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The Sagnac effect: 100 years later / L'effet Sagnac : 100 ans après

Georges Sagnac: A life for optics

Georges Sagnac : Une vie pour l'optique

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ABSTRACT

Georges Sagnac is mostly known for the optical effect in rotating frames that he demonstrated in 1913. His scientific interests were quite diverse: they included photography, optical illusions, X-ray physics, radioactivity, the blue of the sky, anomalous wave propagation, interferometry, strioscopy, and acoustics. An optical theme nonetheless pervaded his entire œuvre. Within optics, an original theory of the propagation of light motivated most of his investigations, from an ingenious explanation of the Fresnel drag, through the discovery of the Sagnac effect, to his quixotic defense of an alternative to relativity theory. Optical analogies efficiently guided his work in other domains. Optics indeed was his true passion. He saw himself as carrying the torch of the two great masters of French optics, Augustin Fresnel and Hippolyte Fizeau. In this mission he overcame his poor health and labored against the modernist tide, with much success originally and bitter isolation in the end.

RÉSUMÉ

Georges Sagnac est principalement connu pour l'effet optique des faisceaux tournants, qu'il démontra en 1913. Ses intérêts scientifiques étaient très divers, incluant la photographie, les illusions d'optique, la physique des rayons X, le bleu du ciel, la propagation anormale des ondes, l'interférométrie, la strioscopie et l'acoustique. Le thème de l'optique habite néanmoins son œuvre toute entière. Dans le domaine de l'optique, une théorie originale de la propagation de la lumière a motivé la plupart de ses recherches, depuis une explication ingénieuse de l'entraînement de Fresnel, en passant par la découverte de l'effet Sagnac, jusqu'à son combat de Don Quichotte en faveur d'une alternative à la théorie de la relativité. Les analogies optiques ont efficacement guidé son travail dans d'autres domaines. En effet, l'optique était sa vraie passion. Il se voyait comme porte-flambeau de deux grands maîtres de l'optique française, Augustin Fresnel et Hippolyte Fizeau. Dans cet apostolat, il surmonta sa faible santé pour travailler à contre courant du modernisme, rencontrant d'abord beaucoup de succès, puis un isolement amer à la fin.

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1. Introduction

In 1997 the director of the Commission des plis cachetés of the Académie des sciences, Roger Balian, asked me to report on two *plis cachetés* (sealed letters) deposited on 28 March and 24 July 1898 by Georges Sagnac. At that time, I only knew this physicist for the effect that bears his name. I had assumed he was just one more of these French masters of experimental optics who collected the fruits of a superior interferometry. So I was surprised to see that the two *plis* did not belong to optics *per se*. They dealt with the secondary rays emitted by matter under the impact of X-rays. The *pli* of 24 July bears the title "Transformation des rayons X par la matière : influence de l'azimuth des rayons X et des rayons secondaires S émis" and describes an oscillation of the penetrating power of the secondary rays as a function of the angle under which they are emitted. Sagnac suggests that this oscillation might have to do with the diffraction of waves of wavelength smaller than the interatomic spacing of the target. The following year, Sagnac publicly confirmed the heterogeneity of the secondary rays, but he gave up the idea of a diffraction-related oscillation. The *pli* of 28 March describes an experiment demonstrating the existence of an electrically charged component of the secondary rays. I soon found out that a third *pli* of 18 July 1898 contained an improved version of this experiment and had been opened and published at Sagnac's request in 1900.[1]

I thus became aware of Sagnac's important role in the new field of research that Wilhelm Röntgen's discovery of X-rays had opened in late 1895. As I learned from the historian Bruce Wheaton, Sagnac had discovered that X-rays were transformed by impact on matter into rays of lower penetrating power then called S rays or Sagnac rays, in a phenomenon now called X-ray fluorescence. He had established the heterogeneous and specific character of the secondary radiation emitted by heavy elements, thus anticipating later X-ray spectroscopy. And he had discovered the existence of an electrically charged component of the secondary rays, thus inaugurating studies of the X-ray photoelectric effect.

These were not the last *plis cachetés* deposited by Sagnac. On 23 February 1902, he wrote one in which he suggested an experimental test for the hypothesis of a gravitational origin of radioactivity. Having again to report on this *pli*, I found out that Sagnac had performed an improved version of this experiment a few months later and published the negative result in 1906. The last of Sagnac's *plis* is the one of 18 August 1913, in which he gives the first account of the effect for which he is most famous. Sagnac's frequent recourse to *plis cachetés* conveys the image of a man who knew the thrills of discovery in multiple circumstances and in different fields of physics.

Although the next generation of X-ray physicists recognized the importance of Sagnac's pioneering work in this domain, this part of his oeuvre is now largely forgotten presumably because the techniques on which it was based became obsolete after Max Laue's discovery of X-ray diffraction in 1912.[2] In contrast, the Sagnac effect is very well known, though not in the manner hoped by his discoverer. In the relevant experiment, which dates from 1913, the interference of light in a rotating interferometer of a special kind proves to depend on the rotation (with respect to an inertial frame). Sagnac announced this result as a proof of the existence of the ether. Although there still were, in 1913, many physicists to welcome such a claim, the increasingly powerful adepts of relativity theory brushed it away. The experience remained important as an optical counterpart of Foucault's pendulum experiment or as a rotational counterpart of the Michelson–Morley experiment, namely: the latter experiment shows the absence of fringe shift caused by the uniform translation of an interferometer, Sagnac's shows the existence of a fringe shift caused by the uniform rotation of an interferometer. The Sagnac experiment soon became a textbook classic, and experts in relativity theory felt compelled to explain it both in special and in general relativity. Numerous variants of the experiment have been performed from the interwar period to these days. Interest in the Sagnac effect grew enormously when laser technology turned it into an efficient gyroscopic device.[3]

The contrast between the diversity of Sagnac's endeavors and the modern focus on a single experiment of his raises a number of questions. Was his discovery of the Sagnac effect an isolated, felicitous hit in a fairly calm career? Is there any connection between his works on X-rays, on radioactivity, and in optics? Was he a mostly experimental physicist or was he guided by theory? The purpose of this essay is to answer these questions through a scientific biography that will take us from his student years at the École normale supérieure to his last lectures at the Sorbonne.

In Section 1, we will see how the young Sagnac developed a passion for optics and began original research on the propagation of light and on optical illusions, both theoretical and experimental. As is recounted in Section 2, in 1896 he interrupted this project to devote himself to the study of X-rays and related radiations. This change of topic did not imply a change of perspective. Optics remained Sagnac's main source of inspiration, in three manners: he showed that some optical illusions had X-ray counterparts that jeopardized some of his colleagues results; he systematically explored the analogy between the (inelastic) scattering of X-rays and optical fluorescence; and he discussed the propagation of X-rays through matter by means of an extension of his earlier theory of the propagation of light. The fluorescence analogy was also important in bridging Sagnac's researches on S rays with the Curies' work on radioactivity. Marie Curie indeed regarded radioactivity as a kind of fluorescence induced by otherwise undetected radiation from the cosmos. Sagnac and Pierre Curie's

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[1] The *plis cachetés*, introduced by the Academy in 1735, have often been used by physicists who wished to protect their priority without publication. In relatively rare cases, after some time the author of the *pli* judges its contents to be ripe for publication, and he or she requests its opening. In most cases the *pli* remains sealed. In 1976, the Academy created a commission in charge of opening the *plis* that had remained sealed hundred years after being deposited. Cf. Berthon [1], Carosella and Buser [2]. My report on Sagnac's two *plis* is in the Sagnac folder in the archive of the Académie des sciences.

[2] Cf. Quentin [3].

[3] Ollivier [4, vol. 3, pp. 574–582] for a first textbook account; Pauli [5, p. 565] for a review. On relativistic interpretation and on variants, cf. Martinez-Chavanz [6]. On recent, laser-based developments, cf. MacKenzie [7].

collaboration on the charged component of secondary rays resulted from their common interest in generalized fluorescence. Sagnac's aforementioned speculation about a gravitational origin of radioactivity also resulted from this interest.

As soon as he could, in 1899, Sagnac returned to optics proper and to the theory of the propagation of light in which he had placed his highest hopes. Section 3 is devoted to this theory and some interesting byproducts. Through a simple kinematics of waves multiply scattered by clouds of material points, Sagnac retrieved basic laws of the propagation of light through transparent bodies, including the Fresnel drag for waves propagating in moving bodies. He thus established the ingenious *principle of the effect of motion* according to which the motion of a transparent body affects the propagation time through it by the same shift as if the body were empty of all matter. And he showed that this principle implied the absence of effect of a global uniform translation on optical experiments to first order in the translation velocity. Through the same picture of multiple scattering by a cloud of point-like molecules, he derived and verified laws for large-angle diffraction by a glass grating and he also argued (wrongly) that the blue of the sky was caused by the upper layers of the atmosphere only. In 1903, he studied the distribution and phase of light near a focus. This last study soon entered optics textbooks as an important extension of the Gouy phase shift. It was a byproduct of Sagnac's early idea that the scattering of light by atoms was analogous to the behavior of light near a focus.

The intermezzo Section 4 is about Sagnac's only venture in mathematical physics: his attempt of 1905 to mathematically develop the idea of a delayed counter-reaction of photographic plates to their impression by light. An exchange with Lorentz on this matter seems to have discouraged Sagnac from completing the theory. Section 5 opens with Sagnac's more fertile realization, in 1908, that his principle of the effect of motion implied a phase-shift on any optical circuit for which the circulation of the ether flow with respect to the earth does not vanish. In the following years he designed contrary-beams interferometers that would detect this phase-shift. In an experiment of 1910 he thus excluded any significant drag of the ether by the earth (a reasonably extended drag would imply a shearing, therefore rotational, flow of the ether). The ether being stationary, its flow relative to the earth still is slightly rotational owing to the diurnal rotation of the earth. The effect being too small to be detectable by his interferometer, Sagnac had the idea of installing the interferometer on a turning table. This is how, in 1913, he discovered the "optical whirling effect."

Section 6 is devoted to anticipations of Sagnac's ether-wind considerations by Oliver Lodge, Albert Michelson, and Theodor Kaluza, and to a related experiment of 1911 by Franz Harress. Lodge [8] and Michelson [9] both had the idea of a double-beam interferometric experiment for optically detecting the rotation of the earth. Lodge even thought of replacing the rotating earth with a rotating table, but he judged the experiment to be too difficult to be worth trying. Sagnac's stronger determination resulted from the theoretical motivation of his experiment, and his success from the related superiority of his interferometric technique. In particular, his reliance on an even number of mirrors (instead of the three mirrors in a typical square-circuit arrangement) provided the necessary stability of the interference fringes with respect to aerial perturbations and optical defects. The Harress case is more complicated. His rotating interferential setup, which was meant to measure the value of the Fresnel drag in moving glass, can retrospectively be seen as a Sagnac-effect experiment with glass instead of air as the propagation medium. Unfortunately, a blunder in the definition of the dragging coefficient led Harress to a crudely flawed interpretation of his data. Several physicists, including Albert Einstein and Max Laue, contributed to correct this interpretation. The end result is good evidence for a Sagnac effect in glass of the same magnitude as in air, with a precision similar to Sagnac's.

Section 7 is a second intermezzo about Sagnac's war efforts to develop acoustic means of detection and communication, again by optical analogy. Section 8 shows an aging Sagnac engaged in a quixotic quest for a conservative substitute to relativity theory along the lines of his principle of the effect of motion. The basic idea was to distinguish the behavior of wave groups from the behavior of elementary sine waves. While the wave groups traveled like in an emission theory with the velocity c with respect to their source, the elementary waves traveled very nearly as disturbances in a stationary ether. A peculiar kind of dispersion conciliated these "two mechanics." The theory agreed with all known experiments in the optics of moving body and had two original predictions that Sagnac believed to be confirmed: silences of radio-communication, and oscillations of the spectrum of some double stars. Being presented in a sketchy, immodest, and somewhat obscure manner, it failed to attract attention beyond the province of incompetent anti-relativists.

In sum, Sagnac's researches were either in optics or guided by optical analogy, expect for a few scattered contributions to electrodynamics.[4] Two strong ideas shaped them: the propagation of light as a multiple scattering by clouds of point-like atoms, and the transformation of radiation by fluorescence. These ideas connect his seemingly disparate contributions to X-ray physics, optical illusions, photography, interferometry, ether-wind detection, and anomalous propagation. Although Sagnac developed them mostly by himself, he was no scientific marginal. This will be appreciated in Section 9, which is devoted to Sagnac's friendships, to his career, to the recognition of his accomplishments, and to his temperament.

While preparing this work, I have benefited from a few insightful historical studies on various aspects of Sagnac's scientific life. In his Paris dissertation of 1980, Regino Martinez-Chavanz [6] gave a thorough critical account of Sagnac's ether-wind experiments, their theoretical context, their anticipations, later experiments of the same kind, and various relativistic interpretations. Most recently, in 2011, Roberto Lalli [15,16] gave a penetrating history of Sagnac's ether-wind experiments, including Sagnac's motivations and the French reception. Lalli discovered that the Philippe Sagnac collection of documents (*fonds* in French) of the Archives nationales contained a box of papers of Georges Sagnac: Fonds Sagnac, dossier

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[4] Sagnac [10–14].

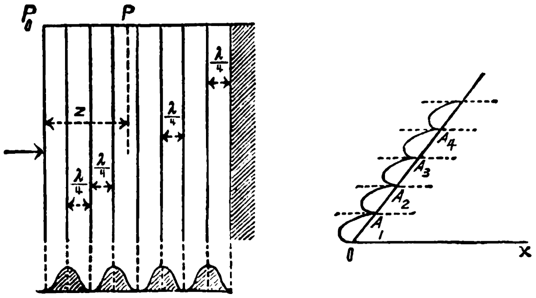

Fig. 1. Periodic layers of silver deposit on a Lippmann plate (on the left); Sagnac's geometric representation of the sum of the reflected vibrations in the case $\lambda = \lambda'$. From Sagnac [21].

AB/XIX/3534 (Philippe, the brother of Georges, was a renowned historian). Lalli has made good use of this archive, and so have I tried to do. On Sagnac's X-ray works and on possible anticipations of his discovery of X-ray fluorescence, there is a useful article by Michel Quentin [3]. In a lucid history of Paul Langevin's early works, Benoît Lelong [17] compared Langevin's and Sagnac's approaches to secondary rays. Lastly and most recently, Roberto de Andrade Martins [18] demonstrated the importance of the Sagnac–Curie connection in sustaining a fundamental guiding hypothesis in the Curies' researches. Altogether, these historical studies suggest the optical theme that I am now going to develop.[5]

2. A passion is born

Georges Marc Marie Sagnac was born in Périgueux on 14 October 1869 into an old bourgeois family of the Périgord. After the early loss of his father, his mother raised him with the help of an important uncle who would soon become Mayor of Périgueux. He entered the École normale supérieure in 1890 with a strong predisposition for optics and some familiarity with Isaac Newton's and Christiaan Huygens's writings on this subject. At the École, he studied the works of the French masters Augustin Fresnel and Hippolyte Fizeau, and he began to meditate on a new theory of the propagation of light. Optics indeed was the great passion of his life, and it motivated most of his scientific activity. Plagued by poor health, he spent much time at home with his mother. His main distraction, alpinism, gave him an opportunity to verify an optical theory of his. His fondness for music and his good hearing helped him to develop acoustic analogues of optical instruments during the war.[6]

Optics was the obvious choice for an aspiring French physicist. Owing to Fresnel's accomplishments and to the connection with astronomy, this field had enormous prestige and its cultivation had helped more than one to climb the French Academic ladder. At the end of his studies at the École normale in 1893, Sagnac became *agrégé préparateur* in charge of optical experiments in Edmond Bouty's teaching laboratory at the Sorbonne. He then projected a dissertation on general optics. His first publication, in 1893, was an account of Gabriel Lippmann's theory of a new process of color photography. In this process, monochromatic light induces a periodic deposit of silver particles in the sensitive layer of the photographic plate, as a consequence of the standing wave formed by reflection of the light on the silvered back of this plate; subsequently exposed to white light, this periodic reflecting deposit produces colors by interference in the manner of iridescent bodies. In order to compute this interference, Sagnac constructed a curve by vector addition of the infinitesimal vectors representing the vibrations reflected by successive infinitesimal layers for a given incoming periodic vibration. The vector between the origin and the end of this curve gave him the amplitude and phase of the resulting vibration. In this way, he could easily show that the net reflected light had much higher amplitude for the Fourier components of the incoming light whose wavelength λ' agreed with the wavelength λ of the light that had produced the periodic deposit (see Fig. 1). A few years later, Sagnac published a theory of diffraction by parallel slits along the same lines. The implied style of reasoning is typical of Sagnac: he usually avoided algebraic calculation and tried to reason on simple theoretical ideas in geometric or kinematic guise.[7]

For two more years Sagnac worked on two optical topics: the propagation of light through transparent matter, and optical illusions. We will later see how he hoped to renew the first topic. On the second, in 1896 he explained an illusion produced by the rotating beam of electric lighthouses: for someone far enough from the lighthouse and looking in the opposite direction, the beam (visible by diffusion) seems to be rotating around a center situated on the horizon. This illusion, Sagnac explained, is an effect of perspective similar to the apparent rotation of parallel tree lines around their vanishing point when seen from a train. The analogy derives from the following circumstance: when the beam is close enough to the direction

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[5] The archive of the Wellcome Library in London holds a few Sagnac manuscripts under the reference MSS. 4332–4334. I have not been able to consult them.

[6] Cf. P. Sagnac [19]; Sagnac to Lorentz, 6 January 1901, Archive for the history of quantum physics (AHQP). Sagnac's brother Philippe, a renowned historian of the French revolution, was his best biographer. Most biographical information in this paper comes from him. Further institutional information is found in Sagnac [20] and in Archives nationales, "Dossier professionnel de Georges Sagnac," AJ/16/6149 (see Lalli [15, p. 65, note 27]).

[7] Sagnac [21,22]; Lippmann [23]. Sagnac borrowed the vector representation of vibrations from Fresnel and Alfred Cornu.

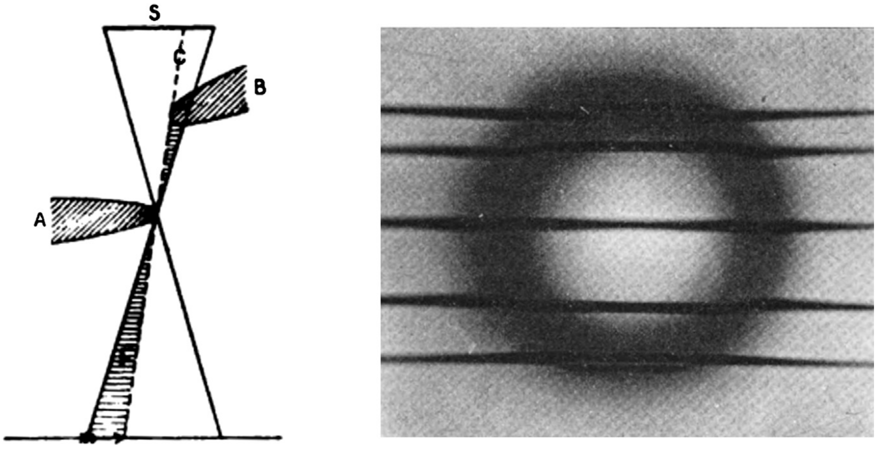

Fig. 2. (a) (left): Mutual attraction of two shadows. From Sagnac [33]. (b) (right): Deformation or doubling of the shadow of a wire when passing through the penumbra of a ring. From Sagnac [34].

of the observer, its successive positions are approximately parallel lines in relative translational motion with respect to the observer. In 1901, Sagnac gave a similar explanation of another illusion: the divergence of sunbeams through holes in a cloudy sky. In perspective, the quasi-parallel beams seem to be diverging from a point below the horizon at 180° from the sun.[8]

3. The optics of X-rays

In December 1895, Wilhelm Röntgen's discovery of X-rays shook the entire world of science. As is well known, Röntgen encountered the new rays and their amazing properties in the course of experiments on the cathode rays created by electric discharge in rarefied gases. Even physicists who had never worked with discharged tubes switched to the newly open field. Following Bouty's "insistent advice" Sagnac gave up his first dissertation project and devoted himself to the study of X-rays.[9]

Sagnac's approach was decidedly optical. As a working hypothesis, he assumed that X-rays were electromagnetic waves of very high frequency, a kind of ultra-ultra-violet light. They were therefore analogous to ordinary light and, at first glance, should be expected to enjoy the same properties of reflection, refraction, diffraction, and polarization. Röntgen's original failure to observe these properties led him to identify his new rays with longitudinal waves in the ether. Other investigators believed they could diffract X-rays, thus supporting the analogy with light. In contrast, Sagnac and a few British experts understood that electromagnetic radiation of very high frequency would not be dispersed if the frequency was much higher than the proper frequency of material oscillators and that it would not be diffracted if the wavelength was much smaller than the characteristic length of the diffracting system. From his own failure to diffract X-rays by a dense alignment of wires, Sagnac concluded that their wavelength could not exceed 0.04 μm. When he and J.J. Thomson failed to polarize them by means of crystal blades, he refused to see this negative result as an argument in favor of Röntgen's hypothesis of longitudinal vibrations.[10]

3.1. Optical X-ray illusions

Most interestingly, Sagnac proceeded to show that early claims of X-ray diffraction collapsed under analogy with the following optical illusion. Let the extended luminous source S project a shadow of the opaque object A on a screen (Fig. 2a). This shadow has a penumbra delimited by the cone C of rays from S through the extremity of the body A. Let a second opaque body B penetrate this penumbra. Then "the shadow of A seems to be attracted by the shadow of B." The reason is that the body B, while penetrating the cone C, blocks an increasing fraction F of the light rays that feed the penumbra of A, so that its shadow seems to be increasing. Through more detailed reasoning, Sagnac explained the strange appearance of the shadow of wires near or within the penumbra of a ring (Fig. 2b). Possibly, he had investigated effects of this kind before working on X-rays, as part of his interest in optical illusions. He now saw that the bending of X-ray alleged in some recent publications was the exact counterpart of the effects optically generated in Fig. 2b. Their principal cause was the large width of early X-ray sources, which were the glass walls of Crookes tubes. They disappeared when the source was properly narrowed by a diaphragm or when the source became the small anticathode of the next generation of X-ray tubes.

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[8] Sagnac [24,25].

[9] Röntgen [26–28]; Sagnac to Poincaré, 15 Sep 1900, in Walter [29, p. 328]. In conformity with French usage, I capitalize the X in X-rays (the most common old English spelling was "x rays").

[10] Sagnac [30]; [31, p. 538]. On early interpretations of X-rays, cf. Wheaton [32, pp. 16–20].

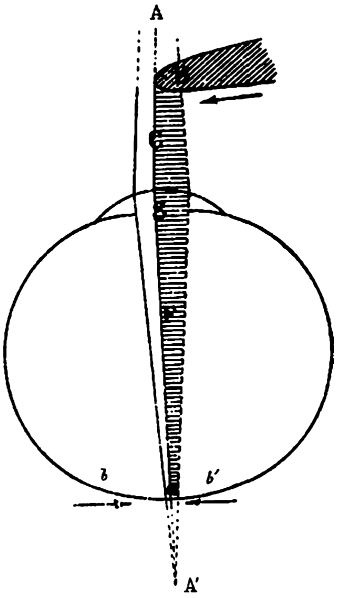

Fig. 3. The attraction of unfocused ocular images according to Sagnac. From Sagnac [35].

Sagnac drew the moral: "It is clear that the comparison of the effects of X-rays with the effects of light under the same conditions is indispensible in every research."[11]

A purely optical corollary of Sagnac's insights into the illusions of penumbra was his explanation of illusions of ill-accommodated sight, published in the following year. Let a point-like object A be placed too close to the eye for accommodation on the retina to be possible. Then an image A′ of A is formed beyond the retina *bb′*, so that A is seen unfocused as the intersection *a* of the retina with the cone of rays falling on A′ from the pupil S. Introducing the opaque body B in the incoming cone of rays C blocks the shaded fraction F of the rays and thus crops the diffuse image *a* on one side, so that this image seems to be sharper and to have moved to the opposite side. The net effect is a seeming attraction of the image of A by the body B. Anyone can observe this phenomenon with a minimal apparatus: eye and fingers (Fig. 3).[12]

3.2. From dissemination to fluorescence

In 1897 Sagnac reviewed his and others' works on the propagation of X-rays for the readers of *L'Éclairage électrique*. He began with a clear statement of his own method:

"I have constantly endeavored to compare the properties of X-rays with the properties that ultra-violet light of extremely small wavelength could have. This method of work will remain necessary and logical as long as no new fact will force us to formally distinguish X-rays from the transverse vibrations of the ether that constitute light waves. So far the hypothesis of X-rays as ultra-violet rays suffices for the interpretation of every known fact."

