

MAX-PLANCK-INSTITUT FÜR WISSENSCHAFTSGESCHICHTE

Max Planck Institute for the History of Science

2004

PREPRINT 265

Michel Janssen and John Stachel

**The Optics and Electrodynamics
of Moving Bodies**

THE OPTICS AND ELECTRODYNAMICS OF MOVING BODIES*

Michel Janssen and John Stachel

INTRODUCTORY SURVEY

The title of this paper will immediately remind most modern readers of “On the Electrodynamics of Moving Bodies,” the 1905 paper in which Albert Einstein (1879–1955) first introduced the special theory of relativity. The developments in 19th century ether theory to be discussed in this chapter were essential to the development of Einstein’s theory, a circumstance that has almost inevitably shaped our presentation to a certain extent. It is our aim, however, to discuss these developments in their own right. Our focus will be on a specific issue in the optics and electrodynamics of the 19th century. For comprehensive discussion of these important fields in 19th century physics, we refer to other articles in this volume.

What will concern us here is the question of the state of motion of the ether, the hypothetical medium thought to carry light waves, or more generally, as one came to believe in the second half of the century, electromagnetic fields. Is the ether immobile and completely undisturbed by matter moving through it, or does moving matter drag along—in whole or in part—the ether in its vicinity and/or in its interior? The phenomenon of stellar aberration strongly suggested the former alternative; or rather a variant of it in which most of the ether is immobile while transparent matter carries along some. Augustin Jean Fresnel (1788–1827) introduced this variant in 1818. Although the physical mechanism underlying the ether drag effect remained unclear, it came to be generally accepted that in order to render the earth’s presumed motion through the immobile ether invisible one has to assume that all transparent matter drags along any light propagating through it with a fraction of its own velocity. This fraction, which depends only on the index of refraction, is called the Fresnel (dragging) coefficient. The effect ensured that, within the limits of accuracy then attainable, terrestrial optics follows the same laws that would hold in a frame of reference in which the (bulk of the) ether is at rest, and thus explained the consistently negative results of so-called first-order optical ether drift experiments (i.e., experiments aimed at detecting the earth’s presumed motion through the ether that are accurate to first order in the aberration constant, the ratio of the mean velocity of the earth in its orbit around the sun and the velocity of light). The absence of such first-order effects was confirmed in numerous experiments, and proofs of increasing generality were put forward to show that these results could all be accounted for if only the Fresnel coefficient were added to the hypothesis of an immobile ether. Despite the success of Fresnel’s formula, however, his interpretation in terms of partial ether drag remained problematic, and many authors embracing the former explicitly distanced themselves from the latter. The need to invoke the Fresnel coefficient to explain the phenomena of dispersion and double refraction was especially troublesome in this regard. Since the index of refraction depends on the frequency of the refracted light, transparent matter, on Fresnel’s interpretation, would have to drag along a different amount of ether for every different color. Likewise, it would have to drag along different amounts for the ordinary and the extraordinary rays in double refraction.

* This paper will be published in Italian in the encyclopedic series, *Storia della scienza*. It is printed here by kind permission of Prof. Sandro Petruccioli at the Istituto della Enciclopedia Italiana in Rome. The English version will appear in John Stachel’s forthcoming book, *Going Critical* (Dordrecht: Kluwer).

There was, of course, a simple alternative explanation of these experimental results, in which there would seem to be no need for the peculiar partial dragging effect in transparent matter. If all ether inside matter were fully dragged along by it, the ether at the surface of the earth would be at rest with respect to the earth, which would explain automatically why no ether drift was ever detected. In and of itself, the concept of a dragged along ether was, moreover, much more natural than that of an immobile ether. Polarization phenomena had made it clear that light waves are transverse rather than longitudinal, which, in turn, implied that the ether, if it could be modelled as a mechanical system at all, could not be a gas or a fluid, but had to be an elastic solid which had to have a high degree of rigidity to explain the high speed of light. Most theoreticians working on mechanical models of this elastic solid apparently did not worry about the problem, but they would probably have conceded, had they stopped to think about it, that it was rather implausible that the earth and all other matter in the universe would move through a rock solid medium without in the least disturbing it. It was mainly this implausibility that prompted George Gabriel Stokes (1819–1903) in the 1840s to develop an ether model in which the earth drags along the ether. Stellar aberration continued to provide the strongest argument against such a model, and much of Stokes' effort went into trying to show that aberration could be accounted for on the basis of a dragged-along as well as on the basis of an immobile ether.

In 1851 Hippolyte Fizeau (1819–1896) succeeded in demonstrating directly the Fresnel coefficient in moving water. In earlier experiments, the coefficient had always been invoked to compensate some other effect of ether drift that one would expect to observe but that proved to be undetectable. An important advantage of the hypothesis of a dragged-along ether had been that the negative results of ether drift experiments could be accounted for without introducing the Fresnel coefficient. In order to account for the result of the Fizeau experiment, it now had to be introduced after all. So, Fizeau's result lent strong support to the hypothesis of an immobile ether conjoined with Fresnel's coefficient.

In 1881, however, Albert Abraham Michelson (1852–1931) performed a second-order ether drift experiment the negative result of which, he claimed, refuted Fresnel's hypothesis of an immobile ether and strongly supported Stokes' hypothesis of a dragged-along ether. This conclusion was overhasty, if for no other reason than that the experimental error was about half the size of the effect expected on the basis of the immobile ether hypothesis. In 1886, as a preliminary to repeating the 1881 experiment, Michelson, together with his new collaborator Edward Williams Morley (1838–1923), repeated the Fizeau experiment with improved accuracy. The experiment confirmed Fresnel's prediction. Michelson and Morley now concluded that Fresnel had to be right and Stokes had to be wrong. However, the famous Michelson-Morley experiment of 1887 gave the same negative result as Michelson's first attempt in 1881 with reduced experimental error. They were at a loss. Both Fresnel's and Stokes' hypotheses appeared to be untenable.

Meanwhile, Stokes' hypothesis had become problematic for other reasons. First, in an important 1886 review article on ether drift experiments, Hendrik Antoon Lorentz (1853–1928) argued that Stokes had made contradictory assumptions about the behavior of the ether in order to explain aberration. Second, it turned out to be extremely difficult to explain all optical phenomena by incorporating any sort of ether drag into Maxwell's theory of electrodynamics. In his article, discussing optics independently of electrodynamics, Lorentz had argued that all experiments could be accounted for on the basis of a theory somewhere in between Fresnel's and Stokes', a theory that contains the Fresnel coefficient and in which all moving matter partially drags along the ether. Lorentz's highly successful elaboration of Maxwell's theory in the 1890s,

however, was based on a strict separation of ether and matter that left no room for any ether drag, not even for the Fresnel coefficient. One of the early successes of Lorentz's theory, however, was that in 1892 he was able to derive the Fresnel coefficient from his theory, reinterpreting it as due to an interaction between ether and matter that required no ether drag whatsoever.

In 1895 Lorentz produced a more general derivation of the Fresnel coefficient with the help of an auxiliary quantity called 'local time.' Formally, this derivation is very close to the derivation of the dragging coefficient in special relativity based on the relativistic addition theorem for relative velocities. 'Local time' was one of the auxiliary variables used in Lorentz's so-called 'theorem of corresponding states.' In 1895, he derived a first-order version of this theorem and used it to give a very general explanation of the null results of a broad class of optical first-order ether drift experiments. Lorentz's theorem connects pairs of electromagnetic field configurations, one in a system at rest in the ether and one in a system in uniform motion through the ether, and says that, if one member of the pair is allowed by the laws of electrodynamics, so is the other. The theorem works as follows. The mathematical description of the configuration in the moving system in terms of various auxiliary quantities introduced by Lorentz (such as 'local time' instead of real time) is the same as the description of its corresponding state in the system at rest in terms of the real quantities. The auxiliary quantities for the moving system are chosen in such a way that, as long as second-order quantities are neglected, they satisfy the same laws as the real quantities in the system at rest. Lorentz showed that two field configurations related to one another by the theorem of corresponding states agree with one another in many of their observable properties, in particular, that they give rise to identical patterns of brightness and darkness. Ether drift experiments, which eventually boil down to the observation of such patterns, as do most experiments in optics, will therefore give negative results.

To arrive at this conclusion, one more condition needs to be satisfied, namely that material systems—such as the configuration of light sources, lenses, mirrors, etc. in some optical experiment—producing some field configuration at rest in the ether will, when set in motion, produce the corresponding state of that field configuration in the system that is moving with it. In the context of the first-order version of Lorentz's theorem and the experiments Lorentz wanted to apply the theorem to, the condition will hold as long as the Galilean principle of relativity of Newtonian mechanics holds for macroscopic material systems, as Lorentz assumed it would.

With the exact version of the theorem of corresponding states, which Lorentz first derived in 1899, the situation became more complicated. The pattern of brightness and darkness given by a field configuration in a system in motion through the ether is shortened ever so slightly in the direction of motion when compared to the pattern given by that configuration's corresponding state in a system at rest. Hence, Lorentz's theory will only predict negative results for second-order ether drift experiments the way it did for first-order ones if—contrary to what one would expect on the basis of the Galilean principle of relativity—macroscopic material systems undergo the same contraction that the exact theorem of corresponding states says field configurations undergo.

This contraction hypothesis had, in fact, already been proposed—by George Francis FitzGerald (1851–1901) in 1889 and by Lorentz in 1892—for the specific purpose of reconciling the hypothesis of an immobile ether with the negative result of the Michelson-Morley experiment. Although the contraction hypothesis seemed dubious at first, it had come to be widely accepted in the course of the 1890s that any theory based on an immobile ether would have to incorporate it, just as it had incorporated the Fresnel coefficient, to be compatible with the absence of any evidence of motion with respect to the ether.

When Lorentz began to consider microscopically the matter configurations giving rise to electromagnetic field configurations related to one another via the theorem of corresponding states, he found that he had to introduce more unexpected assumptions if he wanted his theory to predict negative results in a broad class of second-order ether drift experiments. He had to assume that forces, masses, and the periods of processes in a moving system, all depend on the system's velocity with respect to the ether. The absolute velocity dependence in all these cases is formally just the same as the relative velocity dependence required by special relativity. For the case of mass, Walter Kaufmann (1871–1947) and others put this velocity dependence to the test in experiments on high-speed electrons from β -radiation. The first of these experiments were performed shortly after the turn of the century and they continued well into the 1910s before a consensus developed that the best experimental results agree with the predictions of Lorentz and Einstein.

The origin of the complications mentioned above, needed to adjust Lorentz's theory to account for all experimental results, is that the theory combines Newtonian mechanics, which is invariant under Galilean transformations, with his form of Maxwellian electrodynamics, which is inherently invariant under Lorentz transformations. The great breakthrough of special relativity was the recognition that the invariance of dynamical physical laws under Lorentz transformations, which in Lorentz's theory is nothing but a mathematical peculiarity of the laws of electrodynamics, reflects a new kinematical space-time structure, just as invariance under Galilean transformations reflects the old space-time structure inherent in Newtonian theory. This meant, among other things, that Galilei-invariant Newtonian mechanics had to be replaced by a new Lorentz-invariant mechanics. The absolute velocity dependence of lengths, periods, masses, and forces, which Lorentz introduced as exceptions to the rules of Newtonian mechanics, are simply the norm for relative velocities in this new, relativistic mechanics. (For a comprehensive discussion of the optical phenomena discussed in this chapter from a relativistic point of view, see, for instance, Sommerfeld 1965, Ch. II).

STELLAR ABERRATION AND THE IMMOBILE ETHER

The phenomenon of stellar aberration was discovered in the 1720s by James Bradley (1692–1762), who had set out to find stellar parallax. The two phenomena are illustrated in Fig. 1, parallax on the left, aberration on the right.

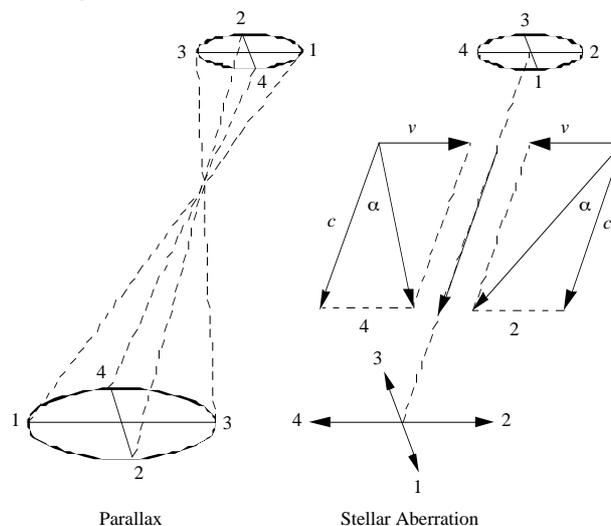


Figure 1: Parallax and aberration

Consider parallax first. Because of the change in position of the earth over the course of a year, the direction in which a star is observed changes in the manner indicated by the numbers 1 through 4 labeling points on the earth's orbit and the corresponding points of the apparent position of the star. The parallax effect is proportional to the ratio of the diameter of the earth's orbit to its distance from the star. Even for the closest stars, this ratio is so small that no such effect was observed until the late 1830s. However, Bradley did observe another systematic variation in the apparent position of stars, which, he realized, reflects changes in the *velocity* rather than in the *position* of the earth over the course of a year. This aberration effect is illustrated in the drawing on the right. The orbit of the earth has been shrunk to a point to indicate that the star is so far away that its parallax is unobservable. The arrows labeled 1 through 4 represent the earth's velocity at the points of the earth's orbit labeled 1 through 4 in the drawing on the left. The directions in which the star is observed are likewise labeled 1 through 4. Comparing the annual variation in the apparent direction of the star on the left and on the right, one sees immediately that the variation on the right can not be due to parallax. The variation on the right lags behind the variation one would expect on the basis of parallax by roughly three months. The phenomenon can readily be understood on the basis of the then-prevailing Newtonian ballistic theory of light. To this day it is, in fact, routinely explained with the help of an analogy this suggests. For someone walking down the street in the rain on a wind-free day, the apparent direction in which the rain falls is given by the vector sum of the rain's velocity minus his or her own velocity (both velocities taken with respect to the earth). Just as a person walking in the rain must tilt his umbrella to keep dry even when the rain is coming straight down, an astronomer aiming her telescope at a star will have to tilt the telescope ever so slightly to see the light coming from a star even if the star is directly overhead. The relevant vector diagram is shown in Fig. 1 for the points 2 and 4 (the angle α is called the aberration angle; the vectors labeled v are *minus* the velocities of the earth at the corresponding points 4 and 2). The observed effect is proportional to the ratio of the velocity of the earth in its orbit around the sun, to c , the velocity of light. This ratio v/c , called the aberration constant, is of the order of 10^{-4} . The effect is small, but still considerably larger than that of parallax.

