energy spectrum of the electrons). The success of the polarization observations of the Crab Nebula has inspired other polarization studies in *T* Tauri stars, an extragalactic nebula (M 87), a cometary nebula (NGC 2261); etc... It is now widely believed that all filamentary nebulae are remnants of super-nova shells, as is the Crab nebula.

Despite the efforts made at Palomar the spectra of supernovae are not much better understood than ten years ago. As for the novae some progress has been made. The recent outburst of the recurrent Nova RS Ophiuchi has been studied extensively at various observatories. In a general way the spectroscopic behavior was similar to that observed at previous outbursts. Among the puzzling results there remains, as in 1933, the strong emission at λ 6827 which had been tentatively assigned to [Kr III], but which probably is not due to this element. Thackeray has studied two interesting post-novae: η Carinae (the [Fe II] star) and RR Telescopii (which exhibited an increase in excitation, from [Fe II] to [Fe VII]). Most of the unidentified features mentioned ten years ago remain unassigned although some progress has now been made on [Fe IV]. From the beautiful photometric and spectrographic studies on Nova (DQ) Herculis and other post-novae, one begins to wonder if all post-novae are not close binaries. This question arises also for the related SS Cygni stars.

Some progress has been made in our knowledge of the Wolf-Rayet and Of-stars. The spectroscopic observations of W-stars have been extended into the photographic infrared region, and a good start has been made on the corresponding identification thanks to Edlén's laboratory work. An Of-star, g Sagittae, has been investigated in greater detail; other Of-stars have also been examined. Actually shallow and weak lines are common in these hot stars; they have been studied at Edinburgh by averaging many tracings; by this technique weak or shallow broad lines become visible; accurate photoelectric scans will be of great help in the future.

Little by little one is acquiring an interpretation of the selcted emission lines of N III and C III found in Of-stars. It clearly appears that a complete understanding of these hot stars will require accurate spectrophotometric data, instead of the usual visual estimates. A possible binary character of all W-stars is sometimes mentioned; the fact is not proved yet. The queer symbiotic objects, combining spectroscopic features of very high and very low excitation, have continued to be the object of interesting spectroscopic investigations. The binary character of TCBr is now well established, but we are not yet sure of the binary character of the other objects. Their general spectroscopic evolution has been fairly well followed. For the first time the near infrared spectrum of a symbiotic object, BF Cygni, has been examined, unfortunately with too low resolution: many strong emissions appear longward of H_α; some of them remain unassigned, the case of the possible identification of [S I] being particularly puzzling. The relative behavior of the triplet- and quintet-transitions of O I is interesting since the triplet may arise in a fluorescence mechanism excited by Lyman β, but not the quintet. No trace of [Fe I] (strongest line $a\,{}^5D_4 - a\,{}^3F_4$, $\lambda\,8347.55$) has been found as yet.

The massive Trumpler stars remain a puzzle. We have no clear idea of their masses yet. If the observed red shifts are assigned to a relativistic effect we must admit very large masses or very small radii. Yet we have good reasons to believe that the masses do not exceed 75 solar masses. What then causes the red shifts?

Going down the temperature scale we now reach the B, A, F and G-stars. The needed surveys of identifications in high dispersion spectra of standard stars remain to a large extent, to be done. To be sure, a few hot and cool stars have been studied. The typical B-star γ Pegasi has been investigated by Miss Underhill from high dispersion spectrograms: the laboratory analysis of the Fe III-spectrum by Glad was especially rewarding. Other B and A, M and S stars have been examined. Generally the red and near infrared region has been neglected. We have made very little progress with the identifications in the stars of medium temperature, F, G and K. Determinations of abundances have been made by L. H. Aller and by the Burbidges. We shall later on say a few words about this matter of abundances when speaking of the sun. Anomalous B- or A-stars require more spectroscopic work. The hydrogen poor-stars should be rediscussed, and the range covered by their spectra extended. Great progress on the rare-earth stars may soon be expected, since an effort is now being made by laboratory spectroscopists to analyse the rare-earth spectra. Other abundance anomalies which have been recently discovered include a star with strong P II- and P III-lines. Long desired investigations on the carbon F-star, RCBr, are now under way. The "blanketing effect" due to the absorption lines, which has an effect on the color of the star, may vary appreciably within the same spectral type.