Sagnac concluded that X-rays failed to be reflected, refracted, diffracted, or polarized by current experimental means. The only property they shared with light (besides ray propagation) was their "dissemination" when traveling long distances through air. Sagnac had suspected this phenomenon from the veiling of radiographies taken at large distance from the object; Röntgen had recently confirmed it; he and Sagnac had further observed dissemination by metallic objects; and Sagnac believed that the maximum of intensity observed on photographic plates at the border between shadow and penumbra was due to a non-local action of the X-rays on the plate, implying secondary radiation. His review ended with the following observation:[13]

"As the extreme smallness of the wavelength of X-rays prevents us from realizing most of optical experiments with them, for further progress it is natural to study the phenomena of diffusion that truly dominates the history of these new rays."

This is exactly what Sagnac began to do in mid-1897. In his first communications on this matter, he explained that by "dissemination" he meant either true diffusion or luminescence. By true diffusion he meant Rayleigh scattering, which required a wavelength of the X-rays not too much larger than the size of the scattering molecules. This was compatible with the failure of usual diffraction experiments, and it could explain the higher penetrability of rays after traveling a long distance of air as an effect similar to the dominant scattering and absorption of blue light in the optical case (the transmitted

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[11] Sagnac [33, p. 880]; [34, p. 409].

[12] Sagnac [35,36].

[13] Sagnac [31, pp. 531, 539]; Röntgen [26, pp. 6–7] (reflection–diffusion by metals); Röntgen [28, pp. 18–20] (diffusion by the air).

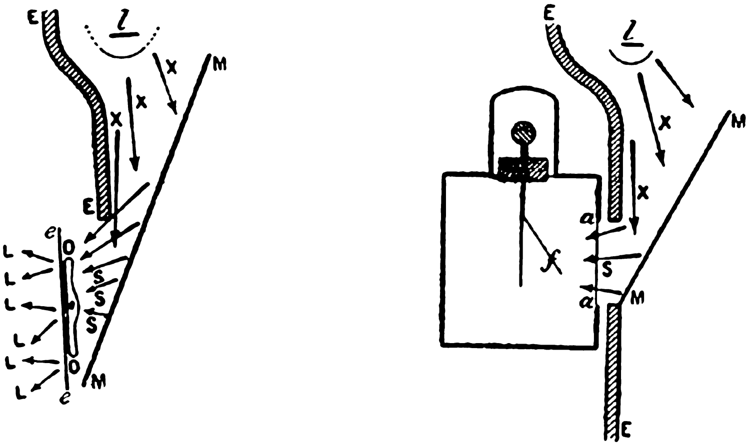

Fig. 4. Two ways of detecting secondary rays. The X-rays from the anticathode *l* hit the metal plate M to produce the secondary rays S. These rays, selected by the lead screen E, impress the photographic plate *cc* (producing a radiographic image of the interposed object OO); or they discharge an electroscope through the thin aluminum foil *aa* and the gold foil *f*. From Sagnac [42, p. 37].

red light being less easily absorbed). Sagnac nonetheless believed luminescence to be the more likely cause of the dissemination, by analogy with the fluorescence excited by UV light. In particular, he argued that the electric conductivity of gases subjected to X-rays was comparable with the physical and chemical alterations observed in fluorescent or phosphorescent bodies.[14]

At this point, it is good to remember that luminescence had been generically defined by Eilhard Wiedemann as the absorption of a radiation of a given type (wavelength) followed by the emission of radiation of different type, with no delay in the case of fluorescence and a significant delay in the case of phosphorescence. In optics, luminescence was known to imply an increase of wavelength, a law first stated by George Gabriel Stokes in 1852. Sagnac expected the same thing to happen in the case of X-rays conceived as ultra-ultra-violet light.[15]

As explained by Quintin, Sagnac was not the first to suggest X-ray fluorescence. Röntgen had raised this possibility: "I have not yet been able to decide whether the rays emerging from the irradiated bodies are of the same kind as the incoming rays; in other words, whether a diffuse reflection or a process analogous to fluorescence occurs." Other investigators had found some evidence in favor of the latter option, but Sagnac was the first to provide unambiguous proofs and to launch a systematic study of the secondary rays. In the summer of 1897 he demonstrated that the surface of most metals except aluminum, when exposed to X-rays, emitted rays that could penetrate only a few millimeters of air and then impress a photographic plate. These rays were easily absorbed by thin sheets of metals or other materials. The activity of the metallic surface depended both on the hardness of the impacting X-rays and on the nature of the metal. It was stronger for the heavier elements. Sagnac further suggested that the transformed rays could be transformed again by impact on a second metal. He concluded: "Plausibly, we will be able to gradually fill up the unoccupied interval that separates the X-rays from the known ultra-violet rays and perhaps to identify them with such rays."[16]

Sagnac soon proved that the "secondary rays" were in many ways similar to X-rays: they propagated in straight lines; they could not be reflected in a mirror-like manner; they could not be refracted; and they were able to discharge electrified metallic conductors. Sagnac insisted on this last property, for it provided a more precise electroscopic method to detect and measure the secondary rays (see Fig. 4). The secondary rays nonetheless differed from X-rays by being much more easily absorbed, to an extent depending on the generating metal.[17]

3.3. S-rays

Sagnac called the secondary rays "S-rays," perhaps because he wanted to emphasize the transformed character of the secondary radiation (although he meant the letter S to stand for secondary, other physicists soon spoke of "Sagnac rays"). In early 1898, he introduced what he henceforth advertised as the best proof of transformation: the asymmetry of the effect of an absorbing plate placed before and after the diffusing body (see Fig. 5). In his teaching (see Fig. 6) and in systematic expositions of his researches, he liked to explain this asymmetry through an optical analogy: in the setups of Fig. 7, the

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[14] Sagnac [31, p. 534]; [37, pp. 169–171].

[15] Wiedemann [38]; Sagnac [39]. On Stokes's "fluorescence", cf. Darrigol [40, p. 250].

[16] Quintin [3]; Röntgen [28, pp. 19–20]; Sagnac [41, p. 232].

[17] Sagnac [42,43].

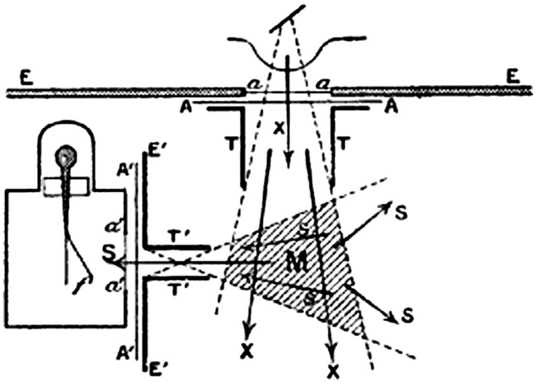

Fig. 5. Sagnac's proof of transformation of X-rays by permutation of absorber and scatterer. (Ironically, Sagnac introduced this setup in the case of scattering by air, for which the transformation soon became controversial (see below)). Later variants of this setup (e.g., Sagnac [44, p. 11]) included a transforming metal plate in the region M.) The X-rays from the tube induce S-rays in the region M. These rays discharge the foil f of the electroscope. A metal sheet has a stronger attenuating effect when placed at the entrance of the electroscope (position A′A′) than when placed at the exit of the tube (position AA). From Sagnac [45, p. 522].

Fig. 6. Sagnac teaching (with two assistants on his sides). From the inscription on the blackboard, it appears that Sagnac was teaching luminescence, photographic action, X-rays, and transformed rays in the same lesson. The two drawings illustrate the permutation of scatterer and absorber as a proof of transformation (probably for light, as the letters L and L′ suggest). X-ray tubes and Ruhmkorff coils can be seen on the desk. The lamp on the right corner may be part of setup for showing the transformation of light by a solution of fluorescein. From Archives nationales.

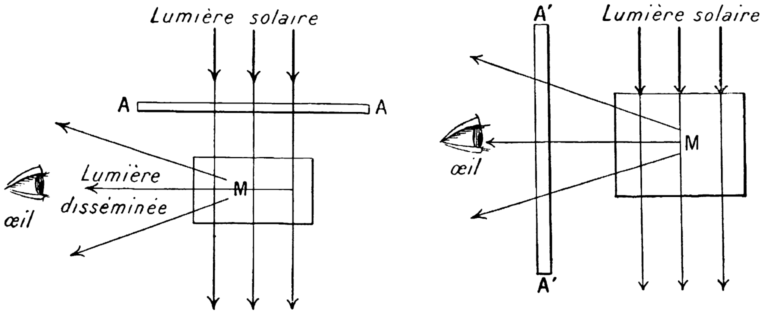

Fig. 7. Sagnac's optical analogy for the effect of permuting scatterer and absorber. The intensity of the light perceived by the eye is much smaller when the absorbing plate of blue glass AA is placed after the scattering solution of fluorescein M. From Sagnac [44, p. 11].

transformation of light when scattered by a solution of fluorescein is proved by comparing the effects of an absorbing plate placed before and after the fluorescent scatterer.[18]

3.4. S-ray analysis and a controversy

In 1898–1899, Sagnac showed that the penetrating power of the secondary rays from metal "most often" decreased with their atomic weight, thus anticipating Moseley's law. He also established a rough connection between emission and absorption: the rays most absorbed by a given element are those that best excite secondary emission by this element. He recognized that the secondary radiation from the same element was heterogeneous. And he had the idea that the S-rays could be used for chemical analysis, although the means he had for separating rays of different absorbing power were rather primitive. A pervasive difficulty of his experiments, which he himself emphasized and tried to circumvent, was the fact that any absorber also emitted secondary or tertiary radiation that acted on the detector placed behind the absorber. The matters were further complicated by the ambient air, which considerably absorbed and diffused secondary rays.[19]

Although air, water, and aluminum were far less active than heavier metals and although their secondary rays did not clearly differ from X-rays, Sagnac assumed that all elements transformed X-rays, to a degree decreasing with their lightness. In early 1898, he even believed to have proved that air transformed X-rays by his permutation method (see Fig. 5) and he compared this transformation with the transformation of light by a solution of fluorescein. In the April 1898 issue of the proceedings of the Academia dei Lincei, the Modena-based X-ray physicists Carlo Bonacini and Riccardo Malagoli denied that Sagnac's method was precise enough for the lighter diffusing bodies. In their opinion, there were two classes of bodies: lighter bodies for which ordinary diffusion occurred alone, and heavier bodies for which a mixture of ordinary diffusion and transformation occurred. Their own method of observation, based on photography and simultaneous comparison of the radiation from two different bodies, gave no evidence of a transformation for air or aluminum. In early 1899, Sagnac defended the superiority of his electric method and criticized many aspects of the experiments of his Italian competitors. The exchange turned sour. Bonacini and Malagoli sharpened their objections, and a visibly annoyed Sagnac dismissed the whole discussion as pointless: his adversaries had read him too superficially and too selectively; although his hypothesis of a gradually decreasing transformation was simpler than the Italian two-class hypothesis, he after all had "no preference for one hypothesis or the other."[20]

The later history of the subject has partially confirmed Bonacini and Malagoli's opinion: the action of X-rays on air and aluminum differs qualitatively from the action on metals for which the absorption edge belongs to the spectrum of the X-rays. The early methods of X-ray physics were just too imprecise to decide this question. Sagnac was not entirely wrong, however: the ionization of the air and the Compton effect do transform the incident rays; and Rayleigh (Thomson) scattering globally alters their spectrum.[21]

3.5. Perrin's metal effect

As a consequence of his optical method and interest, Sagnac did not pay much attention to the electric effects of X-rays and S-rays. He used them only as a means of detection. In contrast, Jean Perrin, who had experimented to prove that cathode rays carried an electric charge, focused on the electric effects induced by X-rays. With the help of the *normalien* Paul Langevin, he studied the discharge of electrified conductors by X-rays, a phenomenon simultaneously discovered by Röntgen in Würzburg, by J.J. Thomson in Cambridge, by Louis Benoist and Dragomir Hurmuzescu in the research laboratory

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[18] Sagnac [43, p. 469]; [45, p. 522]; [46, pp. 69–70].

[19] Sagnac [47–50] (heterogeneity of the secondary rays), [51–53] (on p. 208 of [53], Sagnac speculates that the transforming power might be related to the size of atoms).

[20] Sagnac [45,54]; [55, p. 110]; Malagoli and Bonacini [56,57].

[21] Cf. Quentin [3].

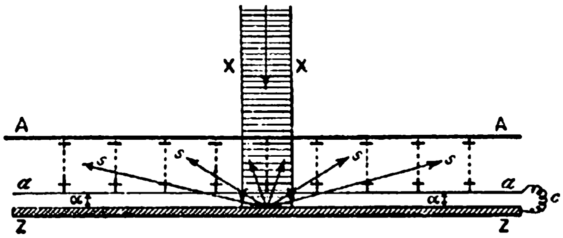

Fig. 8. Sagnac's experiment reducing Perrin's metal effect to secondary radiation. The X-rays fall on a condenser made of the (mostly inactive) aluminum foils AA and *aa*. The zinc plate ZZ, placed at the distance α of *aa* and electrically connected to *aa* emits S-rays that contribute to the discharge of the condenser. The discharge is maximal when ZZ touches *aa*. Removing *aa* at that stage increases the discharge by 10% only, as expected if the metal effect is caused by S-rays slightly absorbed by the foil *aa*. From Sagnac [59, p. 47].

of the Sorbonne, and by Augusto Righi in Bologna. Whereas Benoist and Hurmuzescu believed this effect to result from an action of the rays on the surface of the conductor (in analogy with the photo-electric effect), Perrin and J.J. Thomson traced it to an induced conductivity of the gas around the conductor. In the thesis he defended at the Sorbonne in June 1897, Perrin opted for a dual explanation: ionization of the gas, and "metal effect" implying ionization next to the metal at a rate depending on the nature of the metal.[22]

Sagnac soon denied the existence of the latter effect and argued that the metal-dependent part of the discharge depended on secondary radiation from the metal. Through careful experiments he showed that this radiation acted at a much larger distance from the metal than Perrin's explanation would allow (see Fig. 8). In a letter to Langevin, Perrin lamented: "Sagnac has just demolished one third of my dissertation."[23]

3.6. Langevin's parallel discovery

Since the summer of 1897 Langevin was working at the Cavendish laboratory in Cambridge. The director, J.J. Thomson, had just approved Perrin's metal effect and wanted to know more about it, if only because he did not want this effect to interfere with his studies of ionization in gases. Langevin set about studying the effect quantitatively by measuring how the discharge of a double-plate capacitor depended on the distance of the plates, on the nature of the active plate, and on the pressure of the gas (see Fig. 9). He found that for distances inferior to 1 cm the discharge depended on the distance between the two plates in a non-linear manner and that at every distance the discharge remained proportional to the pressure of the gas. These results contradicted Perrin's localization of the metal effect on the surface of the metal and instead suggested the production of secondary rays that ionized the gas. A few years later Langevin described this unpublished work with the following preamble: "At the beginning of my stay in the Cavendish Laboratory (October 1897), I was led, at the same time as Mr. Sagnac, and in a totally independent way, to discover the existence of these secondary rays, and to carry on their study using purely electrometric methods."[24]

As Lelong remarks, Sagnac's approach was mainly optical, qualitative, and macrophysical, while Langevin's was electric, quantitative, and microphysical. Sagnac found theoretical guidance in optical (dys)analogies, Langevin in the atomistic of ions. Whereas Sagnac vaguely measured the discharging time of an electroscope in vaguely defined geometrical conditions, Langevin used plane condensers and precise electrometers. Being less quantitative, Sagnac's experiments were more flexible but less rigorous. Their optical motivation gave central importance to the secondary rays as a kind of fluorescence. For Langevin and J.J. Thomson, those rays were only a parasitic phenomenon in an investigation of the kinetics of ions. This might explain why Sagnac published his findings before Langevin even thought of doing so.[25]

3.7. Radioactivity, luminescence, and S-rays

As we just saw, Sagnac's secondary rays mattered in X-ray studies of a different kind than his. As recently argued by Martins, they also mattered in early studies of radioactivity. On 20 January 1896, the mathematician Henri Poincaré communicated a few early radiographies to the French Academy. Henri Becquerel, who was in the attendance, asked Poincaré whether Röntgen had determined the origin of the rays. Poincaré answered that the rays came from the luminous spot of the glass wall that received the cathode rays. Becquerel "immediately thought of examining whether the new emission was not a manifestation of the vibratory motion that induced the phosphorescence and whether every phosphorescent body emitted such rays" and communicated this idea to Poincaré. The next day Becquerel started a series of experiments in which he had cathode rays fall on phosphorescent bodies placed next to a photographic plate wrapped in black paper within a Crookes tube. The plate remained unimpressed. On January 30th, the *Revue générale des sciences* published a text in which

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[22] Perrin [58]. On the earlier works, cf. Lelong [17, pp. 95–96].

[23] Sagnac [59]; Perrin to Langevin, undated, cited in Lelong [17, p. 106].

[24] Langevin [60, pp. 521–534, p. 517 (citation)]. Cf. Lelong [17, pp. 100–103].

[25] Lelong [17, pp. 105–106].

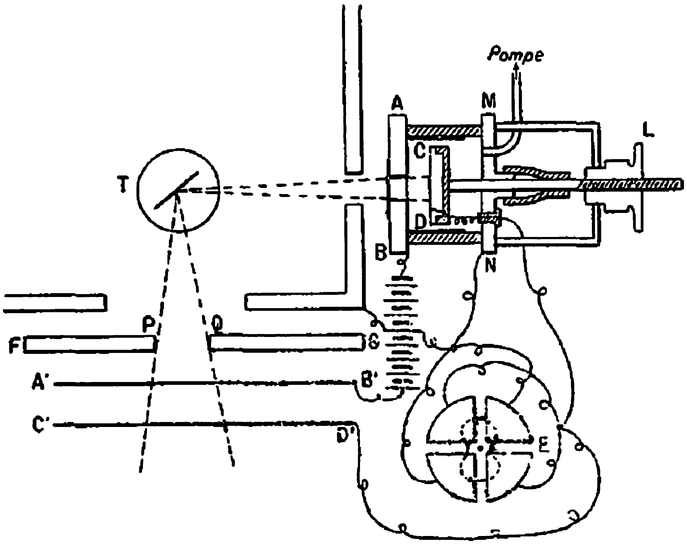

Fig. 9. Langevin's apparatus for studying the metal effect. The discharges induced by the same X-ray tube T in the two condenser ABCD and A′B′C′D′ are balanced by adjusting the opening PQ of the lead screen FG, the balance being judged by the electrometer E. The X-rays enter the condenser ABCD through a thin aluminum window and impact the active metal CD, whose distance can be varied through the screw L. The cavity ABMN can be filled with various gases at various pressures. From Langevin [60, p. 522].

Poincaré wondered "whether any body whose fluorescence is sufficiently intense emits, besides light rays, the X-rays of Röntgen, *whatever the cause of their fluorescence may be*? Then the phenomena would no longer depend on an electric cause. This is not very probable, but this is possible and should be fairly easy to check." The query prompted a few physicists, including Becquerel, to investigate whether phosphorescent bodies emitted X-rays even when they were not impacted by cathode rays. On February 24th, Becquerel announced to the Académie des sciences that he had obtained a positive result with a uranium salt earlier exposed to sunlight. He believed that this activity depended on the previous exposition to the sun and that it could be understood as an anomalous kind of phosphorescence in which radiation of optical frequency was turned into X-ray radiation of higher frequency (against Stokes' law).[26]

Young Marie Curie soon contradicted this view by showing that the ionizing activity of the rays from uranium salts did not depend on previous illumination. She also established that radioactivity depended only on the presence of an active element (uranium or thorium) and not on the way it was chemically combined. A simple explanation of the mysterious phenomenon then came to her mind:

"*Analogy with the secondary rays of the Röntgen rays*. – The properties of the rays emitted by uranium and thorium are very similar to those of the secondary rays of the Röntgen rays, recently studied by Mr. Sagnac.... To elucidate the spontaneous radiation of uranium and thorium we could imagine that the entire space is permanently crossed by rays analogous to the Röntgen rays, but much more penetrating and absorbable only by certain elements with a large atomic weight, such as uranium and thorium."

Pierre and Marie Curie's close friendship with Sagnac probably eased this analogy. Marie Curie's paper (her first) was read to the Académie des sciences on 15 April 1898. In the same month, an article by Sagnac on luminescence and X-rays appeared in the *Revue générale des sciences* with the footnote:[27]

"It is fit to remind here the discovery due to H. Becquerel of new invisible radiations emitted for several months, without noticeable weakening, by uranium salts and especially by uranium constantly kept in darkness. Up to this day there seems to be no limit for the duration of these phenomena, for which S.-P. Thompson proposed the name *hyperphosphorescence*. We do not know whether there really is a transformation of radiations or simply a spontaneous radiation due to a new mechanism. Anyhow, these remarkable *uranium rays* are fairly close to the X-rays by their electrical properties."

The analogy between uranium rays and Sagnac rays reinforced Marie Curie's conviction that radioactivity was a property of chemical *elements* (contrary to ordinary fluorescence, which is a property of compounds). When the Curies discovered that pitchblende, against that view, was more active than its uranium content implied, they suspected the presence of small quantities of an unknown element of higher activity than uranium. This insight, together with an extraordinary amount

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[26] Becquerel [61, p. 3]; Poincaré [62, p. 56]; Becquerel [63–65]. There is no textual evidence for the traditional view that the conjecture of a relation between X-ray and phosphorescence emanated from Poincaré. And there is no reason to distrust Becquerel's account (cited above). However, Poincaré was plausibly the first to entertain the possibility of X-ray emission without cathode-ray excitation (the emphasis is his in the citation from [62]).

[27] M. Curie [66, p. 1103]; Sagnac [39, p. 314n]. Cf. Martins [18]. The closeness of the friendship between Sagnac and the Curie is well illustrated in the moving letter that Sagnac, wrote to Pierre Curie on 23 Apr 1903 to alarm him about his wife's physical condition and to press the frenetic couple to adopt a healthier lifestyle: cf. Reid [67, pp. 127–129].

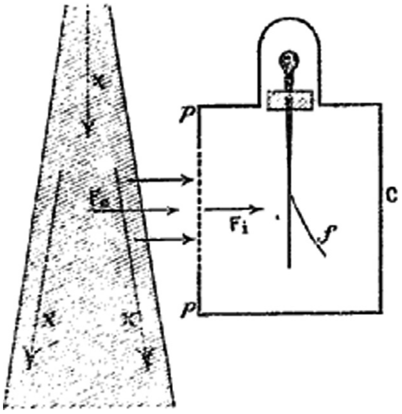

Fig. 10. Sagnac's device for proving the electric charge of S-rays. The secondary rays from the X-ray beam are subjected to the electric field F_e toward the electroscope and to the field F_i of the charged foil f. The electroscope is covered with the metal sheet C and with a metallic grid or with a pierced lead screen pp on the left side. From Sagnac [73].

of chemical labor, led to their discovery of polonium and radium. In the fall of the same year, they learned that Johann Elster and Hans Geitel had failed to observe any decrease of radioactivity in an 850-meter-deep pit. The Curies nevertheless maintained the fluorescence hypothesis. When, in 1899, they discovered induced radioactivity, they again relied on analogy with Sagnac's secondary radiation:[28]

"The phenomenon of induced radioactivity is a type of secondary radiation due to the Becquerel rays. However, this phenomenon is different from the one that is known for Röntgen rays. Indeed, the secondary rays of the Röntgen rays that have been studied up to now are born immediately when the bodies that emit them are hit by the Röntgen rays and they cease immediately with the suppression of the latter rays."

3.8. The charged component of secondary rays

In the same year 1899, it became clear that part of the uranium rays could be magnetically deviated. This contradicted the analogy between radioactive rays and S-rays, following which they should both be electromagnetic radiation of very high frequency. The Curies nevertheless confirmed that the rays from radium carried electric charge by precise electrometry à la Pierre Curie. The analogy could still be restored if X-rays themselves carried electric charge; or if the S-rays had an electrically charged component. The Curies must have known that Sagnac had contemplated the latter possibility and that in unpublished experiments of 1898 he had obtained evidence for it. Pierre Curie and Sagnac soon collaborated to investigate whether X-rays and S-rays carried electric charge. Their experiments proved that X-rays did not and that S-rays did. From then on, Sagnac regarded the secondary rays as a mixture of electromagnetic radiation and charged particles similar to the β component of the Becquerel rays.[29]

In his experiment of July 1898, Sagnac used an electroscope and the secondary rays emitted by air traversed by an X-ray beam (see Fig. 10). The electroscope was covered with a metal sheet to make it a Faraday cage, and the secondary rays entered it through holes in the cage. Sagnac found that an external field applied to the secondary rays outside the cage accelerated or decelerated the discharge of the electroscope according as the field was directed toward or outward the cage. He concluded that the electroscope was bombarded by a flux of charged particles, and compared this flux to a slow version of cathode rays. The complicated electric circumstances of this experiment may explain why Sagnac deposited his results as a *pli cacheté* to the Académie des sciences and waited more definite results before publishing the contents in early 1900.[30]

The later experiment of Curie and Sagnac benefited from Pierre Curie's refined electrometric skills. In the first of the two devices they used (Fig. 11), a foil cc of the metal M is placed in the middle of the rectangular cavity ABCD, which is made of a different metal N. The X-rays from the anticathode l enter the cavity through the foils f and induce secondary rays both on the internal foil cc and on the walls of the cavity, at a rate depending on the choice of the metals M and N. The air is evacuated from the cavity in order to avoid absorption and ionization. A quartz-controlled electrometer, connected to the foil cc, detects any electric charge associated with the secondary rays. Curie and Sagnac found the highest charge for platinum and lead, and the least for aluminum. They thus established the existence of an electrically charged component of the secondary radiation of heavy metals. They understood that this charged component shared the high ionizing power of cathode rays:

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[28] P. and M. Curie [68, pp. 715–716]. Cf. Martins [18].