Bradley's observations of stellar aberration provided the first direct astronomical evidence for Copernicus' heliostatic model of the solar system. More importantly, it allowed a rough determination of the velocity of light. There had been only one other phenomenon, the explanation of which involved a finite and fixed velocity of light. In 1670 Ole R mer (1644–1710) had invoked this notion to explain the observed variations in the period between two successive eclipses of Jupiter's moon Io. The period appears smallest when the earth happens to be moving directly toward Jupiter and largest when the earth is moving directly away from it. These variations could be explained by taking into account the time it takes light to get from Jupiter to earth. The velocity of light calculated on the basis of observations of stellar aberration was of the same order of magnitude as the velocity of light calculated on the basis of observations of eclipses of Io. This supported the idea that there is such a thing as *the* velocity of light, an idea that is very natural in a wave theory, but not in a ballistic theory where light particles could conceivably be emitted with a whole range of velocities depending, for instance, on the mass of the emitting body, and even if constant should be fixed relative to the source.

With the recrudescence of the wave theory of light at the beginning of the 19th century, the phenomenon of stellar aberration became important in yet another way. The simple explanation of aberration in the ballistic theory can be adapted to the wave theory if one can still represent the velocity of a star's light with respect to a terrestrial observer by the simple vector diagram shown

in Fig. 1. In a wave-theoretic setting, the velocities added in this diagram must be interpreted as velocities with respect to the luminiferous ether, the medium in which the light waves were thought to propagate. Any motion of the ether lying between the star and the terrestrial observer would affect light waves travelling between them. So, the motion of the light relative to the earth would be more complicated and the simple explanation of stellar aberration borrowed from the ballistic theory would fail. In other words, stellar aberration seemed to call for a completely stationary or, as we prefer to call it, immobile ether. As Thomas Young (1773–1829), who together with Fresnel revived the wave theory in the early 19th century, put it in an oft-quoted passage: “Upon considering the phenomena of the aberration of the stars I am disposed to believe, that the luminiferous ether pervades the substance of all material bodies with little or no resistance, as freely perhaps as the wind passes through a grove of trees” (Young 1804, pp. 12–13).

Although the ray analysis implicitly used in the argument above gives the right answer, a satisfactory treatment of aberration in the context of the wave theory should be based on Huygens’ principle. Fortunately, on the assumption of an immobile ether, such an analysis is very simple. Consider the plane wave front coming from a star directly overhead (the horizontal line through P in the figure below).

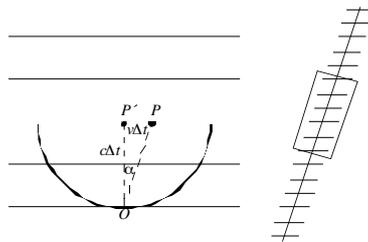


Figure 2: Aberration and Huygens’ principle

Suppose the earth is moving through the immobile ether with a velocity \mathbf{v} parallel to the wave front. In other words, the ether is moving with respect to the earth with velocity $-\mathbf{v}$ as indicated in the figure. Consider an arbitrary point P on a wave front at time t_0 . According to Huygens’ principle P will be the source of a secondary spherical wave, and the envelope of the secondary waves emitted by all points on the wave front will constitute the new wave front at time $t_0 + \Delta t$. Because of the motion of the ether, however, P will not be the center of the secondary wave for an observer on earth at time $t_0 + \Delta t$; rather the point P' a distance $v\Delta t$ to the left of P will be. A similar construction can be carried out for all points on the wave front through P . The resultant envelope forming the wave front at $t_0 + \Delta t$ will thus be a horizontal line through O . Notice, however, that for an observer on earth the horizontal wave front moves in the direction OP rather than in the direction of the normal to the wave front, the direction OP' . The angle between OP and OP' is, of course, just the aberration angle that we found above:

$$\operatorname{tg} \alpha = \frac{PP'}{OP'} = \frac{v}{c}.$$

On the right in Fig. 2, a telescope is shown aimed at a star directly overhead. Notice that the wave fronts remain horizontal, even though the telescope has to be tilted by the aberration angle α in order to allow the light to go through it.

Once the refraction of light in the lenses of a telescope is taken into account, the situation turns out to be more complicated, but we shall postpone discussion of this until the next section. Here we focus on what might appear to be another complication.

At first sight, it looks as if just assuming the ether to be immobile is not enough to adapt the ballistic theory's explanation of stellar aberration to the wave theory. One might think that one would need the stronger assumption that the immobile ether is at rest with respect to the "fixed" stars. With the help of Fig. 3, we shall explain why this is not the case.

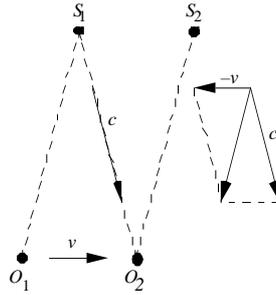


Figure 3: Aberration with both source and observer moving through the ether

The figure shows light travelling from a source S to an observer O moving through the ether with velocity \mathbf{v} . Suppose the positions of S and O at the time the light is emitted are S_1 and O_1 , respectively. The light that reaches the observer is the light sent in the direction S_1O_2 , where O_1O_2 is the distance the observer travels during the time it takes the light to reach the observer. For the observer, due to the aberration effect (see the vector diagram in the figure), light coming from the direction S_1 will appear to be coming from the direction S_2 . If the source is at rest in the ether, its apparent position (S_2) will thus be different from its actual position (S_1). If, however, the source itself is moving through the ether with the same velocity as the observer, the apparent position will actually coincide with the actual position (both being S_2). More generally, any velocity component source and observer have in common will not result in a shift of the source's apparent position.

It is for two reasons that we draw attention to this. First, it shows that it is sufficient to assume that the ether is immobile, and that there is no need for the stronger assumption that it is at rest with respect to the "fixed" stars.

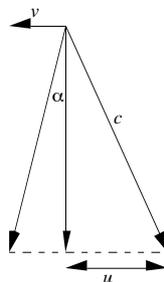


Figure 4: Aberration with the star moving through the ether

Fig. 4 shows the vector diagram illustrating aberration for a star directly overhead in case the earth is moving with velocity \mathbf{v} with respect to the star and both the star and the earth are in addition moving with velocity \mathbf{u} with respect to the ether. The aberration angle α is not exactly the same as before, but the difference is of the order $v u^2/c^3$, which is completely negligible. The second point we want to make with the help of Fig. 3 is that the actual and apparent positions of a fixed terrestrial source always coincide, even though both source and observer are assumed to be moving through the immobile ether.

The absence of any observable effects of aberration with terrestrial sources is, of course, even more readily explained on the basis of the wave theory if it is assumed that the earth drags along the ether in its vicinity, so that in all terrestrial experiments source and observer are in fact at rest with respect to the ether. The problem is that the assumption of a dragged-along ether seems to be incompatible with the observed effects of stellar aberration. Suppose the earth is accompanied in its motion by an 'ether atmosphere.' The moment starlight enters this ether atmosphere, it will propagate through the atmosphere, partaking in the earth's motion and thereby in the motion of all telescopes, with which terrestrial observers are looking at the star. Hence there is no need to adjust the direction of the telescope to correct for the earth's velocity.

Nonetheless, in 1845 Stokes attempted to account for stellar aberration on the basis of a theory, in which the earth drags along the ether in its vicinity. The attempt involves careful consideration of how the wave fronts of stellar light change direction upon entering the earth's ether atmosphere. On Stokes' account, rather than an apparent motion, the light ray really is "refracted" during its passage through the ether. Stokes was interested in such an alternative account of aberration because he felt the hypothesis of an immobile ether to be highly implausible. Young and Fresnel had originally thought of light waves in analogy with sound waves, and, accordingly, of the ether as a fluid. However, on the assumption that light, like sound, consists of longitudinal waves the wave theory had been no match for the particle theory in accounting for the polarization phenomena studied by Étienne Louis Malus (1775–1812) in 1808 and David Brewster (1781–1868) in 1815. In 1817/8, Young and Fresnel realized that polarization could be explained easily in the wave theory by assuming that light consists of transverse rather longitudinal waves. In order to allow such transverse waves, the ether needed to have enough rigidity to supply the forces to oppose the distortions produced by the waves. In other words, the ether, if a mechanical system, could not be a fluid; it had to be a solid. This new picture of the ether is hard to reconcile with the hypothesis of an immobile ether undisturbed by the motion of matter. It was much more natural to assume that matter drags along the ether. Apparently, Augustin-Louis Cauchy (1789–1857) was the first seriously to suggest this alternative in 1831. It was Stokes, however, who became the champion of this view. He put forward a model of the ether that has been described as the "Silly Putty" model (Schaffner 1972, pp. 66–67). Stokes' ether behaves as a rigid solid for the high-frequency oscillations constituting light and as a fluid for the relatively slow motion of celestial bodies travelling through it. The latter motion, however, no longer leaves the ether undisturbed. At the earth's surface, the ether will be at rest with respect to it. The price that Stokes had to pay for his more realistic model of the ether was therefore a more complicated explanation of aberration. He had to assume the ether to be an incompressible fluid in irrotational motion for the slow motion of the earth, in order to show quantitatively that the resultant bending of the wave fronts of starlight, as they pass from the undisturbed ether far from the earth to the dragged-along ether near the surface of the earth, produces the observed aberration α of starlight.

THE FRESNEL COEFFICIENT: THE FORMULA AND ITS PHYSICAL INTERPRETATION

In our discussion of aberration in the preceding section, we did not address the problem of the refraction of light in bodies moving through the ether, such as prisms and the lenses of our telescopes. When refraction is taken into account, the explanation of the observed stellar aberration on the basis of the hypothesis of an immobile ether gets somewhat more complicated, even though there is no question that the phenomenon still strongly support the basic idea of an immobile ether.

The problem of refraction in moving bodies became an issue in the wave theory of light because of an experiment performed in 1810 by François Arago (1786–1853) in the context of the particle theory. He wanted to determine whether light particles entering a prism would be refracted differently depending on their velocity with respect to the prism. To this end, he considered the refraction of light from the same star over the course of a year. Changes in the velocity of the earth with respect to the star would presumably produce changes in the relative velocity of the earth and the light particles emitted by the star. Arago observed no such effect on the refraction of the star’s light. Refraction always followed Snell’s law, $\sin i = n \sin r$ (with i the angle of incidence, r the angle of refraction, and n the index of refraction for the average wavelength of starlight), as long as the angle i is determined on the basis of the apparent position of the star and *not* on the basis of the star’s position after correction for the effect of stellar aberration. The rather implausible explanation that Arago was eventually forced to adopt is that stars emit light particles with a wide range of velocities, but that, to be visible to an observer, the relative velocity of the light particles and the observer has to lie in a narrow interval. That would imply that the light particles whose refraction Arago had been studying all had essentially the same velocity with respect to the prism, independently of the relative motion of the earth and the star emitting those particles. Arago asked Fresnel whether the wave theory could account for these observations more simply. In a famous letter to Arago in 1818, Fresnel introduced an important modification of the immobile ether hypothesis to account for Arago’s result, a modification that became the focus of many investigations, both theoretical and experimental, for the remainder of the century and beyond.

To explain Fresnel’s modification, we return to the phenomenon of stellar aberration. Our discussion of aberration would have been perfectly adequate if the positions of stars were determined with the sort of primitive telescope drawn on the left in Fig. 5.

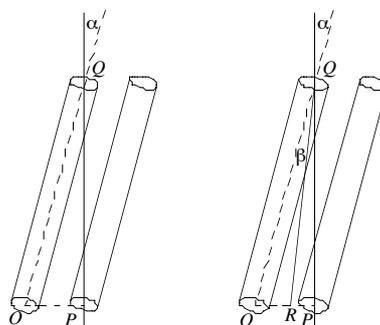


Figure 5: Aberration, refraction, and the Fresnel coefficient (ray analysis)

This “telescope” is just a long hollow cylinder that we aim at the star. From the geometry of the figure, one easily recovers the equation

$$\operatorname{tg} \alpha = \frac{OP}{PQ} = \frac{v}{c}$$

for the aberration angle of a star directly overhead. The drawing on the right shows the same primitive telescope, but now with a glass cylinder fitted inside with flat surfaces at both ends. Would we measure the same aberration angle with this device? As we will see later, observation indicates that we would. The question is how the wave theory can account for that result. As in our discussion of aberration in the preceding section, we will discuss the issue in terms of light rays first and then show that an analysis on the basis of Huygens’ principle leads to the same result.

If no further assumptions were added to the hypothesis of an immobile ether, the aberration angle measured with the glass-filled cylinder would be different from the aberration angle measured with the empty cylinder. Because of refraction upon entering the glass cylinder at Q , the light would follow the path QR . Observation indicates that the path will be QP , just as on the left. Hence, we must assume that, upon entering the glass, light picks up some fraction f of the velocity v of the glass that ensures the path remains QP . From the geometry of the figure, we can determine how large this fraction must be. First note that the angles α and β are much smaller than in the figure, so small, in fact, that sines and tangents can be used interchangeably. Hence, to a good approximation, Snell’s law can be written as $\operatorname{tg} \alpha = n \operatorname{tg} \beta$. Because of the smallness of α and β , the angle ORQ can, moreover, be considered a right angle in evaluating $\operatorname{tg} \beta$. Hence, to a good approximation, $\operatorname{tg} \beta = OR/RQ$. Using that $OP = v \Delta t$, $RP = f v \Delta t$, and $QR = (c/n) \Delta t$ —where Δt is the time it takes for the telescope to get from O to P and the light to get from Q to P —we find that

$$\begin{aligned} \operatorname{tg} \alpha &\approx n \operatorname{tg} \beta \\ &\approx n \frac{OR}{RQ} \\ &= n \frac{OP - RP}{RQ} \\ &= n \frac{v - fv}{c/n} \\ &= n^2 (1 - f) \frac{v}{c}. \end{aligned}$$

It follows that the aberration angle with the glass cylinder will be the same as without it if and only if glass drags along the light travelling through it with a fraction

$$f = 1 - \frac{1}{n^2}$$

of its own velocity. This fraction is called the Fresnel (dragging) coefficient. It can be shown that the result holds not only for stars directly overhead, but for stars in any direction.

