AMERICAN JOURNAL of PHYSICS

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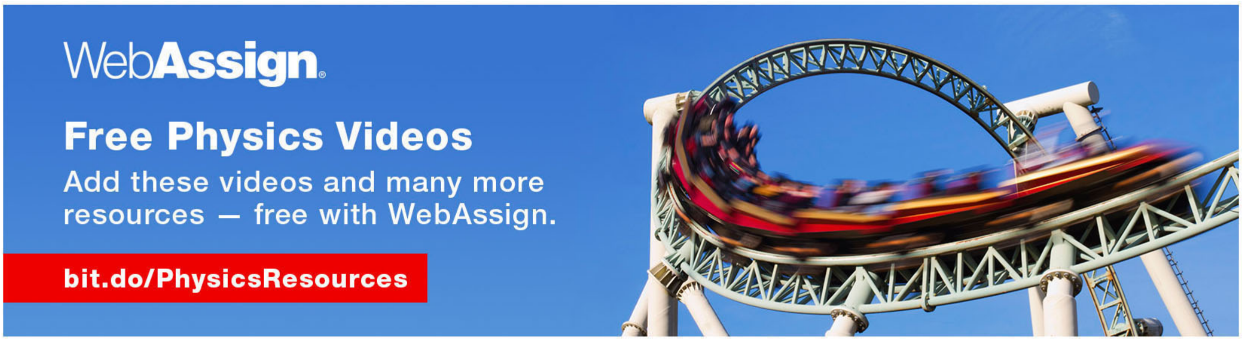
Citation: American Journal of Physics **32**, 16 (1964); doi: 10.1119/1.1970063
View online: http://dx.doi.org/10.1119/1.1970063
View Table of Contents: http://scitation.aip.org/content/aapt/journal/ajp/32/1?ver=pdfcov
Published by the American Association of Physics Teachers



Michelson–Morley Experiment*

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(Received 16 July 1963)

The Michelson–Morley experiment, performed in Cleveland in 1887, proved to be the definitive test for discarding the Fresnel aether hypothesis which had dominated physics throughout the 19th century. The experiment had been suggested to Michelson by his study of a letter of James Clerk Maxwell, and a preliminary but inconclusive trial had been made at Potsdam in 1881. It seems certain that the experiment would never have been repeated except for the urging of Kelvin and Rayleigh at the time of Kelvin's Baltimore Lectures in 1884, which Michelson and Morley attended. The conclusive null result of the Cleveland experiment was decisive in its influence on Lorentz, FitzGerald, Larmor, Poincaré, and Einstein in developing their theories of the electrodynamics of moving bodies, which culminated in the special theory of relativity. The present account contains material from extensive notes and correspondence related to the work of Michelson and Morley which the writer has assembled during the past years.

I. INTRODUCTION

THE revival and development of the wave theory of light at the beginning of the nineteenth century, principally through the contributions of Young and Fresnel, raised a problem which proved to be of major interest for physics throughout the entire century. The question was on the nature of the medium in which light is propagated. This medium was called the aether and an enormous amount of experimental and theoretical work was expended in efforts to determine its properties. On the experimental side, a long series of electrical and optical investigations was carried out attempting to measure the motion of the earth through the aether medium. For many years, the experimental precision permitted measurements only to the first power of the ratio of the speed of the earth in its orbit to the speed of light ($v/c \simeq 10^{-4}$), and these "first-order experiments" uniformly gave null results. It became the accepted view that the earth's motion through the aether could not be detected by laboratory experiments of this sensitivity. With the development of Maxwell's electromagnetic theory of light, and especially with its extensions by Lorentz in his electron theory, theoretical explanations for the null results obtained in the first-order aether-drift experiments were provided. This situation was in harmony with the Galilean–Newtonian principle of relativity in mechanics, which asserts that the essential features of all uniform motions are independent of the frame of reference in which they are described. In Maxwell's electromagnetic theory, however, the situation was different when quantities of the second order in (v/c) were considered. According to the Maxwell theory, effects depending on $(v/c)^2$ should have been detectable in optical and electrical experiments. The presence of these effects would reveal a preferred reference frame for the phenomena in which the aether would presumably be at rest. At first, this feature of Maxwell's theory, which implied that aether-drift effects to the second order in (v/c) might be observed, raised a purely hypothetical question because the accuracy needed for such experiments was about one part in a hundred million, and no experimental techniques then known could attain this sensitivity.[1]

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* This paper is the result of three talks given by the the writer. The first was on 19 December 1952 when the Cleveland Physics Society celebrated the centenary of the birth of Michelson. The second was at the New York meeting of the American Association of Physics Teachers on 30 January 1959, and the third was at a symposium on 24 November 1962 organized by The American Physical Society for its Cleveland meeting to commemorate the 75th Anniversary of the Michelson–Morley experiment.

[1] James Clerk Maxwell, article on aether in Encyclopaedia Britannica 9th ed., Vol. 8; also, in *Scientific Papers* (Dover Publications, Inc., New York, 1952), Vol. 2, pp. 763–775. "If it were possible to determine the velocity of light by observing the time it takes to travel between one station and another on the earth's surface, we might, by comparing the observed velocities in opposite directions, determine the velocity of the aether with respect to these terrestrial stations. All methods, however, by which it is practicable to determine the velocity of light from terrestrial experiments depend on the measurement of the time required for the double journey from one station to the other and back again, and the increase of this time on account of the relative velocity of the aether equal to that

Michelson pondered this problem and it led him to invent the Michelson interferometer and to plan the aether-drift experiment, which he carried to completion in collaboration with Edward W. Morley at Cleveland in 1887. This famous optical-interference experiment was devised to measure the motion of the earth through the aether of space by means of an extremely sensitive comparison of the velocity of light in two mutually perpendicular directions. The experiment as carried out in 1887 gave a most convincing null result and proved to be the culmination of the long nineteenth-century search for an aether. At that time, the definitive null result of the Michelson–Morley experiment was a most disconcerting finding for theoretical physics, and indeed for many years repetitions of this experiment and related ones were performed with the hope of finding positive experimental evidence for the earth's motion through the aether. These later experiments, however, have all been shown to be consistent with the original null result obtained by Michelson and Morley.[2] In the years following 1887, their experiment led to extensive and revolutionary developments in theoretical physics. It proved to be the major incentive for the work of FitzGerald, Lorentz, Larmor, Poincaré, and others, leading finally in 1905 to the special theory of relativity of Albert Einstein.

II. ANNAPOLIS AND WASHINGTON

In the years immediately following Michelson's graduation from the U. S. Naval Academy in 1873, his researches in optics were exclusively concerned with measurements of the speed of light. While serving during 1875–1879 as instructor in physics at Annapolis, he made his first determination of this quantity with a demonstration for the students in November 1877 in which he repeated, with essential improvements, the rotating-mirror experiment of Foucault. These simple trials gave such good results that he decided to repeat and extend them with improved apparatus. This led to his transfer in 1879 to the Nautical Almanac Office in Washington, D. C., where Professor Simon Newcomb was director. Newcomb was the leading scientist in Washington, and he obtained ample support for their measurements of the speed of light made between stations at Fort Myer, Virginia, and the Old Naval Observatory and the Washington Monument.