[29] P. and M. Curie [69]; Sagnac, *plis cachetés* of 28 March and 18 July 1898, Archives de l'Académie des sciences; Curie and Sagnac [70–72]. Cf. Martins [18].

[30] Sagnac, *plis cacheté* of 18 July 1898; Sagnac [73].

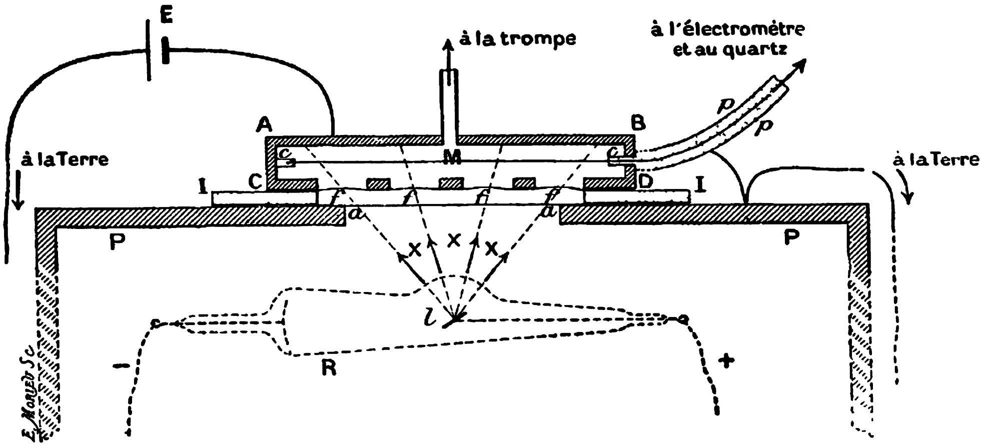

Fig. 11. One of Curie and Sagnac's setups for proving the existence of an electrically charged component of secondary rays. From Curie and Sagnac [70, p. 1014].

"The whole set of observed effects suggests that the *secondary electric emission* of heavy metals has properties analogous to those of cathode rays and of the deflectable rays of radium: the particles of negative electricity of the rays are able to dissociate the neutral electricity of gases in positive and negative quantities of electricity, considerably superior to the negative quantity of electricity of the rays, as long as the gas under study is not overly rarefied."

They did not fail to note that their new effect, the production of electrically charged radiation by the impact of X-rays on metals, much resembled the electric flux Philipp Lenard had recently obtained by exposing non-electrified metal plates to extreme UV light. They concluded:

"The negative electrification of secondary rays brings a new analogy between X-rays and ultra-violet rays. It thus becomes more and more probable that the secondary rays contain rays of the same species as the incoming X-rays that produce them by diffusion or transformation."

Through his collaboration with Pierre Curie, Sagnac thus gained a new argument in favor of the analogy between X-rays and ultraviolet light. In return, the Curies could protect Marie Curie's hypothesis of a deep analogy between radioactivity and secondary emission.[31]

3.9. Radioactivity and gravitation

Although Ernest Rutherford and Frederick Soddy's contemporary discovery of the link between radioactivity and transmutation reduced the appeal of Marie Curie's hypothesis, Sagnac and the Curies defended it for a few more years. At the first international congress on radiology and ionization held in 1905 in Liège, Sagnac explained how his and Pierre Curie's discovery protected the analogy between radioactive emission and secondary rays, and he offered the following wisdom:

"Some tried to ruin [Marie Curie's] hypothesis by arguing that it is hardly philosophical to imagine an unknown, undetected radiation to explain effects that have their evident seat in the radioactive atoms. However, pushing this objection to the extreme, we could say that luminous or electromagnetic vibrations have no existence outside their source and their material receiver since they do not produce any observable effect in vacuum and since you know them only through their action on matter. Then we would suppress the concept of luminous ether as anti-philosophical. We may describe luminous phenomena without mentioning the ether. But that is not a satisfactory description.… It does not give the satisfaction we feel by eliminating direct action at a distance.… As long as we refuse to renounce this satisfaction, the hypothesis according to which radioactive bodies borrow their energy from an ambient medium that still exists in a vacuum will be as worth conserving as the hypothesis of the luminous ether."

Sagnac went on to explain that the same ambient medium could provide the solar, gravitational, and radioactive energies.[32]

The following year in the *Journal de physique*, Sagnac published a more detailed speculation of this kind together with an experimental test he had performed in Pierre Curie's laboratory in 1902. The starting idea was that gravitation, in analogy to Georges Lesage's old theory and according to a more recent speculation by Lorentz, could be explained as a shadow effect for the continual bombardment of celestial bodies by a pervasive, isotropic, and highly penetrating radiation. Whereas this radiation could only rebound on ordinary atoms, Sagnac made it able to dissociate radioactive atoms. This dissociation would modify the momentum transfer from which gravity derives in Lesage's conception. Consequently, the gravitational mass of radioactive bodies should be smaller than their inertial mass. Sagnac's tested this effect by measuring the period of

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[31] Curie and Sagnac [72, pp. 20, 21].

[32] Sagnac [74, p. 155].

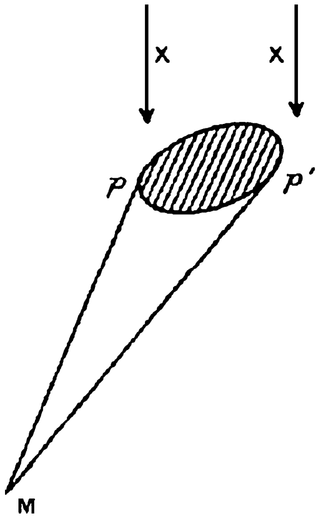

Fig. 12. Sagnac's diagram to explain the softening of X-rays by particle diffraction. For a finite wave train of incoming X radiation, the vibration at M originating from the point p' of the diffracting particle is still active when the vibration from p has ceased. From Sagnac [81, p. 184].

oscillation of a torsion balance loaded successively by equal weights of a radium salt and of a barium salt. The result was negative at the precision of the measurement (1%).[33]

3.10. The thesis, a turning point

On 21 December 1900, Sagnac defended his doctoral thesis at the Sorbonne in front of Gabriel Lippmann (president), Bouty (director and examiner), and Émile Duclaux (examiner). The title of the dissertation, *De l'optique des rayons de Röntgen et des rayons secondaires qui en dérivent*, captures Sagnac's optical approach. The exposition is roughly chronological. The first part deals with the (dys)analogy between X-rays and light, the second with the secondary rays and their properties beginning with the absorption properties and finishing with the experiments of Curie and Sagnac. Besides the optical leading thread, a general characteristic of the dissertation is its avoidance of microphysical considerations. Ions, electrons, or corpuscles (J.J. Thomson's word for the electron) nowhere occur in the text. Although Sagnac does occasionally approve J.J. Thomson's concept of X-rays as an electromagnetic disturbance caused by the stopping of charged corpuscles and although he holds a molecular conception of matter, he ignores the British and German tendency to consider cathode rays, X-rays, and their ionizing properties as an entry into a new microphysics of ions and electrons. In this regard he follows the French preference for a more phenomenological approach to the new radiations, of which the Cambridge-trained Langevin may have been the only significant exception. Even Jean Perrin, who would later offer proofs of molecular reality, avoided atomistic considerations in his early researches on X-ray ionization.[34]

This does not mean that Sagnac did not have any molecular theory in the back of his mind. As was already mentioned, he believed that his own theory of the propagation of light through matter implied vanishing dispersion and refraction when the wavelength became small compared to the spacing of the molecules of matter.[35] In this range of wavelengths, he argued that the absorption of vibrations by matter should increase as the wavelength increased. For this reason and by analogy with Stokes' law, he associated the higher absorption of transformed radiation with a longer wavelength. He explained the transformation of X-rays as an effect of the finite size of the particles of matter: if the incoming X-rays are damped wave trains of the form $e^{-\alpha t}\cos(\omega t+\varphi)$, he reasoned, then the wave trains resulting from diffraction by a finite particle are longer and more regular because of the different traveling times from the various points of the diffracting particles (see Fig. 12). Their Fourier spectrum is therefore shifted toward lower frequencies.[36]

After completing his dissertation, Sagnac taught physics as *maître de conférences* at the University of Lille until 1904. He ceased to work on X-rays and secondary radiation, except for systematic reports he had to prepare for a treatise on

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[33] Sagnac [75]. Sagnac's *pli cacheté* of 23 Feb 1902 propounds a simpler pendulum experiment, with the additional conjecture that the ratio of the (inertial) atomic mass to the atomic number was the same for barium and radium, which gives a 20% relative difference in the pendulum frequencies. On Lesage's theory, cf. Chabot [76–78].

[34] Sagnac [79]; [80, pp. 431–432] (J.J. Thomson's X-ray concept). On the French approach, cf. Lelong [17]. On contemporary debates on the nature of X-rays, cf. Wheaton [32, Chap. 2]. The dominant hypothesis was the electromagnetic impulse hypothesis, which did not much differ from Sagnac's wave packet hypothesis for practical purposes.

[35] Sagnac was also aware of Helmholtz's theory of dispersion, based on the coupling between ether waves and material oscillators, and leading to the same result in the limit of vanishing wavelength (Sagnac [80, pp. 431–432]).

[36] Sagnac [39, p. 316]; [49, p. 555]; [81, pp. 183–185].

radiology and for the international congress of 1905. Major events in this field, such as Charles Glover Barkla's discovery of X-ray polarization in 1904 and Max Laue's discovery of X-ray diffraction in 1912 failed to win him back. He left to Barkla, William Henry Bragg, Henry Moseley, Maurice de Broglie, and a few others the pleasure to develop X-ray spectroscopy, his idea of chemical analysis based on X-rays, and the X-ray photoelectric effect he had discovered with Pierre Curie. Judging from a letter he wrote to Lorentz in 1901, he seems to have regarded his work on X-rays as an unwanted distraction from his interest in pure optics: "Since 1896 I have unfortunately been carried away in researches [*entraîné dans des recherches*] on X-rays which, added to my obligatory occupations, hardly leave me any time. It is in fact for this reason that I left aside my researches in optics since 1897."[37]

4. The propagation of light

Sagnac was impatient to resume his optical researches. A year before he defended his dissertation, he found time to publish some of his ideas on the propagation of light in matter. In order to understand the timeliness of these ideas, some of the earlier history of wave optics must be recalled.

4.1. The separation of ether and matter

In the oldest mechanical theories of the optical medium, those of Fresnel, Charles Augustin Cauchy, and Franz Neumann, there was only one effective medium with characteristic properties (mainly density and elasticity) depending on the amount and kind of matter mixed with the ether. Although this approach correctly represented the propagation, reflection, and refraction of light, it failed to account for the observed laws of optical dispersion. This is the main reason why the next generation of optical theories involved two separate media, ether and matter, affecting each other in various manners. In a sense the separation was not yet complete, because the matter molecules modified the structure of the interstitial ether, typically its density or its elasticity. In the 1860s Adhémar Barré de Saint-Venant and his disciple Joseph Boussinesq argued that such modification was implausible and Boussinesq devised a theory in which the ether between the molecules remained completely unchanged. The molecules only modified the ether at their location, through a coupling inspired by hydrodynamic analogy. In this framework, Boussinesq could account for all known optical phenomena, even those of the optics of moving bodies (to which I will return in a moment).[38]

In 1870s, the discovery of anomalous dispersion prompted a few physicists, including Wolfgang Sellmeier and Hermann Helmholtz, to represent the interaction between light and transparent matter as the mutual coupling between ether waves and material oscillators. Anomalous dispersion occurred when the frequency of the waves exceeded the characteristic frequency of the material oscillators. In conformity with Saint-Venant's views, this mechanism made any modification of the interstitial ether irrelevant. In the 1878, the young Hendrik Antoon Lorentz, who was one of the few continental believers in James Clerk Maxwell's electromagnetic theory of light, gave an electromagnetic version of the Sellmeier–Helmholtz theory. More broadly, Lorentz conceived an electromagnetic counterpart of Boussinesq's theory in which the electromagnetic ether remained totally unaltered in the presence of material molecules and in which the interaction between ether and matter depended on the electromagnetic coupling between electromagnetic fields and molecular ions. In the 1890s, Joseph Larmor and Emil Wiechert developed similar views, and electrons came to replace Lorentz's ions. By the end of the century the leading experts on optics and electromagnetism agreed that Lorentz's theory was the only one that could account for the whole range of known optical and electromagnetic phenomena. In particular, Lorentz was able to explain seemingly incompatible results of the optics of moving bodies.[39]

4.2. Early inspirations

When he developed his own theory of the propagation of light through matter, Sagnac was unaware of Lorentz's theory. According to letters he wrote to Lorentz and Poincaré in 1900–1901, he reached the main ideas of his theory while studying at the École normale in 1890–1891 and after being exposed to atomism in chemistry, mineralogy, and crystal optics. Later, in 1892–1893, he integrated ideas from Louis Georges Gouy's memoir on the anomalous propagation of light near a focus and from Heinrich Hertz's theory of electric oscillators, which he heard Poincaré teach at the Sorbonne. From the beginning Sagnac had been concerned with the optics of moving bodies and with Fizeau's result regarding the drag of light waves by running water. After being long lost in complicated calculations, he arrived at a very simple explanation of this phenomenon around 1895 and at a new theory of reflection and refraction in 1896. But his X-ray work forced him to delay publication.[40]

Sagnac's early concern with the discontinuity of matter contradicts the well-spread view that French physicists of the time favored a macroscopic approach to physics and liked to question atomism. It is true that most of them were ill-informed of the recent kinetic-molecular theories of Maxwell and Boltzmann and that they did not let atomistic considerations guide their experimental work. Nevertheless, most of them believed in the molecular structure of matter and some

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[37] Sagnac to Lorentz, 6 Jan 1901, AHQP. On the development of X-ray physics after Sagnac, cf. Wheaton [32], Heilbron [82].

[38] Boussinesq [83]. Cf. Darrigol [84, pp. 244–258]. On the first ether theories of the nineteenth century, cf. Buchwald [85].

[39] Lorentz [86–88]. Cf. Buchwald [89]; Darrigol [90, Chap. 8].

[40] Sagnac to Lorentz, 6 Jan 1901, AHQP; Sagnac to Poincaré, 15 Sep 1900, in Walter [29].

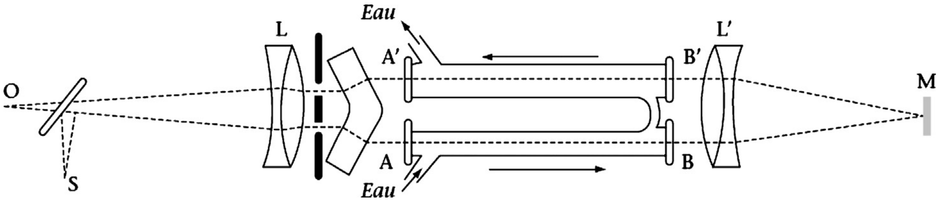

Fig. 13. Fizeau's experiment on the dragging of light waves by running water. The light from the source O is turned into two parallel beams though the combination of the lens L, the double diaphragm and the double thick glass plate. Those beams travel a first time through two water columns AB and A′B′ that move in opposite directions. After crossing the lens L′ and being reflected on the mirror M, they exchange path and direction of motion. Their superposition is observed at S after reflection on an inclined glass plate.

of them, especially Saint-Venant and Boussinesq, pursued molecular theories in the wake of the Laplacian and Amperean tradition of the early nineteenth century.[41]

Although in his letter to Lorentz Sagnac claimed to have known only Fresnel's and Franz Neumann's ether theories at the beginning of his researches, he plausibly heard about Boussinesq's theory (Boussinesq was then a Sorbonne professor) and from it he may have drawn the general idea of molecules interspersed in an immovable ether. If he did, he must have disliked the dryly formal way in which Boussinesq represented the coupling between ether and molecules. What Sagnac wanted was a simple, visual picture of the way in which an incoming wave interacted with a succession of molecules regarded as centers of diffusion:

> "I consider the luminous vibrations inside a body as propagating by means of *a medium identical to the ether of vacuum*. The density and the elasticity of this vibrating medium do not differ from their values in a vacuum. I do not either consider *mechanical reactions* between ether and matter. I directly exploit the *discontinuity of matter* according to a principally *kinematic* mechanism."

Through this statement, Sagnac introduced the first sketch of his theory in the November 1899 issue of the *Comptes rendus*. The first two sentences seem reminiscent of Boussinesq's theory or later French variants. The exclusion of "mechanical reaction" signals how Sagnac departs from that theory. The emphasis on *kinematics* became a leitmotiv of Sagnac's approach. He purported to show that effects that had so far been explained by complex, highly formalized dynamics could in fact be explained by simple kinematic considerations.[42]

Sagnac went on to assume that the "particles or atoms" of matter reemitted a well-defined fraction of the energy of the incoming vibration in every direction, as a tiny Hertz resonator would do when interacting with an incoming electromagnetic wave. This "reflection–diffraction," thus described in broad terms, sufficed to explain how the presence of matter affected the velocity of light. Suppose the transparent body to be delimited by a plane P and to be met by a parallel monochromatic plane wave. This wave is multiply reflected by the particles of the body. The net transmitted wave on a plane S within the body is the resultant of waves that have been reflected an even number of times. The phase of the component waves depends on the length of their zigzagging path, and their amplitude decreases exponentially with the number of reflections. The phase of the net wave is obtained by superposing these component waves. The spacing of the particles being much smaller than the wavelength, this phase is easily seen to increase linearly with the distance from the limit P of the transparent body except for very small values of this distance. The rate of increase yields the wave number. The optical index is the excess of this rate over its vacuum value. As is typical with Sagnac, there are no equations and all reasoning is intuitive.[43]

4.3. The Fresnel drag

In his second communication on the propagation of light, Sagnac dealt with the dragging of light waves in a moving transparent media. Early in the century, Fresnel had shown that in order that the laws of refraction be unaltered by the motion of the earth through the ether, light waves had to be dragged by a moving transparent body at a rate given by $(1 - 1/n^2)u$, if n denotes the optical index of the body and u its velocity with respect to the ether. In an interferometric experiment of 1851, Fizeau found that the phase of waves traveling through running water was shifted to the amount predicted by Fresnel (see Fig. 13). An ingenious feature of Fizeau's setup should be emphasized: it involves the interference between two beams of light that have traveled on the same circuit in opposite directions. This is indeed the only way to detect a phase shift occurring over a travelling length much longer than the coherence length. As we will see in a moment, Michelson, Lodge, and Sagnac later relied on the same subterfuge for the same reason.[44]

In the 1870s, thanks to the efforts of Éleuthère Mascart in Paris and of Wilhelm Veltmann in Holzminden, it became clear that the Fresnel drag played a central role in explaining the absence of (first-order) effects of the ether wind in a great variety of terrestrial optical experiments. At the same time, Fresnel's old explanation of the drag by conservation of the

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[41] On late nineteenth-century French molecular theories, cf. Principe [91].

[42] Sagnac [92, p. 756]. On this theory, cf. Martinez-Chavanz [6, pp. 37–43].

[43] Sagnac [92].

[44] Fresnel [93]; Fizeau [94]. Cf. Whittaker [95, pp. 109–113]; Darrigol [40, pp. 258–261]. As Mascart and Lorentz later realized, in Fizeau's setup the Doppler frequency-shift in the running water slightly modifies the Fresnel drag.

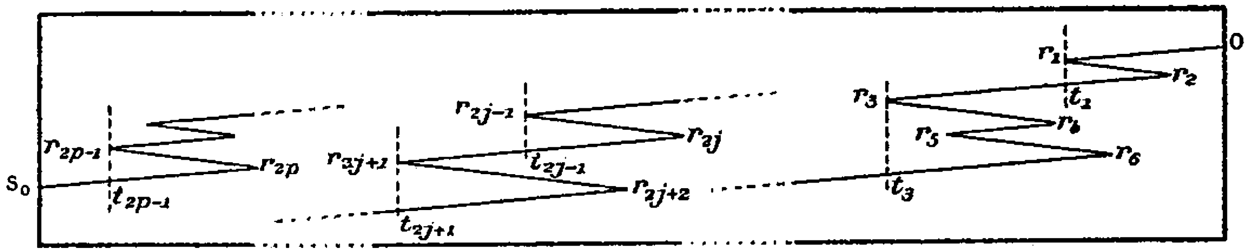

Fig. 14. Sagnac's drawing of a light path in a moving transparent body. From Sagnac [96].

ether flux[45] fell apart because a different dragging coefficient was needed for different frequencies in dispersive media or for different directions of propagation in anisotropic media. In the aforementioned memoir of 1868, Boussinesq succeeded in deriving the Fresnel drag formula with a completely stationary ether, as an effect of the convection of the molecules of the moving transparent bodies. In 1892 Lorentz did the same in the context of his own electromagnetic theory. Assuming that Sagnac heard about these theories, they involved more algebra than he could digest. His own explanation of the Fresnel drag required no more than the multiple reflection defined in his first communication.[46]

4.4. The principle of the effect of motion

First consider a solid narrow transparent body moving at the velocity u through the ether. After entering the body in O, the light zigzags at the vacuum velocity c in the intermolecular space and exits the body in S_0 as indicated on Fig. 14. The motion of the body from right to left increases the time of the travel from the reflection point r_{2j} to the reflection point r_{2j+1} in the proportion $c/(c-u)$ because the latter point recedes during this travel; and it decreases the traveling time from r_{2j+1} to r_{2j+2} in the proportion $c/(c+u)$. Call t_{2j-1} the point of the segment $[r_{2j}, r_{2j+1}]$ that is at the same distance from the entrance of the body as the point r_{2j-1}. To first order in u/c, the motion of the body does not affect the traveling time in the portion $[r_{2j-1}, r_{2j}, t_{2j-1}]$ of the path; and it affects the remainder of the path in the proportion $c/(c-u)$. Since this remainder has the same length as the direct path from O to S_0, the net first-order effect of the motion of the body is to increase the traveling time by ul/c^2, wherein l is the length of the body. Sagnac thus reached the following remarkable result: the correction to the traveling time of light in a moving transparent body is the same as if the body had been emptied of all its matter. This is what Sagnac called the *principle of the effect of motion*.[47]

In the case of water moving through a pipe as it does in Fizeau's experiment (Fig. 13), the water flows off the pipe laterally at B while the light proceeds from A to B. Consequently, the light travels a length of water that differs from the length l of the tube by the amount $-u\tau$ if τ denotes the traveling time of the light from one end of the tube to the other. For vanishing u, the velocity of light in water is c/n and $\tau = nl/c$. The resulting first-order correction to the traveling time in the moving water is $(-u\tau)/(c/n) = -n^2ul/c^2$. Adding this outflow correction to the convective correction ul/c^2, Sagnac got $\delta t = (1-n^2)ul/c^2$ for the total Fizeau effect. This prediction agrees with Fresnel's partial drag hypothesis because according to this hypothesis the velocity of light in the moving water is $V = c/n + (1 - 1/n^2)u$ (in the laboratory frame) and the corresponding decrease in traveling time is $l/V - l/(c/n) \sim (1-n^2)ul/c^2$.

4.5. Kinematics first

When he presented his theory to the Société française de physique, Sagnac placed much weight on his principle of the effect of motion. On the one hand, this principle results from Sagnac's concept of multiple reflection in an immovable ether. On the other, it can be inferred from Fizeau's experimental result by subtracting from the measured phase-shift the phase-shift corresponding to the outflow of the running water. Sagnac further showed that his principle immediately explained the negative result of all of Mascart's first-order ether-wind experiments. For instance, the independence of birefringence from the motion of the earth results from Sagnac's principle separately applied to the proper modes of propagation in a crystal. This principle even more evidently implies the absence of fringe shift when altering the orientation of an interferometer in which the interfering rays travel through different substances. In retrospect, Sagnac's principle does exactly what a first-order Lorentz transformation does in explaining the lack of first-order effects of the motion of the earth.[48]

As was mentioned, Sagnac also believed that his theory, once extended to the limit of wavelengths much smaller than the interval between two molecules, explained or at least was compatible with the behavior of X-rays in matter. In this case he expected the reflection by individual atoms to be so small that much of the ethereal vibrations travelled through matter

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[45] If the slower velocity of the waves in a medium of higher optical index is traced to a higher density of the ether in this medium, then the conservation of the ether flux at the interface between two different media implies the Fresnel drag.

[46] Boussinesq [83]; Lorentz [87,88]; Sagnac [96]. Cf. Janssen annd Stachel [97]; Darrigol [40, p. 257].

[47] Sagnac [96].