The situation shown on the right in Fig. 5 is a special case of the phenomenon Arago was studying, viz. the refraction of light striking a moving surface. It thus illustrates how the Fresnel coefficient explains Arago’s results on the basis of a wave theory that has the earth moving through an immobile ether. From the point of view of a terrestrial observer, the light in the situation on

the right in Fig. 5 strikes the glass surface at the top of our primitive telescope perpendicularly. So, if the usual law of refraction holds from the terrestrial observer's point of view, the light should not be refracted at all; it should continue to move in the same direction. From the point of view of someone at rest in the ether—the point of view from which Fig. 5 is drawn—this is the direction QP . As we have just seen, the Fresnel coefficient ensures that this is indeed what happens. Without this effect, the light would travel in the direction QR . In that case, the light would be refracted according to Snell's law from the point of view of someone at rest in the ether, but *not* from the point of view of the terrestrial observer. In other words, *the Fresnel coefficient ensures that the refraction of light in a moving body follows Snell's law from the point of view of an observer moving with the body.*

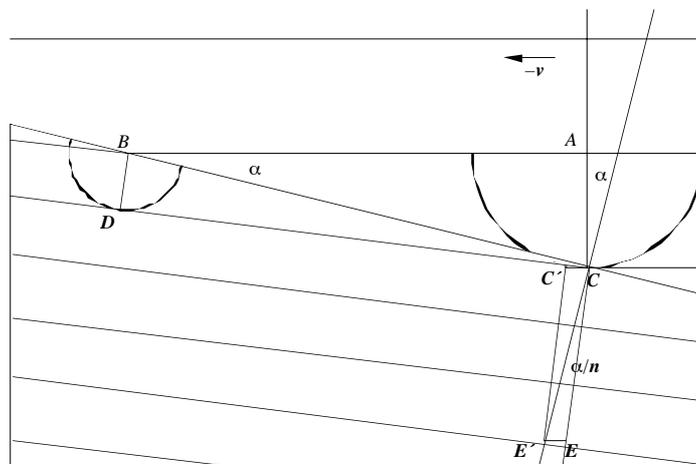


Figure 6: Aberration, refraction, and the Fresnel coefficient (analysis on the basis of Huygens' principle)

The analysis given above in terms of light rays can also be given in terms of wave fronts (see Fig. 6). A wave front strikes a glass surface at a small angle α . First consider the case that the glass is at rest with respect to the ether (for the time being, ignore the arrow marked $-v$ in the figure as well as the points C' and E'). In that case, the figure simply illustrates the standard explanation of refraction on the basis of Huygens' principle. Consider the points A and B on the wave front striking the glass. Both points will be the source of secondary spherical waves. After some time Δt , the secondary wave emitted by A is represented by a half circle around A with radius $AC = c\Delta t$, while the secondary wave emitted by B is represented by a half circle around B with radius $BD = (c/n)\Delta t$. The resultant envelope after Δt will be the wave front CD . From the geometry of the figure one easily recovers Snell's law of refraction, $\sin i = n \sin r$, where i is equal to $\angle ABC$ and r is equal to $\angle BCD$. For small α it follows that $\angle BCD = \alpha/n$.

We now turn to the case when the ether is moving with respect to the glass with velocity $-v$ (cf. Fig. 2). Let $\alpha \approx \text{tg } \alpha = v/c$ be the aberration angle. Hence, from the point of view of an observer moving with the glass, the wave front strikes the glass perpendicularly. If Snell's law of refraction holds for an observer moving with the glass, the wave front must continue to move in that direction for this observer, i.e. in the direction CE' (which differs from the direction CE normal to the wave fronts). To assure this, we assume that the glass drags along the ether inside of it with a fraction f of its velocity v with respect to the ether. The ether in turn will drag along the light waves. Notice that it would suffice to assume that the light waves are dragged along, but the

possibility that the light waves be dragged without the ether carrying them being dragged does not seem to have been explored until the end of the century. If we assume that the glass drags along the ether with a fraction f of its velocity, the velocity of the ether inside the glass with respect to the glass is not $-\mathbf{v}$ but $-(1-f)\mathbf{v}$. Consider the secondary wave originating from point C . In the time Δt it takes for this wave front to become a half circle with radius $CE = C'E' = (c/n)\Delta t$, its center will be carried along by the ether drift over a distance $CC' = EE' = (1-f)v\Delta t$. Examining the triangle $E'C'C$, one easily sees that the fraction f has to be the Fresnel coefficient. The sine rule tells us that

$$\sin \angle C'CE' = \frac{\sin \angle C'E'C}{C'C}.$$

Upon inspection of the figure, one sees that $\angle C'CE' = \frac{\pi}{2} - \alpha$ (note that $\angle BCC' = \angle ABC$) and that $\angle C'E'C = \alpha/n$. Because of the smallness of α ,

$$\sin \left(\frac{\pi}{2} - \alpha \right) = \cos \alpha \approx 1 \text{ and } \sin \frac{\alpha}{n} \approx \frac{\alpha}{n}.$$

Hence, the relation above turns into:

$$\frac{1}{(c/n)\Delta t} = \frac{\alpha/n}{(1-f)v\Delta t},$$

which can be rewritten as:

$$1 - f = \frac{ac}{vn^2}.$$

Since $\alpha \approx v/c$, it follows that f is indeed the Fresnel coefficient $f = 1 - \frac{1}{n^2}$. To reiterate, this dragging effect guarantees that the apparent refraction of light in moving bodies from the point of view of an observer moving with the body follows Snell's law.

Figs. 5 and 6, of course, only illustrates this result for a very special case, namely for light striking the moving body perpendicularly from the point of view of the co-moving observer. However, it can be shown, using either Huygens' construction or Fermat's principle of least time, that it holds for any angle of incidence, as long as quantities of order v^2/c^2 and smaller are neglected. This then both accounts for Arago's observations and completes the account of aberration on the basis of the hypothesis of an immobile ether. Return to the diagram on the left in Fig. 5. Given that we can apply the usual laws of refraction as if the telescope is at rest in the ether and the position of the star is in the direction OQ , it is clear that if lenses are added at both ends of our primitive telescope, it will still be aimed at the star when tilted at the angle α . These considerations concerning refraction also apply, of course, to light coming from terrestrial sources. Without the Fresnel coefficient, we would expect deviations of order v/c from Snell's law in laboratory experiments on refraction, which would in principle enable us to measure the velocity of the earth with respect to the ether. With the Fresnel coefficient there are no such deviations, and the motion is undetectable.

In accordance with this prediction, all attempts to detect the motion of the earth with respect to the ether by refraction experiments had negative results. Such experiments were carried out, for

instance, by Lorenzo Respighi (1824–1889) and by Martinus Hoek (1834–1873) in the 1860s. George Biddell Airy (1801–1892), in an experiment first suggested by Rudjer Josep Boskovic (1711–1787) in 1776 in the context of the particle theory, confirmed that filling the tube of a telescope with water does not affect the measured angle of aberration. Fresnel had explicitly noted this consequence of the dragging coefficient in his 1818 letter to Arago, and our introduction of the Fresnel coefficient was inspired by this celebrated experiment.

What all such explanations of these experimental results have in common is that the Fresnel coefficient compensates some otherwise detectable effect of the earth's motion through the presumed immobile ether, thus nullifying the effect. There is one important exception to this rule. In 1851, shortly after he and Jean Foucault (1819–1868) had shown that it is possible to determine the velocity of light in the laboratory (rather than as previously from astronomical observations), Fizeau devised a method for putting Fresnel's predicted value for the velocity of light in moving media directly to the test. The experiment is illustrated in Fig. 7.

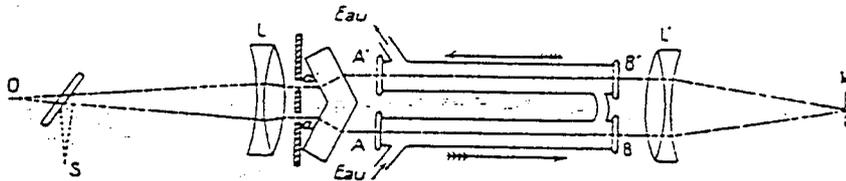


Figure 7: The Fizeau Experiment

Fizeau examined the effect of a water flow ($ABB'A'$) on the interference pattern produced by light travelling with the flow (AB) and counter to the flow ($A'B'$). He observed a shift in the interference pattern of roughly the size one would expect on the basis of the Fresnel coefficient for water. Fizeau's result strongly supported the theory of an immobile ether as emended by the Fresnel coefficient. To account for it, Stokes' rival theory of a dragged-along ether also had to incorporate the Fresnel coefficient, whereas one of its chief attractions had been that the coefficient was not needed to explain the results of terrestrial refraction experiments. Another way to turn Fizeau's result into an objection to Stokes' theory can be found in Einstein's writings (see, e.g., Einstein 1915, p. 704): according to the Fresnel coefficient a non-refractive medium (a medium for which $n = 1$), such as the earth's atmosphere, does not drag along the ether.

Despite the undeniable success of the Fresnel coefficient in accounting for the observed phenomena, the physical mechanism underlying the effect was unclear. When Fresnel introduced his coefficient, he also proposed a physical mechanism, but the mechanism did not enjoy the undisputed success of the formula. Following Young, Fresnel assumed that the ether density in a transparent medium was proportional to the square of the medium's index of refraction. For any classical wave, the speed of propagation is given by $\sqrt{T/\rho}$, where T is the tension and ρ is the density. If the tension is assumed to be constant, as Fresnel did, the velocity c/n is proportional to $1/\sqrt{\rho}$. Hence, $\rho \propto n^2$. Fresnel further assumed that, in optically dense media, only the ether density in excess of that pervading all space would be carried along by the medium. Let the density outside the medium be ρ and let the density inside be $\rho' = n^2\rho$. On average the ether inside the medium moving through the ether with velocity \mathbf{v} will then move with velocity

$$\left(\frac{\rho' - \rho}{\rho'}\right) \mathbf{v} = \left(1 - \frac{\rho}{\rho'}\right) \mathbf{v} = \left(1 - \frac{1}{n^2}\right) \mathbf{v}.$$

This provides a physical underpinning of sorts for the Fresnel coefficient. It is not clear how seriously Fresnel himself took this particular mechanism. For him, as for many subsequent researchers, the primary justification for introducing the Fresnel coefficient was undoubtedly that it explained a wide range of phenomena. This fits in with the general character of Fresnel's work in optics. As one historian put it: "he succeeded in accounting for the phenomena in terms of a few simple principles, but was not able to specify an aether which would in turn account for these principles" (Whittaker 1951/53, p. 125).

One objection that can immediately be raised against Fresnel's model of the Fresnel coefficient is that it introduces a distinction between two kinds of ether, a universal kind unaffected by matter, and a kind peculiar to and carried along by transparent media. This objection can be taken care of by assuming that transparent matter carries along *all* the ether in its interior with a *fraction* of its own velocity rather than *some* of it with its *full* velocity. Stokes first suggested this alternative in 1846. Others put forward more complicated variants, combining the basic mechanisms of Fresnel and Stokes. A third possible alternative does not seem to have been explored before the work of Lorentz: that something is dragged along to account for the Fresnel coefficient, but that this something is not the ether. As we shall see, that is essentially Lorentz's explanation of the Fresnel coefficient. The most damning objections against the mechanisms that were explored came from two experimental results, established by Éleuthère Élie Nicolas Mascart (1837–1908) and Wilhelm Veltmann (1832–1902) in the early 1870s. Originally, it had been assumed that the index of refraction occurring in the Fresnel coefficient referred to some average frequency of starlight. Veltmann, however, showed that the coefficient must be applied to each frequency of light individually. From the phenomenon of dispersion, we know that the index of refraction depends on color, which means that in Fresnel's simple model transparent bodies would have to drag along different amounts of ether for different colors of light. Mascart arrived at a similar result for double refraction. He found that the Fresnel coefficient applies to the ordinary and the extraordinary ray individually. Since the index of refraction is different for the two rays, it follows that in Fresnel's model different amounts of ether have to be carried along for each of the two rays.

The work of Mascart and Veltmann illustrates an important trend in the optics of moving bodies. Together with a growing belief in the empirical adequacy of the Fresnel coefficient, there was a growing skepticism about the literal interpretation of the effect in terms of actual ether drag. Passages stressing the importance of the Fresnel coefficient but including a disclaimer about its physical interpretation can be found, for example, in the work of Mascart, Veltmann, Fizeau, August Beer (1825–1863), and Eduard Ketteler (1836–1900). Lorentz and Henri Poincaré (1854–1912) made similar comments in the late 1880s. The dominant attitude toward the Fresnel coefficient in the second half of the century, it seems, was that, whatever physical mechanism lay behind it, the coefficient had to be part of any optical theory based on the hypothesis of an immobile ether if such a theory was to explain why (at least to first order in v/c) terrestrial optical experiments always seem to follow the same laws that would hold if the earth were at rest with respect to the ether. Mascart summarized this conclusion in what may be called an optical form of the principle of relativity: "... que le mouvement de translation de la Terre n'a aucune influence appréciable sur les phénomènes d'optique produits avec une source terrestre ou avec la lumière solaire, que ces phénomènes ne nous donnent pas le moyen d'apprécier le mouvement *absolu* d'un

corps et que les mouvements *relatifs* sont les seul que nous puissions atteindre” (Mascart 1874, p. 420).