The most ambitious program on abundances in stellar atmospheres is probably that started by J.L. GREENSTEIN who uses dispersions up to 1.1 A/mm in the blue region. Among the standard stars investigated or under scrutiny, are representatives of the following classes: B (τ Sco), F 2 V, F 5 IV, F 5 V, G 8 III, G 9 III, early R (one with C^{13} present, the other without C^{13}, H and CH), etc... RCBr is also being investigated. The differences between young and old stars are being studied. Once fulfilled GREENSTEIN'S program will provide an extremely valuable basis for discussions on nucleogenesis.

One of the most exciting studies on A-stars concerns the "magnetic" stars discovered by H.W. BABCOCK. This investigation has been under way for about a decade. Now that the essential phenomena have been established BABCOCK is refining the data for a few of the outstanding variables of large magnetic amplitude; he also endeavors to broaden the basis for statistical discussions. BABCOCK favors a hydromagnetic oscillator model, while Deutsch prefers the rigid magnetic-rotator model. These objects are of utmost importance in relation to magnetohydrodynamics. It has been thought at times that positronium may be produced in magnetic stars; however no trace of the Balmer series of positronium has been found by DEUTSCH on the infrared coudé-spectrograms.

Considerable spectroscopic work has been devoted to the white dwarfs, especially by GREENSTEIN. Among the still unidentifiable bands, one at λ 4670 is especially outstanding in cool white dwarfs.

The most strategically located prototype of class G is of course our Sun, since we are able to use very high resolutions and to cover the widest spectral range; indeed for the sun our spectroscopic data extend from the X-rays to the radio waves, although quite a few gaps still exist. The revised Rowland Table prepared by Mrs. SITTERLY and the Utrecht group will contain intensities as well as wavelengths and assignments. Progress has been made in the identifications, f. ex. for the bands of OH, CH and CN. There is no reliable evidence for the presence of technetium which is strong in certain coll stars. Severny thinks that the ratio Th:Pb is about 100 times smaller in the sun than on the earth. The question of the existence of deuterium is not yet completely solved despite various investigations by SEVERNY, KINMAN, GOLDBERG-MULLER.

I said a few words on spectroscopic instrumentation earlier. Under conditions of good seeing the Michigan vacuum spectrograph, which eliminates the instrumental turbulence, gives lines which have a zig zag appearance; hence the temperature-and velocity fluctuations in the solar atmosphere may now be directly observed in the Fraunhofer spectrum, at least for elements about 2 seconds of arc (or 3000 km) in diameter or larger. On the basis of these observations it appears that some of the discrepancy between theory and observation may vanish by allowing for the fluctuations in observed central intensity. Actually the theoretical problem of the abundances in the sun, while progressing, especially thanks to the efforts of the Michigan group, is still in a rather unsatisfactory state. It is not my intention to go into this matter in any detail; I should then rather have done it for the general problem of the stellar atmospheres. It is indeed difficult to reach reliable abundances on the basis of the Fraunhofer spectrum, even in the case of the sun, although great efforts have been devoted to models of the solar photosphere. Not only do we need atomic data which we do not always known with sufficient precision, such as transition probabilities, areas for collisional excitation or for absorption of radiation, etc. . . We still have to consider possible departures from thermodynamical equilibrium, and these departures may be fourfold: from the Kirchhoff-Planck formula (field of radiation), the Boltzmann formula (populations of states), the Saha formula (ionization) and its equivalent for molecular dissociation, and the Maxwell formula (velocity distribution). These four types of departure are correlated in complicated ways. The effects of granulation, of turbulence, of inhomogeneities in temperature are complex. Even the profile of H_α has been the object of various discussions in recent years, involving, in addition, the Stark effect. The centre-limb variations help considerably; in this connection the effects on molecular bands, such as were studied by PECKER, are especially interesting. The difficulties involved with departures from the local thermodynamic equilibrium are illustrated in the case of the abundance of titanium which PECKER increased by a factor of 10. Time is too short to discuss the most recent aspects of the problem of the curves of growth. Let us still mention that certain profiles of Fraunhofer lines are affected by the hyperfine structure.

As far as I know the study of the sunspot spectra does not seem to have made much progress recently. Good spectrograms have been obtained at the Göttingen Observatory, under Prof. TEN BRUGGENCATE; I understand that these will be used for the study of the center-limb variations of spots, an important problem indeed. Yet I regret that Mrs. SITTERLY'S call for the taking of a homogeneous set of sunspot spectrograms was not answered during the last sunspot maximum. Spectrograms should be taken with the same spot, over the shole spectral range. There are still thousands of unassigned lines in spot spectra, and their investigation would certainly be rewarding.