[48] Sagnac [98, pp. 170–171]. As we will see in a moment, Sagnac later became aware of the connection with Lorentz's local time.

without any reflection. Consequently, there was no phase delay and no refraction. The residual scattered light was isotropic because the wave packets reflected by different atoms were too far apart to interfere.[49]

Sagnac did not believe that his theory, in its present form, could explain every optical phenomenon. However, he regarded it as methodologically important to introduce the hypotheses of the theory one by one, in the order of increasing complexity of the investigated phenomena. For the moment he knew that rectilinear propagation, refraction, the Fresnel drag, and much of the optics of moving bodies could be understood in a mostly kinematic manner, through the simple idea of scattering centers in a homogeneous ether. Polarization properties, anisotropic propagation, and anomalous dispersion surely required a more precise description of the scattering centers. But this could be done in a cumulative manner, without losing the transparency of the simpler phenomena:

“In a general manner, I believe it is useful to eliminate the dynamical or electromagnetic hypotheses as much as possible and to reduce, in each case, the hypotheses to the *minimum necessary* to solve the problem under study. Whenever it will be indispensable to complete or to modify the already made assumptions, by treating the problems *as independently as possible from each other* we will better see from what phenomenon the insufficiency of the theory depends, which are the hypotheses to be conserved and which are the hypotheses to be modified or to be added to the former ones.”

To a broader audience he explained:[50]

“This way of simplifying the theory equally satisfies the philosopher who wishes to account for the nature of things in the most direct possible manner and to entangle the essential causes in the clearest possible manner, and the physicist who, in order to work efficiently needs the *research instrument* provided by a theory to be able to give direct solutions as simple as the nature of each problem allows.”

4.6. The Lorentz jubilee

Around that time Sagnac was invited to contribute to the Lorentz jubilee volume which appeared in 1900. Most likely, his reputation as an X-ray expert justified this invitation. Yet Sagnac did not write on the Sagnac rays. Instead he contributed a piece on optical theory, which was both dearer to him and closer to Lorentz’s interests. As Sagnac explained in a footnote to this memoir and as he told Lorentz in private, he studied Lorentz’s electromagnetic only in the spring of 1900, after Lorentz sent him his memoir of 1899 on a simplified optics of moving bodies (in reaction to Sagnac’s having sent his own memoir on this topic). Sagnac’s footnote went on as follows:

“My elementary optical theory and the theory both electrical and optical of Prof. H.A. Lorentz have extremely different forms. I was all the more struck by the following fact, which the reader will easily verify: the very simple law of *the effect of motion* which is the essential part of my elementary theory is in the end equivalent to the change of variable introduced by Lorentz.”

Indeed the propagation-time correction derived by Sagnac exactly corresponds to the difference between absolute time (t) and “local time” ($t - ux/c^2$) in Lorentz’s first-order theory, and it serves the same purpose of justifying the absence of effects of the earth’s motion through the ether.[51]

As Sagnac conceded, Lorentz’s theory has much wider scope than Sagnac’s and it is based on a precise, fundamental description of the interaction between electromagnetic radiation and electronic motion. Through averaging procedures it yields relations between macroscopic fields and thus determines their propagation and their behavior at the interface between two different media. However, it does not provide any simple picture of how the induced vibrations of electrons contribute to the total field. In many experimentally accessible cases, no one knew or knows how to solve Lorentz’s equations. A good example of this difficulty is large-angle diffraction, for which the Kirchhoff approximation no longer holds. In contrast, Sagnac’s theory leads to fairly simple calculations in that case. In 1895 Sagnac found that his idea of scattering centers, completed by the hypothesis that the radiation from every scattering center was identical with the radiation from a Hertzian dipole even at distances very small compared to the wavelength, had precise quantitative implications for the intensity and polarization of the light diffracted by a thin glass grating at large angle. He verified the resulting laws in 1896–1897 in Bouty’s laboratory, long kept them unpublished for the aforementioned reason, and finally presented them to Lorentz for his jubilee.[52]

The naïveté of some of Sagnac’s assumptions and the lack of a precise mathematical formulation do not inspire much trust in his results. The very few later references to his theory are vague and only retain the idea of summing over individual scattering centers.[53] Lorentz’s reaction was nonetheless positive. It may be inferred from Sagnac’s reply to his lost thank-you letter: “I am very pleased to see that my article interests you and that you intend to treat [the same question] by your own methods.... What you kindly say about my works is very flattering and I thank you very sincerely for that.” In the same letter Sagnac admits that his approximations need better control and he alludes to unpublished attempts to treat the case of

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[49] Sagnac [98, p. 173].

[50] Sagnac [98, p. 174]; [99, p. 20]. Cf. Lalli [15, pp. 59–60].

[51] Sagnac [100, pp. 377n–378n]; [101]. Retrospectively, Lorentz’s local time is the first-order approximation of the Lorentz-transformed time. Lorentz used the local time in a formal manner, as a way to retrieve the electromagnetic equations for a body at rest in the ether. The interpretation of the local time as the time given by optical synchronization was first given by Poincaré in his own contribution to the Lorentz jubilee. See Darrigol [90, Chaps. 8–9].

[52] Sagnac [100, p. 393n for the dates].

[53] Natanson [102], for example.

Fig. 15. Sagnac alpinist. Ascending *La Tournette* (Haute-Savoie) in August 1901 (with the boater), and resting (with the white beret) near Mont Blanc. Archives nationales.

crystals. He also gives the information I have earlier used about the origins of his theory. He concludes his letter in modest terms:[54]

"When I received your memoir [101], I clearly saw that my publication came too late. I was nonetheless comforted to see that I had unveiled just the principle that you too regard as fundamental; also, the methods were very different and I thought, as you kindly write to me, that one method could be better adapted than the other to the resolution of a given problem. However, my work is very modest in comparison to your oeuvre, and the benevolence with which you are willing to judge it deeply touches me."

4.7. Out of the blue

In his theory of the propagation of light and in his discussions of X-ray scattering, Sagnac liked to refer to the blue color of the sky as evidence for the existence of discrete scattering centers in all matter. He knew about Rayleigh scattering, according to which the amount of scattered light varies as the fourth power of the frequency of the incoming light, and he was aware of David Brewster's suggestion that the particles responsible for the blue color of the sky were the molecules of the air (and not dust particles as Rayleigh originally suggested). In 1902, Sagnac published a long discussion of this matter in the *Annuaire du Club alpin français*, including semi-popular accounts of the contributions of Rayleigh, Brewster, and John Tyndall.[55]

Sagnac's own contribution was the assertion that at low elevation the air was too dense for significant scattering to occur. He reasoned that in a dense medium there were many scattering particles within a wavelength, so that the secondary waves from the particles of a layer parallel to the wave planes interfered destructively in every direction except the forward one (in analogy with Fresnel's explanation of rectilinear propagation by the Huygens–Fresnel principle). If this reasoning applies to atmospheric air, the amount of Rayleigh scattering should be negligible at moderate elevations and the intensity of the blue light from the sky should be about the same in the Alps as at sea level. Enter Sagnac the alpinist (Fig. 15). Through photographic measurements he verified that this intensity did not significantly vary between 400 and 3000 meters, and he

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[54] Sagnac to Lorentz, 6 Jan 1901, AHQP.

[55] Sagnac [103]. On the history, cf. Rayleigh [104], Lilienfeld [105].

called fellow alpinists to perform similar measurements. Without waiting for the result, he confirmed the poet's intuition: "To some extent the appearance of an azure vault corresponds to a reality."[56]

Later accounts of the blue of the sky ignored Sagnac's contribution, for good reason. It is indeed not true that the scattering of light vanishes in a gas of density higher than the inverse cube of the wavelength. As Rayleigh suspected, the intensity of the light scattered by a volume element of the gas remains the sum of the intensities of the lights scattered by the individual molecules because the irregular spatial distribution of the molecules prevents the kind of interference needed in the application of the Huygens–Fresnel principle. This interference would occur if the molecules were regularly distributed on a lattice (as in a crystal) or if they were so closely packed that the distances between nearest neighbors would vary little (as in a liquid or in a glass). The impurity of the air at lower elevation might explain why Sagnac failed to see any decrease of the intensity of the blue diffuse light at low elevation.[57]

4.8. *The Gouy phase*

Sagnac was more successful in his analysis of anomalous propagation near a focus. In the aforecited letter to Lorentz, he mentioned that in an early version of his propagation theory he assimilated the particles of matter with centers of anomalous propagation in the sense defined by the Lyon-based physicist Georges Gouy in an important memoir of 1891. Near a center of emission, Gouy argued, acoustic or optical vibrations do not have a well-defined velocity and their phase varies rapidly. The center of emission may be a small material oscillator or it may simply be the focus of converging waves. In the latter case, Gouy demonstrated, the phase of the incoming waves differs from the phase of the outgoing waves by π (far from the focus). This is what is now called the Gouy phase shift. Gouy gave two different proofs. In a simplified version of the first proof, the vibration is given as an isotropic solution to the scalar wave equation $\Delta\varphi - \frac{1}{c^2}\frac{\partial\varphi}{\partial t^2} = 0$. It therefore has the general form $\varphi = \frac{1}{r}f(r-ct) + \frac{1}{r}g(r+ct)$, which is the superposition of a converging and of a diverging spherical wave. There being nothing but air or vacuum at the center, the wave (more exactly the associated energy) must remain finite at the origin. This implies $g = -f$. Consequently, the sign of a positive perturbation of finite length changes when passing the center; and the phase of a wave train is therefore shifted by π. This argument is not very realistic, as it implies complete spherical waves. In the laboratory, the converging waves are laterally limited by the extent of the lens that produces them. This is why Gouy favors another reasoning in which the Huygens–Fresnel principle is applied to a truncated spherical wave. Summing the partial waves from the spherical calotte, he finds that the resulting vibration undergoes the expected fringe shift at a large distance beyond the focus of the calotte. In principle this method should have enabled him to compute the exact phase variation around the focus. He did write the relevant integral, but he computed only its asymptotic value.[58]

Others, including Pieter Zeeman, believed they could determine the phase variation near a focus by analogy with the phase variation near an oscillator. This gave a gradual variation confined to a distance of the order of the wavelength. Gouy and Zeeman tried to measure the phase shift by observing the interference between the converging–diverging wave and a (quasi-)plane wave. Their experiments sufficed to observe the global fringe shift, but were too imprecise to determine the variation near the focus. In 1903, Sagnac applied the Huygens–Fresnel principle to Gouy's problem, in a manner slightly different from Gouy's: he summed the partial vibrations from the flat circular opening of a plane screen exposed to a converging wave. Calling s the distance of a point P of this opening from its center, r its distance from a point M on the axis, f the focal distance, and λ the wavelength, the phase of the partial vibration from P at M is approximately given by $\frac{s^2}{2\lambda}(\frac{1}{r} - \frac{1}{f})$. In his usual manner, Sagnac summed the partial vibrations graphically and arrived at the diagram of Fig. 16 for the variation of the total vibration on the axis.[59]

In order to verify this theoretical prediction, Sagnac improved on Zeeman's astute exploitation of a birefringent lens. The lens, being made of Iceland spar,[60] has two different foci corresponding to the ordinary and extraordinary rays, and it therefore produces two different images of a given point source. In the spirit of chromatic polarization, the ordinary light and the extraordinary light are brought to interfere by placing the lens between two orthogonal polarizers. In the vicinity of one of the images, one of the vibrations is approximately plane, so that its interference with the other yields the desired information on the phase. By using a lens less convergent than Zeeman's, a smaller diaphragm, and a magnifying lens to observe the fringes, Sagnac succeeded in seeing the fringes very near the image, and he thus confirmed his theory of the propagation anomaly.[61]

Sagnac contributed this theory to the Boltzmann Festschrift of 1904. In 1903 he proposed a less fortunate application of the same theory to the N rays of Prosper-René Blondlot. When passed through a quartz lens, these rays allegedly produced multiple foci, which Sagnac identified with the intensity oscillation given by his lens-diffraction theory. The mutual distance of the successive foci required a wavelength of a fraction of a millimeter. Blondlot rejected this estimate even before the

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[56] Sagnac [103, p. 501]; [106].

[57] Rayleigh [104, p. 383]; Lorentz [107]. For a modern approach, cf. Jackson [108, pp. 422–423]. I thank Jean-Michel Raimond for an illuminating discussion on this subject.

[58] Gouy [109].

[59] Sagnac [110–112].

[60] The optical axis of the crystal must of course coincide with the optical axis of the lens.

[61] Sagnac [114–116].

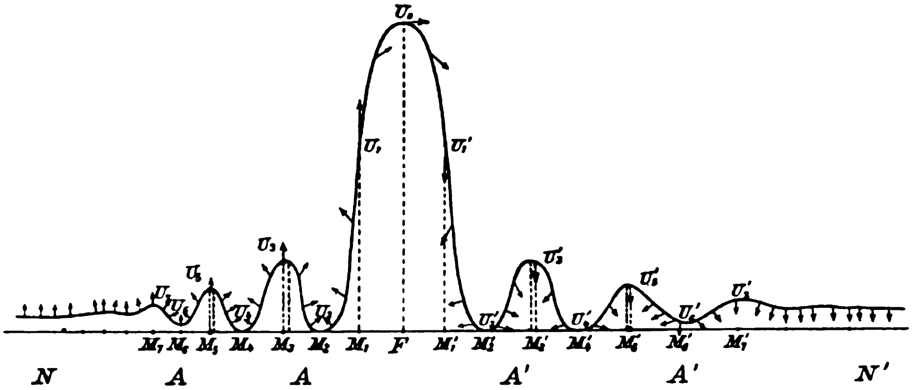

Fig. 16. Sagnac's diagram for the phase variation of monochromatic light near a focus F. The curve gives the intensity on the optical axis around the focus F. The little arrows indicate the phase. From Sagnac [113, p. 535].

N rays had gone to the dustbins of history. He, who then believed to have firmly determined the wavelength of the new rays with a grating, should have applied to himself the comment he made about his colleague: "Mr. Sagnac will have an opportunity to meditate on the dangers of precipitation."[62]

5. Intermezzo: an inconclusive venture

In 1904, besides the honor of contributing to the Boltzmann Festschrift, Sagnac received the Jérôme Ponti prize of the Academy of Science, and, most important, he returned to Paris to become *chargé de cours* at the Sorbonne. This should have given him more time for research. Yet he did not publish anything new between 1905 and 1910. One reason may have been that he was a devoted teacher, as may be inferred from a letter of Pierre Curie to Gouy: "Sagnac succeeded me at the P. C. N. [*chargé de cours du certificat d'études physiques, chimiques et naturelles*] and I must say he makes much stronger efforts that I did; he does many simple, clearly demonstrative experiments, and I believe his teaching his excellent." At least four additional circumstances contributed to the pause in Sagnac's research output: recurrent health problems, years of efforts to set up a large facility for optical experiments in the basement of his laboratory of the Rue Cuvier,[63] the secrecy he wished for his new experiments on the ether wind, and the failure of a venture into a more mathematical physics.[64]

That venture occurred in 1905, soon after Sagnac visited Lorentz at his home in Leiden. Back in Paris, Sagnac sent to Lorentz the manuscript of two memoirs on a mathematical theory of phosphorescence and photographic action, based on the idea of ionization followed by delayed recombination. A similar idea already occurred in his dissertation, in an explanation of photographic illusions that some early X-ray experimenters had mistaken for diffraction fringes: the photographic layer, when subjected to light, undergoes not only a direct alteration proportional to the intensity of the light but also a retarded reaction to this alteration at a rate proportional to the amount of alteration. This reaction implies that for an increasing time of exposure the impression first reaches a maximum, then goes to a fairly low minimum and oscillates for a while until it reaches a stable value. The first minimum explained the well-known phenomenon of photographic inversion, according to which an increased exposure may annihilate the initial impression; and the oscillation explained the fringes sometimes observed at the limit of a shadow and sometimes mistaken for diffraction fringes.[65]

The 1900 version of this reasoning was mostly qualitative, although Sagnac gave the relevant delay differential equation in a footnote: $f'(t) = a - bf(t - \tau)$ for the impression $i = f(t)$. When he returned to this problem in 1905, he sharpened the physical basis and developed the mathematics. The alteration of the photographic layer now became an ionization process, and the reaction became a delayed recombination of the ions. Sagnac solved the delayed differential equation of the problem through the characteristic equation. Unfortunately, he missed some roots of the latter equation. Lorentz wrote a twelve-page letter of comments to Sagnac, warning Sagnac about the preceding error and yet expressing a vivid interest in his theory. Here is an extract of Sagnac's reply:

"I thank you with all my heart for having read with so much benevolence the two memoirs which you kindly returned to me. Your precious encouragements give me a renewed ardor. I am happy to feel like you are sheltering me from the grave errors of the leading theory. I committed a grave and inexcusable error by attributing only a real root to the characteristic equation."

Lorentz's encouragements did not suffice, as Sagnac never published this theory.[66]

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[62] Sagnac [117–119]; Blondlot to Poincaré, 23 Dec 1903, in Walter [29], on p. 70. On N rays, cf. Nye [120].

[63] On this laboratory, cf. P. Sagnac [19, p. 43].

[64] P. Curie to Gouy, 31 Jan 1905, cited in Barbo [121, p. 267].

[65] Sagnac [80, pp. 422–426]. Sagnac also conceived a spatial diffusion of the negative reaction. On Sagnac's visit to Lorentz, see Lorentz to Sagnac, 18 Apr 1905, Archives nationales.

[66] Sagnac [80, pp. 425n–426n]; Lorentz to Sagnac, 11 Aug 1905, Archives nationales; Sagnac to Lorentz, undated reply to the former, AHQP.

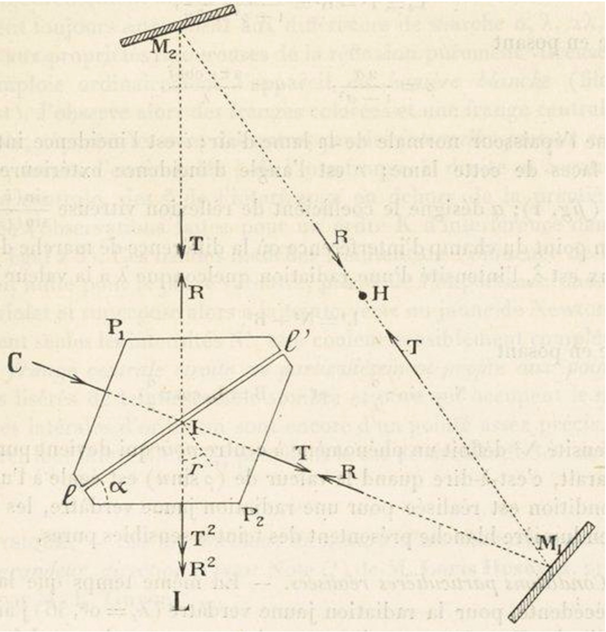

Fig. 17. Sagnac's second interferometer. From Sagnac [124, p. 1677].

6. The optical whirling effect

6.1. From Sagnac's principle to rotational ether flow

Sometime in 1908 Sagnac started a new series of researches based on an important new idea. As was mentioned, he knew that his "principle of the effect of motion" accounted for the failure of first-order ether-wind experiments. This is true in particular for experiments based on interference. In 1873 Veltmann had treated this case on the basis of the following theorem: the time taken by light to travel on a closed loop is unaffected by the motion of the earth no matter how many reflections or refractions it undergoes on its path. Veltmann's proof of this theorem was based on the remark that the laws of reflection and refraction in the earth-based frame are the same as in the ether frame if the ether is dragged in the amount assumed by Fresnel. As Sagnac explained in 1905, his principle gives a very simple and direct proof the theorem: the resulting expression of the time correction, $\delta t = \int \mathbf{u} \cdot \mathrm{d}\mathbf{r}/c^2$, evidently vanishes over a loop ($\mathbf{u}$ being the velocity of the earth through the ether). In 1905 Sagnac used this result to give a new derivation of stellar aberration, based on the vanishing of the Veltmann integral on the triangle made by the star and two points of a wave front from the star. In this reasoning, the ether is strictly stationary and **u** denotes the translational velocity of the earth through it, or the opposite of the velocity of the uniform ether wind with respect to the earth. In 1908 Sagnac realized that his principle more generally implied $\delta t = -\int \mathbf{v}(\mathbf{r}) \cdot \mathrm{d}\mathbf{r}/c^2$, if $\mathbf{v}(\mathbf{r})$ denotes the velocity of the ether wind at point **r** on the earth.[67]

Being friend to Vilhelm Bjerknes, who had extended Kelvin's circulation theorem to compressible fluids, Sagnac recognized Kelvin's circulation in the integral $\oint \mathbf{v} \cdot \mathrm{d}\mathbf{r}$. In fluid-mechanical terms, the time correction on a light circuit may be non-zero if the ether wind within this circuit is rotational. This will for instance be the case if the ether is dragged by the earth at a rate decreasing with the elevation. In this way Sagnac knew he could test a basic hypothesis of his and Lorentz's optics of moving bodies, the stationary ether, by observing (the lack of) a fringe shift in a vertical interferometer. The coherence length of ordinary light being small, the only practical way to do so is to observe the interference of two beams that have traveled on the same closed path in opposite directions. This was Sagnac's original motivation for constructing double inverse path interferometers, now called Sagnac interferometers. The inspiration plausibly came from Fizeau.[68]

6.2. A new interferometer and a test of the ether drag

After some groping about, Sagnac arrived at the arrangement of Fig. 17 in which the light from the source C is partially reflected and partially transmitted by the air gap *ll'* between the two glass prisms P$_1$ and P$_2$ (according to Sagnac, this

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[67] Veltmann [122]; Sagnac [123]. The date 1908 is from Sagnac [124, p. 1676].

[68] Sagnac [125, p. 311] for the reference to Kelvin and Bjerknes. In 1910, Sagnac [126,124] described two versions of his interferometer before giving the motivation. On the relevance of Bjerknes's theorem, cf. Lalli [15, p. 62].

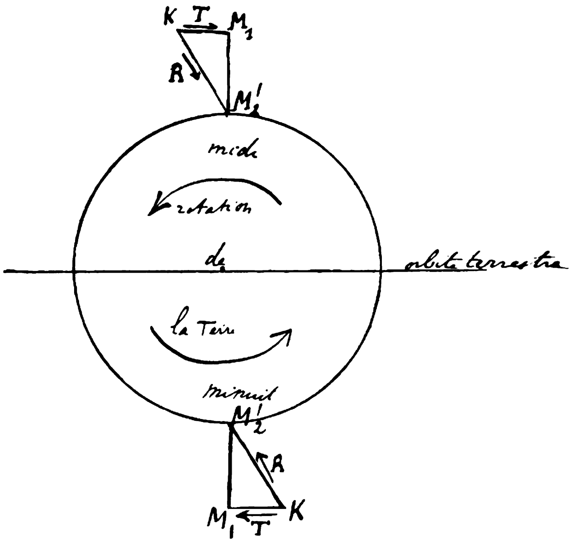

Fig. 18. The reversal of the effect of the ether drag on Sagnac's interferometer between noon and midnight. KM_1M_2' is the vertical projection of the optical circuit KM_1M_2 (a triangle). The letters T and R refer to the transmitted and reflected beams. From Sagnac [127, p. 224].

is better than a semi-reflecting plate à la Michelson because the incidence can be adjusted so that the transmitted and reflected light have exactly the same intensity for a given wavelength when the light from C is polarized perpendicularly to the plane of reflection). The two light beams are then reflected on the mirrors M_1 and M_2 and their superposition is observed through the telescope L.[69]

When the interferometer is perfectly adjusted, the phase difference is the same for all interfering rays in the field of observation and this field is uniform. Fringes are obtained by slightly rotating the separating double prism (for instance). The shift of the central fringe owing to the circulation of the ether is proportional to the surface embraced by the closed light path and to the transverse gradient of the ether wind (according to Stokes' theorem). For a vertical, East–West oriented circuit, this shift should reach two extreme opposite values at noon and midnight since the main ether wind is the one caused by the rotation of the earth around the sun (see Fig. 18).[70]

With an optical circuit of 20 m^2 and with painstaking attention to the possible perturbations of his sensitive apparatus, Sagnac determined that the ether shear, if any, could not exceed the fraction 0.3×10^{-7} of the velocity of the earth for an elevation of one meter (see Fig. 19). He finished this experiment in early 1910 and gave a full account of it at the International congress of radiology and electricity in Brussels in the fall of the same year. There he framed his experiment in the context of the "relativity principle" of Mascart, Poincaré, and Einstein, following which the result of optical experiments can only depend on the relative motion of the implied material bodies. The experiment indeed tested the stationary character of the ether, which, together with the principle of the effect of motion, Sagnac regarded as the basis of first-order relativity.[71]

6.3. *Interferential strioscopy*

While adjusting his ultra-sensitive interferometer, Sagnac noticed that the central dark field he observed through his telescope under the condition of destructive interference became luminous whenever a warm object like the hand was close to the beam. He thus got the idea of new kind of *strioscopie*. This word comes from the German *Schierenmethode*, through which August Töpler denoted the visualization of optical perturbations in a transparent medium by a method he developed in the 1860s. This technique, which turned out to be very useful to visualize flows, originated in an idea by Léon Foucault whose principle is illustrated on Fig. 20. The lens centered in O forms the image A′B′ of the bright opening AB of a diaphragm. An opaque object exactly covers A′B′ and therefore blocks all the light from AB on the right side of A′B′. The screen E contains the image S′ of the point S on the axis before the lens. If any thermal or motional perturbation of the air occurs near S, the light from AB is deviated by this perturbation and thus fails to be blocked by A′B′. Luminous "streaks" (*Schieren*, or *stries*) appear on the screen.[72]

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[69] Sagnac [124].