In the course of the 19th century, it was shown that the Fresnel coefficient ensures that this is true not only for refraction phenomena, but also for all reflection, diffraction, and interference phenomena. The status accorded to the Fresnel coefficient in the light of these results, and the problems with its physical interpretation, is nicely summarized in a comment by Veltmann: “Fresnel’s hypothesis is ... nothing more than the necessary and sufficient condition for the applicability of the laws derived from the undulatory theory governing the change of direction of rays in a medium at rest to the relative rays in moving media” (Veltmann 1873, pp. 510–511).

DECIDING BETWEEN STOKES AND FRESNEL: THE EXPERIMENTS OF MICHELSON AND MORLEY

Shortly after he published the seminal paper in which he first identified light as electromagnetic waves, James Clerk Maxwell (1831–1879) designed and performed an experiment aimed at detecting the effect on refraction of the earth’s presumed motion through the ether (the inverse motion of the ether with respect to the earth is often called the “ether drift”). He reported the negative result of the experiment in a paper he sent to Stokes in 1864 for publication in the *Proceedings of the Royal Society*. When Stokes informed him that Arago had long ago performed similar experiments and that Fresnel had been able to account for the negative results of such experiments through the introduction of the dragging coefficient, he withdrew the paper.

Shortly before his death, Maxwell returned to the problem of the earth’s motion with respect to the ether. In an entry on “Ether” for the ninth edition of the *Encyclopaedia Britannica*, he argued that the only way to measure the earth’s velocity with respect to the ether in a laboratory experiment is to look for variations in the velocity of light travelling back and forth between two mirrors. A simple calculation, which we shall give below, shows that the effect due to ether drift that one expects in such an experiment is of order v^2/c^2 , which Maxwell thought too small to be measurable. However, he had thought of an astronomical determination of the solar system’s velocity with respect to the ether, in which the effect to be measured was of order v/c . The method involved precise measurement of the periods between successive eclipses of the moons of Jupiter, which, as Römer had shown, could be used to determine the velocity of light. Maxwell’s idea was to analyze the data on such eclipses spanning a period of twelve years, the period of Jupiter’s orbit around the sun. On the assumption that the velocity with respect to the ether of the solar system as a whole remains roughly the same over such periods of time, the velocity of light determined by using Römer’s method should vary from $c - v$, when the light from Jupiter to earth is moving against the ether drift through the solar system, to $c + v$ six years later, when the light is moving with the ether drift. Maxwell wrote to the American astronomer D. P. Todd (1855–1939) to inquire whether the existing data on Jupiter and its satellites were accurate enough for this determination of the velocity of the solar system with respect to the ether. Todd had to disappoint him. Maxwell died shortly afterwards and his letter to Todd was published in *Nature*. In the letter, Maxwell reiterated that the method he proposed involved a first-order effect, whereas terrestrial experiments involved second-order effects, which would not be measurable.

Maxwell’s letter caught the attention of Michelson, a young officer in the U. S. Navy, who had already earned himself a reputation for high precision measurements of the speed of light. He took up the challenge to measure the terrestrial effect that Maxwell thought could not be measured. Fig. 8 schematically shows the instrument Michelson designed for this purpose, an instrument now known as a Michelson interferometer.

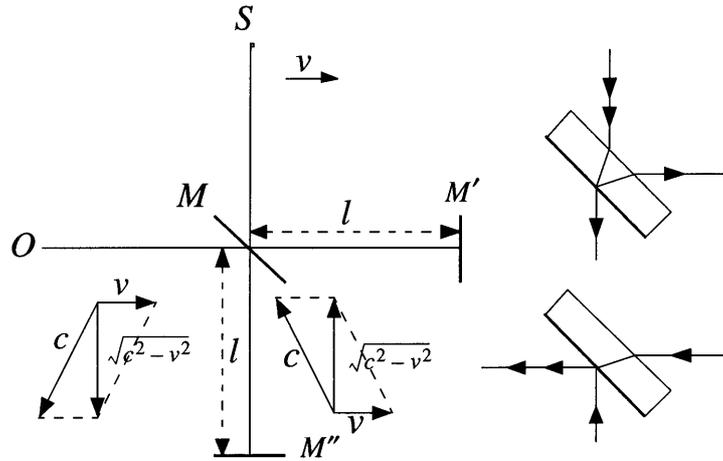


Figure 8: Michelson interferometer

Light from a source S falls on a so-called beam splitter M , a half-silvered mirror that partly reflects, partly transmits light, as is shown in somewhat greater detail on the right of Fig. 8. The reflected beam travels back and forth in one “arm” of the interferometer (MM'), the transmitted beam in the other (MM''). The two beams are reunited at M and parts of both are reflected and transmitted so as to travel together in the direction MO . At O , an observer examines the interference pattern produced by the two beams.

The principle of interference by division of amplitude employed in this experiment—as opposed to division of wave front employed, for instance, in a two-slit experiment—had been pioneered by French physicists such as Fizeau, Marie Alfred Cornu (1841–1902), and especially Jules Jamin (1818–1886), who in 1856 had designed an instrument called an “interferential refractometer,” that can be seen as a precursor to the Michelson interferometer. Whereas Jamin had used the beams reflected at the back and the front of a plate of glass, Michelson’s crucial innovation was to use the beams transmitted and reflected by M to produce the interference pattern. This innovation allowed Michelson to examine the interference pattern of two light beams travelling at right angles with one another, which was just what is needed for his ether drift experiment.

Suppose the ether is moving with respect to the interferometer with a velocity v as indicated in Fig. 8. The time it takes light to travel back and forth in the arm MM' of length l parallel to v is given by:

$$\frac{l}{c+v} + \frac{l}{c-v} = \frac{2lc}{c^2-v^2} \approx \frac{2l}{c} \left(1 + \frac{v^2}{c^2}\right).$$

The time it takes light to travel back and forth in the arm MM'' of the same length l but perpendicular to v is given by:

$$\frac{2l}{\sqrt{c^2-v^2}} \approx \frac{2l}{c} \left(1 + \frac{1}{2} \frac{v^2}{c^2}\right).$$

(As can be seen with the help of the vector diagrams in Fig. 8, light travelling back and forth in the arm MM' has a velocity $\sqrt{c^2 - v^2}$ with respect to the interferometer.) Note that the effect of ether drift on these travel times is indeed of the order v^2/c^2 as Maxwell had pointed out. From the two expressions above one infers that a round-trip in the arm parallel to the ether drift takes longer than a round-trip in the equally long arm perpendicular to the ether drift by approximately

$$\frac{1}{c} \frac{v^2}{c^2}.$$

Michelson originally thought that the ether drift would only affect the travel time in the arm parallel to it and that the travel time in the arm perpendicular to it would simply be $2l/c$ just as if the interferometer were at rest in the ether. As a result, he overestimated the time difference between the two trips by a factor 2.

The interference pattern at O depends on the difference in phase between the light waves coming from the arms MM' and MM'' . To obtain the phase difference produced by the ether drift, the travel time difference must be multiplied by the frequency f of light used. When the wavelength λ is substituted for c/f , this phase difference can be written as:

$$\frac{1}{\lambda} \frac{v^2}{c^2}.$$

This expression clearly shows why it should be possible in principle to measure the effect. Even though the ratio v^2/c^2 is very small, of the order of 10^{-8} , the ratio of the length of the arms to the wavelength of the light used can be made very large.

Unfortunately, it is only *changes* in the phase difference that can be observed as changes in the interference pattern. For this reason, Michelson constructed an interferometer that can be rotated (see Fig. 9 below). If the arm MM' is in the direction of \mathbf{v} , as in Fig. 8, the phase of the light from MM' will lag behind the phase of the light coming from MM'' . If the apparatus is rotated 90° , the roles of the two arms are reversed and the phase of the light from MM' will be ahead of the phase of the light from MM'' . As the interferometer is rotated, one would therefore expect to see a change in the phase difference of twice the amount given in the expression above.

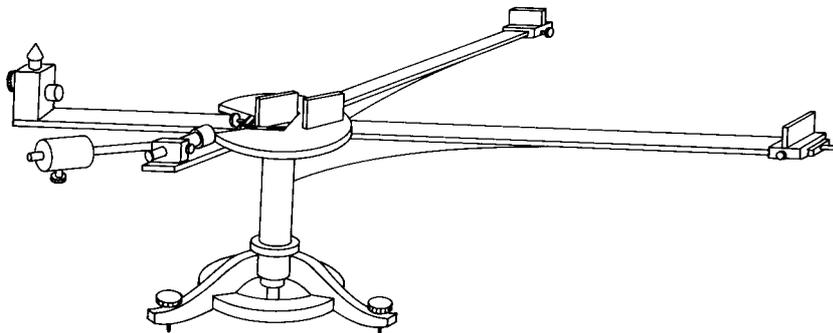


Figure 9: The Michelson interferometer of 1881

In late 1880, Michelson was granted a leave of absence from the Navy to pursue his researches in Europe. He developed the idea for his ether drift experiment in Paris and then went on to Berlin, where he started preparations for the actual experiment in the laboratory of Hermann von Helmholtz (1821–1894). Fig. 9 shows the interferometer he had constructed for the experiment.

The length of the arms of this instrument is about 120 cm. On the assumption that the velocity of the earth with respect to the ether is of the same order of magnitude as the velocity of the earth in its orbit around the sun and has a sizable component in the plane spanned by the arms of the interferometer, Michelson expected to find a phase shift of about one tenth of a fringe upon rotating the apparatus. This is very small effect that would easily be obscured by temperature fluctuations, bending of the brass arms upon rotation, not to mention vibrations due to Berlin traffic which made it almost impossible to produce a stable interference pattern at all. To avoid this last difficulty, Michelson in the end decided to move the apparatus to nearby but then still-rustic Potsdam. There he was able to control the various sources of error, but he did not observe any systematic phase shift. The largest phase shift he observed was about 0.02, which appeared to be due entirely to residual disturbances of various kinds.

In the 1881 paper, in which he described the experiment and its negative result, Michelson drew a rather bold conclusion: “The interpretation of these results is that there is no displacement of the interference bands. The result of the hypothesis of a stationary ether is thus shown to be incorrect, and the necessary conclusion follows that the hypothesis is erroneous” (Michelson 1881, p. 128). He concludes his paper by quoting a paragraph from a paper by Stokes (1846b) expressing the desirability of finding an experiment that would decide between Fresnel’s theory based on an immobile ether and his own theory based on a dragged-along ether. The use of this quotation indicates that Michelson was under the impression that he had provided such an experiment.

The experiment did not attract much attention at first, and Michelson returned to his measurements of the speed of light. He did not even bother to publish the correction of the erroneous factor 2 due to his neglect of the effect of ether drift on the travel time in the arm perpendicular to the ether’s motion. Alfred Potier (1840–1905) first drew his attention to this error when Michelson demonstrated his interferometer in Paris in late 1881. Michelson’s interest in the ether drift experiment was rekindled only in 1884 when he attended a series of lectures by William Thomson (1824–1907), better known as Lord Kelvin, in Baltimore. He had meanwhile been discharged from the Navy and had been appointed professor of physics at the recently founded Case School of Applied Science in Cleveland. Accompanying him on his trip to Baltimore was one of his colleagues at the Case School, Edward Williams Morley (1838–1923), professor of chemistry. This was the beginning of a few years of close collaboration between the two men, which ended rather abruptly, when Michelson accepted a position at Clark University in 1889.

Thomson and John William Strutt (1842–1919), better known as Lord Rayleigh, who had also come to Baltimore and with whom Michelson had been corresponding for some time, urged Michelson to repeat his 1881 ether drift experiment. As a preliminary, they recommended a repetition of Fizeau’s experiment of 1851 to test more accurately the Fresnel coefficient. Using a technique very similar to that in the 1881 ether drift experiment (see Fig. 10), Michelson and Morley were able to confirm Fresnel’s formula with much greater accuracy than Fizeau.

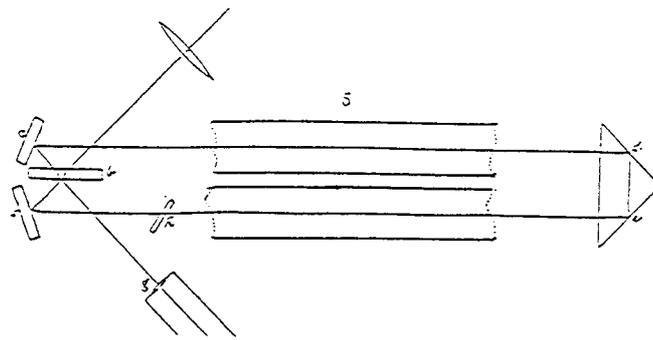


Figure 10: The design of Michelson and Morley’s repetition of the Fizeau experiment

When they published their results in 1886, with the same boldness as Michelson in 1881, Michelson and Morley drew the exact opposite conclusion from the one drawn in 1881: “the result of this work is therefore that the result announced by Fizeau is essentially correct: and that *the luminiferous ether is entirely unaffected by the motion of the matter which it permeates*” (Michelson and Morley 1886, p. 386; emphasis in the original).