Our knowledge of the structure of the chromospehre is essentially based on the spectrograms taken at the time of eclipses, on the observation of the central intensities of certain strong Fraunhofer lines or of He-lines, such as λ 10830, and from the far ultraviolet emission lines obtained from rockets. In all these fields progress has been made recently. For example, the CN bands were studied in the low chromospehre; the profiles of H, K, H_α, H_β were reexamined. Moreover high dispersion spectra of prominences were obtained and studied at various observatories, especially at Göttingen. These observational investigations were accompanied by many theoretical discussions. The rocket spectrograms will certainly help greatly in understanding the physical mechanisms of the chromosphere.

This will be true also for the corona. Some progress has been made in the identifications, intensities and profiles of coronal lines, but much is still expected to come from rocket or satellite observations.

The last ten years have seen several spectacular identifications in the cool stars. The strong absorption near λ 4050 in the carbon stars—which corresponds to an intense cometary emission—has now been assigned to the tricarbon molecule C_3. The strong violet opacity in the late N-stars is probably due to the same radical, although this is not quite certain. The long unidentified Merrill-Sanford bands of the N-stars are due to SiC_2, but we still need much information on this band system, especially on its isotopic effect. The strong bands found near λ 10,500 in the late M-stars, such as R Leo or R Cas, are due to VO. There still remain a few strong unassigned bands in S stars, especially λλ 5849, 8263, 8464, 8610 and 8820: they probably belong to oxides. Technetium has been found in S-stars, and also in certain carbon stars; this discovery gives rise to impartant problems of nucleogenesis, as does the strength of certain rare earths in S-stars. Another puzzling observation is that of the strength of the Li-resonance transition in T Tauri and related stars. Indeed one sometimes finds in T Tauri-stars an abundance ratio of Li to normal metals one hundred times that in the sun, i.e. equal to or greater than the abundance on the earth. The explanation of such a high abundance is not yet certain: there may have been spallation by cosmic rays during the early period of star formation, or maybe Li was stored in the interstellar dust grains.

Contrary to the T Tauri stars the abundance of Li in the cool normal stars, relative to a metal such as V, is never significantly in excess of that in the sun. There are large fluctuations of Li-abundance, but no correlation with luminosity. The relation of this problem to the question of convective mixing in the stars is obvious.

The problems related to the molecules in the cool stars have been discussed extensively in my chapter of Volume 50 of the Handbuch der Physik. I refer to it for the details, and only wish to add here two points. The role of molecules in the continuous opacity is becoming a little clearer. The continuous absorption by H_2^+ is important, as well as the Rayleigh diffusion by H_2. The continuous absorption by H_2^- may possibly also play a role. As a matter of fact spectrophotometry of cool stars is especially difficult on account of the strong "blanketing effect" (cumulative effect of many absorption lines and bands): the importance of the latter has even been found for stars of intermediate type.

Two questions of extreme interest have arisen recently in relation to cool stars. The loss of mass, long stressed (in hot stars of high luminosity) by the Russian astrophysicists has now been proved by spectroscopic observations of red giants (A. DEUTSCH). For example, in the case of α Her, the mass loss may be computed. Cirumstellar lines are found in many late type giants; the loss of mass is obviously favored by low densities and surface gravity. It seems that about one half of the present mass of interstellar gas may once have been inside red giants. The circumstellar cores are found in H and K for all giants and supergiants later than MO; other elements begin to show circumstellar cores when the equivalent width of the K-core exceeds 300 mA.

Using the emission line widths of the H- and K-lines, O. C. WILSON is able to determine absolute magnitudes: a single observation has a probable error of about 0.3 mag. for giants and subgiants; the accuracy is less for main sequence stars. An important new method of determining absolute magnitudes is thus found.

