Einstein for Everyone
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Michel Janssen

19th Century Ether Theory.[1]

Scientists working on the wave theory of light in the 19th century took it for granted that there had to be a medium for the propagation of light waves. This medium was called the luminiferous [= "light carrying"] ether. One of the central questions about this medium concerned its state of motion. There were two options: (1) The ether is completely undisturbed by matter moving through it (stationary or immobile ether); (2) Matter drags along the ether in its vicinity and/or in its interior (dragged-along ether). Stellar aberration provided the main argument for the first option (even though a special dragging effect in the case of transparent matter had to be built into the theory to account for refraction). Polarization provided the main argument for the second option. These two options and the arguments pro and con will be explained in more detail below.

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.

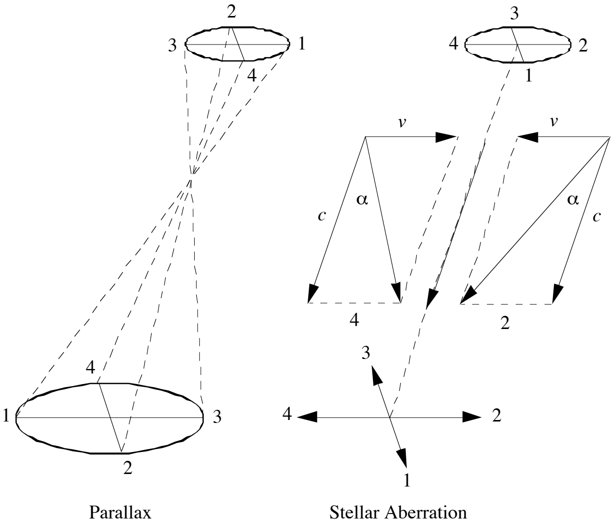

Figure 1: Parallax and aberration

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

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[1] This handout is based on: Michel Janssen and John Stachel, The Optics and Electrodynamics of Moving Bodies. To appear in: Sandro Petruccioli (ed.), *Storia Della Szienza* . Istituto della Enciclopedia Italiana.

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 particle 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 _ is called the aberration angle). The observed effect is proportional to the ratio of v, 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 Römer (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 particle 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 revival of the wave theory of light at the beginning of the 19th century through the work of Thomas Young (1773–1829) and Augustin Jean Fresnel (1788–1827), the phenomenon of stellar aberration became important in yet another way. The simple explanation of aberration in the particle 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 particle 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 Young put it: "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).

In 1845 George Gabriel Stokes (1819–1903) nonetheless 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. Young and Fresnel came to realize 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.

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. Arago asked Fresnel (1788–1827) whether the wave theory could account for these observations. 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. 2.

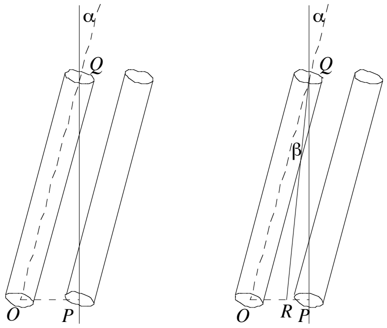

Figure 2: Aberration, refraction, and the Fresnel coefficient (ray analysis)

This “telescope” is just a long hollow cylinder that we aim at the star. 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.

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 $\mathbf{v}$ of the glass that ensures the path remains QP. From the geometry of the figure, we can determine that this fraction must be:

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

This fraction is called the Fresnel (dragging) coefficient.

The situation shown on the right in Fig. 2 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. 2 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. 2 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.*

These considerations concerning refraction also apply 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. In 1871, George Biddell Airy (1801–1892) 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), Hippolyte Fizeau (1819–1896) 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. 3

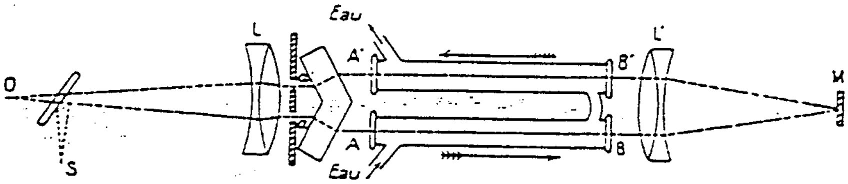

Figure 3: The Fizeau Experiment

Fizeau examined the effect of a water flow (*ABB´A´*) on the interference pattern produced by light travelling with the flow (*ABB´A´*) and counter to the flow (*A´B´BA*). 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. He 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. He showed that it follows from these assumptions that on average the ether inside the medium moving through the ether with velocity $\mathbf{v}$ will move with a fraction $f = 1 - \frac{1}{n^2}$ of that velocity. 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. One of the most damning objections against the mechanisms that were explored came from an experiment done by 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.

The work of 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. 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. 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.

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. Maxwell wrote to the American astronomer D. P. Todd (1855–1939) to inquire whether the existing astronomical data were accurate for this method to work. 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 Albert Abraham Michelson (1852–1931), 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. 4 schematically shows the instrument Michelson designed for this purpose, an instrument now known as a Michelson interferometer.