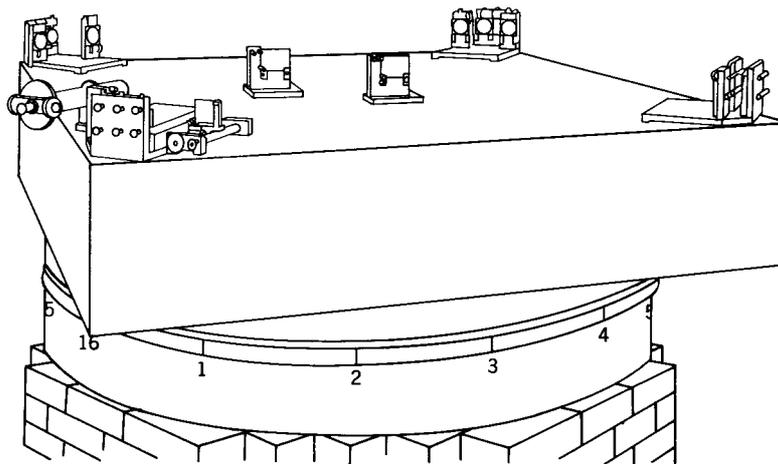


Figure 11: The Michelson interferometer of 1887

The next task was to repeat Michelson’s experiment of 1881 to see whether a more accurate version of that experiment would after all reveal the ether drift to be expected on the basis of the hypothesis of an immobile ether. Further motivation for this undertaking was provided by the appearance of a lengthy article by Lorentz in 1886, in which he reviewed both experimental and theoretical work on the question of whether or not the ether is dragged along by the earth. Lorentz criticized Stokes’ explanation of stellar aberration, pointing out that the ether’s motion cannot be both irrotational and vanish at the earth’s surface, as Stokes assumed. The ether can only be partially dragged along by matter for an explanation of stellar aberration along the lines suggested by Stokes to be viable. Lorentz proposed a theory combining elements of the theories of Fresnel and Stokes, a theory incorporating the Fresnel coefficient for transparent matter and partial

dragging of the ether in the vicinity of all matter. The result of Michelson's 1881 experiment, which is discussed at length in Lorentz's paper, can easily be reconciled with such a theory. Lorentz also made it clear that Michelson's conclusion that he had refuted Fresnel's theory was highly premature given the large margin of error of his 1881 experiment (especially given the erroneous factor 2 in Michelson's analysis which, of course, did not escape Lorentz's notice).

Fig. 11 shows the interferometer Michelson and Morley constructed for the repetition of the experiment in 1887. The most noticeable improvement in the design is that this interferometer can be rotated much more smoothly than the one used in 1881. The optical components are mounted on a large sandstone slab, which itself floats in a cast-iron trough filled with Mercury. The second improvement is that the light is reflected back and forth several times in the arms of the interferometer before the two light beams are reunited to produce the interference pattern. As a result, the effective length of the arms of this new interferometer is almost ten times the length of the arms of the 1881 interferometer. The expected effect of ether drift accordingly is increased tenfold. The expected phase shift was about 0.4. With this new instrument Michelson and Morley felt it should be possible to measure phase shifts as small as 0.01. When they began the actual measurements, however, they did not find any phase shifts exceeding this threshold. There was, of course, the remote possibility that at the time of the experiment the overall velocity of the earth with respect to the ether (the vector sum of the earth's velocity with respect to the sun and the velocity of the sun with respect to the ether) happened to be very small. To rule out that eventuality, Michelson and Morley originally planned to repeat the experiment at six-month intervals. After the disappointing initial results of the experiments, they abandoned this plan.

Michelson and Morley were more cautious this time in formulating the conclusion they wanted to draw from their results: "It appears, from all that precedes, reasonably certain that if there be any relative motion between the earth and the luminiferous ether, it must be small" (Michelson and Morley 1887, p. 341). They continued more confidently, stating that the new result does refute "Fresnel's explanation of aberration" (*ibid.*), i.e., the hypothesis of an immobile ether. They noted that Lorentz had shown Stokes' alternative of a fully dragged-along ether to be incompatible with the observed stellar aberration, leaving only Lorentz's hybrid theory. Michelson and Morley express doubt at whether such a theory could account for their result: "If now it were legitimate to conclude from the present work that the ether is at rest with regard to the earth's surface ... [Lorentz's] own theory also fails" (*ibid.*). Since, by Michelson and Morley's own admission, their result only shows that the velocity of the earth with respect to the ether is "probably less than one-sixth the earth's orbital velocity, and certainly less than one-fourth" (*ibid.*), it is not clear whether the prospects for a theory based on partial ether drag were as dire as this comment suggests.

A theory based on partial ether drag, however, faced a much more serious problem. In the same year as the Michelson-Morley experiment, Heinrich Hertz (1857–1894) succeeded in generating electromagnetic waves; optics was now definitively regarded as a branch of electrodynamics, and it turned out to be exceedingly difficult to incorporate any sort of ether drag into Maxwell's theory, while retaining the theory's ability to explain such optical phenomena as aberration and the Fizeau effect.

MAXWELLIAN ELECTRODYNAMICS AND THE RELATION BETWEEN ETHER AND MATTER

While mankind had been dealing since time immemorial on a practical level with phenomena now included under the rubric "optics of moving bodies" (after all, sunlight comes from a body moving with respect to the earth), it was only around the end of the first third of the nineteenth century

that induction phenomena—the first such phenomena to be classed under the rubric “electrodynamics of moving bodies” (in the narrower sense, i.e., including only electric and magnetic effects)—came to be investigated, first by Arago, and notably by Michael Faraday. (1791–1867) (see Darrigol 1993 and the article on “Electromagnetism and the Field”). Two classes of theories were developed to treat such phenomena: macroscopic phenomenological theories, such as Franz Neumann’s (1798–1895), which attempted to subsume inductive effects under a set of principles closely related to the observed phenomena; and microscopic theories, such as Wilhelm Weber’s (1804–1891), which attempted to explain such phenomena on the basis of a microscopic model of electric and magnetic forces between charged particles. Both Neumann’s and Weber’s theories were based on the concept of direct, instantaneous action-at-a-distance interactions between macroscopic charge and current elements or closed circuits (Neumann), or charged particles at rest or in motion (Weber). Also common to both theories was the conclusion that induction phenomena only depended on the state of relative motion of conductors, magnets, etc.

This dichotomy between phenomenological, descriptive and microscopic, explanatory theories continued throughout the development of 19th century electrodynamics of moving bodies, even after the great shift, under the impetus of Faraday and Maxwell, from action-at-a-distance to field-theoretical models of electromagnetic interactions. (see the article on “Electromagnetism and the Field”). We shall discuss only a few outstanding examples of the field-theoretical approach: The closely related macroscopic, phenomenological theories of Hertz and Oliver Heaviside (1850–1925), and, in the next section, Lorentz’s theory and its further development by Poincaré on the microscopic, explanatory level (similar theories were put forward by Emil Wiechert (1861–1928) and Joseph Larmor (1857–1942)); and finally Emil Cohn’s (1854–1944) macroscopic, phenomenological electrodynamics. Both approaches start from the work of Maxwell, who first developed Faraday’s visual, qualitative concepts of the electric and magnetic fields into a full-fledged mathematical electromagnetic field theory that embraces optics. It is not simple to characterize Maxwell’s work in terms of the dichotomy mentioned above. He originally based himself on a mechanical ether-theoretical model of the electromagnetic field; but by the time of his *Treatise* this model had receded into the background, giving way to a description of electricity, magnetism and matter in terms of certain vector fields in space, presumably having the ether as their support, but not associated with any explicit mechanical model. The fact that the equations governing these fields could be derived from a Lagrangian was taken as sufficient to characterize the theory as a “dynamical model,” with the understanding that an underlying mechanical model would ultimately be supplied. (As Maxwell (1879, Vol. 2, p. 831) recognized, and as was emphasized later by Poincaré, an infinity of such mechanical models were compatible with the field Lagrangian, which did much to dampen further mechanical speculations.) But in the sense that Maxwell posited the existence of four vector fields \mathbf{D} , \mathbf{B} , \mathbf{E} , and \mathbf{H} , \mathbf{D} and \mathbf{B} being the electric and magnetic “quantities,” and \mathbf{E} and \mathbf{H} being the corresponding “intensities;” and had to add macroscopic constitutive relations relating the intensities to the quantities, his theory may be regarded as a macroscopic, phenomenological one. The constitutive relations were simply posited for each medium, including the ether, without any attempt to derive them from the macroscopic structure of the medium.

Maxwell himself did not develop a full electrodynamics of moving bodies, presumably because it would have required him to make detailed assumptions about the relative motion of ether and matter that he felt still to be premature. But he did show that his field-theoretical model of inductive phenomena also resulted in the prediction that such effects should depend only on the

state of relative motion of the material systems involved, and not on their state of motion relative to the ether.

Heaviside and Hertz supplied the missing element needed to develop a complete electrodynamics of moving bodies. They assumed that, inside matter, the state of motion of the ether coincides with the state of motion of the matter itself—all presumably with respect to the state of motion of the vast sea of ether far away from all matter. (The state of motion of the parts of the ether just outside of matter is left unclear by Hertz and Heaviside.) On the basis of this assumption, it followed that the electromagnetic field equations, and hence all phenomena that can be deduced from them, take the same form when referred to any rigid frame of reference, regardless of its state of linear or rotational motion.

“It follows that the absolute motion of a rigid system of bodies has no influence on any of the internal electrodynamic processes as long as the bodies being considered, including the ether, take part in the motion” (Hertz 1890)

This certainly explains why the motion of the earth did not have to be taken into account in the consideration of any terrestrial electric or magnetic phenomena; but since Maxwell’s theory embraced optics as well, it raised the problem of explaining Fizeau’s experimental result (which had just been confirmed with much greater quantitative precision by Michelson and Morley), which, it will be remembered, was then interpreted as resulting from a “partial dragging” of the ether inside a moving transparent medium.

Hertz and Heaviside were well aware of the conflict between their theories and known results of the optics of moving bodies. As Hertz wrote:

“The few indications we have about this motion [of the ether] suggest that ... ether moves independently of matter, even inside matter” (ibid.)

But, like Maxwell, he felt it premature to make a detailed postulate about their relative motion, preferring to rest content for the moment with showing the possibility of developing a complete and consistent electrodynamics of moving bodies, even if it could not explain all optical effects. The result of the Michelson-Morley experiment made the situation even more confusing, since it could be easily explained if the ether were totally dragged along by matter; but the result of Fizeau’s experiment seemed to preclude this assumption. Here was a challenge to electrodynamic theory: explain the results of both the Fizeau and the Michelson-Morley experiments. In the next section we shall see how Lorentz and Cohn, in rather different ways, rose to this challenge.

LORENTZ’S IMMOBILE ETHER THEORY: THE THEOREM OF CORRESPONDING STATES AND THE CONTRACTION HYPOTHESIS

In his 1886 article on the optics of moving bodies, Lorentz had kept open the possibility of a partially dragged-along ether. His famous electron theory, however, developed in the 1890s, is based on the hypothesis of a totally immobile ether. Unlike Hertz and Heaviside, Lorentz built his theory upon a strict separation between ether and matter. In his view, the only way in which the two can interact is through tiny charged particles—first called ‘ions’ and later ‘electrons’ and assumed to be present in large quantities in all matter—which generate electric and magnetic fields in the ether that obey Maxwell’s equations. These charged particles in turn are acted upon by those fields via the Lorentz force $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$. In his microscopic theory, Lorentz

postulated the existence of only two fundamental fields. In terms of Maxwell's four fields (see above) he simply identified \mathbf{E} and \mathbf{D} and \mathbf{B} and \mathbf{H} in the ether. It was a task of the macroscopic theory to derive the constitutive relations for material media from the vacuum field equations together with a microscopic model of the atomistic structure of each material medium. For example, the electric field of an electromagnetic wave incident on the charged particles in a transparent medium displaces these particles from their equilibrium positions, setting them into a simple harmonic motion about these positions. The resulting time-dependent dipole moment of each charge sets up a secondary wave emanating from the charge. The net resultant of the coherent interference of the primary wave, propagating with velocity c , and all of the secondary waves from the charges in the medium is to produce a net wave that propagates with velocity c/n , where n is the index of refraction of the medium, which is thereby related to the constants of the charged simple harmonic oscillators, and their number per unit volume of the medium.

Lorentz faced the formidable task of explaining on the basis of his electron theory why optical experiments consistently failed to detect the earth's motion with respect to the immobile ether posited by the theory. It was not just the result of the second-order experiment of Michelson and Morley that seemed to contradict the basic tenets of his theory; it was also far from obvious how to account for the negative results of all first-order experiments performed over the course of the century, the explanation of which involved the Fresnel coefficient. Lorentz somehow had to derive this coefficient from his version of electromagnetic theory without introducing any ether drag. In 1892, he succeeded, in his first extensive treatment of the electrodynamics of moving bodies (Lorentz 1892a, pp. 524–526). He derived the equations governing the propagation of electromagnetic waves in a dielectric moving through the ether in the frame of reference moving with the dielectric, and found that a wave propagating, for instance, along the direction of motion of a frame moving with velocity v , must have a velocity $c/n - v/n^2$ in that frame (to order v/c). Hence, the velocity of this wave with respect to the ether is $(c/n - v/n^2) + v = c/n + (1 - 1/n^2)v$, in accordance with the Fresnel coefficient. Thus, it is the waves that are partially dragged by the medium and not the ether. From a microscopic point of view, what happens when an electromagnetic wave is incident on a moving transparent medium may be described as follows: (1) The effect of the electric field of the wave on the moving charged particles of the medium is to displace them from their equilibrium positions when at rest, just as if they were not moving (see above); (2) due to their common motion, however, the particles are also subject to an additional Lorentz force $\mathbf{v} \times \mathbf{B}$ from the wave's magnetic field. When both of these effects on the secondary waves produced by the charged particles are taken into account, the net velocity of propagation of the wave in the moving medium is reduced by a factor v/n^2 from its value c/n when the medium is at rest in the ether. The wave is only partially dragged along by the medium in which it propagates.

The effect of Lorentz's accomplishment was to facilitate the jettisoning of the ether. As one historian put it: "Un éther totalement entraîné, comme celui de Stokes et de Hertz, devait être une réalité matérielle; de même un éther entraîné partiellement dans la mesure de sa condensation comme celui de Fresnel; seul un éther absolument immobile, et qui échappait toujours et tout à fait aux mouvements de la matière pouvait être regardé comme dépourvu de toute réalité physique" (Sesmat 1937, p. 525).