[70] Sagnac [125,127,128]. Sagnac operated with white light, so that his central fringe had the "teinte sensible" for which the brightest spectral component is extinguished.

[71] Sagnac [127, p. 217] for the reference to Mascart, Poincaré, and Einstein. On this experiment, cf. Martinez-Chavanz [6, pp. 43–49].

[72] On the earlier history of strioscopy, cf. Sagnac [129, p. 241].

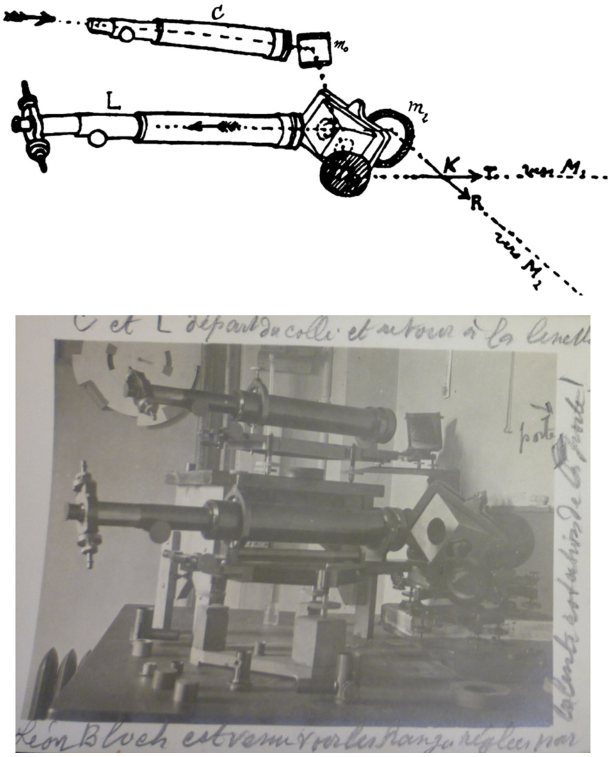

Fig. 19. Sagnac's drawing of the collimator C, the telescope L, and the separating double prism between the auxiliary mirrors m_0, m_1, m_2 (from Sagnac [127, p. 227]), and a photography of this apparatus (from Archives nationales). The beams from the separator intersect at K and are reflected by the distant mirrors M_1 and M_2 on the walls of the room. In the margin, Sagnac wrote: "Léon Bloch came to see the fringes adjusted by the slow rotation of the door!" (the weight of the door (*porte*) was indeed sufficient to bend the wall to which the mirrors M_1 and M_2 were attached and thus controlled the spacing of the interference fringes: see Sagnac [124, p. 232]).

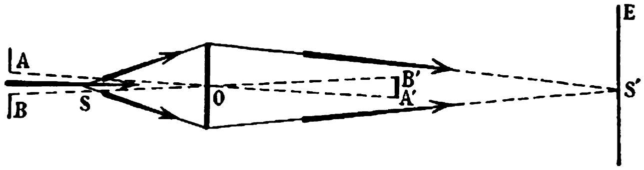

Fig. 20. Foucault's strioscopic setup. From Sagnac [130, p. 82].

Although this effect in some cases involves diffraction, it is understandable in the context of geometrical optics and it does not involve interference. In contrast, Sagnac's interferential strioscopy implies the perturbation of a destructive interference. In the case of Sagnac's original two-mirror interferometer (and for any even number of mirrors), the rays of the two opposite interfering beams travel exactly on the same path, so that aerial perturbations affect both of them equally. This circumstance minimizes the effect of the perturbations, which was an advantage in Sagnac's tests of ether drag. For enhanced sensitivity to the perturbations, Sagnac switched to the three-mirror interferometer of Fig. 21. Half of the parallel beam from the collimator C is blocked by the diaphragm B. The other half it both transmitted and reflected by the double prism P_1P_2. The transmitted beam and the reflected beam travel on the two sides of the central ray until they finally overlap on their way to the telescope L. The interferometer is adjusted so that the field of observation is uniformly dark by destructive interference. A jet of gas introduced at g through the little pipe (bottom right of the figure) or a rotating helix h on the way of the transmitted beam illuminates the observed field in a manner depending on the index variation. Sagnac did the experiments as well as the theory of the images thus formed.[73]

6.4. The Sagnac effect

In the following months, Sagnac described a less sensitive but more practical variant of his interferential strioscope, and he also showed that his interferometer could be used to measure phase shifts at an interface (a silvered plate for instance)

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[73] Sagnac [131,129,132,130]. About odd/even number of mirrors, see Sagnac [129, p. 251].

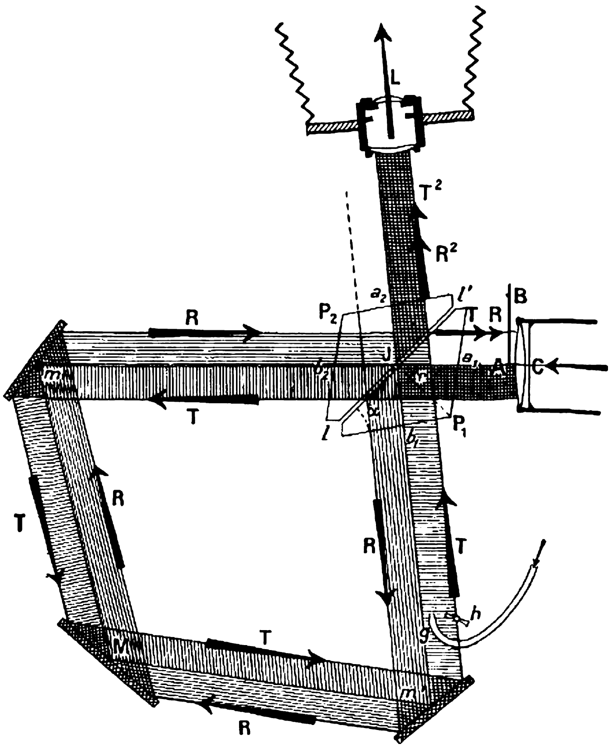

Fig. 21. Sagnac's strioscope. From Sagnac [129, p. 243].

with exquisite precision.[74] Plausibly, these results were but an instrumental diversion and he already had a grander project: the demonstration of a rotational ether wind. Remember that he originally conceived his interferometer for this purpose. The first case of rotational ether wind he investigated, an altitude-dependent drag, was not the most obvious. For someone familiar with Bjerknes' atmospheric vortices, the most obvious case should have been the relative ether wind implied by the earth's diurnal rotation in a stationary-ether theory. Plausibly, that was Sagnac's first idea[75] but he immediately realized that the detection of this tiny effect would require an excessively large interferometer. In 1909 he realized that a much stronger effect of the same kind would be obtained by placing the interferometer on a uniformly rotating table.[76] The difficulty of this experiment probably explains why four years elapsed before he completed it. He described the results in a *pli cacheté* of 18 August 1913 (Fig. 22) and then in two communications of 27 October and 22 December 1913 to the Académie des sciences.[77]

In the final setup, represented in Fig. 23, a circular table of 50 cm in diameter is brought to rotate at two turns per second. The entire interferometer, including source and camera, is rigidly connected to this table. Once uniform rotation has been reached, the lamp O is turned on. Its light goes through the objective C_0, the Nicol polarizer N, the mirror *m*, and the vertical slit F; then it is partly reflected partly transmitted by the air-gap separator *s*; the two resulting beams travel a full cycle by reflection on the four lateral mirrors and then recombine before reaching the telescope L and the photographic plate *pp*′. The four mirrors (instead of the two mirrors of Sagnac's original interferometer) are needed to maximize the surface S embraced by the optical circuit. Inverting the rotation velocity, Sagnac found a relative fringe shift of 0.07 for indigo light, in agreement with his circulation formula (see Fig. 24). The absolute shift had the sign predicted by the theory. Therefore, this shift could not be caused by a centrifugal deformation of the apparatus, which would not depend on the sign of rotation. Nor could it be caused by relative rotation of the air above the interferometer, for a fan placed above the interferometer at rest failed to displace the fringes.[78]

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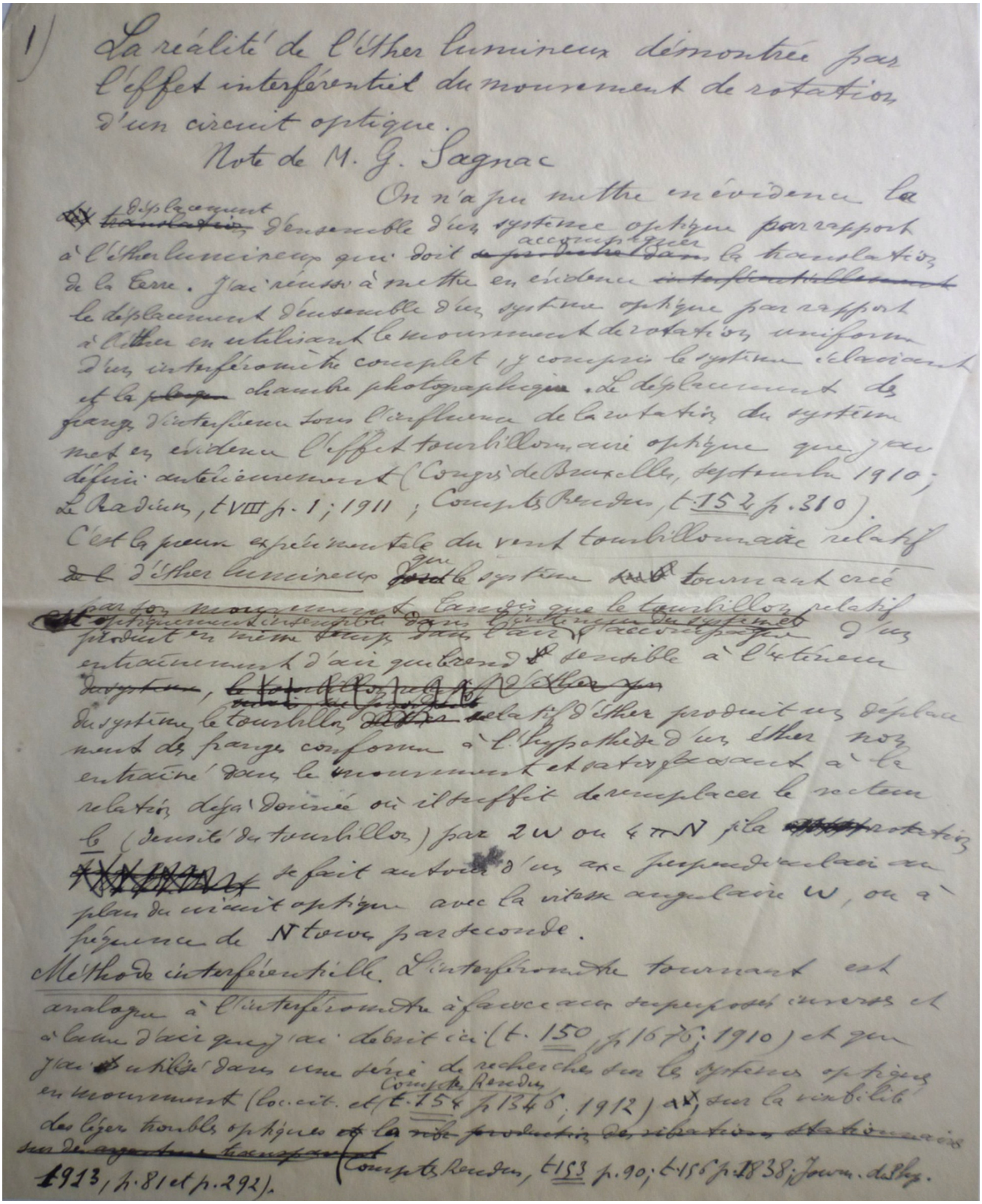
[74] Sagnac [133,134].

[75] Sagnac suggests so much in Sagnac [135, p. 709]. In a letter to Lucien Poincaré of 20 Jan 1919, Sagnac mentioned that in 1914 Brillouin had come to see his experiments "on the motion of the earth," presumably meaning that his experiments of 1910 and 1913 had to do with his early idea to detect an effect of the rotation of the earth: cf. Lalli [15, p. 65].

[76] Sagnac confided this idea to Lippmann in 1909. At that time, he regarded a negative outcome of the experiment as possible in a proper emission theory (Walther Ritz had published his theory the preceding year). Cf. Sagnac [136, p. 194].

[77] Sagnac [135,137]. On this experiment, cf. Martinez-Chavanz [6, pp. 27–36].

[78] Sagnac [135,137,136]. Although Sagnac does not explicitly state the precision of his fringe-shift measurement, it must have been about 10% judging from the photographs and the numbers he gave.



1) La réalité de l'éther lumineux démontrée par l'effet interférentiel du mouvement de rotation d'un circuit optique.

Note de M. G. Sagnac

On n'a pu mettre en évidence le ~~translation~~ déplacement d'ensemble d'un système optique par rapport à l'éther lumineux qui doit ~~[illegible]~~ accompagner la translation de la Terre. J'ai réussi à mettre en évidence ~~[illegible]~~ le déplacement d'ensemble d'un système optique par rapport à l'éther en utilisant le mouvement de rotation uniforme d'un interféromètre complet, y compris le système éclairant et la ~~plaque~~ chambre photographique. Le déplacement des franges d'interférence sous l'influence de la rotation du système met en évidence l'effet tourbillonnaire optique que j'ai défini antérieurement (Congrès de Bruxelles, septembre 1910; Le Radium, t VIII p. 1; 1911; Comptes Rendus, t. 152 p. 310).

C'est la preuve expérimentale du vent tourbillonnaire relatif ~~de l~~ d'éther lumineux ~~[illegible]~~ que le système ~~[illegible]~~ tournant crée par son mouvement, ~~tandis que le tourbillon relatif~~ ~~est optiquement insensible dans l'intérieur du système et~~ ~~produit en même temps dans l'air~~ s'accompagne d'un entraînement d'air qui [illegible] sensible à l'extérieur ~~du système~~, ~~le tourbillon [illegible] d'éther qui~~ du système, le tourbillon ~~[illegible]~~ relatif d'éther produit un déplacement de franges conforme à l'hypothèse d'un éther non entraîné dans le mouvement et satisfaisant à la relation déjà donnée où il suffit de remplacer le vecteur b (densité du tourbillon) par 2ω ou $4\pi N$ pla ~~[illegible]~~ rotation ~~[illegible]~~ se fait autour d'un axe perpendiculaire au plan du circuit optique avec la vitesse angulaire ω, ou à fréquence de N tours par seconde.

Méthode interférentielle. L'interféromètre tournant est analogue à l'interféromètre à faisceaux superposés inverses et à lame d'air que j'ai décrit ici (t. 150 p. 1676; 1910) et que j'ai utilisé dans une série de recherches sur les systèmes optiques en mouvement (loc. cit. et Comptes Rendus t. 154 p. 1346; 1912) ~~et~~, sur la visibilité des légers troubles optiques ~~et la [illegible] production de vibrations stationnaires sur des [illegible] transparent~~ (Comptes Rendus, t. 153 p. 90; t. 156 p. 1838; Journ. de Phys. 1913, p. 81 et p. 292).

Fig. 22. The first page of Sagnac's *pli cacheté* of 18 August 1913. Sagnac writes: "This is the experimental proof of *the whirling relative ether wind* that the rotating system creates through its motion." From the Archives de l'Académie des sciences.

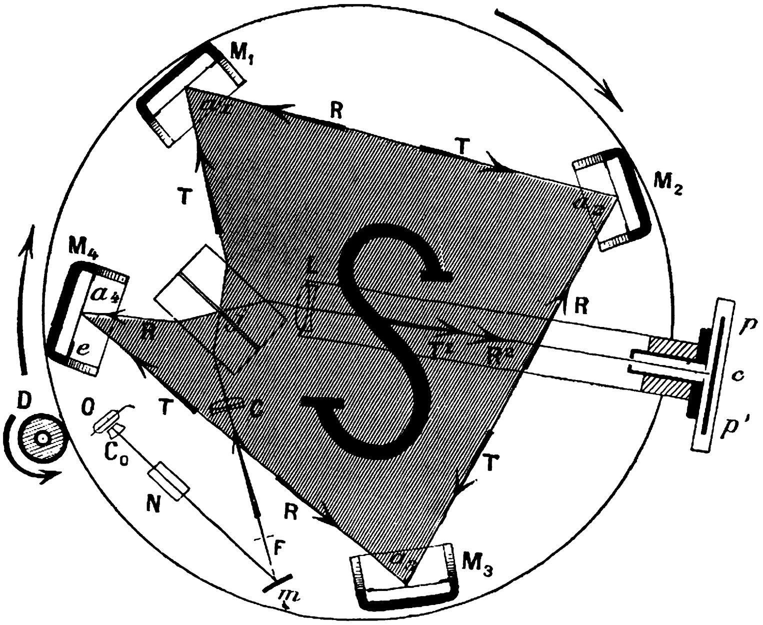


Fig. 23. Sagnac's setup for detecting the optical whirling effect. From Sagnac [137, p. 1412].

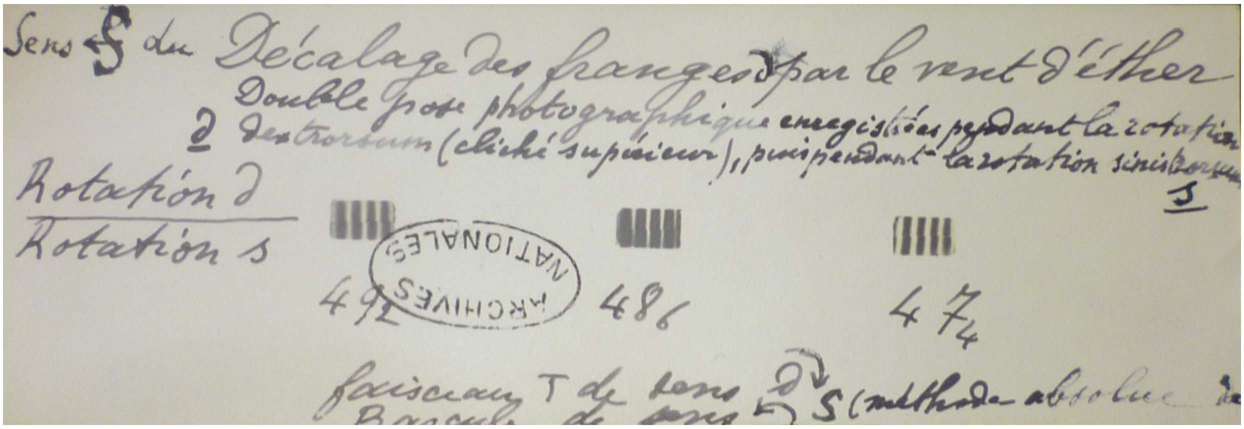

Sens ∫ du Décalage des franges par le vent d'éther
Double pose photographique enregistrées pendant la rotation
∂ dextrorsum (cliché supérieur), puis pendant la rotation sinistrorsum
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Fig. 24. One of Sagnac's fringe-shift photographs. The upper half of the fringes, slightly shifted to the left, corresponds to the *dextrorsum* (clockwise) rotation of the table; the lower half to the *sinistrorsum* (counter-clockwise) rotation of the table. From Archives nationales.

As we saw, the reasoning that led Sagnac to this experiment was based on his theory of the propagation of light, which required a stationary ether. In his view his experiment was analogous to the Michelson–Morley ether-drift experiment, except that it gave a positive result. In the new experiment, motion with respect to the ether had a measurable effect, and this effect was of first order in the implied velocities. Sagnac believed he had struck a fatal blow on relativity theory by proving the existence of the ether. He concluded:

> "The observed interferential effect proves to be the optical whirling effect caused by the motion of the system with respect to the ether, and it directly manifests the existence of the ether, necessary carrier of the luminous waves of Huygens and Fresnel."

The title of the first note in the *Comptes rendus* expresses the same conviction: "The luminous ether proved by the effect of the relative ether wind in a uniformly rotating interferometer."[79]

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[79] Sagnac [135, pp. 708, 710].

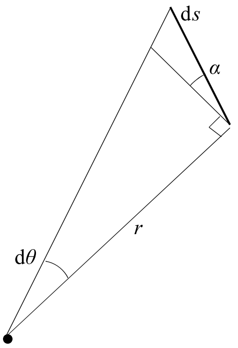

Fig. 25. Diagram for Sagnac's direct derivation of the rotational fringe shift.

6.5. *Optical gyroscopy and the angular effect*

Sagnac published a fuller account of his experiment in the March 1914 issue of the *Journal de physique*. There he suggested that his optical whirling effect could be used to detect and record the rolling of ships by means of an optical circuit around the ship hull. He also improved on his earlier theoretical derivation of the effect. That derivation implicitly assumed that the propagation of light in vacuum or air remained rectilinear in the approximation of geometrical optics. Sagnac knew this was not the case. In 1911 he had derived the "angular optical whirling effect" according to which the (uniform) curl $\nabla\times\mathbf{v}$ of the velocity $\mathbf{v}$ of the ether implies the angular deviation $(\nabla\times\mathbf{v})\times\mathbf{D}/c$ of the image of the focus of a telescope by a second telescope pointed toward the first at the large distance $\mathbf{D}$. In 1914 he traced this deviation to the curvature $|\nabla\times\mathbf{v}|/c$ of the light rays between the two telescopes, with a Poincarean comment: "Beings living in a sufficiently rotational ether [of large $|\nabla\times\mathbf{v}|$] in which they would establish their geometry on the basis of experimental optics, would be brought, if they did not discover the rotationality of their ether, to establish a non-Euclidean geometry." At any rate, the radius of curvature of the light rays was too small in comparison with the distances between the mirrors of Sagnac's setup to affect the calculation of the phase shift.[80]

Sagnac derived the angular optical effect in a manner similar to his derivation of stellar aberration, by compensating for the time shift on a closed light path made of two different rays connecting the focus of the first telescope to that of the second. Alternatively, we may combine his principle of the effect of motion with Fermat's principle of least time. This gives, for rays in an ether moving at the velocity $\mathbf{v}(\mathbf{r})$, paths obeying $\delta\int_A^B \mathrm{d}t=0$, with $\mathrm{d}t=n\mathrm{d}s/c-\mathbf{v}\cdot\mathrm{d}\mathbf{r}/c^2$. Varying under the integral and integrating by parts, we get the differential equation of the paths:

$$\frac{\mathrm{d}n\mathbf{T}}{\mathrm{d}s}-\nabla n+\frac{1}{c}(\nabla\times\mathbf{v})\times\mathbf{T}=0,\quad \text{with}\ \mathbf{T}=\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}s}$$

This means that in a vacuum ($n=1$), the tangent vector rotates along the path of a ray at the constant rate $|\nabla\times\mathbf{v}|/c$: the rays have the constant curvature $|\nabla\times\mathbf{v}|/c$.[81]

6.6. *A simple derivation of the Sagnac effect*

The negligibility of the rays' curvature being established, there is a simple direct way to derive the fringe-shift formula for the Sagnac effect. Sagnac gave it in his memoir of 1914, as a favor to readers unfamiliar with his personal theory of the propagation of light. The ether being stationary, he reasoned, the only significant effect of the rotation of the table (as judged by an ether-bound observer) is that the element ds of the optical circuit moves ahead of the waves when they travel from the beginning to the end of the element. The resulting delay is

$$\delta t=\frac{\mathrm{d}s}{c-\omega r\cos\alpha}-\frac{\mathrm{d}s}{c}\sim\frac{\omega r^2\cos\alpha\,\mathrm{d}s}{c^2}$$

if ω denotes the angular velocity of the turntable, r the distance of the element ds from the center of rotation, and α the angle that this element makes with the linear velocity of the corresponding point of the table (Fig. 25). If dθ denotes the angle under which ds is seen from the center, we also have $\mathrm{d}s=r\mathrm{d}\theta/\cos\alpha$. Consequently, the time shift is simply given by $\delta t=\omega r^2\mathrm{d}\theta/c^2=2\omega\mathrm{d}S/c^2$, wherein d$S$ is the surface of the infinitesimal triangle defined by the center of rotation and the element ds. The total phase shift on the circuit is therefore equal to $4\pi\omega S/\lambda c$, and the shift of the phase difference between the lights traveling in the two opposite direction on the same circuit is twice this quantity.[82]

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[80] Sagnac [136], p. 191 (ship rolling), 185n (citation); Sagnac [125, pp. 312–313] (angular effect). On the angular effect, cf. Martinez-Chavanz [6, pp. 48–49].

[81] Sagnac [125, 312–313]; [136, pp. 183–186]. At first order in υ/c, special relativity gives the same result since it is optically equivalent to Sagnac's principle.

[82] Sagnac [136, pp. 180–182].