Perhaps the most important event which occurred for Michelson while he was at the Nautical Almanac Office was his opportunity to study a letter dated 19 March 1879 from James Clerk Maxwell to David Peck Todd,[3] then also associated with the Nautical Almanac Office. In this, Maxwell inquired whether the existing observations of the eclipses of Jupiter's satellites made at several epochs of the earth's orbital motion were of sufficient accuracy to permit a determination of the absolute motion of the earth through space by an extension of Roemer's method, which Maxwell had proposed. The essential contents of this letter, for Michelson, were in the final paragraph containing the statement that all terrestrial methods for measuring the velocity of light could not detect the earth's motion through space, since "in the terrestrial methods of determining the velocity of light, the light comes back along the same path again, so that the velocity of the earth with respect to the ether would alter the time of the double passage by a quantity depending on the square of the ratio of the earth's velocity to that of light, and this is quite too small to be observed."

Michelson's interest was keenly aroused by the discussions of this problem with Todd and Newcomb, and especially by Maxwell's belief that no experiment to measure the speed of light could be devised with sufficient sensitivity to make possible a terrestrial measurement of the earth's motion through the aether. This was the challenge which led Michelson to his studies of optical interference methods and to his determination to pursue this problem as the principal objective of his study and research in Europe while on a leave of absence from regular Navy duty, which had been arranged for him by Simon Newcomb.

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of the earth in its orbit would be only about one hundred millionth part of the whole time of transmission, and would therefore be quite insensible."

[2] R. S. Shankland, S. W. McCuskey, F. C. Leone, and G. Kuerti, Rev. Mod. Phys. **27**, 167 (1955).

[3] J. C. Maxwell letter to D. P. Todd, reprinted in Nature 21, 314–317 (1880); Proc. Roy. Soc. (London) **A30**, 109–110 (1880); reply of Todd to Maxwell (19 May 1879) furnished to the writer by his daughter, Mrs. Millicent Todd Bingham, of Washington, D. C.

III. STUDIES IN EUROPE AND THE MICHELSON INTERFEROMETER

When Michelson, Master, U. S. Navy, sailed with his family for Europe in September 1880 for two years of study and research, he already was well-known for his precise measurements of the speed of light. Following brief stays in London and Paris, where he had letters of introduction to leading physicists from Simon Newcomb, he went on to Berlin. His plans for the optical-interference experiment, which he had started in a preliminary way at the Nautical Almanac Office, were continued at von Helmholtz's laboratory in the Physikalisches Institut at the University of Berlin, where he began his studies in the winter semester. This laboratory of von Helmholtz had a distinguished reputation and had attracted many students from abroad. "From America in 1876 had come Henry A. Rowland with all the plans and specifications already on paper, for his now famous 'Berlin Experiment' on the magnetic effect of electric convection. Helmholtz had furnished Rowland a research room, materials with which to construct his apparatus, and then had 'let him alone' to carry out his famous experiment. Later Henry Crew, James S. Ames, Arthur Gordon Webster, Michael Pupin, and D. B. Brace were to study and carry on research in Helmholtz's laboratory. In spite of his brilliance and high position and the awe in which he was held by the whole scientific world of Germany, Helmholtz was in fact a kindly, quiet and benevolent man who showed a deep interest in any proposed plan of study or research of a student. After his 10 a.m. lecture on Experimental Aspects of Physics, Helmholtz would walk around the laboratory talking in a friendly way on the progress of the experiments of his younger colleagues and research students, who at the time of Michelson's visit, included Otto Lummer, Ernst Hagen, and Heinrich Hertz."[4]

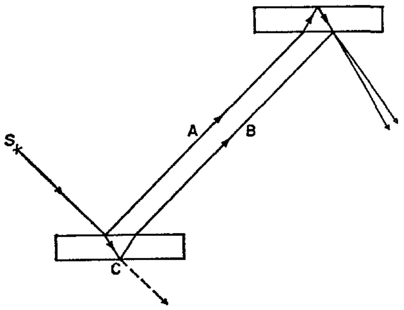

FIG. 1. Jamin interferometer.

It was in this congenial atmosphere that Michelson's studies led him to the invention of his interferometer. It is, of course, impossible to trace all the threads that lead to a great invention, but it is probable that Michelson was influenced by careful consideration of the interference devices developed by Jamin[5] in which the entire wavefront is *divided in amplitude* at a plane parallel plate set at an angle to the incident beam, and then recombined at a second plane parallel plate of exactly equal thickness and set approximately parallel to the first. Figure 1 shows the Jamin form of interferometer.

This device although having the advantage that it produces two coherent beams by *division of wave amplitude*, with correspondingly high intensity, nevertheless suffers from the limitation that the separation of the two beams is small, being limited by the thickness of the glass plates employed. Michelson realized, however, that, by using the coherent light beams (B) and (C) separated at the second surface of the first Jamin plate, he could then reflect these from widely spaced mirrors and then reunite them to produce interference fringes. The great advantage of Michelson's method over the Jamin interferometer is that beams (B) and (C) can be separated to accomodate apparatus of many forms, whereas using the beams (A) and (B) in the Jamin instrument limits the possible experiments to those requiring only a relatively small separation of the two coherent beams. Although in principle the two beams in Michelson's method may travel at various angles,[6] in the usual form of his interferometer the beams are oriented at 90°, as shown in Fig. 2.[7] Michelson's first trials of his interferometer were made by fastening the optical parts to a pier by pieces of wax. It took several hours of continuous

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[4] Letters from Professor Henry Crew to the writer (26 Nov. 1950; 7 Aug. 1952).

[5] J. Jamin, Ann. Chim. Phys. **52**, 163, 171 (1858).

[6] A. A. Michelson, (a) *Studies in Optics* (University of Chicago Press, Chicago, 1927), pp. 21–26; (b) *Light Waves and Their Uses* (University of Chicago Press, Chicago, 1903), pp. 35–43.

[7] A. A. Michelson, Am. J. Sci. **22**, 120 (1881).

searching to find the white-light fringes in this way.[8]

It may perhaps seem only a simple step from Jamin's apparatus to the Michelson interferometer and indeed many years later Mascart referred to it as one in which the optical parts, "sont disposées comme dans l'appareil interferentiel de M. Jamin."[9] But, however great may be Michelson's debt to his predecessors for their development of interference methods, it must be remembered that his form of interferometer was devised for the express purpose of measuring an effect of the earth's motion on the speed of light[10] and that his interferometer and the famous experiment for which it was the elegant and simple tool are alike the product of the genius revealed in all his optical researches.

As had been his custom in America, Michelson reported frequently to Simon Newcomb on the progress of his work, and a most interesting letter of this period is the following[11]:

Berlin, November 22, 1880

Dear Sir,

Your very welcome letter has just been received. It will give me much pleasure to let you know how I am progressing.

At present the work in the laboratory is quite elementary, and I am trying to get over that part somewhat hurriedly.

Besides this work I attend the lectures on Theoretical Physics by Dr. Helmholtz, and am studying mathematics and mechanics at home.

I had quite a long conversation with Dr. Helmholtz concerning my proposed method for finding the motion of the earth relative to the ether, and he said he could see no objection to it, except the difficulty of keeping a constant temperature. He said, however, that I had better wait till my return to the U. S. before attempting them, as he doubted if they had the facilities for carrying out such experiments on account of the necessity of keeping a room at a constant temperature.