In the course of his 1892 treatise, Lorentz availed himself of various auxiliary quantities to give the equations for specific problems in systems moving through the ether a more manageable form. In a book he published three years later, he did so more systematically. He now introduced a set of auxiliary quantities, with the help of which he could, to first order in v/c , give the equations

governing the propagation of light in moving media the same form as the equations for media at rest in the ether. The most important of these auxiliary quantities was a new time variable. In a system moving through the ether with a velocity v in the x -direction, this new time variable t' is related to the ordinary time t by:

$$t' = t - (v/c^2)x,$$

where x is the x -coordinate of the moving system. Because of its dependence on position, Lorentz called this auxiliary time variable the 'local time.' He also replaced the real electric and magnetic fields in the moving system by auxiliary fields, the components of which are linear combinations of components of the real fields with coefficients depending on v . As long as quantities smaller than those of order v/c are neglected, these auxiliary fields considered as functions of the spatial coordinates and the local time in the moving system satisfy the same equations as the real fields considered as functions of the spatial coordinates and the ordinary ("real") time in a system at rest in the ether. To every field configuration that is a solution of the equations in a system at rest in the ether there thus corresponds a field configuration, which, to a good approximation, is a solution of the equations in a moving system. The description of the former in terms of the real quantities can be used as a description of the latter in terms of the corresponding auxiliary quantities. Using the relations between the auxiliary and the real quantities in the moving system, one can then reexpress this auxiliary field configuration given as functions of the spatial coordinates and the local time as a real field configuration given as functions of the spatial coordinates and "real" time in the moving system. Two such configurations of real fields, one in a system at rest, the other in a system moving through, the ether are called 'corresponding states.' The 'theorem of corresponding states' says that if one of the two is allowed by the electromagnetic field equations, so is the other.

With the help of this theorem, Lorentz showed that no first-order optical experiment which eventually boils down to the observation of a pattern of brightness and darkness, as most experiments in optics do, will ever detect the earth's motion with respect to the ether. Lorentz's argument was very simple. What is perceived as darkness is the vanishing of the electric and magnetic fields constituting a light wave averaged over a time period that is long in terms of the frequency of the light. What is perceived as brightness is a large value of such averages. To describe a pattern of brightness and darkness in a system at rest in the ether it thus suffices to specify where the electric and magnetic fields vanish on average and where they do not. In the corresponding state in a moving system the auxiliary fields take on the same values as the real fields in the corresponding points in the system at rest. Since the components of the real fields are linear combinations of the components of the auxiliary fields, the real fields vanish whenever the auxiliary fields do. Conversely, they are large whenever the real fields are. It follows that corresponding states produce identical patterns of brightness and darkness. This then explains the negative result of a broad class of first-order optical experiments, if one adds the assumption, as Lorentz tacitly did, that the electromagnetic field configuration produced by a configuration of optical apparatus in the moving system is just the corresponding state of the field configuration produced by the same configuration of optical apparatus in a system at rest in the ether. This assumption holds as long as the Galilean principle of relativity is assumed to hold for the material systems involved.

Note that it is crucial for Lorentz's argument that patterns of brightness and darkness are by their very nature stationary situations. If this were not the case, the x -dependence of the local time would lead to complications. If it is dark simultaneously at two different points in ordinary time

in a system at rest in the ether, it will be dark simultaneously at the corresponding points in the moving system in *local* time. It is only because it will remain dark at both points for a considerable length of time that it will also be dark simultaneously in ordinary time.

With the help of the notion of local time, Lorentz was able to give a very simple derivation of the Fresnel coefficient. Suppose in a medium at rest in the ether there is a plane wave propagating with velocity c/n along the x -axis of a Cartesian coordinate system at rest in the ether. The components of the electric and magnetic fields describing this wave depend on x and t only via the combination $t - \frac{x}{c/n}$, which governs the phase of the wave. In the corresponding state in a system moving through the ether with velocity v in the x -direction, the components of the auxiliary fields as well as the components of the real fields therefore depend on the coordinate x of the moving system and the local time t' only via $t' - \frac{x}{c/n}$. This means that they depend on x and the ordinary time t only via

$$t - (v/c^2)x - \frac{x}{c/n} = t - (v/c^2 + n/c)x.$$

From this expression, one can read off that the velocity of the wave relative to the moving medium is

$$\frac{1}{\frac{v}{c^2} + \frac{n}{c}} = \frac{\frac{c}{n}}{\frac{v}{nc} + 1} \approx \frac{c}{n} \left(1 - \frac{v}{nc}\right) = \frac{c}{n} - \frac{v}{n^2}.$$

The velocity of the wave with respect to the ether is therefore $c/n + (1 - 1/n^2)v$, in accordance with the Fresnel coefficient.

Note that this new derivation does not explicitly involve electromagnetic theory at all. The crucial ingredient in the derivation is simply the expression for local time. Before the advent of Einstein's relativity theory, for Lorentz local time was nothing but an auxiliary quantity with no physical meaning. However, by 1900, if not earlier, Poincaré realized that clocks in motion through the ether, if synchronized by a co-moving observer with the help of light signals, would actually read the local time. The work of one of his teachers, Potier, may have been a factor in Poincaré's recognition of the physical significance of the local time. As we have emphasized, the importance of the Fresnel coefficient is that it is the necessary and sufficient condition for the laws of optics to be the same (to first order in v/c) in systems at rest and in systems in motion through the ether. Typically this condition is formulated in terms of an extra *velocity* to be added to the velocity of light propagating through moving media. In 1874, however, Potier formulated it in terms of extra *time* to be added to the travel time of light propagating through moving media. This alternative formulation is very natural if the Fresnel coefficient is derived using Fermat's principle of least time, as was done, for instance, by Fresnel, Veltmann, and Mascart. In effect, these derivations show that all the laws of optics in a moving system will be the same as those in a system at rest in the ether if each optical path is evaluated in terms of the local rather than the ordinary time. The extra travel time of light in moving media needed according to Potier's reformulation of the Fresnel coefficient follows from the position-dependent term in the expression for local time. The essentially relativistic kinematical nature of the Fresnel coefficient, which even Einstein originally missed, would eventually be understood without the sort of reformulation given by Potier. In 1907, Max Laue (1879–1960) showed that the Fresnel coefficient follows from a straightforward application of the relativistic addition theorem of velocities. Laue's derivation is

mathematically equivalent to Lorentz's derivation of 1895. From this relativistic perspective, Lorentz's 1895 derivation shows that a wave propagating through some medium in the x -direction with velocity c/n for a co-moving observer (using time coordinate t') has, in first-order approximation, velocity $c/n + (1 - 1/n^2)v$ for a second observer (using time coordinate t) with respect to whom the first is moving with velocity v in the x -direction, where t and t' are interpreted as the ordinary times in each system.

In the final chapter of his 1895 book, Lorentz examined several experiments that he could not account for on the basis of the first-order theorem of corresponding states. The most important of these is the Michelson-Morley experiment. Lorentz repeated the explanation he had proposed three years earlier (Lorentz 1892b), an explanation which, as Lorentz had meanwhile discovered, had already been suggested in 1889 by FitzGerald. The basic idea behind the Michelson-Morley experiment is that it takes light longer to travel back and forth in an interferometer arm parallel to the ether drift than in an arm of the same length perpendicular to the ether drift. FitzGerald and Lorentz suggested that the negative result of the experiment can be explained by assuming that bodies in motion through the ether experience a contraction in the direction of motion by a factor of $\sqrt{1 - v^2/c^2}$. In that case, the length l of the arm must be replaced by $l\sqrt{1 - v^2/c^2}$ in the calculation of the travel time if the arm is parallel to the ether drift:

$$\frac{l\sqrt{1 - v^2/c^2}}{c + v} + \frac{l\sqrt{1 - v^2/c^2}}{c - v} = \frac{2l\sqrt{c^2 - v^2}}{c^2 - v^2} = \frac{2l}{\sqrt{c^2 - v^2}}.$$

This is exactly the same as the travel time if the arm is perpendicular to the ether drift. (Lorentz actually allowed for the possibility of other changes in the dimensions of bodies due their motion through the ether as long as the ratio of the change in the direction of motion to the change perpendicular to the direction of motion is $\sqrt{1 - v^2/c^2}$.)

Lorentz tried to make his contraction hypothesis plausible with the help of a result he had found in electrostatics: if a charge distribution were in static equilibrium in a system at rest in the ether, it would be in static equilibrium in a system in motion through the ether when contracted by a factor $\sqrt{1 - v^2/c^2}$ in the direction of motion, the same factor needed to explain the Michelson-Morley experiment. Lorentz derived this result in a way that is reminiscent of his treatment of optics in moving bodies on the basis of the theorem of corresponding states. He introduced various auxiliary quantities to give the equations for electrostatics in moving systems (i.e., the equations governing charge distributions in which there is no relative motion, only an overall constant velocity with respect to the ether) the same form as the equations for electrostatics in systems at rest in the ether. The most important of these auxiliary quantities are new spatial coordinates, which depend on the system's velocity through the ether. For a system moving with velocity v in the x -direction, only the x -coordinate is replaced by a new auxiliary coordinate:

$$x' = \frac{x}{\sqrt{1 - v^2/c^2}}.$$

For any charge distribution in a system at rest in the ether, there will be a corresponding charge distribution in a moving system, the description of which in terms of the auxiliary quantities will be the same as the description of the one at rest in the ether in terms of the real quantities. The distances between charges in the moving system in terms of the auxiliary coordinates, for instance,

will be the same as the distances between the corresponding charges in the system at rest in terms of the real coordinates. Since a distance $\Delta x' = l$ in terms of the auxiliary coordinates corresponds to a real distance $\Delta x = l\sqrt{1 - v^2/c^2}$, the charge distribution in the moving system will be a factor $\sqrt{1 - v^2/c^2}$ shorter in the direction of motion than the corresponding charge distribution in the system at rest in the ether. If the configuration at rest in the ether were in static equilibrium, the contracted configuration in motion through the ether would be too.

Lorentz realized that this result, suggestive as it is, provides at best a plausibility argument for the contraction hypothesis. According to a theorem proved in 1831 by Samuel Earnshaw (1805–1888) there is no such thing as a purely electrostatic equilibrium. Other forces are needed to keep a static charge distribution stable. Whatever the nature of the forces between the molecules of the arm of an interferometer, they must include some non-electrostatic forces. Still, it was striking that these electrostatic considerations give precisely the contraction factor needed to explain the Michelson-Morley experiment.

Lorentz made it clear in the title of his 1895 book that the theory of the optics and electrodynamics of moving bodies that he had to offer was only provisional. He was able to give a very general explanation of many first-order experiments based on the theorem of corresponding states, but had to resort to special hypotheses to deal with a few individual second-order experiments. A few years later, Lorentz formulated an exact version of the theorem of corresponding states, with the help of which he could give a unified treatment of a broad class of first- and second-order experiments. The first version of this exact theorem and of the theory built around it can be found in a paper published in 1899.

The exact theorem of corresponding states is obtained by combining the auxiliary quantities used in the first-order version of the theorem and the auxiliary quantities used in the discussion of electrostatics in moving systems. In a system moving through the ether with velocity v in the x -direction, the auxiliary coordinates and the local time can be written as:

$$x' = lx, y' = ly, z' = lz, t' = l(t/\gamma - \gamma(v/c^2)x), \quad \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}.$$

The factor l is an overall scaling factor, differing from 1 only by a term in the order of v^2/c^2 . We shall immediately set this factor equal to 1, as Lorentz would eventually do in 1904. In that case, the equations above are essentially equivalent to a Lorentz transformation from the coordinates (x_0, y_0, z_0, t_0) for an observer in a system, which from Lorentz's point of view would be at rest in the ether to the coordinates (x', y', z', t') for an observer in the moving system. Note that the coordinates (x, y, z, t) are related to (x_0, y_0, z_0, t_0) by the Galilean transformation:

$$x = x_0 - vt_0, \quad y = y_0, \quad z = z_0, \quad t = t_0.$$

Combining the transformation from (x_0, y_0, z_0, t_0) to (x, y, z, t) with the transformation from (x, y, z, t) to (x', y', z', t') (with $l = 1$), we recover the Lorentz transformation in its familiar form:

$$x' = \gamma(x_0 - vt_0), \quad y' = y_0, \quad z' = z_0, \quad t' = \gamma(t_0 - (v/c^2)x_0).$$

The last of these expressions is found as follows:

$$\begin{aligned}
 t' &= t/\gamma - \gamma(v/c^2)x \\
 &= t/\gamma - \gamma(v/c^2)(x_0 - vt_0) \\
 &= \gamma(t_0[1/\gamma^2 + v^2/c^2] - (v/c^2)x_0).
 \end{aligned}$$

The expression in square brackets in the last line is equal to 1.

For Lorentz's exact theorem of corresponding states it is the transformation from the coordinates (x, y, z, t) to the auxiliary coordinates (x', y', z', t') of the moving system that matters. As he had done in 1895 to first order in v/c , Lorentz was able to show exactly that auxiliary fields considered as functions of the auxiliary coordinates and the local time in the moving system satisfy the same equations as the real fields considered as functions of the real coordinates and the ordinary time in the system at rest in the ether. To see how this result can be used to explain the negative results of optical ether drift experiments, we need to examine, as we did for the first-order version of the theorem, the relation between the pattern of brightness and darkness associated with some field configurations in a system at rest in the ether and the pattern associated with its corresponding state in a system moving through the ether. If it is dark (light) at a point P with real coordinates (a, b, c) in the pattern in the system at rest in the ether, it will be dark (light) at the point P' in the corresponding pattern in the system in motion through the ether with the same *auxiliary* coordinates (a, b, c) , i.e., with real coordinates $(a/\gamma, b, c)$. As in the case of electrostatic charge distributions considered above, this means that the pattern of brightness and darkness in the moving system is a factor $\sqrt{1 - v^2/c^2}$ shorter in the direction of motion than the corresponding pattern in the system at rest in the ether. For Lorentz's theory to predict that observations of patterns of brightness and darkness will never reveal ether drift no matter how accurate the relevant experiments, it has to be assumed that the configurations of optical components producing such patterns experience the same contraction due to their motion with respect to the ether as those patterns themselves. In conjunction with the exact theorem of corresponding states, the contraction hypothesis, which Lorentz and FitzGerald had originally introduced for *one* such experiment, thus explains why *no* such experiment will ever detect ether drift. What prompted Lorentz's new more general theory was in fact a variant on the Michelson-Morley experiment proposed in 1898 by Alfred Liénard (1869–1958). Liénard wanted to repeat the Michelson-Morley experiment with some transparent medium in the arms of the interferometer. In that case, the Lorentz-FitzGerald contraction would no longer ensure that the travel time in an arm of an interferometer is independent of whether the arm is parallel or perpendicular to the ether drift. Liénard did not actually perform the experiment, but both he and Lorentz strongly suspected that the outcome, as the outcome of so many experiments before, would be negative. As Lorentz emphasized in his 1899 paper, his new theory could account for such a negative result.