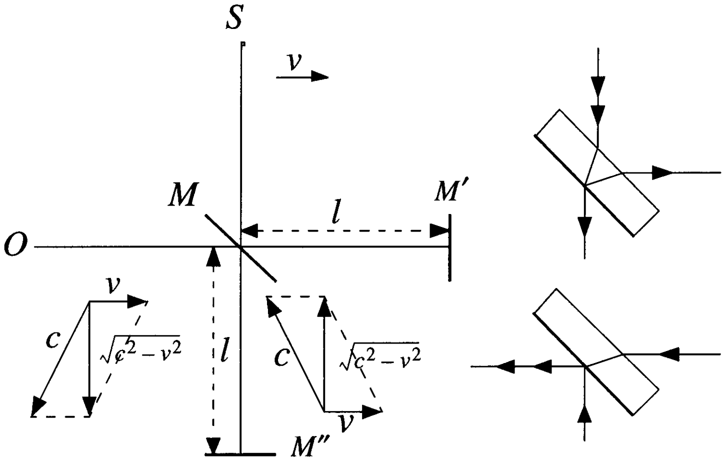

Figure 4: Michelson interferometer

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. 4. 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.

Suppose the ether is moving with respect to the interferometer with a velocity **v** as indicated in Fig. 4. 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. 4, 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

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

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:

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

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. 5 below). If the arm MM' is in the direction of $\mathbf{v}$, as in Fig. 4, 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.

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. 5 shows the interferometer he had constructed for the experiment.

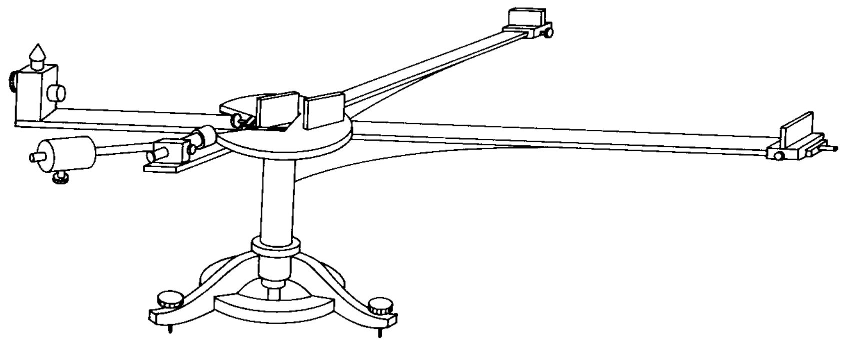

Figure 5: The Michelson interferometer of 1881

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. 6), Michelson and Morley were able to confirm Fresnel’s formula with much greater accuracy than Fizeau.

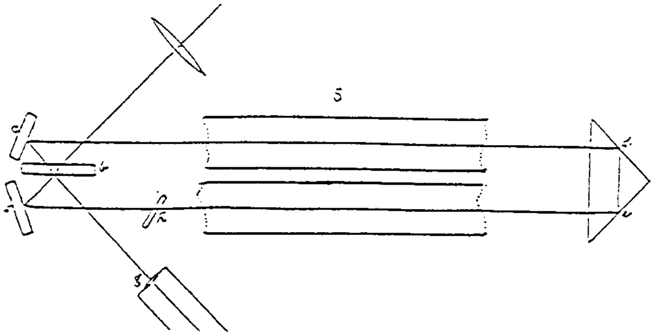

Figure 6: The design of Michelson and Morley’s repetition of the Fizeau experiment

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).

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 an article published in 1886 by Hendrik Antoon Lorentz (1853–1928). In this article, Lorentz 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, showing that the various assumptions that Stokes had made about the motion of the ether were incompatible with one another. So the ether at the earth's surface could not be at rest with respect to the earth, but at this point (he would change his mind in the 1890s) Lorentz left open the possibility that the ether at the earth's surface was at least partially dragged along by the earth.

Fig. 7 shows the interferometer Michelson and Morley constructed for the repetition of the experiment in 1887.

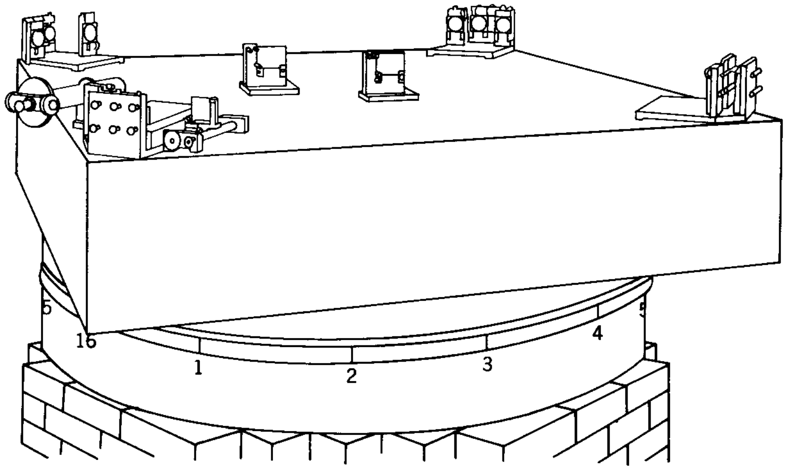

Figure 7: The Michelson interferometer of 1887

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 theory of a partially dragged along ether. 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 things as aberration and the Fizeau experiment.

Lorentz and the Completely Immobile Ether Theory: A New Derivation of the Fresnel Coefficient 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. 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. These fields in turn exert forces on the charged particles.

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 (Lorentz 1892a, pp. 524–526). In Lorentz's account, it is the waves that are partially dragged by the medium and not the ether.

Later in 1892, Lorentz also proposed an explanation for why the Michelson-Morley experiment had failed to detect ether drift (Lorentz 1892b). He later discovered that this explanation had already been suggested in 1889 by George Francis FitzGerald (1851–1901). 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. The contraction hypothesis thus explains the negative result of the Michelson-Morley experiment.

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