Variability tends to characterize certain phases of a star's life, and spectroscopy remains the best way to obtain physical data on this variability. Take, for example, the case of irregular explosive variables such as AE Aqr; the explosions last an hour or more, and during this time a strong ultraviolet continuum emerges which is now often believed to be due to synchrotron radiation; the polarization is explained likewise. It is becoming more and more important to study systematically chosen typical specimens of variable stars, combining accurate photometric, spectroscopic and spectrophotometric observations: simple visual estimates are no longer sufficient. Even classical cepheids require much spectroscopic work, including the measurement of radial velocities at various phases, for lines of different excitation potential. As for the cepheids of population II their spectroscopic study has hardly been started. Indeed one could consider all types of variable stars, and find a wide variety of unsolved spectroscopic problems. In particular the variable stars in nebulosities will play an increasingly important role in our ideas on the origin and development of stars. A good start has been made for the young T Tauri-stars.

The long period variables raise many important spectroscopic problems. An S-variable, R Cygni, showed hundreds of sharp metallic emission lines at the abnormally low maximum of 1957; these emissions may result from a succession of shocks. MERRILL has listed 1347 absorption lines in the region λ 3528 — λ 4462 of Mira Ceti (M 6e); they are mostly atomic, but not all of them are identified. Not much progress has been made in the interpretation of the emission lines of ordinary long period variables by the mechanism of monochromatic excitation; there is a great need for increasing the spectral range toward the photographic infrared as well as the ultraviolet. On the other hand an important discovery has been made by G. H. HERBIG in χ Cygni near minimum: a large number of emissions are rotational lines of AlH belonging to well defined rotational quantum numbers. This selectivity is due to a very pure mechanism of induced predissociation. Similar phenomena take place in other long period variables near minimum. This reminds us of KARL WURM'S old suggestion (1935) of chemical luminescence to explain certain emission lines in long period variables.

The sky offers us very clear and simple geometrical examples in the case of supergiant eclipsing variables, in which the extended atmosphere of a cool supergiant eclipses progressively and periodically a small normal hot star. We are thus able to obtain valuable information on the distribution of the physical conditions in the atmospheres of supergiants. Actually three such eclipses involving bright stars will take place in 1961 and 1962: ζ Aurigae (total elipse: 38 days; partial: 1.5 day; April 1961), 32 Cygni (resp. 13 and 4 days; April 1962) and 31 Cygni (resp. 61 and 2 days; 1962). We may be sure that many stellar spectroscopists will study these valuable eclipses.

Actually the spectroscopic study of binary stars, especially of close pairs, is most rewarding. In many cases matter escapes from one or both components through the Lagrangian points. For β Lyrae the loss of matter may be estimated spectroscopically; it amounts to 5×10^{22} gr/sec; hence the life expectancy of β Lyrae should be only of the order of 100,000 years if the process continues unperturbed. The spectroscopic investigations, especially by STRUVE and his associates, have shown that many close binaries have gaseous rings or streams, and many have changing periods. Collaboration between photometrists and spectroscopists is required. Quite a number of very interesting close pairs have not yet been investigated.

Using the high dispersion (1.1 A/mm) now available at Mt WILSON considerable detail many be obtained in the profiles of the interstellar lines. Actually a resolution of 0.02 A is possible; as an example the interstellar H and K lines reveal at least 5 components in ε Orionis. One reaches thus a better separation of the interstellar clouds. A new identification has been made recently, that of λ 3579.04 which is due to CH^+. An ultraviolet line of CH has been found. Unfortunately no assignment has been found as yet for the diffuse interstellar features, whose number has been increased. Gradually data are accumulating on what SPITZER appropriately calls "interstellar meteorology", the problem of the motions and transformations of the interstellar clouds. This involves not only ordinary dynamics, but also the effects of absorbed and emitted radiation. The interstellar phenomena are greatly affected by large-scale magnetic fields and by cosmic rays.

To end with the solar system let us mention simply a few interesting spectroscopic problems regarding the planets, the earth and the comets.

The most important spectroscopic observation on planets is probably that of Mars by W. M. SINTON at the 200''. He examined the region around 3.5 μ and found three distinct absorptions which occur chiefly in the dark areas and only weakly in the bright areas. The bands furnish strong evidence for plant life in the dark areas on Mars.

Progress has been made in the observation of the spectrum of the nightglow which has been extended into the near infrared, and also has been studied with higher resolution. The identifications have been considerably improved in recent years. To illustrate how much remains unsolved let us remark that the region λ 4439 to λ 4916 contains 15 still unexplained emissions and only 5 satisfactorily assigned lines. Better spectra of aurorae have been obtained; certain rotational intensity distributions within bands have been well studied, giving thus reliable rotational temperatures. But a systematic discussion of the identifications makes it clear that we need spectrograms of higher resolution.