The physical assumption that needs to be added to the purely mathematical theorem of corresponding states in order to predict negative results in a broad class of ether drift experiments actually involves much more than the contraction effect originally proposed by Lorentz and FitzGerald. Stated more accurately, the assumption that is needed is that the configuration of optical components which produces a certain pattern of brightness and darkness in a system at rest in the ether will, when set in motion, turn into the configuration producing the corresponding pattern of brightness and darkness in the moving system. It will be recalled that the same assumption was made tacitly in the context of the 1895 first-order version theorem of corresponding states. In that context, the assumption was satisfied as long as macroscopic material

systems behave in accordance with the Galilean principle of relativity. This is no longer true in the context of the exact version of the theorem. As we already noticed, the assumption entails that, contrary to this principle, material systems contract when moving through the ether.

It also entails, as Lorentz explicitly noted in his 1899 paper, that the frequency of oscillating electrons generating the light waves is lower in systems in motion than in systems at rest in the ether. This can be read off of the expression for local time. According to the theorem of corresponding states, the period of oscillation of light waves in a system at rest in the ether in real time will be equal to the period of the corresponding light waves in the moving system in local time. A period T in local time means a (longer) period $\gamma T = T/\sqrt{1 - v^2/c^2}$ in real time. In other words, the frequency of the light in the moving system is lower than the corresponding frequency in the system at rest by a factor $\sqrt{1 - v^2/c^2}$. In Lorentz's classical theory, the frequency of light is equal to the frequency of the oscillating electrons generating it. So, if the system at rest in ether is to turn into the system producing the corresponding state in the moving system when set in motion, the frequency of the electrons must also change. Lorentz only mentioned this important result in passing. It was found independently and presented more prominently in 1900 by Larmor.

This new effect should be taken into account for a full analysis of the Michelson-Morley experiment (although the contraction hypothesis suffices to account for the experiment's negative result). What is measured in the experiment is the difference in phase between light from one arm of the interferometer and light from the other. The phase difference is obtained by multiplying the difference in travel time by the frequency of the light. As we have seen, the travel time in the arm of a moving interferometer is a factor $1/\sqrt{1 - v^2/c^2}$ longer than the travel time in the corresponding arm of an interferometer at rest. The contraction hypothesis ensures that this is true no matter whether the arm moves parallel or perpendicular to the ether drift (and thus explains the negative result of the Michelson-Morley experiment). The frequency of the light in the moving interferometer is a factor $\sqrt{1 - v^2/c^2}$ shorter than in the interferometer at rest. It follows that the phase differences in the moving interferometer are exactly the same as in the interferometer at rest.

Lorentz realized that the general assumption he added to the exact theorem of corresponding states has further unexpected ramifications. He found that the oscillations of the electrons generating light in the moving system only satisfy Newton's laws of motion if it is assumed that the forces acting upon them and even their masses depend on their velocity with respect to the ether in a particular way. That the mass of a charged body depends on that body's velocity had been suggested before, so Lorentz was prepared to accept this consequence of his new theory. A few years later, the velocity-dependence of the electron mass could be tested empirically by studying the deflection of β -radiation in electromagnetic fields. The early experiments by Kaufmann seemed to support an alternative formula for the velocity-dependence of the electron mass due to Max Abraham (1875–1922). In the 1910s, however, a consensus developed that the experiments confirmed Lorentz's formula, which is also the formula predicted by special relativity.

In his 1899 paper, Lorentz merely outlined his new theory, mainly to show that his approach in terms of corresponding states provided the resources to account for possible negative results in such experiments as the one proposed by Liénard. In 1904, Lorentz published a systematic exposition of the fully developed theory. The 1904 paper was prompted in part by Poincaré's sharp criticism of the contraction hypothesis and by several recent second-order ether drift experiments. These experiments were aimed explicitly at testing the contraction hypothesis.

First, Morley had found a new collaborator in Dayton C. Miller (1866–1941) to continue the work he and Michelson had started in the 1880s. In 1904, they repeated the Michelson-Morley experiment with an interferometer with arms made out of wood, in an attempt to see whether the contraction depends on the material that is used. They did not detect any systematic phase shifts. In 1905, they would take their interferometer up to a mountain, thinking that maybe the ether had been trapped in the basements in which the experiment had so far always been conducted. It is fair to say that Morley and Miller were out of touch with theoretical developments at this point. Given the success of Lorentz's theory, the notion of a dragged-along ether had been all but abandoned in favor of an immobile ether in the physics community. Miller nonetheless persisted in his search for ether drift and would carry out another series of experiments in the 1920s.

More important than the experiments of Morley and Miller, were experiments in 1902 by Rayleigh and in 1904 by De Witt Bristol Brace (1859–1905) to see whether the Lorentz-FitzGerald contraction would make certain crystals doubly refracting, and an experiment in 1903 by Frederick T. Trouton (1863–1922) and his research student Henry R. Noble trying to detect a turning couple acting on a moving capacitor, trying to align its plates with the direction of motion. The latter experiment grew out of another ether drift experiment involving a capacitor in a torsion pendulum suggested by FitzGerald shortly before his death (Trouton 1902). Before the Trouton-Noble experiment was even performed, Larmor had already argued that one could account for the negative result of the Trouton-Noble experiment on the basis of the contraction hypothesis. The Trouton-Noble experiment is especially interesting because it is a non-optical second-order ether drift experiment.

In 1899, Lorentz had already extended his theorem of corresponding states from optics to optics and electrostatics, and in 1904, he set up his theory in such a way that it could, at least in principle, be applied to the whole field of electrodynamics. In 1895, he had formulated the theorem of corresponding states for the macroscopic equations governing the propagation of light in transparent media. In 1899, and more systematically in 1904, he formulated the theorem for the microscopic Maxwell-Lorentz equations themselves. In this new version of the theorem he also replaced charge and current densities by auxiliary quantities. In practice, the applicability of Lorentz's theory continued to be restricted to the static and stationary situations encountered in optics, electrostatics, and magnetostatics. This was mainly because Lorentz still failed to recognize that local time and most of the other auxiliary quantities he defined for moving systems are actually the quantities measured by a co-moving observer. This is, in fact, true for all auxiliary quantities introduced in Lorentz's 1904 paper, except for the auxiliary charge and current densities.

Lorentz not only changed the formulation of the theorem of corresponding states somewhat in 1904, he also changed the way in which he added physical assumptions to the theorem to turn it into a theory predicting negative results for a broad class of ether drift experiments. Rather than adding the general assumption that material systems in different states of motion change in such a way that the field configurations they produce will always be the relevant member of a family of corresponding states, he added a number of more specific physical assumptions from which the general assumption might be derived. The most important of these were the assumption that all forces and all masses would have the velocity-dependence that Lorentz had first suggested in 1899. Rather than simply postulating the latter feature, Lorentz presented a concrete model of the electron whose mass exhibited the desired velocity-dependence if only the undetermined factor l in the expressions for the auxiliary quantities is set equal to 1. Lorentz's electron was a spherical surface charge distribution subject to a microscopic version of the Lorentz-FitzGerald

contraction. Its mass was due entirely to the interaction of the electron with its self-field. Max Abraham pointed out shortly afterwards that the model was inconsistent. Lorentz had not provided any mechanism to stabilize his purely electromagnetic electron. Such a mechanism was provided shortly afterwards by Poincaré, who had hit upon the same problem in Lorentz's model as Abraham. Only a decade or so later, it became clear that the velocity-dependence for which Lorentz sought to give a detailed explanation with the electron model he proposed in 1904 is, in fact, a generic property of particles described by the new relativistic mechanics.

In the same paper in which he proposed his amendment to Lorentz's electron model, Poincaré also perfected the proof of Lorentz's theorem of corresponding states. He replaced the auxiliary quantities that Lorentz had introduced for charge and current densities with slightly different ones. Unlike Lorentz, Poincaré realized that the auxiliary quantities are the measured quantities for the moving observer. This tremendously simplifies the task of accounting for the negative result of ether drift experiments on the basis of the theorem of corresponding states. Recall that the theorem says that the auxiliary quantities for the moving observer satisfy the same equations as the measured quantities for an observer at rest in the ether. If the auxiliary quantities are, in fact, the measured quantities in the moving system, there is no need, as Lorentz thought, for any further arguments showing that corresponding states agree in many of their observable properties (such as patterns of brightness and darkness). Poincaré coined the phrase Lorentz transformations for the transformations from the measured quantities in one system to the measured quantities in another. By introducing the new expression for the charge and current densities in the moving system, he completed the proof that the Maxwell-Lorentz equations are invariant under Lorentz transformations, to use the new way of expressing the content of the theorem of corresponding states. Poincaré also showed that Lorentz transformations form what mathematicians call a group. Roughly, what this means is that the inverse of a Lorentz transformation and the composite of two Lorentz transformations performed one after the other are themselves Lorentz transformations. The physical hypothesis which, as Lorentz had recognized in 1899, needs to be added to the theorem of corresponding states if the theory is to predict negative results in ether drift experiments can now be stated as the requirement that the laws governing the non-electromagnetic part of the systems studied in these experiments are Lorentz invariant, just as the equations governing the electromagnetic part. Such a theory is empirically fully equivalent to special relativity. It was only with the advent of the latter theory, that the implications of the Lorentz invariance of all physical laws were fully worked out, but as we have seen some of them—the Fresnel coefficient, relativity of simultaneity, length contraction, time dilation, mass increasing with velocity—had been anticipated in pre-relativistic ether theory.

Lorentz first used the interpretation of his auxiliary quantities as measured quantities in the moving system in a series of lectures in 1906 at Columbia University published in 1909. Lorentz gave all the credit for this reinterpretation to Einstein and curiously failed to mention Poincaré. Lorentz, however, did not accept Einstein's interpretation of Lorentz invariance as reflecting a new space-time structure. To the end of his life, Lorentz held on to the pre-relativistic notions of space and time, looking upon Lorentz invariance as a property accidentally shared by all laws governing systems in a Newtonian space-time. Lorentz found it particularly hard to abandon the notions of absolute simultaneity and of the ether as a substratum carrying the electromagnetic field.

As mentioned in the preceding section, Lorentz's theory was not the only theory of the electrodynamics of moving bodies current around the turn of the centuries. There were also the theories of Cohn, Larmor, and Wiechert. The first two authors were highly indebted to Lorentz's work. Wiechert independently found some of the results found by Lorentz. Here we shall just

discuss briefly the theory developed by Cohn in the early 1900s. The challenge facing Cohn was that of constructing a theory that could account both for the Fizeau experiment and the Michelson-Morley experiment. As an adherent of Ernst Mach's (1838–1916) philosophical viewpoint, which taught skepticism about all concepts not directly accessible to experience, it was presumably easier for Cohn than some others to take what must have seemed to him a logically necessary step: if an electromagnetic theory employing the ether concept must make contradictory assumptions about the motion of the ether inside matter to explain different experiments, one must eliminate the ether concept from electromagnetic theory. Cohn was well aware that Lorentz's macroscopic theory accounted for all first-order electrodynamic and optical effects without the introduction of the contraction hypothesis. (Lorentz, of course, derived these macroscopic equations from a microscopic model, but as a good Machian Cohn was at pains to eliminate all atomistic hypotheses as well.) Lorentz's 1895 explanation of these effects, as we have seen, was based on the invariance of Lorentz's equations to *first order* under an *embryonic* version of the Lorentz transformation that does not involve the contraction factor $\sqrt{1 - v^2/c^2}$.

So Cohn looked for, and found (1900), a *second-order* modification of Lorentz's macroscopic equations that is *exactly* invariant under the 1895 version of the Lorentz transformations for the space-time coordinates and the fields. Again in the spirit of Mach, he interpreted the velocity \mathbf{v} of matter as referring to motion not with respect to the ether but with respect to the fixed stars; so Cohn's theory still employs a preferred state of rest, but now an empirically observable one. Using these equations, Cohn could account for the result of Fizeau's experiment formally in much the same way as did Lorentz (but without reference to the ether, of course). But now, Lorentz's proof that motion through the ether had no first-order effect on terrestrial optical phenomena could be turned into an exact proof that motion with respect to the fixed stars had no effect on these phenomena, thus explaining the negative result of the Michelson-Morley experiment as well.

In a later development (1904) of his theory, Cohn interpreted the local time as the time given by terrestrial clocks if they are synchronized by optical signals, but suggesting that mechanical methods of synchronization would still give the absolute time. Many criticisms of Cohn's theory were offered, including its paradoxical prediction that, under certain circumstances, the velocity of light in a moving medium could exceed c in both the forward and backward directions. With the advent of Einstein's solution to the problems of the electrodynamics and optics of moving bodies by a reinterpretation of Lorentz's theory, Cohn's theory quickly faded from physicists' horizon.

BIBLIOGRAPHY

(a) Sources

- Arago 1910* Arago, François. "Mémoire sur la vitesse de la lumière, lu à la première classe de l'Institut, le 10 décembre 1810. *Académie des sciences* (Paris). *Comptes Rendus* 36 (1853): 38–49.
- Beer 1855* Beer, August. "Über die Vorstellungen vom Verhalten des Aethers in bewegten Mitteln." *Annalen der Physik* 4 (1855): 428–434.
- Brace 1904* Brace, Dewitt Bristol. "On Double Refraction in Matter Moving Through the Aether." *Philosophical Magazine* 7 (1904): 317–329.
- Cohn 1900* Cohn, Emil. "Über die Gleichungen der Elektrodynamik für bewegte Körper." *Archives néerlandaises des sciences exactes et naturelles* 5 (1900): 516–523.
- Cohn 1901* ——. "Über die Gleichungen des elektromagnetischen Feldes für bewegte Körper." *Annalen der Physik* 7 (1902): 29–56.