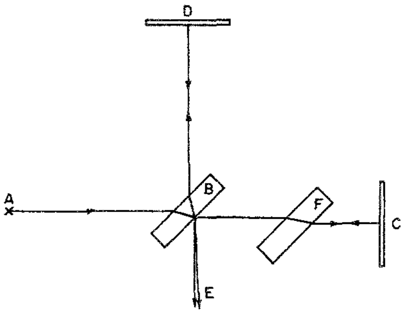

FIG. 2. Michelson interferometer.

With all due respect, however, I think differently, for if the apparatus is surrounded with melting ice, the temperature will be so nearly constant as possible.

There is another and unexpected difficulty, which I fear will necessitate the postponement of the experiments indefinitely—namely—that the necessary funds do not seem to be forthcoming.

Dr. Helmholtz was however quite willing to have me make experiments upon light passing through a narrow aperture—but did not give much encouragement. In his opinion the polarization arises purely from reflection from the sides of the slit.

The change in color, he ignores entirely.

With many thanks for your kind interest in my affairs I remain,

Very truly yours,
Albert A. Michelson

Prof. Simon Newcomb, U.S.N.
Supt. Naut. Almanac

The necessary funds (£100) referred to in this letter were furnished by Alexander Graham Bell at the suggestion of Simon Newcomb, and Michelson then selected the firm of Schmidt and Haensch in Berlin to build an instrument. This firm had specialized in the construction of optical-polarimeter equipment, but they could not supply the precise optical flats needed for the interferometer. These Michelson obtained from "Maison Breguet" in Paris, who were well-known suppliers of optical plates for Jamin interferometers.

When the Schmidt and Haensch instrument was ready, Michelson set up the new interferometer in von Helmholtz's laboratory. A perspective drawing of this apparatus is shown in Fig. 3. The light beam from the source (a) was divided in amplitude at the glass plate (b) set at 45° on the axis of the instrument. The two

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[8] Dayton C. Miller to writer (10 Apr. 1933).

[9] M. E. Mascart, *Traité d'optique* (Gauthier-Villars et Fils, Paris, 1893), Vol. 3, p. 111.

[10] Reference 6(b); pg. 159. "The experiment is to me historically interesting, because it was for the solution of this problem that the interferometer was devised. I think it will be admitted that the problem, by leading to the invention of the interferometer, more than compensated for the fact that this particular experiment gave a negative result."

[11] The existence of this letter was reported to the writer by Dr. Loyd S. Swenson, Jr., of the University of California, Riverside. The fourth paragraph clearly assumes that Newcomb was acquainted with the general plan of Michelson's experiment, and thus indicates that it had been discussed with Newcomb while Michelson was still in Washington. This paragraph also emphasizes the importance of good temperature control for the experiment—a matter of concern throughout the long history of the repetitions and refinements of the experiment.

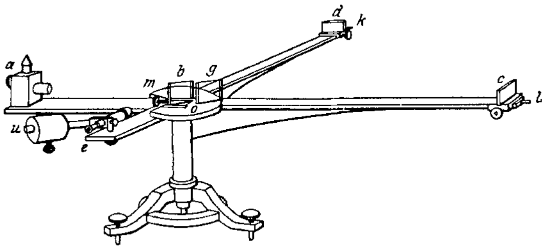

FIG. 3. Michelson interferometer used at Berlin and Potsdam.

coherent beams traveled at right angles to each other along the two arms of the interferometer and were then reflected back by the mirrors (c) and (d). With these set at the extreme ends of the arms, the two optical paths were each 120 cm. The interference fringes were found by first using a sodium light source and after adjustment for maximum visibility, the source was changed to white light and the colored fringes then located. White-light fringes were employed to facilitate observation of shifts in position of the interference pattern. These were viewed and measured on a scale ruled on glass in the small telescope (e), which was focussed on the surface of the mirror (d), where the interference fringes were most distinct. In his first description of this device, Michelson referred to it as an "interferential refractor."

The experiment to observe "the relative motion of the Earth and the luminiferous ether," for which this instrument was devised was planned by Michelson as follows. When the interferometer is oriented, as in Fig. 4, with the arm L_1 parallel to the direction of the earth's velocity v in space, the time required for light to travel from M to M_1 and return to M in its new position is

$$t_{\parallel}^{(1)}=\frac{L_1}{c-v}+\frac{L_1}{c+v}=\frac{2L_1}{c}\frac{1}{1-\beta^2}\quad\left(\beta=\frac{c}{v}\right).$$

The time for light to make the to and fro journey to the mirror M_2 in the other interferometer arm L_2 is

$$t_{\perp}^{(1)}=[2L_2(1+\tan^2\alpha)^{\frac{1}{2}}/c],$$

and since $\tan^2\alpha=v^2/(c^2-v^2)$

$$t_{\perp}^{(1)}=\frac{2L_2}{c}\frac{1}{(1-\beta^2)^{\frac{1}{2}}}.$$

In his first analysis, Michelson incorrectly assumed that the time required for light to travel along the arm at right angles to the earth's motion to mirror M_2 would be unaffected by this motion, thus assuming incorrectly that

$$t_{\perp}^{(1)}=2L_2/c.$$

When the interferometer is rotated through 90° in the horizontal plane so that the arm L_2 is parallel to v, the corresponding times are

$$t_{\parallel}^{(2)}=\frac{2L_2}{c}\frac{1}{1-\beta^2};$$

$$t_{\perp}^{(2)}=\frac{2L_1}{c}\frac{1}{(1-\beta^2)^{\frac{1}{2}}}.$$

Thus, the total phase shift (in time) between the two light beams expected on the aether theory for a rotation of the interferometer through 90° is

$$\Delta t=\frac{2L_1}{c}\left[\frac{1}{1-\beta^2}-\frac{1}{(1-\beta^2)^{\frac{1}{2}}}\right]+\frac{2L_2}{c}\left[\frac{1}{1-\beta^2}-\frac{1}{(1-\beta^2)^{\frac{1}{2}}}\right]=\frac{2(L_1+L_2)}{c}\left[\frac{1}{1-\beta^2}-\frac{1}{(1-\beta^2)^{\frac{1}{2}}}\right].$$

For equal interferometer arms, as used in this experiment,

$$L_1=L_2=L,\text{ and, since }\beta\ll 1,$$

$$\Delta t\simeq\frac{2L}{c}\beta^2.$$

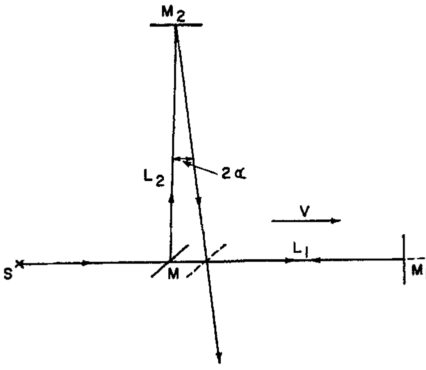

FIG. 4. Michelson experiment.

However, the observations give the positions of the fringes, rather than times, so the quantity of importance for the experiment is the change in optical path in the two arms of the interferometer.

$$A = c\Delta t = 2L(v/c)^2.$$

This is the quantity of the second order in (v/c) referred to by Maxwell,[1] which started Michelson thinking about this problem.

