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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

[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].