This simple derivation of the Sagnac effect does not require the concept of ether wind and it can easily be transposed in the context of Lorentz's theory or in the context of special relativity. Yet Sagnac never ceased to see his experiment as a proof of a relative ether whirling. Remember that he arrived at this experiment by exploring the consequences of his "principle of the effect of motion," which implied a relation between the phase shift on a light circuit and the circulation of the relative ether flow. Sagnac meant his experiments of 1910 and 1913 to test the rotational character of that flow. In France, he was not alone in regarding the motion of the ether as a basic open question. Reviewing recent advances in optics for the *Revue générale des sciences* in 1914, the Marseilles professor Louis Houllevigue adorned his account of Sagnac's experiment with the comment:

> "M. Sagnac seems to have taken all the cautionary measures we might imagine in order to shelter himself from errors. If he has not omitted anything, the result of his experiment is one of the most important that optics has registered since Fresnel, since it would unquestionably prove the existence of a wave-carrying medium independent from material media. Thus would be closed, in favor of the ether, a still much undecided debate."

Foreign experts in the optics and electrodynamics of moving bodies would not have so easily embraced this conclusion. A good proportion of them had already been seduced by Einstein's ether-less theory. Most of them accepted Lorentz's electromagnetic theory, in which the question of the motion of the ether became futile. In earlier times, however, this question had been the center of attention of several important physicists, so much so that one may wonder whether the kind of experiments Sagnac conceived in the 1910s had not been discussed before him. Indeed they had been.[83]

7. Anticipations of the Sagnac effect

7.1. Dilemmas of the optics of moving bodies

Before discussing anticipations of Sagnac's ether-wind experiments, it will be useful to remember some nineteenth-century optics of moving bodies. Until the 1880s there were roughly two competing theories in this field. In Fresnel's theory, the ether was stationary in a vacuum and it was partially dragged by moving transparent bodies. The stationary character explained stellar aberration. The partial drag was adjusted so that the motion of the earth did not affect the laws of refraction. In Stokes' theory, the ether was completely dragged by the earth (its relative motion with respect to the earth vanished near the earth). This assumption immediately implied the absence of effect of the motion of the earth on terrestrial optical experiments; and Stokes believed he could conciliate it with stellar aberration if the ether motion was irrotational. Most French physicists of course favored Fresnel's theory, the more so because they believed that Fizeau had confirmed the Fresnel drag in 1851. British physicists tended to favor Stokes' theory in part because it was in harmony with Maxwell's electromagnetic theory of light, which assumed a single ether-matter medium moving at a well-defined velocity; and also because, Fizeau's result, which no one had yet cared to confirm, weighed little against the accumulated evidence that the motion of the earth had no effect on terrestrial optical experiments.[84]

In 1881 the American physicist Albert Michelson performed an experiment in which he had two light beams from the same source interfere after making roundtrips in the two perpendicular arms of an interferometer of his own (Fig. 26). The idea was to compare the relative velocities of light in two perpendicular directions. If the ether was fully dragged as Stokes required, these two velocities should of course be equal. If it was stationary as Fresnel required, a computable and measurable second-order fringe-shift had to occur. Michelson found none and concluded that Fresnel's theory had to be abandoned. Although Michelson's announcement soon turned out to be premature, he was able to confirm the absence of fringe-shift in 1887 with a much more sophisticated apparatus in collaboration with Edward Morley.[85]

One year earlier, in 1886, the two Americans had performed an accurate variant of Fizeau's running-water experiment of 1851. They thereby relied on Fizeau's idea of splitting a light beam into two beams traveling on opposite circuits, except that the splitting was now obtained with Michelson's signature semi-reflecting plate (Fig. 27). They thus confirmed the Fresnel–Fizeau drag.[86] In combination with the double-arm experiment of 1887, this result perplexed Michelson: whereas the former experiment seemed to confirm Stokes' theory, the latter seemed to confirm Lorentz's. One could perhaps imagine a variant of Stokes' theory that would integrate the Fresnel–Fizeau drag. Alas this subterfuge was no longer available, because Lorentz had recently detected a serious internal contradiction in Stokes' theory: the complete drag of the ether and the irrotational character of its motion are mathematically incompatible.[87] As is well known, George Francis FitzGerald (in 1889) and Lorentz (in 1892) rescued Fresnel's theory by assuming a proper contraction of the longitudinal arm of Michelson's interferometer. To many, this sounded like an ad hoc move and the question of ether motion remained open.[88]

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[83] Houllevigue [138, p. 442]. On the anticipations of Sagnac's ether-wind experiments, cf. Post [139]; Martinez-Chavanz [6, Chap. 2]; Anderson, Bidger, and Stedman [140].

[84] On the history of the optics of moving bodies, cf. Whittaker [95]; Janssen and Stachel [97]; Darrigol [90, pp. 314–319]; [84, pp. 258–261].

[85] Michelson [141]; Michelson and Morley [142]. On Michelson's ether-drift experiments, cf. Swenson [143].

[86] Michelson and Morley [144]. On Michelson's interferometry and silvered plates, cf. Staley [145, pp. 47–49].

[87] The irrotational motion of an incompressible fluid is completely determined by the Neumann boundary condition of zero normal velocity on the surface of the earth, and the resulting motion has a non-zero tangential velocity.

[88] Cf. Hunt [146, pp. 189–197]; Darrigol [90, pp. 317–319].

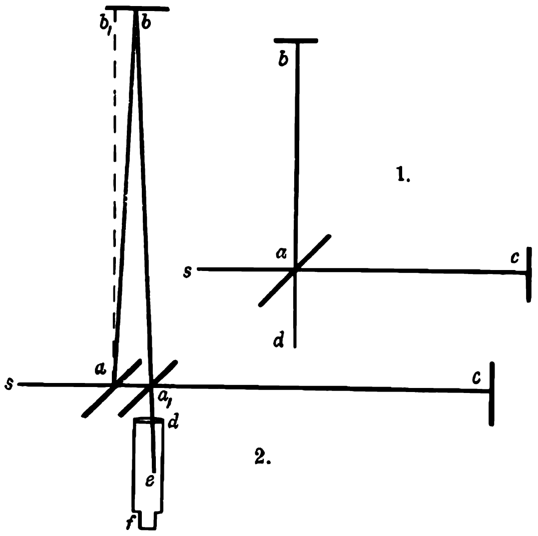

Fig. 26. Michelson's setup for comparing the relative velocities of light in two orthogonal directions. The light from the source *s* is split into two orthogonal beams by the silvered glass plate *a*, then reflected by the mirrors *b* and *c*. The interference of the recombined lights along *d* is observed through the telescope *f*. If the setup moves with respect to the ether (case 2), the silvered plate moves from the position *a* to the position $a_/$ in the ether during the roundtrip $aba_/$ of the reflected light. From Michelson [142, p. 335].

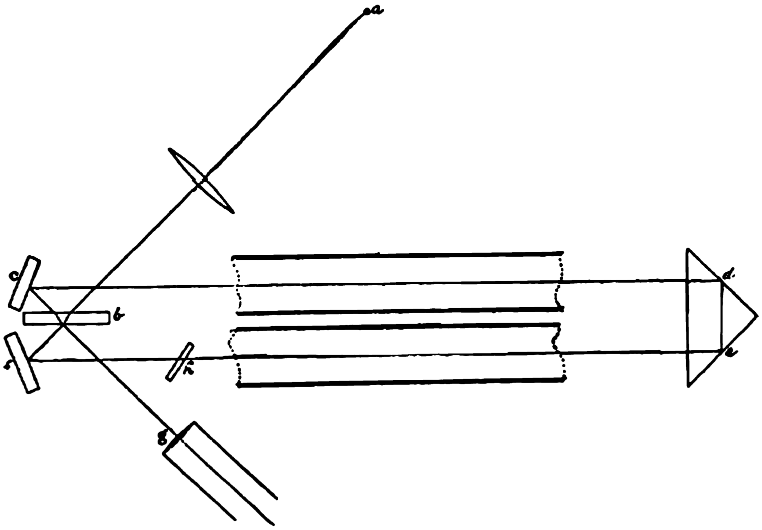

Fig. 27. Michelson and Morley's set up for measuring the Fresnel–Fizeau drag. The parallel light from the source *a* and the lens is divided into two beams by the silvered glass plate *b*. By reflection on the mirrors *c* and *f* and on the rear faces *d* and *e* of a glass prism, they travel on two opposite circuits, along or against the flow in two water pipes on the *cd* and *ef* axes. Their interference is observed through the telescope *g*. From Michelson and Morley [144, p. 381].

7.2. Lodge on ether whirling

In order to test the stationary character of the ether, the leading Maxwellian physicist Oliver Lodge built an "ether-whirling machine" in which the light beams of an interferometric device traveled in the thin gap between two heavy, fast rotating steel disks. From Michelson, Lodge borrowed the idea of making the light travel both ways on a (multiple) circuit after splitting by a semi-reflecting plate (see Fig. 28). If the ether followed the rotation of the disks, then light would take a different time to travel in opposite directions on the optical circuit, and the interference fringes would be shifted. In 1893 Lodge informed the Royal Society that the expected shift did not occur. The stationary ether seemed confirmed and the Michelson–Morley result looked more mysterious than ever.[89]

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[89] Lodge [147]. Cf. Martinez-Chavanz [6, pp. 14–16]; Hunt [148].

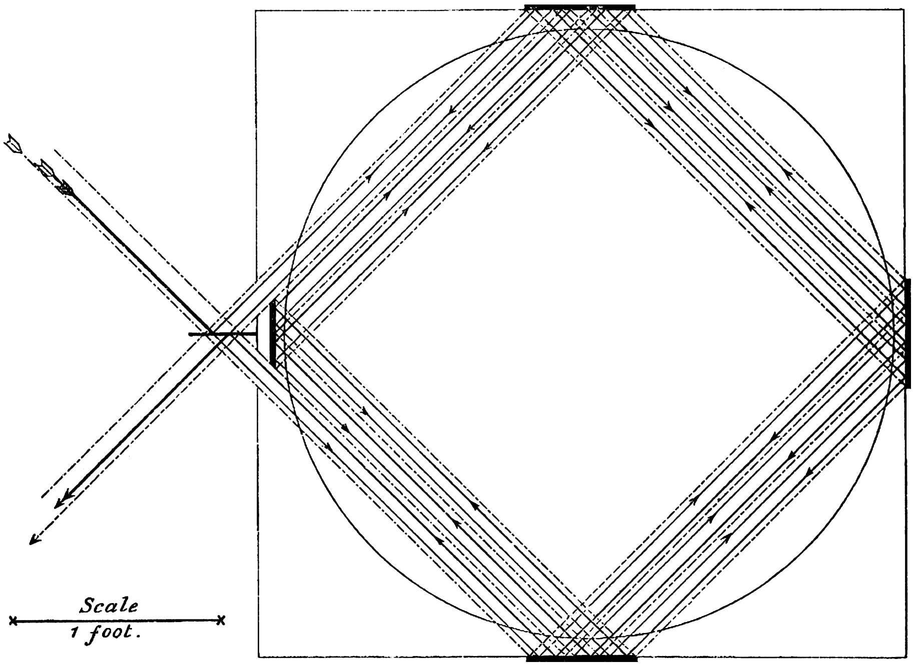

Fig. 28. Lodge's interferometric technique for his ether-whirling experiment. A narrow parallel beam from the source is both reflected and transmitted by the horizontal silvered plate. The two resulting beams make three turns in opposite direction by reflection on the four mirrors before recombining. The big square represents the rigid wooden box that holds the mirrors. The inserted circle represents the projection of the limit of the rotating steel disks. From Lodge [147, p. 757].

Lodge's and Sagnac's ether-whirling experiments differ in several respects. In the former experiment, the interferometric apparatus (source, mirrors, and telescope) are at rest (with respect to the earth), whereas they are on a rotating table in the latter. Whereas Lodge is testing the drag of the ether by nearby moving matter, Sagnac is testing the absence of drag of the ether by nearby moving matter. For Lodge a fringe shift would imply ether drag; for Sagnac, the observed fringe-shift results from the absence of ether drag. Sagnac's setup is a detector of absolute rotation and can work as a kind of gyroscope, Lodge's cannot.

Lodge nonetheless derived the Sagnac formula $4\pi\omega a^2/\lambda c$ for the phase shift in the case of a square optical circuit of radius a immersed in ether rotating at the angular velocity ω, with the parenthetical comment:

"(Evidently the larger the square the better, and a large enough square might show even the earth's rotation effect, only it is difficult to see how to imitate the effect of stopping and reversing the rotation, at least with the unwieldy size of frame necessary.)"

Lodge seems to have meant an experiment in which the optical frame (source, lamps, and telescope) would be at absolute rest while the ether would rotate together with the earth. Again, that is not the Sagnac effect. The humorous remark about reversing the rotation of the earth points to a genuine difficulty in any interferential detection of the rotation of the earth: the fringe shift remains undetectable as long as no way to determine the absolute position of the central fringe is known.[90]

Four years later at the Royal Society, Lodge made his suggestion a little clearer:

"Now, by staking out mirrors at the corners of a field, it is arithmetically quite possible to arrange for a perceptible shift of the bands due to the rotation of the earth, if it carries ether round with it; but it does not seem possible to experimentally observe that shift, unless some method could be devised of making the observer and his apparatus independent of the rotation."

Most interestingly, he went on to consider the symmetric case in which the apparatus and observer move together with the earth and the ether does not:

"It is to be observed, that since a motion of the disks relatively to the observer and the light causes no effect, the ether being stationary, it follows that a motion of the light and observer would produce an effect, since they would be moving relatively to the ether. Hence if, instead of spinning only the disks, the whole apparatus, lantern, optical frame, telescope, observer and all were mounted on a turn-table and caused to rotate, a reversible shift of the bands should be seen."

This is exactly the Sagnac effect. Lodge went on:

"In an actual experiment of this kind, centrifugal force would give some trouble by introducing strains, and rapid rotation would be uncomfortable for the observer; but really rapid rotation should be unnecessary to show the effect. My present

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[90] Lodge [147, pp. 773–774].

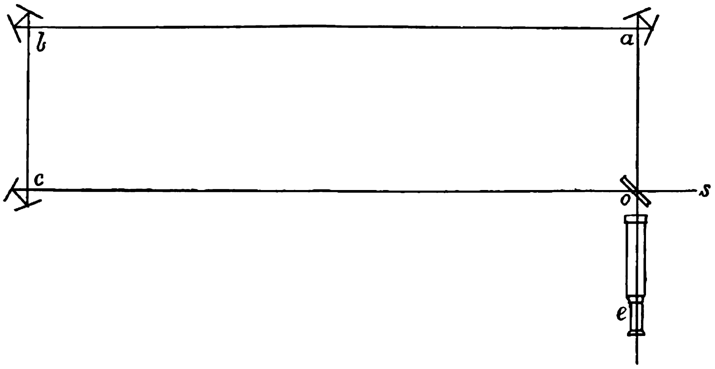

Fig. 29. Michelson's setup for detecting a vertical velocity gradient of the ether. From Michelson [149, p. 475].

optical apparatus mounted on a turn-table revolving 4 times a minute should show something, viz.: $\frac{1}{100}$th band shift each way."

Be it by lack of time or by fear of discomfort, Lodge never performed this experiment (unlike Sagnac, he did not think of using photographic recording with remote control). He also considered the effect of the motion of earth on a large terrestrial interferometer:

"If the ether is stationary near the earth, that is, if it be neither carried round nor along by that body, then a single interference square, 1 kilometer in the side, would show a shift of rather more than one band width, due to the earth's rotation in these latitudes."

The difficulties with the size of the interferometer and with the irreversibility of the rotation of the earth deterred him from attempting this second experiment.[91]

7.3. Michelson's ether-drag test of 1897

In the same year 1897, Michelson had a more practicable idea for testing the drag of the ether by the earth. He presumably reasoned that his setup for measuring the drag of the ether by running water could as well be used to detect different velocities of the ether on two parallel light paths. His new setup (Fig. 29) was indeed very similar. The light from the source *s* is split by the silvered glass plate *o* into two beams that travel around the squares *ocba* and *oabc* and then recombine in the telescope *e*. The rectangle being set vertically, this interferometer detects the vertical difference of horizontal ether velocity that a drag of the ether by the earth would imply. Calling υ the velocity difference for the paths *ab* and *oc* of length L, the expected phase shift is $4\pi\upsilon L/\lambda c$. With his 60 m × 15 m rectangle and with $L/\lambda = 10^8$, Michelson found that the fringe-shift difference between noon and midnight did not exceed 1/20. This gives $4\upsilon L/\lambda c \leq 1/20$, so that the velocity gradient of the ether must be less than 4 cm/s over 15 m (or less than 10^{-7} the velocity of the earth around the sun (about 30 km/s), to be compared with 0.3×10^{-7} in Sagnac's similar experiment). Assuming an exponential diminution of the relative velocity, Michelson found that the earth's influence on the ether would have to extend over distances comparable to the diameter of the earth. This being highly implausible, he judged that Fresnel's stationary ether may after all be preferable: "One is inclined to return to the hypothesis of Fresnel and to try to reconcile in some other way the negative results obtained in the [Michelson–Morley experiment]."[92]

We thus see that thirteen years before Sagnac, Michelson conceived and performed a similar test of ether drag with the same negative result and a comparable sensitivity. The main differences are the geometry of the experiment (square instead of triangular circuit) and the way in which the effect of fluctuations in the air is avoided. Sagnac minimized these perturbations by using two separate rooms for the optical circuit and for the observation of the interference fringes, and he reduced their perturbing effect by using an even number of mirrors. In contrast, Michelson, whose circuit was significantly longer than Sagnac (150 m instead of 30 m), could not obtain stable fringes in the air and had to make his light beams travel through pipes evacuated to a hundredth of an atmosphere (one for each side of the rectangle, with glass windows at both ends).[93]

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[91] Lodge [8, p. 151]. Lodge discussed these issues in contemporary correspondence with Joseph Larmor. At the end of murky reasoning and discussion, they privately arrived at Sagnac's phase-shift formula for a circuit of arbitrary shape. Cf. Anderson, Bilger, and Stedman [140, pp. 981–983].

[92] Michelson [149, p. 478] (after this remark, Michelson deplores that any theory that takes all experimental results into account, including Lorentz's, has to make fantastic assumptions about the relation between ether and matter). Cf. Martinez-Chavanz [6, pp. 17–20]; Lalli [15, pp. 60–61].

[93] Cf. Sagnac [127, p. 227]. Despite the rectangular geometry of Michelson's circuit, the number of mirrors is even, because the reflection at the corners of the rectangle is produced by pairs of mirrors. It is not clear why Michelson used pairs instead of single mirrors. He did not relate the parity of the number of mirrors with lower sensitivity to thermal fluctuations. As Jacques Vigué explained to me, Sagnac's success in air may have to do with better mechanical stability of his setup and perhaps also with the smaller number and better quality of his mirrors.

7.4. Michelson's ether-wind experiment of 1904

After his experiment of 1897, Michelson was more willing to assume the stationary character of the ether. For a stationary ether, the motion of the earth through the ether should affect the traveling time of light between two points of the earth. The failure of the Michelson–Morley experiment of 1887 did not mark the end of attempts to detect such consequences. For instance, in 1904 Wilhelm Wien proposed an experiment in which two toothed wheels rotate at the same speed and with the same phase around a common axis that is parallel to the velocity of the earth. Light is sent with the same initial intensity in the parallel and anti-parallel directions between the teeth of the two wheels and the final intensities of the beams are compared. If the ether is stationary, Wien reasoned, the traveling time of light between the two wheels depends on the direction of propagation, so that the final intensities of the two beams should be different. As Emil Cohn soon pointed out, the result depends on the method for synchronizing the two wheels. Optical synchronization should give a null effect, since it assumes isotropic propagation. Mechanical synchronization could give a positive effect if mechanical processes essentially differ from electromagnetic processes.[94]

In an article of 1904 for the *Philosophical magazine*, Michelson made the same comment, adding in a footnote: "Perhaps, however, even mechanical impulses would be affected by the earth's motion in such a way as to neutralize the expected effect." He went on to offer a better way to detect the effect of the earth's motion in the ether, by having beams of light travel on the same parallel around the earth in opposite directions and then interfere. Owing to the rotation of the earth, one of the beams would be retarded while the other would be advanced and the interference fringes should be shifted. More realistically, any optical circuit of large dimensions on the surface of the earth should produce the differential time delay $\frac{2}{c^2}\oint \mathbf{u}\cdot \mathrm{d}\mathbf{r}$, wherein $\mathbf{u}$ denotes the velocity of the point $\mathbf{r}$ of the earth in the ether. From this formula Michelson estimated that the interference fringes would be shifted by about one fringe for a circuit of one square kilometer at a latitude of 45° (he thereby overlooked a factor 2). Like Lodge he noted the difficulty of defining a reference for the position of the fringes, and he suggested using the image of a slit for one of the beams. Some twenty years elapsed before he could measure this effect, in collaboration with Henry Gale and Fred Pearson, astutely centering the fringes by means of a smaller interferometer inserted in the large one.[95]

7.5. Kaluza

A last theoretical anticipation of the Sagnac effect is found in a short communication by the young Theodor Kaluza intended for the *Naturforscherversammlung* of September 1910 in Königsberg. For a Born-rigid[96] rotating disk, Kaluza defined the *Eigengeometrie* of the disk through the orthogonal section of the congruence of world-lines of the material points of the disk and found it to be Lobachevskian, thus anticipating a famous consideration by Einstein. In addition, Kaluza considered the synchronization of clocks on the disk and found that the local synchronicity condition was not integrable. For a loop containing the center of rotation and defined by $r(\theta)$ in polar coordinates, he gave the synchronization error "measured in proper time":

$$\delta = 2\oint \frac{(\omega r^2/c^2)\mathrm{d}\theta}{\sqrt{1-r^2\omega^2/c^2}}$$

where ω is the angular velocity of the disk. Kaluza concluded:

"From the existence of this synchronization error there follows the possibility of a proof of the rotation of the earth by pure optical or electromagnetic means. (No contradiction with relativity theory.) The idea may not be practically feasible at present; in the best case, we are talking about $2\cdot 10^{-7}$ s."

Kaluza was unaware of Michelson's similar suggestion of 1904. His own considerations long remained unnoticed, in part because an illness prevented him from attending the Königsberg meeting. Another reason is the laconic, formal way in which he published his results.[97]

A plausible reconstruction of this non-integrable synchronization argument runs as follows. Assuming that for co-moving observers in the neighborhood of a point of the disk the velocity of light still is the constant c (more exactly, synchronization is defined so that this condition holds), then the Lorentz transformations with translation velocity $u = r\omega$ and with the axis in the orthoradial direction can be used to derive the time and space given by optical synchronization in this neighborhood. Hence we have $\mathrm{d}t = \gamma(\mathrm{d}t' + u\mathrm{d}x'/c^2)$ for the time difference between two neighboring events with respect to observers at rest, if $\mathrm{d}t'$ and $\mathrm{d}x'$ denote the increments of the time and orthoradial coordinates with respect to the disk's observers and with $\gamma = (1-u^2/c^2)^{-1/2}$. Consequently, the t-time lag of two neighboring synchronized clocks of the disk is $\mathrm{d}t = \gamma u\mathrm{d}x'/c^2$. The coordinate x' being measured with rods contracted in the ratio γ^{-1}, and radial rods being unchanged, we also have

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[94] Wien [150]; Cohn [151, pp. 1408–1409]. Cf. Darrigol [90, pp. 368–369].

[95] Michelson [9, p. 716n]; Michelson, Gale, and Pearson [152]. Cf. Martinez-Chavanz [6, pp. 20–21, 63–66]; Anderson, Bilger, and Stedman [140, pp. 975–976].

[96] Born-rigidity, introduced by Max Born in 1909, means constant distance between two neighboring material points in the tangent inertial frame.

[97] Kaluza [153]. Cf. Walter [154, pp. 68–70]. The formulas in Kaluza's article seem to be given for $\omega = c = 1$.

$\mathrm{d}x' = \gamma r \mathrm{d}\theta$. The synchronization error for a clock situated at the distance r_0 and for a synchronization loop embracing the origin is, when measured in proper time,

$$\delta = \gamma(r_0) \oint \gamma^2 \left(\omega r^2 / c^2\right) \mathrm{d}\theta$$

Kaluza's formula gives twice this value, only when the synchronization look is the circle $r = r_0$. Kaluza may have reasoned correctly and forgotten to mention the restriction to a circular loop in his condensed, published statement. The factor two may result from a different convention in the definition of the synchronization error.

In any case, Kaluza's imprecisions do not affect the following deductions. For events occurring at two distant points, the local time difference depends on the line of clocks on which the synchronization is done. For instance, two identical events will be judged non-synchronous if their synchronicity is judged by a dense series of clocks arranged on a circle centered on $r = 0$. As another consequence, light traveling on a loop around the center of rotation will take the local time $t'_\pm \approx t_\pm \mp 2S\omega/c^2$ (the $+$ index being for travel in the direction of rotation, and the index $-$ for travel in the opposite direction), wherein S is the area enclosed by the loop. Since the velocity of light with respect to the disc has been assumed to be the constant c, we must have $t'_+ = t'_-$ and $t_+ - t_- = 4S\omega/c^2$, in conformity with the Sagnac time-shift (in the laboratory frame).