In Michelson's original apparatus, $L = 120$ cm, and in terms of waves of white light ($\lambda \sim 5700$ Å), this distance equals 2×10^6 wavelengths. The orbital speed of the earth around the sun is $v \simeq 30$ km/sec so that $(v/c)^2 = 10^{-8}$. Hence, $A \simeq 4\times10^6 \times10^{-8} \simeq 0.04$ fringe. In neglecting the effect of the earth's motion on the light beam traveling along the interferometer arm L_2, Michelson had anticipated a fringe shift of twice this amount when he rotated the interferometer through 90°.

Michelson made his observations by recording the position of the central black fringe on a graduated scale in the telescope eyepiece when the orientation of the instrument about its vertical axis was set successively at each of the eight points of the compass. When the apparatus was set up on a stone pier in the Physikalisches Institut of the University of Berlin, vibrations due to street traffic made observation of the interference fringes wholly impossible, except during brief intervals after midnight. So von Helmholtz made arrangements with Professor Vogel, Director of the Astrophysicalisches Observatorium at Potsdam, for the experiment to be performed there. It was conducted in the cellar, whose circular walls formed the foundation for the pier of the equatorial telescope. Here, observations were possible, although it was first necessary to return the interferometer to the maker with instructions to make it revolve more easily without a bending of the arms. Michelson finally completed his measurements early in April of 1881. Although he observed shifts in the position of the interference fringes when the apparatus was turned in azimuth, they were smaller than anticipated and, moreover, did not show the proper phase relationship with respect to the earth's motion. Michelson concluded that, "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."[12]

After completing the Potsdam experiment, Michelson remained for more than a year in Europe. Having written up the Potsdam experiment for publication, he took his family to Heidelberg, where he spent the summer semester attending the lectures of Quincke and Bunsen. Quincke had for years been a leader in optics, especially in researches involving interference phenomena in white light. He was an expert in the use of the Jamin-type interferometer, so it was natural that Michelson should go to Heidelberg to discuss the characteristics of this instrument, as well as his own form of interferometer. Quincke had introduced the practice of silvering the back surfaces of the Jamin plates, thus making the interference fringes much clearer.[13]

It was during this period in Heidelberg that Michelson was appointed to the faculty of the newly organized Case School of Applied Science in Cleveland. Professor George F. Barker, of the University of Pennsylvania, knew Michelson and had strongly urged his appointment in a letter to John N. Stockwell, the first Professor of Astronomy at Case.

March 22, 1881

My dear Dr. Stockwell:

I have received your letters of the 10th and 21st insts. and should have acknowledged their receipt before had I not been very busy. I mailed at once the enclosure to Mr. Michelson and also cabled him to the effect that the intentions of the Cleveland people were good. I have also mailed him your letter to me received today.

I can appreciate his position. He is now drawing his support from the Navy. He cannot afford to resign from that position until he has a positive certainty to fall back on. While it may be very true that the Trustees of the Case School are favorably disposed towards him, that favorable disposition would not, in my opinion, warrant his resigning from the Navy. If he does not do this, however, he will be sent to sea.

The chance to secure him for the Case School I regard as one not to be trifled with. He does not ask any salary and will expect to wait until such time as may be necessary before beginning his duties. But he asks (and I think rightly) that he be elected something, even Instructor in Physics as you and Dr. Taylor are, if not a full Professor

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[12] A. A. Michelson, Am. J. Sci. **22**, 120 (1881); Phil. Mag. **13**, 236 (1882); Am. J. Sci. **23**, 395 (1882); J. Phys. (Paris) **1**, 183 (1882).

[13] G. Quincke, Ann. Physik [2] **132**, 321 (1867).

right away, with the understanding that he is not to go on duty until wanted. I can see no reason why some such guarantee cannot be given him, one on which he can have the courage to resign from the Navy and spend another year or more in Europe in Special Study. Then he can select and bring home his apparatus and be ready to go at once to work. I have not heard a word from him since I wrote to you, so I say all this on my own responsibility.

With best wishes,

Cordially yours,
George F. Barker
3909 L
Philadelphia

On 28 March 1881, the Trustees appointed Michelson to the Case faculty: "Resolved, that Albert A. Michelson be and is hereby appointed Instructor in Physics in the Case School of Applied Science, at a salary of $2000 per annum, this appointment, if accepted, to take effect September 1, 1882."[14] Final arrangements were made with the help of Professor Barker who could write to Professor Stockwell:

May 5, 1881

My dear Professor Stockwell:

I am in receipt of a letter from Professor Michelson dated at Heidelberg April 19th announcing the arrival of my telegram and also of a letter from the Secretary of your board of Trustees informing him of his election. He says he has sent his acceptance of the position. So this matter has now been successfully arranged and I believe to the satisfaction of all concerned. I am sure the Case School will never regret this step and I hope they will provide for him the amplest apparatus for experiment and instruction. Physical apparatus is more costly at the outset than chemical, but then the wear and tear is less and the renewals are less frequent. I should not think to judge from my own experience that it would be worthwhile to start with less than $10,000 worth, with the intention of doubling it after 4 or 5 years.

Cordially yours,
George F. Barker

So, on 30 September 1881, Michelson resigned his commission in the Navy. At that time, there was only a freshman class at Case, so Michelson was granted leave of absence to continue his studies and researches in Europe for another year, and later was authorized to purchase the apparatus that he would need in Cleveland.[15]

After the summer semester at Heidelberg was completed, Michelson took his family for a holiday at Schluchsee in the Black Forest. While there in August, he sent a letter to *Nature*[16] criticizing a recent report by Young and Forbes[17] of their measurements of the velocity of light made across the Firth of Clyde in Scotland. These investigators had claimed that the speed of blue light in air exceeded that of red light by 1.8%. Michelson pointed out that, if this were in fact the case, then, in his own measurements made at Annapolis[18] and Washington, the white-light image of the slit as deflected by the revolving mirror would be spread out into a spectrum 2.4 mm in length. Actually, no dispersion was observed although it could easily have been detected in Michelson's apparatus if the velocities of red and blue light in air differed by as much as 0.1%. Michelson's letter to *Nature* attracted the attention of Lord Rayleigh who had already concluded that Young and Forbes must be in error.[19] Thus began the acquaintance and friendship of Rayleigh and Michelson, which continued until Rayleigh's death.

This discussion with Rayleigh about the result of Young and Forbes is especially interesting, for it is part of a recurrent pattern throughout Michelson's career. Each time that he completed an aether-drift experiment (in 1881, 1887, 1897, 1913, 1925, and 1929), he immediately returned to his absorbing passion for optical experiments that would give "numbers"—usually the speed of light. His steady correspondence with Simon Newcomb—from Heidelberg, Schluchsee, and Paris—is almost exclusively concerned with speed-of-light measurements, especially those he was planning for Cleveland. There is not a single mention of the Potsdam experiment in this entire period!

In the autumn of 1881, Michelson moved to Paris to continue his studies and research at Le Collège de France and at l'École Polytechnique. He remained in Paris until his return to America in June 1882. Thus began the very pleasant relationships between Michelson and Mascart, Cornu and Lippmann, who with their great predecessors had made France the leader in optical research for almost a century.

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[14] Minutes, Board of Trustees, Case Inst. Technol. (28 Mar. 1881).