Great progress has been made in our knowledge of comets on the basis of spectra. The red CN system has been definitely identified; it is excited by fluorescence. Although the lower level of the Swan bands of C_2 is no longer considered to be the ground state, it was shown that the Swan bands are definitely excited by fluorescence. High resolution spectrograms of the bright comet 1959*d* (Mrkos) obtained by J. L. GREENSTEIN gave much better assignments to NH_2; they illustrated better than ever before the effect of the Fraunhofer lines on the profile of the CN-emission, and they showed the effects of velocity differences in the head on this profile of CN. For the first time the forbidden lines of [O I] were discovered in comets; their excitation mechanism is not clear yet. Radio observations of Comet Arend-Roland seem to indicate that a discrete emission at 50 cm, due to CH, appears together with a continuum due to the cometary plasma. Discussions on the visible continuum of the head show that it is due to scattering by small solid particles. Our knowledge of the spectrum of the tail is still unsatisfactory. There still remain also a number of unexplained emissions in the head. We need more high dispersion spectrograms of bright comets, especially of those which have a gaseous head. Comet Burnham which is at present bright enough for good spectroscopic observations is an excellent example of a dust-free head; we hope that it is being widely observed.

In conclusion I wish to point out a few topics for which the help of laboratory or theoretical spectroscopists is essential to the progress of astronomical spectroscopy.

For many descriptions of atomic and molecular spectra we need extensions toward the near infrared as well as the vacuum ultraviolet. Astronomical spectra taken in the red and near infrared regions give us much valuable information, but their interpretation is hampered by the lack of laboratory data. New laboratory investigations in the vacuum ultraviolet are needed as well. For example it is impossible to determine the fluorescence which may be excited in comets by the strong solar emissions, such as Lyman α or 304 He II, because we know too little about the spectra of cometary molecules in these regions. Development of satellite astrophysics will enhance the need for far ultraviolet spectra.

We need many descriptions of molecular spectra, even of simple molecules such as H_2, CN, hydrides and oxides. Happily real progress has been made, thanks especially to the efforts of Mrs. SITTERLY, Dr. JENKINS and Dr. PHILLIPS. Several astrophysically important radicals, such as NH_2, HCO, HNO, CH_2 and CH_3 have been studied in Ottawa. I wish to single out the magnificent analysis of the NH_2-absortion spectrum by RAMSAY and DRESSLER which is of great help for the understanding of cometary spectra; we hope that this will be completed by an analysis of the emission spectrum. Other molecules of cometary interest are completely unknown, such as C_2^+. Many atomic spectra are still needed. The recent thorough analysis of Fe III by S. GLAD should be imitated for other doubly ionized metals of high cosmic abundance. I understand that a good start is made on Ti III (J. W. SWENSSON). We need much work on the rare earths: the spectra of several rare earths appear strongly in stars: the different stages of ionization should be well separated in the laboratory and the analysis carried on. It is fully realized that the analysis of these complicated spectra must be based on very accurate measurements and requires the cooperation of theoreticians with the help of electronic calculators. Even "old" atomic spectra such as Fe I, require additional work: 1200 "predicted" lines of Fe I have been found in the sun; they should be found, with many other weak lines, in iron sources. Old descriptions had sometimes been hampered by molecular bands or by the line widening: we now have better sources at our disposal. Incidentally the laboratory study of the line broadening is also very important: it is being carried in various laboratories, especially in Kiel (LOCHTE-HOLTGREVEN) and at Michigan. The use of shock tubes is especially fruitful for studies on broadening (including Holtsmark broadening of H-lines), also for the production of hydrogen continua.

In spite of the considerable progress in the experimental and theoretical determination of atomic and molecular transition probabilities, both permitted and forbidden, much still remains to be done. In particular many *f*-values of molecular bands of great astronomical interest are still unknown. Finally we still need the dissociation and ionization energies of several essential molecules.

Since I am addressing an audience consisting essentially of laboratory spectroscopists my main purpose has been to stress the vitality of astronomical spectroscopy and to point out the variety and importance of the problems in astronomical spectroscopy that are at present under investigation. Progress in astrophysics requires the collaboration and help of our colleagues in laboratory spectroscopy. I shall be happy if this talk helps in enhancing this cooperation.

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