Langevin gave the latter reasoning in 1935, without knowledge of Kaluza's earlier considerations, and with a different derivation of the synchronization error (based on a direct exploitation of the isotropy of light propagation with respect to the disk's observers).[98] The Kaluza–Langevin reasoning shows that the Sagnac effect is compatible with the validity of special relativity in the instantaneous tangent frames at every point of the rotating disk. It also shows that the effect derives from the non-integrabiliy of proximate clock synchronization on the disk. This deep insight of the young Kaluza is preserved in general relativity. Of course, it does not invalidate the more elementary derivations of the effect that Lodge, Michelson, and Sagnac obtained in the ether-frame.[99]

7.6. *Lodge, Michelson, and Sagnac*

To summarize, Lodge [8], Michelson [9], and Kaluza [153] all conceived the Sagnac effect by the rotation of the earth well before Sagnac publicly discussed it. Lodge also anticipated the Sagnac effect on a turntable in 1897. In the same year, Michelson performed a test of ether drag similar to Sagnac's test of 1910. One might wonder how Sagnac could remain unaware of the latter experiment, since it had been published in the same journal (*The American journal of science*) as Michelson's other famous experiments and since two well-read experts on the optics of moving bodies, Lorentz and Wien, attended the Brussels congress in which Sagnac announced his result. Then one should also wonder why Michelson and Sagnac were both unaware of Lodge's suggestions, which appeared in the widely read *Philosophical transactions*. The explanation is simple: the international circulation of knowledge and the refereeing system of the time were not what they are now, despite the relatively small amount of publications.

More interestingly, the motivations and the heuristics of Lodge, Michelson, and Sagnac were quite different, despite the similarity of the experiments they conceived. Whereas Sagnac's experiments of 1910 and 1913 were a consequence of his discussion of interference by means of his principle of the effect of motion, Lodge's and Michelson's experiments derived from the instrumental opportunities offered by Fizeau's inverse-path trick and by Michelson's separating plate. Whereas Sagnac's interest in the effects of rotation (of the ether) derived from the theoretical occurrence of the curl of the ether flow in his phase-shift formula, Lodge's own concern with rotation (of the ether or of the optical apparatus) derived from his appeal to an optical circuit à la Fizeau. Whereas Sagnac's test of the ether drag derived from his focus on rotational ether flow, Michelson's similar test derived from direct analogy with the setup used in his verification of Fizeau's result of 1951. These differences in motivation had consequences on the experimental setups. In particular, Sagnac used optical circuits of variable shape with a variable number of mirrors because he knew in advance that the phase-shift only depended on the (oriented) surface of the circuit (for a constant curl of the ether flow). In contrast, Lodge and Michelson favored a circuit involving two parallel beams, by geometrical simplicity and by continuity with Fizeau's experiment. They were both unaware of the superiority of circuits involving an even number of mirrors (for the broad, weakly coherent beams of the time).[100] So too are modern commentators of Sagnac's experiments. What is now called a Sagnac interferometer truly is a three-mirror rectangular-circuit interferometer, in which Sagnac rather saw a strioscope.

Granted that Lodge was first to conceive the Sagnac effect on a turntable, it remains true that Sagnac was first to experimentally demonstrate the effect. This priority is neither a consequence of Lodge's fear of centrifugal force nor an

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[98] Langevin starts with the Minkowskian metric formula $\mathrm{d}s^2 = c^2\mathrm{d}t^2 - \mathrm{d}r^2 - r^2\mathrm{d}\theta^2$ in polar coordinates and for observers at rest. The coordinate change $\theta' = \theta - \omega t$ gives $\mathrm{d}s^2 = (c^2 - r^2\omega^2)\mathrm{d}t^2 - 2r^2\omega\mathrm{d}\theta'\mathrm{d}t - \mathrm{d}r^2 - r^2\mathrm{d}\theta'^2$. With respect to these coordinates the propagation of light is anisotropic because of the rectangular term in $\mathrm{d}\theta'\mathrm{d}t$. In order to restore the isotropy of light propagation with respect to the disk, Langevin introduces the proper time $t' = \int(\gamma^{-1}\mathrm{d}t - \gamma\omega r^2 c^{-2}\mathrm{d}\theta')$ for which $\mathrm{d}s^2 = c^2\mathrm{d}t'^2 - \mathrm{d}r^2 - (1 - \omega^2 r^2/c^2)^{-1} r^2\mathrm{d}\theta'^2$. The synchronization of neighboring clock obtains for $\mathrm{d}t' = 0$, which is equivalent to the condition $\mathrm{d}t = \gamma^2\omega r^2 c^{-2}\mathrm{d}\theta'$ derived from the local Minkowskian structure.

[99] Langevin [155,156]. Cf. Dieks [157]. For a modern argument, cf. Gourgoulhon [158, Chap. 13]. For the argument in general relativity, cf. Landau and Lifshitz [159, §89].

[100] See footnote 73 above.

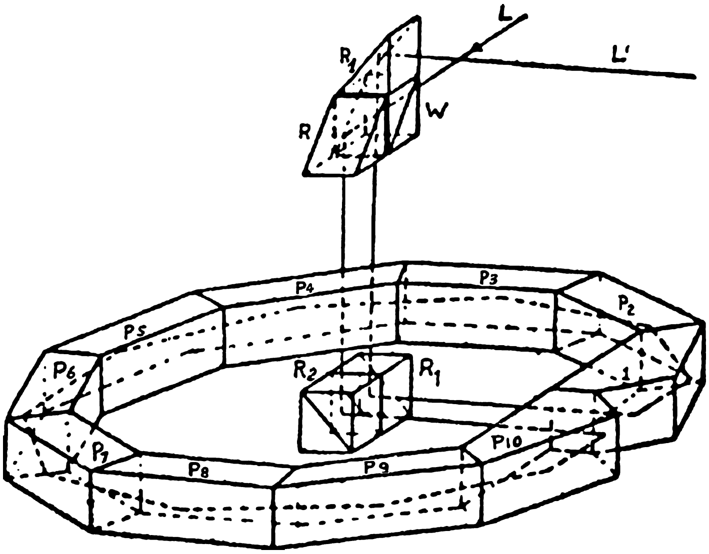

Fig. 30. Harress' rotating glass-ring interferometer (the average radius of the ring is about 20 cm). From Harress [160, p. 30].

automatic consequence of Sagnac's higher commitment. Rather, Sagnac benefited from two advantages of his interferometry: higher fringe contrast thanks to the double-prism separator, and avoidance of aerial fluctuations thanks to the even number of mirrors. Had Lodge or Michelson tried the similar experiment with a square optical circuit they would probably have failed because this arrangement would have been too susceptible to the perturbations caused by the rotation of the table.

7.7. Harress

In the years 1909–1911, the doctoral candidate Franz Harress experimented on the propagation of light in moving glass in the cellars of the observatory of Jena University. Thanks to Rudolf Straubel's support, he benefited from custom-made glass pieces from the Carl Zeiss company. In order to get a high constant velocity of the moving glass, he had the idea of using the rotating polygonal arrangements of glass prisms shown on Fig. 30. The light L from a collimator is divided by the split glass cube W (analogous to Sagnac's double prism) and directed toward the center of the turntable by the glass reflector R. The reflectors R_1 and R_2 then direct the two light beams to the entrance of the polygonal arrangement of ten prisms. By total internal reflection on the walls of the prisms, these beams travel on two contrary polygonal paths within the glass, then return to the glass cube, recombine, and emerge in a single beam L′. All the glass pieces rotate together at uniform speed (about 700 turns/minute) around a vertical axis through the center of the polygon. As the collimator and telescope do no move, the observation must be done for flashes of light sent at a given constant phase of the rotation. Harress found that the rotation caused a shift of the interference fringes (of the order of one tenth of the fringe spacing), and measured this shift with a precision of about 10%.[101]

On the theoretical side, Harress reproduced Fresnel's derivation of the value $1-1/n^2$ for the dragging coefficient α; he recalled the slightly different formula that Lorentz had obtained in his electron theory: $\alpha=1-1/n^2-(\lambda/n)(\mathrm{d}n/\mathrm{d}\lambda)$, and he proved that the latter formula derived (in a first approximation) from Einstein's relativistic composition of velocities if the Doppler shift of the light entering the moving transparent body was taken into account. In the theoretical analysis of his own experiment, he simply added the time shifts caused by the partial ether drag on each portion of the polygonal light path. His result for the total time shift may be rewritten as $\delta t=-2n^2\alpha\omega S/c^2$, wherein n is the optical index of the glass, ω the angular velocity, and S the surface of the light circuit. Drawing the dragging coefficient from the measured phase-shift, he found it to be 30% below the theoretical values given by Fresnel and Lorentz (which differ only by 2% from each other).[102]

Unfortunately, a grave error jeopardized Harress' conclusions. In his derivation of the expression $\delta t=-2n^2\alpha\omega S/c^2$ of the time shift, he used the expression $l/(c/n+\alpha u)$ for the time taken by light to travel the element l of glass moving at velocity u in the direction of light propagation. In reality, the velocity of light with respect to the dragged ether is c/n and the velocity of the dragged ether with respect to the laboratory is αu, so that $c/n+\alpha u$ represents the velocity of light *with respect to the laboratory*. Its velocity with respect to the glass is $c/n+\alpha u-u$, and the time taken by light to travel the length l of glass is $l/(c/n+\alpha u-u)$. Hence α should be replaced by $\alpha-1$ in Harress' formulas, and the correct value of the

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[101] Harress [160]. On the precision, cf. Knopf [161, p. 433].

[102] Harress [160], pp. 3–4 (Fresnel), 6 (Lorentz), 7–13 (relativistic), 59 (total time shift), 70 (results).

total first-order time shift is $\delta t = 2n^2(1-\alpha)\omega S/c^2$. With this correction, Harress' measurements agree with the theoretical dragging formulas within the margin of experimental error.

7.8. Harzer, Einstein, and Laue on Harress

Harress published his highly skilled but flawed dissertation work in 1912. The astronomer Paul Harzer corrected the calculation error in 1914 in the *Astronomische Nachrichten*. For Fresnel's value of the dragging coefficient, the corrected time shift becomes independent of the index n and agrees with the value $2\omega S/c^2$ given by Sagnac's principle of the effect of motion. For Harzer, this was only a coincidence and not a very significant one because he and Harress favored Lorentz's value of the dragging coefficient. As Einstein soon explained in the same journal, in the case of Harress' experiment (unlike Fizeau's) the relevant value of the dragging coefficient is Fresnel's because the light enters the rotating glass polygon perpendicularly and there is no modifying Doppler shift. Harress did not have a say, as he unfortunately died on the battlefield.[103]

After the war, Max Laue convinced Harress' doctoral adviser, Otto Knopf, to publish the details of Harress' experiment in *Annalen der Physik*, because his dissertation was not commonly available and because the analysis of the experimental results needed revision. Laue himself contributed a detailed proof that (special) relativity theory led to the value $2\omega S/c^2$ of the time delay on an optical circuit, whatever be the optical index on this circuit. In 1911 he had already shown that the then competing theories of the optics of moving bodies, those of Lorentz, Cohn, and Einstein all yielded the time-shift formula given by Michelson in his memoir of 1904 on an optical effect of the rotation of the earth. In his article on Harress, Laue explained that the time shift could be obtained either by applying the relativistic law of composition of velocities in the inertial frame tangent to an element of the optical circuit (to put it in modern terms) or in applying the Lorentz coordinate transformation to the times at which the light reaches the two extremities of the element. To first order the latter procedure is strictly equivalent to Sagnac's principle, which Laue ignored. In both cases, it is assumed that the rotation of the system does not significantly alter the light path. As Sagnac and Harzer had earlier argued, this rotation in fact curves the light rays. Laue confirmed that this curvature did not significantly alter the time shift. Following a hint by Wien, he also stated that any general-relativistic effect of centrifugal forces could probably be neglected, for these forces were of the same order as the usual gravitational forces.[104]

Laue mentioned Sagnac's experiment at the beginning of his article, as a variant of Harress' experiment in which air is used instead of glass as the medium of propagation. In passing he noted that "Sagnac's interpretation of his experiment as a proof of the existence of an 'ether' was not compelling at all." The remark had already been made by several physicists, including Luigi Puccianti and Hans Witte in 1914. It is indeed obvious that the Sagnac effect does not contradict special relativity since the latter theory forbids only effects of uniform *translation* on optical experiments. Even without Laue's or others' learned treatments, it is easy to understand that the Sagnac effect comes out the same in special relativity and in any stationary-ether theory, since it can be derived by tracing the progression of light from one moving mirror to the next in the laboratory frame, as known to Lodge, Michelson, and Sagnac. Since the early 1920s, many physicists have discussed relativistic explanations of the Sagnac effect in a deeper manner, also in a general-relativistic context. Their efforts have not prevented the anti-relativist sect to brandish the Sagnac effect as a proof of the ether. Those developments go beyond the intended scope of the present study.[105]

7.9. Harress and Sagnac

Laue's and Knopf's memoirs may be seen as an implicit attempt to give Harress some credit for the discovery of the Sagnac effect, although they do not contain any priority claim. When in 1926 the Hungarian physicist Béla Pogány performed an improved version of Harress' experiment, he called it the "Harress-Sagnac" experiment. This may be seen either as a way to indicate the similarity of the two experiments, or, less likely, as a way to downplay the importance of Sagnac's contribution. Nowadays, some authors use the expression "Harress-Sagnac effect" instead of "Sagnac effect." It is not the historian's business to decide which is fairer.[106]

It is instructive, however, to compare the motivations and achievements of the two physicists. Sagnac was expecting a certain effect for theoretical reasons, and he designed an experiment that was explicitly meant to establish this effect. In contrast, Harress wanted to measure the Fresnel dragging coefficient in glass and his glass-ring interferometer was the instrument of that measurement. In his investigations, the effect of rotation on interference intervened only as a means to relate the measured fringe-shift to the dragging coefficient. He did not regard this effect as something essentially new and rather saw it as a straightforward consequence of the Fresnel drag applied to the elements of a transparent rotating ring. His theoretical expression of this effect was so wrong that it gave a zero effect in the $n = 1$ case, which is precisely the case of Sagnac's experiment.

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[103] Harress [160]; Harzer [162]; Einstein [163]. Einstein's paper triggered a small polemic with Harzer: see Harzer [164], Einstein [165].

[104] Knopf [161]; Laue [166,167].

[105] Laue [166, p. 449]; Puccianti [168]; Witte [169]. On relativistic derivations of the Sagnac effect, cf. Post [139]; Martinez-Chavanz [6, Chaps. 7–8]; Malykin [170,171]; Rizzi and Ruggiero [172]; Gourgoulhon [158, pp. 218–228].

[106] Pogány [173].

It is sometimes said that Harress' measurements provided much more precise evidence for the Sagnac effect than Sagnac's own experiment. In reality the precision was comparable, because what Harress won on higher rotation speed and smaller index fluctuation he lost on smaller surface of the optical circuit and unwanted beam deviations. This is why Knopf and Laue called for a repetition of his experiment and Wien supported Pogány's answer to that call.[107] To sum up, Harress had the general idea that rotation may induce fringe-shift; he verified the existence of such an effect in glass; and he performed measurements that could later be used to confirm the Sagnac effect; however, the theoretical interpretation he gave to his experiment is utterly incompatible with the true Sagnac effect.

8. Intermezzo: war acoustics

In the years following Sagnac's publication of his ether-whirling effect, the war directed Sagnac and other physicists to more urgent problems. Harress lost his life, and Sagnac switched to acoustic researches which he thought could benefit the French army. His activity in this domain was very intensive and a large quantity of relevant manuscript materials can be found in his personal archive. His principal achievement was an acoustic interferential telescope through which the fearful Zeppelins could be detected at night time. Seven hundred fifty such instruments of large size were built and successfully used by the French army on various fronts. Toward the end of the war Sagnac also invented a high-pitch trumpet that permitted communication between the battlefront and the rearguard. The three hundred copies or so he built with his assistant at the Sorbonne served the Champagne army. Even in those times, optics was still inspiring Sagnac's innovations.[108]

9. The double mechanics

After the war, Sagnac resumed his optical researches with a new aim: produce a credible alternative to the relativity theory whose counterintuitive assumptions he and many of his French colleagues strongly disliked. While Arthur Eddington was bringing Einstein's theories to the world's attention through his solar-eclipse expedition, Sagnac began publishing on "an absolute mechanics of undulations" that was doomed to remain a very personal enterprise.

9.1. Outer laws, inner laws, and their liaison

In a series of notes published in 1919–1920 in the *Comptes rendus*, Sagnac distinguished between "outer laws" regarding the (time-)average of the total energy of radiation and "inner laws" regarding the details of wave propagation in the ether. Whereas the former laws strictly obeyed Galilean relativity, the latter depended on the global motion of the system through the ether. At the outer level, the propagation of luminous energy had to be isotropic in a frame attached to the source; a flash of light sent by a source moving at the velocity u in the direction of motion had to travel at the velocity $c+u$, as it would in any emission theory; interference patterns also had to be invariant under a uniform translation of the system, as they would if the ether were completely dragged by the system.[109]

These assumptions seem completely at odd with the assumption of a stationary ether. Sagnac needed to conciliate the Galilean invariance of his outer laws with the inner laws of wave propagation in this ether. To this effect he relied on his old principle of the effect of motion and on analogy with Gouy's distinction between phase velocity and group velocity. Call k_0 and ω_0 the wave number and angular frequency of the wave emitted by a sinusoidal point source at rest in the ether. According to Sagnac's principle, the amplitude at point R for the radiation from a source S is obtained by summing the partial amplitudes of various paths between S and R, each path being a series of free propagations between successive point-like secondary sources (the molecules of matter in the case of propagation in transparent matter, or the points of a hole on a screen in the case of diffraction); and the only effect of the uniform translation of the whole system is a phase shift on each element of the path of propagation. This phase shift corresponds to an alteration of the wave number k depending on the original value k_0 of this number, on the translational velocity $\mathbf{u}$ of the system, and on the angle α that the direction of propagation makes with this velocity. In addition, Sagnac assumes that the frequency ω of the wave is altered in a manner depending on the velocity u only. Euclidean symmetry and homogeneity imply the forms[110]

$$\frac{k}{k_0} = 1 + F\big(u^2/c^2\big)\frac{u}{c}\cos\alpha, \quad \text{and} \quad \frac{\omega}{\omega_0} = G\big(u^2/c^2\big) \tag{1}$$

No matter how the functions F and G are chosen, the relation between ω and k remains linear and there is no dispersion in the usual sense. Undeterred by this difficulty, Sagnac considered the superposition of two waves of the same kind but emitted by sources with the different velocities $\mathbf{u}$ and $\mathbf{u}+\mathrm{d}\mathbf{u}$, the increment $\mathrm{d}\mathbf{u}$ being parallel to the direction of propagation. In the frame moving at the velocity $\mathbf{u}$, the phase difference of the two waves in this direction is

$$\mathrm{d}\varphi = \big[(\omega+\mathrm{d}\omega)t - (\mathbf{k}+\mathrm{d}\mathbf{k})\cdot(\mathbf{r}-t\,\mathrm{d}\mathbf{u})\big] - [\omega t - \mathbf{k}\cdot\mathbf{r}]$$

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[107] Pogány [173, p. 217].

[108] Cf. P. Sagnac [19, p. 144]; Berthelot [174, p. 232]; Sagnac [20, pp. 3–4].

[109] Sagnac [175–181]. On this theory, cf. Martinez-Chavanz [6, pp. 51–56].

[110] Sagnac [175, p. 531].

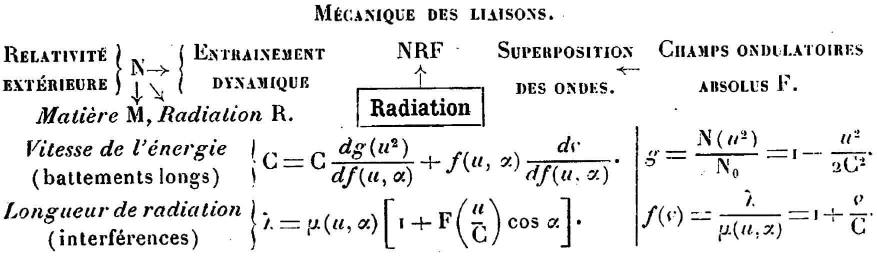

Fig. 31. Sagnac's table explaining how the "absolute wave fields" F lead, by superposition according to the "new absolute mechanics of waves" (NRF) to "external relativity" and "dynamical drag" (energy projected by the source) for the average energies of radiation. The letter N stands for Newtonian relativity. The equations in the right column correspond to the Eqs. (3) below. Those in the central column correspond to Eqs. (1) and (2). From Sagnac [176, p. 644].

The resulting beats travel at the velocity

$$U = \frac{\mathrm{d}\omega}{\mathrm{d}k} + \frac{\mathbf{k}\cdot\mathrm{d}\mathbf{u}}{\mathrm{d}k}$$

In analogy with the ordinary concept of group velocity, Sagnac identifies this velocity with the velocity of propagation of the energy from the source. According to the external principle of relativity, this velocity must be the constant c. This condition and the relations $\mathbf{k}\cdot\mathrm{d}\mathbf{u} = kc\mathrm{d}\upsilon$, $\mathrm{d}u^2 = 2c^2\upsilon\mathrm{d}\upsilon$ with $\upsilon = (u/c)\cos\alpha$ lead to the equation

$$\frac{2\upsilon G' + 1 + \upsilon F}{F + 2\upsilon^2 F'} = 1, \quad \text{or} \quad (F-1) - \upsilon\big(F + 2G'\big) - 2\upsilon^2 F' = 0 \tag{2}$$

The left side of this last equation is a polynomial in $\cos\alpha$ with coefficients that are functions of u only. Its vanishing requires $F - 1 = 0$, $F + 2G' = 0$, and $F' = 0$. The unique solution for which $G(0) = 1$ is $F = 1$ and $G = 1 - u^2/2c^2$. Sagnac thus got the "rigorously true" equations (see Fig. 31)[111]:

$$\frac{k}{k_0} = 1 + \frac{u}{c}\cos\alpha, \quad \text{and} \quad \frac{\omega}{\omega_0} = 1 - \frac{u^2}{2c^2} \tag{3}$$

9.2. Empirical consequences

The first of Eqs. (3) leads to the phase shift $k_0(u/c)\mathrm{d}l\cos\alpha = \omega_0\mathbf{u}\cdot\mathrm{d}\mathbf{l}/c^2$ on the elementary light path $\mathrm{d}\mathbf{l}$ that makes the angle α with the velocity $\mathbf{u}$. Sagnac's old principle of the effect of motion, and the resulting invariance of interference and diffraction phenomena thus hold at any order in u/c. Consequently, the theory explains the null-result of the Michelson–Morley experiment of 1887. It also accounts for the Sagnac effect by giving the value $c \pm |\omega|r$ to the orthoradial velocity of light with respect to the rotating table (r being the distance from the center, and ω the angular velocity). Yet some of its predictions differ from those of the theories of Lorentz, Poincaré, and Einstein. For Sagnac, the clocks in the moving frame still give the absolute time and the measuring rods still give the absolute length, even if they are defined by optical means. The velocity of light flashes (not the phase velocity) depends on the velocity of the source as in an emission theory. Sagnac proposed a crucial experiment in which the velocity of the light from the fast ions of canal rays would be measured by Foucault's method of the rotating mirror. In his theory the Doppler shift of this light should imply a velocity of the emitter in the direction of the emission, which in turn should imply an alteration of the velocity of light in the laboratory frame.[112]

Sagnac also expected the difference between the phase velocity ω/k of the "inner mechanics" of waves and the velocity c of the energy in the "outer mechanics" to be accessible to experience and thus to yield a measurable effect of the motion of the earth through the ether. Somewhat obscurely, he imagined that wave trains sent by an emitter in the direction of the ether wind would undergo a slow periodic inversion of phase with the spatial period $\lambda c/u$ owing to the difference between the velocity c of the front of the train and the phase velocity (about $c \pm u$). For a detector responding to sufficiently large positive disturbances only, the response would depend on the sign of the first (largest) wave of a damped wave train and therefore would vanish at periodic distances from the emitter. The signals of wireless telegraphy could provide the desired damped wave trains, the Branly coherer the sign-dependent detector.[113]

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[111] Sagnac [175], pp. 471 (group velocity), 531 (Eq. (3)). The derivations of Eqs. (2) and (3) are mine. Even in his most detailed accounts [176,182], Sagnac remained allusive.

[112] Sagnac [177], pp. 783 (Michelson), 784 (canal rays), 785 (Sagnac effect); [180].

[113] Sagnac [178].

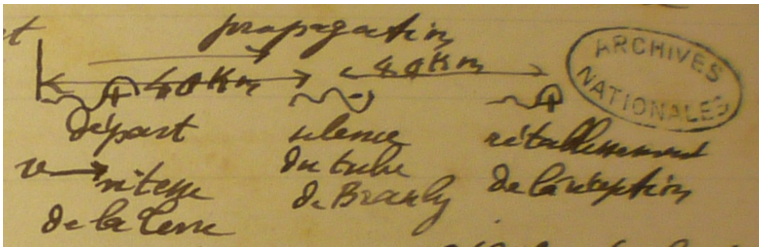

Fig. 32. Sagnac's drawing for periodic silences in telegraphic transmission. The original signal (*départ*) is a bump (+) followed by weaker undulations. At 40 km from the source, the bump becomes a hollow (−) and it is undetected by a Branly tube; and 40 km further the head bump reappears and the reception is reestablished. From Archives nationales.