[15] Minutes, Board of Trustees, Case Inst. Technol. ($7500 appropriated) (3 Nov. 1881).

[16] A. A. Michelson, Nature **24**, 460 (1881).

[17] J. Young and G. Forbes, Nature **24**, 303 (1881).

[18] A. A. Michelson, Nature **18**, 195 (1878); **21**, 94, 120, 226 (1879).

[19] Lord Rayleigh, Nature **24**, 382 (1881).

Michelson took his interferometer to Paris and demonstrated it to the physicists there. Cornu was not convinced that the fringes were produced as Michelson claimed, contending that they were actually Lloyd fringes produced in the first plate. However, when Michelson showed Cornu that the fringes disappeared when a piece of glass was placed in one of the arms, the latter was at once satisfied.[20]

The friendships Michelson made in Paris continued throughout his life, and led to his return a decade later to determine the length of the standard meter in terms of light waves. While in Paris, he published[21] the theory of his new interferometer ("refractometer") and also devised a very sensitive thermometer.[22]

In addition to the original report on the Potsdam experiment, a revised and shortened account was presented at the 20 February 1882 meeting of the Paris Académie des Sciences.[23] In this paper, which was sponsored by Cornu at a meeting with Jamin in the Chair, Michelson acknowledged his error in neglecting the effect of the earth's motion on light traveling in the interferometer arm set at right angles to the motion. When this effect is included, the expected fringe displacement is reduced by half: in the Potsdam interferometer from 0.08 to 0.04 fringe. Michelson credits A. Potier with calling his attention to this matter, although Potier had in fact concluded that the effect would reduce the expected fringe shift to zero.

Neither Michelson himself nor the scientific world generally ever considered the Potsdam trial conclusive, although Lord Rayleigh and Lord Kelvin (then Sir William Thomson) in England and H. A. Lorentz and others on the continent of Europe gave careful and respectful attention to Michelson's first published result on the aether-drift experiment. However, this interest led to no serious revision of the theories then current and even Lorentz's electron theory, which he was continually developing to adapt it to the growth of experimental fact, was not altered because of the Potsdam result. The situation was emphasized by Robert A. Millikan in a letter to the writer[24] in which he states, "This experiment (Potsdam) must have been a very crude one, and it was only after he got to Case that he set up in connection with Morley the outfit which has since gone under the name of the Michelson–Morley Experiment."

IV. CASE PROFESSORSHIP

Michelson came to Cleveland about 1 July 1882, but several years were to pass before he would repeat his interferometer experiment. Time was required to organize the physics laboratory and courses at Case. His early Case students remembered that "Michelson gave the most elegant lectures they ever heard—absolutely clear, everything finished."[25]

Michelson's lectures on light are of special interest. He apparently never mentioned the Potsdam experiment to his Case students. The result of this experiment was still a subject of controversy, and he was reluctant to go into the arguments in the classroom.

However, his Case students were told that "the luminiferous Ether is to some extent a hypothetical substance and if it consists of matter at all must be very rare and very elastic. *It entirely escapes all our senses of perception.*"

It is also a curious fact that Michelson did not describe his own form of interferometer in his lectures at Case, although his treatment of optical interference was detailed and included a complete description of the Jamin type of "refractometer" and he discussed its use in measuring the refractive indices of gases.

On the subject of the velocity of light, however, Michelson gave his students a complete story from the early determinations of Roemer and Bradley, through the work of the great Frenchmen, Fizeau, Foucault, and Cornu, to his own measurements and those of Newcomb.

It is clear from his correspondence at this time with Willard Gibbs and Lord Rayleigh that he was far from satisfied with the Potsdam

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[20] D. C. Miller to writer (10 Apr. 1933); R. A. Millikan, Proc. Natl. Acad. Sci. U. S. **19**, (1938), and letters to writer (31 July 1950; 21 Jan. 1952; 11 Aug. 1952; 18 Mar. 1953).

[21] A. A. Michelson, Am. J. Sci. **23**, 395 (1882); Phil. Mag. **13**, 236 (1882).

[22] A. A. Michelson, J. Phys. (Paris) **1**, 183 (1882); Am. J. Sci. **24**, 92 (1882).

[23] A. A. Michelson, Compt. Rend. **94**, 520 (1882).

[24] Letter from R. A. Millikan to writer (11 Aug. 1952); see, also, Rev. Mod. Phys. **21**, 343 (1949).

[25] Comfort A. Adams (Case Inst. Technol., Class of 1890) to writer (19 May 1950); also, Wm. Koehler (Case Inst. Technol., Class of 1889) (10 Dec. 1950).

result. However, when he again found time for research, he did not take up the aether-drift experiment but returned to his earlier work on precision measurements of the speed of light. An important factor in this decision was the urging and support of Professor Simon Newcomb, who obtained a grant of $1200 from the Bache fund of the National Academy of Sciences which he turned over entirely to Michelson to support his velocity of light experiments in Cleveland. During the two years, 1882–1884, Michelson worked constantly to improve his methods for measuring the speed of light, and here he made three notable contributions.[26] An accurately measured base line along the railroad tracks (N. Y., C. and St. L.) at the rear of the Case campus was prepared by Professor John Eisenmann, and, with an improved optical system and better timing methods than hitherto employed, Michelson obtained 299 850 km/sec for the speed of light reduced to vacuum, a value much superior to his earlier determinations made at Annapolis and Washington. In fact, this measurement of the speed of light made at Cleveland in 1882–1883 was the accepted standard from that time until his own measurements between Mt. Wilson and San Antonio Peak in California were completed in 1927.

The other two important measurements made in Cleveland in 1882–1884 were determinations of the group velocity of light in distilled water and in carbon disulphide. The first of these gave a precision check with the value predicted from the refractive indices of water. Both Foucault and Fizeau had shown that the speed of light in water is less than in air, but Michelson's measurement gave the first accurate value. His measurement of the speed of light in carbon disulphide, however, appeared to be in disagreement with theory. Nevertheless, Michelson reported his result, and it drew the immediate attention of Lord Rayleigh for it provided the first reliable experimental verification of his theory for the difference between wave and group velocities in a dispersive medium.[27] Michelson communicated his results to Lord Rayleigh and, in the latter's presidential address[28] at the Montreal meeting of the British Association in the summer of 1884, he paid special attention to Michelson's measurements. Kelvin also was at the Montreal meeting, as were many of the leading physicists of that time, and thus a much wider acquaintance with Michelson's researches was established.

In October of 1884, Kelvin came to Baltimore to give a series of 20 lectures at The Johns Hopkins University. Professors Rowland and Sylvester had urged this project, and for over two years President Gilman had been in correspondence with Kelvin, inviting him to lecture on any subjects of his choice, emphasizing the strong impulse which such a series of lectures would give to the study of physics in America.

Kelvin lectured on "Molecular Dynamics and the Wave Theory of Light,"[29] dwelling principally on the failures of the wave theory, especially those related to the "Luminiferous Ether." The lectures were attended by a group of twenty-one "coefficients,"[30] including Michelson and Edward W. Morley from Cleveland, Henry A. Rowland, Henry Crew,[31] A. L. Kimball, T. C. Mendenhall, and George Forbes, a visitor from England.