- Cohn 1904a ——. “Zur Elektrodynamik bewegter Systeme” *Königlich Preußische Akademie der Wissenschaften* (Berlin). *Sitzungsberichte* (1904): 1294–1303.
- Cohn 1904b ——. “Zur Elektrodynamik bewegter Systeme. II” *Königlich Preußische Akademie der Wissenschaften* (Berlin). *Sitzungsberichte* (1904): 1404–1416.
- Einstein 1905 Einstein, Albert. “Zur Elektrodynamik bewegter Körper.” *Annalen der Physik* 17 (1905): 891–921.
- Einstein 1915 ——. “Die Relativitätstheorie.” In: *Die Kultur der Gegenwart. Ihre Entwicklung und ihre Ziele*. Paul Hinneberg, ed. Part 3, sec. 3, vol. 1, *Physik*. Emil Warburg, ed. Leipzig: Teubner, 1915. Pp. 703–713.
- Einstein 1953 ——. “H. A. Lorentz als Schöpfer und Persönlichkeit.” In: *Mein Weltbild*. 2nd ed. Carl Seelig (ed.). Zurich: Europa Verlag, 1953.
- Fizeau 1851 Fizeau, Hippolyte. “Sur les hypothèses relatives à l'éther lumineux, et sur une expérience qui paraît démontrer que le mouvement des corps change la vitesse à laquelle la lumière se propage dans leur intérieur.” *Académie des sciences* (Paris). *Comptes Rendus* 33 (1851): 349–355.
- Fresnel 1818 Fresnel, Augustin. “Lettre d'Augustin Fresnel à François Arago sur l'influence du mouvement terrestre dans quelques phénomènes d'optique.” *Annales de chimie et de physique* 9 (1818): 57–66, 286. Reprinted in: *Oeuvres Complètes*. Paris: Imprimerie impériale, 1866–1870. Vol. 2, pp. 627–636.
- Glazebrook 1885 Glazebrook, Richard Tetley. “Report on Optical Theories.” *British Association Reports* (1885): 157–261.
- Heaviside 1892 Heaviside, Oliver. *Electrical Papers*. Vol. 1. London: Macmillan, 1892.
- Hertz 1890 Hertz, Heinrich. “Über die Grundgleichungen der Elektrodynamik für bewegte Körper.” *Annalen der Physik* 41 (1890): 369–399.
- Ketteler 1873 Ketteler, Eduard. *Astronomische Undulationstheorie oder die Lehre von der Aberration des Lichtes*. Bonn: P. Neusser, 1873
- Klinkerfues 1867 Klinkerfues, Ernst Friedrich Wilhelm. *Die Aberration der Fixsterne nach der Wellentheorie*. Leipzig: Von Quandt & Händel, 1867.
- Larmor 1894 Larmor, Joseph. “A Dynamical Theory of the Electric and Luminiferous Medium.” *Royal Society of London. Philosophical Transactions A* 185 (1894): 719–822.
- Larmor 1895 ——. “A Dynamical Theory of the Electric and Luminiferous Medium. Part II: Theory of Electrons.” *Royal Society of London. Philosophical Transactions A* 186 (1895): 659–743.
- Larmor 1897 ——. “A Dynamical Theory of the Electric and Luminiferous Medium. Part III: Relations with Material Media.” *Royal Society of London. Philosophical Transactions A* 190 (1897): 205–300.
- Larmor 1900 ——. *Aether and Matter*. Cambridge: Cambridge University Press, 1900.
- Laub 1908 Laub, Jakob. “Über die experimentellen Grundlagen des Relativitätsprinzips.” *Jahrbuch der Radioaktivität und Elektronik* 7 (1910): 405–463.
- Lorentz 1886 Lorentz, Hendrik A. “Over den invloed, dien de beweging der aarde op de lichtverschijnselen uitoefent.” *Koninklijke Akademie van Wetenschappen* (Amsterdam). *Afdeeling Natuurkunde. Verslagen en Mededeelingen* 2 (1885–86): 297–372. Reprinted in translation: “De l'influence du mouvement de la terre sur les phénomènes lumineux.” *Archives néerlandaises des sciences exactes et naturelles* 21 (1887): 103–176.
- Lorentz 1892a ——. “La theorie electromagnétique de Maxwell et son application aux corps mouvants.” *Archives néerlandaises des sciences exactes et naturelles* 25 (1892): 363–552.
- Lorentz 1892b ——. “De relatieve beweging van de aarde en den aether.” *Koninklijke Akademie van Wetenschappen te Amsterdam. Wis- en Natuurkundige Afdeeling. Verslagen der Zittingen* 1 (1892–93): 74–79. Reprinted in translation: “The Relative Motion of the Earth and the Ether.” In: *Collected Papers* (P. Zeeman and A. D. Fokker, eds.), Vol. 4. The Hague: Nijhoff, 1937. Pp. 219–223
- Lorentz 1895 ——. *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern*. Leyden: Brill, 1895.
- Lorentz 1899 ——. “Vereenvoudigde theorie der electrische en optische verschijnselen in lichamen die zich bewegen.” *Koninklijke Akademie van Wetenschappen te Amsterdam. Wis- en Natuurkundige Afdeeling. Verslagen van de Gewone Vergaderingen* 7 (1898–99): 507–522.

- Reprinted in slightly revised translation: "Simplified theory of electrical and optical phenomena in moving bodies." *Koninklijke Akademie van Wetenschappen te Amsterdam. Section of Sciences. Proceedings* 1 (1898–99): 427–442.
- Lorentz 1904 ——. "Electromagnetische verschijnselen in een stelsel dat zich met willekeurige snelheid, kleiner dan die van het licht, beweegt." *Koninklijke Akademie van Wetenschappen te Amsterdam. Wis- en Natuurkundige Afdeling. Verslagen van de Gewone Vergaderingen* 12 (1903–04): 986–1009. Reprinted in translation as "Electromagnetic Phenomena in a System Moving with Any Velocity Smaller Than That of Light." *Koninklijke Akademie van Wetenschappen te Amsterdam. Section of Sciences. Proceedings* 6 (1903–04): 809–831.
- Lorentz 1915 ——. *The Theory of Electrons and Its Applications to the Phenomena of Light and Radiant Heat. A Course of Lectures Delivered in Columbia University, New York, in March and April 1906*. 2nd ed. Leipzig: Teubner, 1915.
- Mascart 1872 Mascart, Éleuthère Élie Nicolas. "Modifications qu'éprouve la lumière par suite du mouvement de la source lumineuse et du mouvement de l'observateur." *Annales Scientifiques de l'École Normale Supérieure* 2ème série, 1 (1872): 157–214.
- Mascart 1874 ——. "Modifications qu'éprouve la lumière par suite du mouvement de la source lumineuse et du mouvement de l'observateur (deuxième partie)." *Annales Scientifiques de l'École Normale Supérieure* 2ème série, 3 (1874): 363–420.
- Mascart 1893 ——. *Traité d'Optique*. Vol. 3, Ch. 15. Paris: Gauthier-Villars.
- Maxwell 1873 Maxwell, James Clerk. *A Treatise on Electricity and Magnetism*. 2 Vols. Oxford: Clarendon Press, 1873.
- Michelson 1881 Michelson, Albert A. "The Relative Motion of the Earth and the Luminiferous Ether." *American Journal of Science* 22 (1881): 120–129.
- Michelson and Morley 1886 Michelson, Albert A., and Morley, Edward W. "Influence of Motion of the Medium on the Velocity of Light." *American Journal of Science* 31 (1886): 377–386.
- Michelson and Morley 1887 ——. "On the Relative Motion of the Earth and the Luminiferous Ether." *American Journal of Science* 34 (1887): 333–345.
- Poincaré 1889 Poincaré, Henri. *Leçons sur la théorie mathématique de la lumière, professées pendant le premier semestre 1887–1888*. Jules Blondin (ed.). Paris: Carré et Naud, 1889.
- Poincaré 1900 ——. "La théorie de Lorentz et le principe de réaction." *Archives néerlandaises des sciences exactes et naturelles* 5 (1900): 252–278.
- Poincaré 1906 ——. "Sur la dynamique d'électron." *Circolo Matematico di Palermo. Rendiconti* 21 (1906): 129–175.
- Potier 1874 Potier, Alfred. "Conséquences de la formule de Fresnel relative à l'entraînement de l'éther par les milieux transparents." *Journal de physique* 3 (1874): 201–204.
- Potier 1912 ——. *Mémoires sur l'électricité et l'optique*. A. Blondel (ed.). Paris: Gauthier-Villars, 1912.
- Rayleigh 1902 Lord Rayleigh. "Does Motion Through the Aether Cause Double Refraction?" *Philosophical Magazine* 4 (1902): 678–683.
- Stokes 1845 Stokes, George Gabriel. "On the Aberration of Light." *Philosophical Magazine* 27 (1845): 9–15.
- Stokes 1846a ——. "On Fresnel's Theory of the Aberration of Light." *Philosophical Magazine* 28 (1846): 76–81.
- Stokes 1846b ——. "On the Constitution of the Luminiferous Aether Viewed with Reference to the Phenomenon of the Aberration of Light." *Philosophical Magazine* 29 (1846): 6–10.
- Stokes 1848 ——. "On the Constitution of the Luminiferous Ether." *Philosophical Magazine* 32 (1848): 343–349.
- Trouton 1902 Trouton, Frederick T. "The Results of an Electrical Experiment, Involving the Relative Motion of the Earth and Ether, Suggested by the Late Professor FitzGerald." *Transactions of the Royal Dublin Society* 7 (1902): 379–384.
- Trouton and Noble 1903 Trouton, Frederick T., and Noble, Henry R., "The Mechanical Forces Acting on a Charged Electric Condenser Moving Through Space." *Philosophical Transactions of the Royal Society, London* 202 (1903): 165–181.
- Veltmann 1873 Veltmann, Wilhelm. "Über die Fortplanzung des Lichtes in bewegten Medien." *Annalen der Physik* 150 (1873): 497–535.

- Wiechert 1896 Wiechert, Emil. "Über die Grundlagen der Electrodynamik." *Annalen der Physik und Chemie* 59 (1896): 283–323.
- Young 1804 Young, Thomas, "Experiments and Calculations relative to physical Optics." *Philosophical Transactions of the Royal Society* 94 (1): 1–14.

(b) Studies

- Acloque 1984 Acloque, Paul. "Hippolyte Fizeau et le mouvement de la Terre: une tentative méconnue." *Comptes Rendus de l'Académie des Sciences. La Vie des Sciences*. Tome 1, Série Générale, No 2 (1984): 145–158.
- Born and Wolf 1970 Born, Max, and Wolf, Emil. *Principles of Optics. Electromagnetic Theory of Propagation, Interference, and Diffraction of Light*. 4th Ed. Oxford: Pergamon Press, 1970.
- Cantor and Hodge 1981 Cantor, G. N., and Hodge, M. J. S (eds.). *Conceptions of Ether: Studies in the History of Ether Theories 1740–1900*. Cambridge: Cambridge University Press, 1981.
- Darrigol 1993 Darrigol, Olivier. "The Electrodynamics of Moving Bodies from Faraday to Hertz." *Centaurus* 36 (1993): 245–260.
- Darrigol 1994 ——. "The Electron Theories of Larmor and Lorentz: A Comparative Study." *Historical Studies in the Physical and Biological Sciences* 24 (1994): 265–336.
- Darrigol 1995a ——. "Emil Cohn's Electrodynamics of Moving Bodies." *American Journal of Physics* 63 (1995): 908–915.
- Darrigol 1995b ——. "Henri Poincaré's Criticism of Fin de Siècle Electrodynamics." *Studies in History and Philosophy of Modern Physics* 26 (1995): 1–44
- Goldberg and Stuewer 1988 Goldberg, Stanley, and Stuewer, Roger H. *The Michelson Era in American Science 1870–1930*. New York: American Institute of Physics, 1988.
- Hirosige 1966 Hirosige, Tetu. "Electrodynamics before the Theory of Relativity, 1890–1905." *Japanese Studies in the History of Science* 5 (1966): 1–49.
- Janssen 1995 Janssen, Michel. *A Comparison between Lorentz's Ether Theory and Special Relativity in the Light of the Experiments of Trouton and Noble*. Ph.D. Thesis. University of Pittsburgh, 1995.
- Paty 1996 Paty, Michel. "Poincaré et le principe de relativité." In: Jean-Louis Greffe, Gerhard Heinzman, and Kuno Lorentz (eds.). *Henri Poincaré: Science et philosophie*. Paris: Albert Blanchard, 1996. Pp. 101–143.
- Picard 1924 Picard, Émile. *Les théories de l'optique et l'oeuvre d'Hippolyte Fizeau*. Paris: Gauthier-Villars, 1924.
- Schaffner 1972 Schaffner, Kenneth F. *Nineteenth Century Aether Theories*. Oxford, New York: Pergamon Press, 1972.
- Sesmat 1937 Sesmat, Augustine. *Systèmes de référence et mouvement (Physique classique)*. Vol. 6, *L'optique des corps en mouvement*. Actualités scientifiques et industrielles, no. 484. Paris: Hermann, 1937.
- Sommerfeld 1964 Sommerfeld, Arnold. *Lectures on Theoretical Physics. Vol. IV. Optics*. New York: Academic Press, 1964.
- Swenson 1972 Swenson, Loyd S. Jr. *The Ethereal Aether: A History of the Michelson–Morley–Miller Aether-Drift Experiments, 1880–1930*. Austin: University of Texas Press, 1972.
- Warwick 1995 Warwick, Andrew. "The Sturdy Protestants of Science: Larmor, Trouton, and the Earth's Motion Through the Ether." In: Buchwald, Jed (ed.), *Scientific Practice. Theories and Stories of Doing Physics*. Chicago: University of Chicago Press, 1995. Pp. 300–343.
- Whittaker 1951–53 Whittaker, Sir Edmund T. *A History of the Theories of Aether and Electricity*. 2 Vols. London: Nelson, 1951–53.
- Wilson 1972 Wilson, David B. "George Gabriel Stokes on Stellar Aberration and the Luminiferous Ether." *British Journal for the History of Science* 21 (1972): 57–79.