9.3. *Radio-silences and double stars*

In 1920, Sagnac proudly announced that the predicted periodic silences of telegraphic communication had already been observed in the late 1890s by the British admiralty during a systematic study of communication between two ships at increasing mutual distance:

"Wireless telegraphy, unwittingly preceding the theory, discovered in 1895–1902, of the relative motion of the waves and the energy, which unprepared experimenters judged to be a simple effect of interference – an effect truly impossible under the usual conditions at sea."

The inferred value of the velocity of the earth through the ether would be of the order of 100 km/s, in agreement with the known value of the relative velocity of the stars and the solar system. The double mechanics of waves and energy was thus confirmed. Sagnac called the periods of silence "fits" (*accès*) in a transparent allusion to Newton's fits of easy reflection. He indeed regarded his double mechanics of waves and projected energy as similar to Newton's combination of projected light corpuscles and induced ether waves.[114]

In the same year 1920, Sagnac's position at the Sorbonne rose to *maître de conférences* on theoretical physics and celestial physics. A letter to his brother Philippe informs us of the contents of his inaugural lecture. He first reminded his audience how Newton and Fresnel had introduced the ether as a medium of propagation, and how the lack of observed effects of the ether wind had recently led the relativists to reject this intuition. He commented:

"This gigantic error is comparable to the error of a visitor to an alternative-current factory who would mistake the alternative current for a continuous current and would want to use only average-energy receptors that cannot oscillate with the current."

The simple connection between matter and light expressed in the relativity principle, Sagnac continued, only applies to the total energy of light. This energy is normally recorded in a manner independent of the inner undulation, "as the energy of an alternative current is recorded by a thermal apparatus too sluggish to oscillate with the current." This total energy occurs in "*flashes projected by the source* in the manner of the bullets of a gun." There follows an aquatic metaphor:

"In contrast, the waves are bound to the non-dragged ether in which the flash propagates and with which it is bound through its undulation, as an eel swims and follows the undulation it creates on the water; this undulation run along the body of the eel, thus forming sometimes a bump, sometimes a hollow near its head."

Sagnac thus meant to explain the evolution of a telegraphic signal when the distance from the emitter increases: the detector (coherer) fails to detect this signal at periodic intervals of distance because it detects the bumps only (see Fig. 32). Sagnac had some fifteen students and a couple of colleagues in his audience. They were quite attentive and they applauded him.[115]

From his new chair, Sagnac was also required to teach "celestial physics." He used this duty as an opportunity to find astronomical proofs of his theory. In 1922, he became aware of an anomaly in the Doppler shift of the light emitted by some double stars (Cepheids): the extrema of the shift did not coincide with the phases of the motion of the emitting star in which the velocity in the direction of observation was an extremum. Sagnac explained this anomaly by the different retardation of the emitted light when the source is moving toward and against the terrestrial observer. In his theory, a Doppler shift $\delta\lambda/\lambda$ indeed implies the velocity $c - c\delta\lambda/\lambda$ for the propagation of energy from the source. Sagnac found quantitative agreement between this differential retardation and the observed phase anomaly. His remaining publications, until the last in August 1924, all bore on double stars and their observed phase anomalies. They were meant to verify his theory and to disprove general relativity.[116]

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[114] Sagnac [179]; [181, p. 102]; Jackson [183, pp. 268–271] (observed anomaly). Captain Jackson's explanation of the anomaly, based on wavelength differences in the successive wave trains from the emitter, seems reasonable to me.

[115] G. Sagnac to P. Sagnac, undated, Archives nationales.

[116] Sagnac [184–188]. Cf. Martinez-Chavanz [6, pp. 61–62]. Sagnac did not mention that in 1913 Willem de Sitter had failed to observe a prediction of emission theories: the distortion of the orbits of double stars.

9.4. Reception

Not much can be said on the reception of Sagnac's theory. As we saw, the Sorbonne students were quite receptive. So too were a probably large number of Sagnac's colleagues, as relativity theory was still unpopular among French academics.[117] In 1919, Sagnac got a prestigious prize of the Académie des sciences, the Pierson–Perrin prize, for his oeuvre in physics. In his report, the freshly elected academician Daniel Berthelot summarized Sagnac's new theory and judged: "This penetrating synthesis, based on a subtle analysis of phenomena and on a series of ingenious new experiments, reveals a great effort of thought which, beyond mathematical formulas, endeavors to reach the reality of physical phenomena." Interestingly, in his report on Sagnac's candidature for a vacant seat at the Académie des sciences in 1923, Berthelot dropped most of his description of Sagnac's theory as well as the cited praise. Perhaps he then judged that the winds had turned in favor of relativity theory.[118]

Most enthusiastic was the French popularizer of Einstein's theories, Lucien Fabre. In the second edition of his widely ready read *The new figure of the world: Einstein's theories*, published in 1921, Fabre appended an account of Sagnac's theory by Sagnac himself. Fabre's pompous introduction reads:

"M. Sagnac, of whom it may have been written, in an allusion to the sentence that closes this book, that he perhaps was the new Poincaré, the only person able to give a definitive answer about the value of Einsteinian theories, agreed to entrust to this humble volume an original note whose extraordinary importance shall not escape anyone's attention.... I am extremely happy to give to my readers fresh news about a work that seems to contain in germs the most beautiful discoveries."

The final paragraph of the book reads:

"The human mind remains perplexed. On the one hand, the mind's taste for simplification, the incontrovertible fact of universal relativity, the clarity of the doctrine, the mystical drive toward unity, the marvels of Einstein's discoveries, incite the mind to adhere to relativity theory. On the other hand, the quest of the absolute, the instinct of perenniality, the urge for intellectual images, the confusion between the necessary and the given, the sense of immediate causality, bend the mind toward less audacious theories such as Lorentz's. At this moment, what we miss is the lights of a Poincaré."

Fabre's introduction of Sagnac as the Poincaré of the situation is not as farfetched as it might seem. Poincaré was not entirely pleased with relativity theory, although his reasons differed from Sagnac. With Sagnac he agreed that the relativity principle and the associated symmetry were not a sufficient basis for the unification of physics, that they should not compel us to give up our ancestral concepts of space and time, and that the ether should still play an essential role in the new physics. Unlike Sagnac, however, he believed in the strict validity of the relativity principle and he agreed with Einstein that the times and lengths measured by optical means depended on the velocity of the inertial frame (although in his view the measurement performed in the ether frame were the only ones yielding the "true" values).[119]

In the spring of 1922 Einstein visited Paris and gave a detailed report on the theories of relativity at the Collège de France, followed by two rounds of discussions with physicists and mathematicians. Sagnac spoke in the first round. Here is a contemporary account of his intervention by one of the auditors, the physicist and poet Jean-Baptiste Pomey:[120]

"M. Sagnac insisted in throwing a summary of his theories to the attendance.

– What was the attitude there? Did one acclaim the Frenchman who was opposing a clear doctrine to the revolutionary doctrine of the German?

– No. At first, it was a scandal because of the violence of the intervention. Mr. Einstein was quite disconcerted. Perhaps he expected a fight on political grounds, but this brutal attack on scientific grounds flustered him. Fortunately, he was made to understand that the best was to reply nothing. At any rate Mr. Sagnac spoke very fast, with strong, clear, and imperative voice, in incisive sentences, as if he was bringing the absolute and incontrovertible truth and as if he had the sacred duty to make this truth heard in spite of everything. At any rate his address sounded like a manifesto. For he did not do what was needed to make himself understood, and I myself, having read several of his communications without truly grasping their content, would have been happy to get the much desired explanation in this occasion. Unfortunately, I suppose he saw himself as facing irreducible adversaries, and he made no concession to the attendance. He went on and on despite the interjections that came from certain rows, as if he was proclaiming or protesting, without bothering to bring light or to convince. The attendance let the storm pass, and, when he at last took his seat, the discussion started again as if his communication had never happened. As he received a rather important prize at the Institut [de France], I imagine his works must have some interesting content and might have deserved proper scrutiny. But that outburst was totally unfit to induce any exchange of useful observations."

Although Pomey plausibly inflated the incident to amuse his readers, his account confirms a sadly verifiable fact: even in publications Sagnac only sketched his theory and he made little effort to be understood. As a consequence, other experts in the optics of moving bodies or in relativity theory ignored his theory, as Einstein did at the Collège de France. The praise

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[117] Cf. Paty [189]; Biézunsky [190]; Borella [191]; Moatti [192].

[118] Berthelot [174, p. 1231]; Berthelot's report of 1923 in the Sagnac folder of the archive of the Académie des sciences.

[119] Fabre [193, pp. 18, 241]. On Poincaré's views, see Darrigol [194].

[120] Pomey [195, pp. 204–205].

that Sagnac got in his own country came from students or physicists like Berthelot who had no expert knowledge of this domain of physics and a natural antipathy for relativity theory. Berthelot's anti-relativist pamphlet of 1922 was full of crude misunderstandings of both Lorentz's and Einstein's theories.[121] Fabre's *New figure*, though more knowledgeable and more sympathetic to relativity, was but the work of a clever amateur.

The only competent report I have found on Sagnac's theory is the one given by the Belgian astronomer and mathematician Maurice Alliaume in a review of astronomy and relativity for the year 1923. Alliaume correctly observes that an in-depth study of this theory should start with Sagnac's old explanation of the Fresnel drag, and he puts his finger on an essential difference between Sagnac's theory and relativity: whereas Sagnac admits the inner mechanics of the "hidden reality" of phase waves, relativistic mechanics is "essentially based on the principle of identity of indiscernibles." Although Alliaume refrains from explicit judgment, the words through which he introduces Sagnac's theory (and Lenard's double-ether theory of 1923) are not very engaging:

"Einstein has reconciled [the Michelson–Morley result with stellar aberration] by a new theory of light that upsets our most entrenched conceptions and removes the difficulty by negating the ether. His adversaries reconcile [the antagonist facts] and will go on doing so in the framework of the more traditional physics through new theories of light, and each one will have his own theory. We have had the theory of G. Sagnac..."

Besides Alliaume, the only experts who publicly reacted to Sagnac's attempt were the reviewers for the American and German abstracts of physics literature. The general feeling was that the theory could be safely ignored until Sagnac would do enough to make himself understood.[122]

This lack of active, competent feedback may partly be seen as a consequence of the general agreement, among experts on the electrodynamics of moving bodies, that Lorentz's and Einstein's theories were the best theories. Earlier in the century, say until the 1910s, it was still permitted to hesitate between several options: Einstein's theory, its more conservative but empirically equivalent Poincaré–Lorentz version, Emil Cohn's macroscopic theory of 1904, and Walther Ritz's emission theory. In the course of time, however, the superiority of Einstein's approach grew more and more evident to the specialists. New alternatives were not likely to be taken seriously.[123]

9.5. *Critical assessment*

There are, in addition, intrinsic features of Sagnac's theory that make it less credible than earlier alternatives to Einstein's theory. Three issues are at stake here: the compatibility of the theory with experimental facts, its inner consistency, and its scope. Regarding the first issue, around 1920 there was no clear-cut proof that the velocity of light did not depend on the velocity of this source. The most publicized proof, Willem de Sitter's failure to observe any distortion of the apparent orbit of double stars in 1913, was still under debate.[124] Perhaps this is the reason why Sagnac, despite his interest in double stars, ignored this refutation of emission theories. More puzzling is his willingness to regard single, vague observations done in complicated circumstances as strong evidence in favor of his theory. It sounds as if the aging Sagnac, who had been a very careful experimenter, now contented himself with fragile, largely subjective confirmation.

Regarding the issues of consistency and scope, Sagnac's theory fares even worse. At first glance it is tempting to compare this theory with Ritz's and Cohn's theories, which also explain the absence of effects of the earth's translational motion on (most) optical experiments (including the Michelson–Morley experiment) without leaving the framework of Galilean kinematics. Ritz's theory does so by referring wave propagation to the moving source, thus eliminating the ether and even the possibility of simple wave equations. Cohn's theory does so by modifying the Lorentz–Maxwell equations for the electrodynamics of moving bodies in such a manner that their form in a frame moving at the velocity $\mathbf{u}$ (with respect to absolute space) differs from their form in the absolute frame only by the shift $t \rightarrow t + \mathbf{u} \cdot \mathbf{r}/c^2$ of the time variable *at any order* in u/c. This shift being unobservable in optical experiments in which stationary light patterns are observed, the theory is compatible with the observed absence of effects of the motion of the earth.[125]

These two theories were fully worked out in all mathematical details and they embraced electromagnetic phenomena, whereas Sagnac's theory remained rudimentary in its mathematical development and was mostly confined to optics (save for its application to electromagnetic radio waves). This is a first important difference. Still one might hope to develop Sagnac's theory into a theory of comparable power. This task would be easy if one could show that Sagnac's theory is a variant either of Ritz's theory or of Cohn's. The first option is not open, because wave propagation in Ritz's theory is entirely relative to the source, whereas in Sagnac's theory it is only the propagation of the *energy* of the waves that is relative to the source. At first glance, the Cohn option looks more promising because Sagnac's modification of the wave number in a

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[121] Berthelot [196]. For instance Berthelot confused the dilation of time with the Doppler effect (p. 28). He portrayed relativity theory as the work of a wandering Jew who did not need the home of Newtonian space and time: cf. Lalli [15, p. 74].

[122] Alliaume [197, pp. 177–179]. I have consulted the *Science abstracts, section A: Physics*, the *Physikalische Berichte*, and the *Jahrbuch über die Fortschritte in der Mathematik*. Most reviews summarize Sagnac's results without judging them. In his review of Sagnac [181] for the *Jahrbuch*, Herman Müntz writes "Die Ausführung wird nur ganz flüchtig angedeutet.... Es wird nicht gesagt, welches Verhalten der von einer bewegten Quelle ausgehenden Wellen jenen Hypothesen entsprechen muss, wodurch die Grundlagen der Theorie erst geklärt werden würden."

[123] On the early alternatives to Einstein's theory, cf. Darrigol [90, pp. 385–392].

[124] Cf. Martínez [198, p. 16]. For contestations of Sitter's conclusion, see Alliaume [197, pp. 167–168].

[125] On Cohn's theory, cf. Darrigol [199]; On Ritz's, cf. Martínez [198], Darrigol [40].

moving frame is equivalent to the shift $t \to t + \mathbf{u} \cdot \mathbf{r}/c^2$ of the time variable. The similarity stops there, however, because the dispersion relations of the two theories differ:

$$\omega^2 = c^2\big(\mathbf{k} - \omega\mathbf{u}/c^2\big)^2 \quad \text{for Cohn;} \qquad \frac{\omega}{k} = c\frac{1 - u^2/2c^2}{1 + \mathbf{k} \cdot \mathbf{u}/kc} \quad \text{for Sagnac.}$$

Moreover, the predictions of Cohn's theory differ from Lorentz's only at second order in u/c, whereas in Sagnac's theory the projection of electromagnetic energy implies a first-order departure from Lorentz's theory.

The way in which Sagnac conciliates the isotropy of energy propagation from a moving source with his laws (3) of wave propagation from a moving source is quite strange. As we saw, the implied wave groups involve the superposition of waves from sources moving at slightly different velocities. There is no dispersion in the ordinary sense (different phase velocities for different wavelengths), there is only a dependency of the phase velocity on the velocity of the source and the direction of propagation. This would be fine if every wave train in nature was made of the superposition of monochromatic waves from sources moving at different velocities. But I do not see why this should be the case: a typical wave train either comes from a damped source with a well-defined velocity, or it is obtained by chopping the undulation from a permanent source.

A last defect of Sagnac's theory is the lack of any simple wave equation leading to the expressions (3) of the frequency and wave number. In particular, his laws of wave propagation do not agree with the value $c - \mathbf{k} \cdot \mathbf{u}/k$ of the relative phase velocity ω/k that one expects in a stationary-ether theory (it does so only to first order in u/c). Sagnac did not worry about these difficulties, presumably because he reasoned by simple geometric arguments that did not require any differential equation or any precise ether mechanism. All along his career he avoided the extensive mathematical apparatus that had become the norm in theoretical physics.

9.6. Delusion

To sum up, Sagnac's last theory of wave propagation probably deserved being ignored by other theoreticians of optics and electrodynamics. It did not meet common standards of clarity and rigor, and its most specific assumption, a sort of dispersion bridging the propagation of waves with the large-scale propagation of luminous energy, seems highly problematic. While reading Sagnac's series of notes in the *Comptes rendus* one cannot help feeling that he was a victim of some sort of delusion. The occasional bursts of enthusiasm, the obscurity of many sentences, and the pompous announcements of an entirely new physics all suggest that Sagnac no longer was in possession of the qualities that permitted his earlier successes both in theory and in experiments. Intellectual solitude surely aggravated the problem. His only scientific collaborator, his beloved friend Pierre Curie, was no longer there to discuss physics with him; and he seems to have made no effort to discuss with their common friend Paul Langevin, who would no doubt have seen the weaknesses of Sagnac's theory.

"How could a scientific life that started so happily and went on so brilliantly finish so early? For a number of years, the *savant* was no longer himself; he was a *vaincu de la vie*." These are the words of Philippe Sagnac, in the concluding section of the obituary he wrote for his brother. From the same source we learn that Sagnac's health deteriorated in 1924, so much that in 1926 he applied for retirement. Plausibly this decline began earlier: when, after the war, Sagnac indulged in a kind of speculation that he would earlier have been the first to criticize. Although the resulting publications can be safely ignored by today's physicists, they are instructive to anyone interested in Sagnac's scientific life for they extend the style of optical thinking that Sagnac had been defending since the early 1890s: a mostly kinematic approach with few equations and in a persistently Newtonian framework.

10. Friends, honors, and persona

Although Sagnac preferred to work alone or with his laboratory assistant, he had a few high-profile friends and supporters, at home and abroad. The most powerful of them was Daniel Berthelot, son of Marcellin, member of the two academies, and senator. Berthelot wrote the reports that helped Sagnac win important prizes, and he supported his candidatures to the Académie des sciences. Being a physicochemist, he had little competence to judge Sagnac's more theoretical work. His spontaneous dislike of relativity theory made up for that. Sagnac's dearest and closest friend was Pierre Curie, his only collaborator in one occasion only. Curie's accidental death in 1906 affected Sagnac for the rest of his life. The great Henri Poincaré shared Sagnac's passion for optics and he appreciated his accomplishments: he supported one of his candidatures at the Sorbonne; he may have been responsible for Sagnac's invitation to participate to the Lorentz jubilee volume (at least Sagnac thought so); and he exchanged a few letters with Sagnac. To be true, Sagnac did not show the best of himself in this correspondence: in the summer 1899 he believed to have found a violation of the principle of reaction in a unipolar induction device imagined by Wladimir de Nicolaiève. Poincaré immediately corrected him.[126]

In foreign countries, Sagnac's most prominent acquaintance was Hendrik Lorentz. Sagnac's contribution to the Lorentz jubilee prompted a friendly exchange of letters. Sagnac thus came to study the contents of Lorentz's theory and, as we

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[126] On Berthelot, cf. Moatti [192, pp. 154–156]. On Curie's friendship, cf. P. Sagnac [19, pp. 44–45]. On the relation with Poincaré, cf. Walter [29, Chap. 51]. The letters on unipolar induction and the reaction principle are ibid., pp. 324–327.

saw, he related his principle of the effect of motion to Lorentz's local time. After visiting Lorentz and his wife in Leyden in the spring of 1905, he obtained valuable criticism of his mathematical theory of photographic action. Sagnac got to know Philipp Lenard in international congresses of radiology, and corresponded with him on various matters including Hertz's mechanics, the photo-electric effect, and of course the Sagnac effect. In May 1914, Lenard wrote:

"I would like to express my special thanks for the interesting news about the rotating interferometer. We will have a special report on this apparatus and on your work with it at the Heidelberg physics seminar, and I am glad to have your explanations and the good illustration."

Perhaps Lenard, being a visceral anti-relativistic and anti-Semite, appreciated Sagnac's alleged proof of the ether. He nonetheless devoted most of his long letter to shunning Sagnac's request to arrange refereeing in a German publication, arguing that it would serve no purpose. The war put an end to the relations between the two physicists. A far more honest and faithful friend of Sagnac's was the Norwegian meteorologist Vilhelm Bjerknes, whom he may have met while they were both students in Paris and whom he later visited in Oslo. Bjerknes' only extant letter to Sagnac, sent in February 1914, concerns Sagnac experiment on the whirling optical effect. Then in Leipzig, Bjerknes discussed Sagnac's experiment with the eminent optician Otto Wiener and came to the conclusion:

"It is an undeniable fact that your apparatus records its global rotational motion without recourse to any external reference. In this regard your experiment will always remain a fundamental experiment, even one of the most fundamental experiments of physics. Yet it will not suffice to convince the staunch relativists of the existence of the ether. For the relativists are men who purport to imagine waves that propagate in a medium whose existence they deny."

Bjerknes may have enjoyed the discovery of whirling ether winds that Sagnac himself compared to Bjerknes' atmospheric eddies. The rest of his letter shows some familiarity with Sagnac's principle of the effect of motion:

"We would be very curious to know, Mr. Wiener and I, if in your experiment you still measure the velocity of light in vacuum even if the light propagates in water. A positive answer to this question would provide a brilliant confirmation of your theory, and would certainly be much unexpected for most physicists."

Indeed, this variant of Sagnac's experiment is comparable to Harress' experiment for which we saw that Sagnac's principle and relativity theory both give the same phase shift as in a vacuum.[127]

Sagnac's contemporaries recognized and rewarded Sagnac's merits in various manners. They appointed him to increasingly high positions at the Sorbonne: *agrégé préparateur* in 1893–1900, *chargé de cours* in 1904–1912, *professeur adjoint* in 1912–1920, and *maître de conférences* in 1920–1926. He won several academic prizes: the Jérôme Ponti prize in 1904 to finance his optical researches, the Henry Wilde prize in 1917 for his war work, the coveted Pierson–Perrin prize in 1919, and the La Caze grand prize of physics in 1920. In the same year, he celebrated his election to the Conseil des observatoires du Mont-Blanc. For all that, he never obtained a full professorship at the Sorbonne, and he failed in his repeated candidatures to the Académie des sciences (on Violle's seat and on Bouty's seat in 1923, and on Berthelot's seat in 1927). Not too much can be inferred from this failure as his brilliant contemporary Langevin, for instance, did not enter the Académie until 1934.[128]

Sagnac's few extant letters to friends and family, and the testimonies of his brother and of his colleagues convey the picture of a man modest and yet sure of himself, also gentle, attentive, and generous: *un excellent cœur*, summarized Henri Bénard. His occasional displays of aggressiveness, during his polemic with Italians X-ray physicists or during the Einstein event at the Collège de France, probably did not reflect his true temperament. They are easily explained by integrity in defending a lifelong scientific passion. Since his student years, Sagnac believed to have discovered a fundamentally new approach to optics that captured the essence of the propagation of light and offered better guidance in the laboratory than the more complicated theories of Lorentz and others. In spite of his fragile health (so fragile that Lenard believed him to be dead at some point),[129] he spent an enormous amount of time and energy experimenting on light and on radiations he hoped to be similar to light. He thus opened a new subfield of X-rays physics; he explained fine features of the propagation of light such as the Gouy phase inversion; he developed a superior technique of interferometry; and he discovered the effect that now bears his name. Naturally he attributed these successes to his theoretical vision and to his experimental method, and he strongly defended both of them against perceived threats. This great coherence of Sagnac's endeavors explains both his failure to catch the train of more modern theories and his success in discovering new entities, processes, and effects.[130]

Sagnac (Fig. 33) died on 26 February 1928 in Bellevue, aged fifty-nine, "suddenly" according to his brother, "after a long illness" according to Bénard. He lived long enough to see relativity theory and quantum theory shatter the classical-optical worldview that sustained his entire scientific life. A certain effect survived him. A lot more of his life is worth remembering.

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[127] Bjerknes to Sagnac, 1 Feb 1914, Archives nationales.

[128] For Sagnac's Sorbonne career, cf. Maurain and Pacaud [200]. On the prizes, cf. the reports in the *Comptes rendus* and the Sagnac folder at the archive of the Académie des sciences. More biographical information is in Sagnac [20] and in Dostrovsky [201].

[129] Cf. Lenard to Sagnac, 19 Dec 1905, Archives nationales.

[130] Bénard [202, p. 46S]; Lenard to Sagnac, 19 Dec 1905, Archives nationales.

Fig. 33. Georges Sagnac at various ages. First picture from ENS school picture [3]; others from the Archives nationales (there being no name written on these pictures, their identity is not quite certain).

who kindly provided me with documents and information he had on Sagnac, to Jean-Michel Raimond, who helped me understand a few theoretical and experimental points, to Jacques Vigué, who shared his expert opinion on some peculiarities of Sagnac's interferometry, to Regino Martinez-Chavanz, who lent me a copy of his valuable dissertation on the Sagnac effect, and to Sabine Clabecq for her help at the archive of the Académie des sciences. All pictures in this article are reproduced with kind permission of the Archives nationales, Paris, France.

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