The evening before the first lecture, a grand reception was held in Hopkins Hall; many visitors were present and it was a notable affair. The lectures were given in a small lecture room at Johns Hopkins, seating perhaps thirty people. Lord Rayleigh was there for some of Kelvin's lectures, which bore unmistakable signs of having been prepared in haste. In the midst of the

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[26] R. S. Shankland, Am. J. Phys. **17**, 488–489 (1949).

[27] Lord Rayleigh, Proc. London Math. Soc. **9**, 21 (1877); *Theory of Sound*, (The MacMillan Company, London, 1877), Vol. 1, p. 191 and Appendix; see, also, Willard Gibbs, *Collected Works*, (Yale University Press, New Haven, Connecticut, 1948); Vol. 2, pp. 247–254.

[28] Lord Rayleigh, Brit. Assn. Rept. 654; *Scientific Papers* (Cambridge University Press, Cambridge, England, 1884), Vol. 2, p. 348.

[29] Sir Wm. Thomson, "Molecular Dynamics and the Wave Theory of Light," stenographic report by A. S. Hathaway; G. Forbes, Nature **31**, 461, 508, 601 (1884); Lord Kelvin, *The Baltimore Lectures* (Cambridge University Press, Cambridge, England, 1904) (republished in revised form).

[30] So called in suggestion of the twenty-one coefficients by which the most general state of an elastic body is specified.

[31] The writer's picture of the "Baltimore Lectures" has been formed very largely from the privilege of conversation (26 Nov. 1950) and correspondence (29 Nov., 7 Dec. 1949; 25 Oct. 1950; 27 Aug. 1952; 17 Sept. 1952) with Professor Henry Crew, who attended Thomson's lectures as a graduate student and Fellow in Physics at Johns Hopkins.

first lecture, Kelvin once appealed to Rayleigh to verify some statement and inform him on the fact of the case; but Rayleigh merely shook his head, as if to say, "These are your lectures, not mine."

Rayleigh and Rowland sat in easy chairs at the end of the lecture table on which were placed Kelvin's various models. Michelson sat in the row next to the front, a keen-eyed, handsome, young chap with jet black hair, quiet in manner and dress. Already at that early date and among a group of students and well-known physicists from all over the country and abroad, Michelson was an outstanding figure; everyone held him in the highest esteem. The basis of Michelson's distinguished reputation in 1884 was without question his determination of the speed of light in a manner vastly superior to that of Fizeau or of Foucault. In his fifth lecture, Thomson alluded to Michelson's work on the group velocity problem, which had greatly interested Rayleigh, and in the eighth lecture referred again to his improved methods for measuring the speed of light.

Rowland was not able to attend the lectures regularly, as in the autumn of 1884 he was a very busy man working on his second ruling engine, finishing up the determination of the *Ohm* for the U. S. Government and designing his new laboratory. As a result, but with no intended disrespect for Kelvin, he often closed his eyes and dozed beside Rayleigh. Professor Crew also felt that Rowland was so certain of the correctness and beauty of Maxwell's then new electromagnetic theory of light (for which his own experiments on the magnetic effect of electric convection[32] provided an important basis) that he considered Kelvin's elaborate attempt to provide a mechanical basis for optical phenomena as a step backwards.

Michelson, however, was intensely interested and, although he asked no questions during the lectures, it is certain that during his stay in Baltimore he discussed the results of his Potsdam experiment with Kelvin and Rayleigh during the ten-minute intervals between the two parts of each day's lecture when Kelvin chatted with his students; and discussions started at the lecture often were continued at the supper table. Kelvin was always enthusiastic about a "sweet" experiment and no doubt urged Michelson to give his interferometer work another trial, especially since both he and Lord Rayleigh were not convinced that the apparatus used at Potsdam had sufficient sensitivity to give a decisive test; and the weight of scientific opinion was tending more and more to the view that Fresnel's hypothesis of a stationary aether was probably correct.

It also seems likely that during these informal discussions Professor Morley was drawn into the problem. Morley was considerably older than Michelson and was well-recognized not only in chemistry, but in physics and mathematics. He was an acknowledged leader in experimental work, and his theoretical insight was an invaluable addition to the great experimental skills of Michelson.

According to Professor Crew, Morley was the "shark" of the Baltimore Lectures, helping Kelvin over many rough spots and working out the hardest "homework" problems proposed to the "coefficients" by Kelvin. One of these was a complete solution by Morley [see Baltimore Lectures by Kelvin, p. 408 (1904)] of the dynamical model of a molecule consisting of seven mutually interacting particles, giving the fundamental periods of vibration, relative displacements, and the energy ratios between the normal modes. Michelson was already well-acquainted with Morley as they had both come to Cleveland in 1882, but the informal and inspiring atmosphere of the Baltimore Lectures without question contributed greatly to their subsequent collaboration in research.

V. REPETITION OF THE FIZEAU EXPERIMENT BY MICHELSON AND MORLEY

The first joint research of Michelson and Morley was not to repeat the Potsdam experiment, as might have been expected, but to carry out in greatly improved fashion Fizeau's 1851 experiment[33] on the speed of light in moving water, as had been urged at Baltimore by

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[32] H. A. Rowland, Ann. Physik **158**, 487 (1876); Am. J. Sci. **15**, 30 (1878).

[33] H. L. Fizeau, Compt. Rend. **33**, 349 (1851); Ann. Chim. Phys. **57**, 385 (1859).

both Kelvin and Rayleigh.[34] Many theoretical discussions on the aether problem involved Fizeau's measurement, and it was felt that a new experiment should be performed to subject this question to a decisive test.

During the thirty years between 1851 and Michelson's Potsdam experiment of 1881, Fizeau's measurement had been considered as one of the decisive experimental bases of the validity of Fresnel's hypothesis of a stationary aether, on which he had developed his theory of the influence of the motion of a medium on the propagation of light.

The Fresnel theory predicted that the observed speed of light in a moving transparent medium should be

$$u=(c/n)+v[1-(1/n^2)],$$

where c is the speed of light in vacuum, n is the index of refraction of the transparent medium which is moving at speed v, relative to the observer, while u is the observed speed of light in the moving medium. The speed of light is not altered by the full speed v of the moving medium, but by only a fraction $[1-(1/n^2)]$ called the Fresnel drag coefficient.

In obtaining this coefficient, Fresnel had made rather artificial assumptions about the behavior of aether in a moving transparent medium—namely, that only that part of the aether in the moving body constituting the excess over the aether normally present *in vacuo* partakes of the motion, while the remaining aether remains at rest.

Fresnel's[35] theory had originally been developed to explain the experiment of Arago which demonstrated with reasonable precision that starlight is refracted in a prism by the same amount as is light from a terrestrial source, regardless of the orientation of the prism to the direction of motion of the earth in its orbit. An achromatic prism is employed for the experiment so that the deflection of the light is insensitive to Doppler shifts, caused by the earth's motion and the radial velocity of the stars.

Fresnel had also correctly predicted the result of the experiment of Airy,[36] who had demonstrated at the Greenwich Observatory that the aberration angle of the star γ Draconis determined with a water-filled zenith telescope (35.3-in. tube with special lens) is the same as that originally found by Bradley[37] with an ordinary telescope.

The Fresnel theory had had other notable successes in explaining the null results obtained in experiments by Hoek,[38] Mascart and Jamin,[39] Maxwell,[40] and others, which had failed to detect an influence of the Earth's motion on the propagation of light in transparent media.

It is true that all experiments before Michelson's were capable only of detecting effects to the first order of (v/c), while his method permitted observation of effects to the second order of this ratio; but the preponderance of the evidence supporting Fresnel's hypothesis of a stationary aether in space was so great that little serious attention was given to the Potsdam result. This was especially true after it was known that Michelson had originally overestimated his expected fringe shifts by a factor of two.

However, the Fizeau experiment was not as conclusive as could be desired, for his observed drag coefficient of 0.5 ± 0.1 differed considerably from Fresnel's theoretical value of 0.438 for water. Furthermore, J. J. Thomson[41] had recently obtained a theoretical value of exactly $\frac{1}{2}$ for the drag coefficient by an argument based on Maxwell's electromagnetic theory of light.

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[34] Letter of A. A. Michelson to Simon Newcomb: "I have been asked by Sir Wm. Thomson and Lord Rayleigh to repeat Fizeau's experiment for testing the question of the effect of motion of medium on the velocity of light; could I use the remainder of the [Bache] money yet in my possession for that purpose?" (30 Jan. 1885); see also a letter from Michelson to Willard Gibbs dated Cleveland, Ohio, 15 Dec. 1884, in Lynde P. Wheeler, *Josiah Willard Gibbs* (Yale University Press, New Haven, Connecticut, 1951).

[35] A. J. Fresnel, Ann. Chim. Phys. **9**, 57 (1818), including a reprint of Fresnel's famous "Letter to Arago." Arago's result was published much later—D. F. Arago, Compt. Rend. **8**, 326 (1839); **36**, 38 (1853).

[36] G. B. Airy, Proc. Roy. Soc. (London) **20**, 35 (1871); **21**, 121 (1873); *Autobiography* (Cambridge University Press, Cambridge, England, 1896), pp. 240, 286, 291, 294.

[37] J. Bradley, Phil. Trans. Roy. Soc. **35**, 637 (1728).

[38] M. Hoek, Arch. Néerl. Sci. **3**, 180; **4**, 443 (1868); Astron. Nach. **73**, 193 (1869); Compt. Rend. Acad. Sci. Amsterdam **2**, 189 (1868).

[39] M. E. Mascart and J. Jamin, Ann. École Norm. **3**, 336 (1874); *Traité d'Optique* (Gauthier-Villars et Fils, Paris, 1889); Vol. 1, p. 462, Vol. 3, pp. 109–111 (1893).

[40] J. C. Maxwell, Phil. Trans. Roy. Soc. **158**, 532 (1868); *Scientific Papers* (Dover Publication, Inc., New York, 1952), Vol. 2, p. 769.

[41] J. J. Thomson, Phil. Mag. 9, 284 (1880); repeated with no references to the work of Michelson, Morley, or Lorentz in *Recent Researches in Electricity and Magnetism* (Clarendon Press, Oxford, England, 1893), pp. 543–546.

Lorentz[42] later showed that Maxwell's theory in its original form applied only to vacuum, and that its correct application to the propagation of light in material media required the extensions that he developed in his electron theory. Among the many results obtained by Lorentz in this theory is the same value of the drag coefficient as that given originally by Fresnel.

Thus, the situation was confused, and it was generally agreed that a new trial of the Fizeau experiment was desirable. In the words of Michelson and Morley, it was felt that, "Notwithstanding the ingenuity displayed in this remarkable contrivance (Fizeau's apparatus) which is apparently so admirably adapted for elimating accidental displacement of the fringes by extraneous causes, *there seems to be a general doubt* concerning the results obtained, or at any rate the interpretation of these results given by Fizeau. This together with the fundamental importance of the work must be our excuse for its repetition."[43]

The interference technique used by Fizeau for his experiment had suffered from the basic defect that it employed coherent light beams obtained by *division of wavefront*. The interference fringes obtained by this method are either very faint or are extremely narrow, and any attempt to separate the two beams to accommodate the disposition of the apparatus results in a further narrowing of the interference pattern. The closely spaced fringes can be magnified, but only with a corresponding loss of intensity and distinctness. Fizeau had made a slight improvement in his apparatus by use of a biplate, permitting some increased separation of the two beams without a corresponding increase in the angle between them at interference. However, only minor improvements were possible in this way.

The improved method employed by Michelson and Morley in their repetition of Fizeau's experiment is shown in Fig. 5. They used a form of the Michelson interferometer with light source at A, half-reflecting plate at B, and compensating plate at H. The brass tubes (shown only in part in Fig. 5) were 2.8 cm i. d. and in these the distilled water flowed in opposite directions. The two coherent light beams traversed the apparatus in opposite directions; one beam along BCDEHFB to the telescope at G; and the other by BFHEDCB to G. The position of the central fringe in white light was observed with the water flowing in one direction; then its shift was measured when the flow of water was reversed. Fizeau had used a transient flow of water, and, to permit a more accurate observation of the position of the interference fringes, Michelson and Morley employed a steady flow of water from a tank located in the attic of the Case Main Building, 70 ft above their basement laboratory. They also used an ingenious method to determine the velocity distribution of the flow across the diameter of the tube, thus getting an accurate value for the water speed along the optical path.

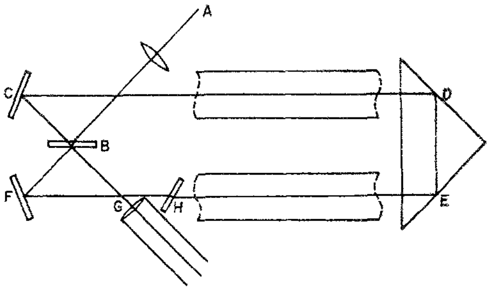

FIG. 5. Michelson–Morley method for the Fizeau experiment.

By employing the modified form of the Michelson interferometer, it was possible to obtain a wide spacing between the optical paths in the tubes carrying the flowing water, while at the same time the distinct and widely spaced interference fringes permitted an accuracy in the optical measurements impossible with Fizeau's apparatus.

A situation which gave Morley the complete responsibility for their experiment during the fall of 1885 was a serious illness of Michelson's. He left Cleveland on 19 September 1885 and did not expect to return. He thought (because of an erroneous diagnosis) that he would never work again, and so asked Morley to complete the experiment, turning over to him his equip-

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[42] H. A. Lorentz, *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern* (E. J. Brill, Leiden, 1895). In this work, Lorentz also showed that for dispersive media an additional term $(\nu/n)(dn/d\nu)$ must be added to the Fresnel drag coefficient, a refinement later beautifully confirmed by P. Zeeman, Proc. Amsterdam Acad. **17**, 445 (1914); **18**, 398 (1915).

[43] A. A. Michelson and E. W. Morley, Am. J. Sci. **31**, 377 (1886).

ment and the unexpended funds of the Bache grant.[44]

Fortunately, Michelson's illness proved much less serious then had been feared,[45] and in mid-December of 1885 he returned to Cleveland to finish the experiment with Morley.

Michelson and Morley made, in all, 65 trials of their experiment, varying the length of the tubes carrying the water and the speed of the liquid. They found that the change in the observed velocity of light was accurately proportional to water speed and was altered by almost the exact amount predicted by the Fresnel formula.

Upon completing their measurements, Michelson and Morley reported the result to Kelvin.

> Cleveland, Ohio
> March 27, 1886
>
> Dear Sir William:
>
> You will no doubt, be interested to know that our work on the effect of the medium on the velocity of light has been brought to a successful termination. The result fully confirms the work of Fizeau. The factor by which the velocity of the medium must be multiplied to give the acceleration of the light was found to be 0.434 in the case of water, with a possible error of 0.02 or 0.03. This agrees almost exactly with Fresnel's formula $1-1/n^2$. The experiment was also tried with air with a negative result. The precautions taken appear to leave little room for any serious error, for the result was the same for different lengths of tube, different velocities of liquid, and different methods of observation. We hope to publish the details within a few weeks. Very respectfully, your obedient servants,
>
> Albert A. Michelson
> Edward W. Morley

Kelvin's prompt and enthusiastic reply[46] stated that he would incorporate their results as an appendix in the final publication of his Baltimore Lectures, as he had urged them to undertake this work during their stay at Johns Hopkins.

Michelson also sent a preliminary report to Willard Gibbs.

> Cleveland, March 1886
>
> My dear Prof. Gibbs,
>
> Your welcome letter was duly received, and I have delayed answering till my experiments were completed. My result fully confirms the work of Fizeau and the result found for $1-1/n^2$ was 0.434 which is almost exactly the number for this expression when for n we put the index of refraction of water. I had heard that the relationship between maximum and mean velocity of liquids in tubes had been worked out–but have not been able to find it–so I made an experimental determination and found the ratio to be 1.165.
>
> I think my result shows that your estimate of Thomson's [Ref. 47] work is correct. The number 0.434 is correct within 2 or 3% and I can say with a good deal of confidence that it is not one half. I also repeated the experiment with air with a negative result.
>
> I expect to publish details in a few weeks.
>
> Very sincerely yours,
> A. A. Michelson

VI. MICHELSON–MORLEY EXPERIMENT

After the publication of the results on the moving-water experiment, there appeared a long article by Lorentz[48] in which he attempted to reconcile Michelson's Potsdam result with a combination of the aether theories of Fresnel and Stokes, and Michelson and Morley's new determination of the Fresnel drag coefficient. Stokes had shown that the aberration of light as observed in either an ordinary telescope[37] or a water-filled telescope[36] can be explained on the wave theory by "supposing that the aether close to the earth's surface is at rest relatively to that surface, while its velocity alters as we recede from the surface, till at no great distance, it is at rest in space."[49] Stokes' theory carried a condition that the motion of the aether must be irrotational, a condition later shown by Lorentz to be inconsistent with other characteristics of motion through the aether. However, in 1886 Lorentz accepted the Stokes theory, but modified it by assuming that the earth

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[44] Letter from A. A. Michelson to Simon Newcomb from New York (28 Sept. 1885); letter from E. W. Morley to his father (27 Sept. 1885).

[45] Letters from A. A. Michelson to E. W. Morley (19, 23 Oct. 1885); letter from A. A. M. to Willard Gibbs (13 Dec. 1885).

[46] S. P. Thomson, in *Life of Lord Kelvin* (The MacMillan Company, London, 1910), Vol. 2, p. 857.

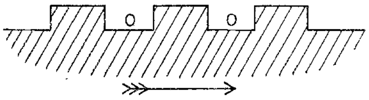
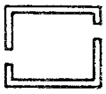
[47] This refers to J. J. Thomson (Ref. 41) in which he had obtained a theoretical value of $\frac{1}{2}$ for the Fresnel drag coefficient.

[48] H. A. Lorentz, Arch. Néerl. **21**, 103–176 (1886). It is of interest to note that in this article Lorentz states that "M. Michelson a réalisé l'interférence au moyen d'un appareil qui' présente quelque analogie avec le réfracteur interférential de Jamin."

[49] G. G. Stokes, Phil. Mag. **27**, 9 (1845); **28**, 76 (1846); **29**, 6 (1846); *Mathematical and Physical Papers* (Cambridge University Press, Cambridge, England, 1880), Vol. 1, pp. 134, 141, 153.

imparts only that fraction of its own motion to the aether within it given by the Fresnel drag coefficient for transparent media, as measured by Michelson and Morley, instead of the full velocity as originally assumed by Stokes. Since the velocity of the aether near the earth's surface would, on this view, be less then half the earth's velocity, the expected displacement of the interference fringes in Michelson's Potsdam apparatus would be correspondingly reduced, and would be less than the experimental accuracy. In this same paper, Lorentz also recomputed the expected fringe shift for the Potsdam experiment, showing it to be only half that originally calculated by Michelson.

Lord Rayleigh wrote to Michelson calling his attention to Lorentz's paper and urged him to repeat his experiment on the relative motion of the earth and the aether. Michelson replied as follows:

> Cleveland, March 6, 1887
>
> My dear Lord Rayleigh,
>
> I have never been fully satisfied with the results of my Potsdam experiment, even taking into account the correction which Lorentz points out.
>
> All that may be properly concluded from it is that (supposing the ether were really stationary) the motion of the earth thro' space cannot be very much greater than its velocity in its orbit.
>
> Lorentz' correction is undoubtedly true. I had an indistinct recollection of mentioning it either to yourself or to Sir. W. Thomson when you were in Baltimore.
>
> It was first pointed out in a general way by M. A. Potier of Paris, who however was of the opinion that the correction would entirely annul any difference in the two paths; but I afterwards showed that the effect would be to make it one half the value I assigned, and this he accepted as correct. I have not yet seen Lorentz' paper and fear I could hardly make it out when it does appear.
>
> I have repeatedly tried to interest my scientific friends in this experiment without avail, and the reason for my never publishing the correction was (I am ashamed to confess it) that I was discouraged at the slight attention the work received, and did not think it worth while.
>
> Your letter has however once more fired my enthusiasm and it has decided me to begin the work at once.
>
> If it should give a definite negative result then I think your very valuable suggestion concerning a possible influence of the vicinity of a rapidly moving body should be put to the test of experiment; but I too think the result here would be negative. [This experiment, yielding a negative result, was later performed by Sir Oliver Lodge.[50]]
>
> But is there not another alternative?
>
> Suppose for example that the irregularity of the earth's surface be crudely represented by a figure like this:
>
> 
>
>
> If the earth's surface were in motion in the direction of the arrow, would not the ether in 00 be carried with it?
>
> This supposes of course, contrary to Fresnel's hypothesis, that the ether does not penetrate the opaque portions, or if it does so penetrate, then it is held prisoner. Fizeau's experiment holds good for transparent bodies only, and I hardly think we have a right to extend the conclusions to opaque bodies.
>
> If this be so and the ether for such slow motions be regarded as a frictionless fluid—it must be carried with the earth in the depression.
>
> Would this not be partly true, say in a room of this shape?
>
> 
>
> If this is all correct then it seems to me the only alternative would be to make the experiment at the summit of some considerable height, where the view is unobstructed at least in the direction of the earth's motion.
>
> The Potsdam experiment was tried in a cellar, so that if there is any foundation for the above reasoning, there could be no possibility of obtaining a positive result.
>
> I should be very glad to have your view on this point.
>
> I shall adopt your suggestion concerning the use of tubes for the arms, and for further improvements shall float the whole arrangement in mercury; and will increase the theoretical displacement by making the arms longer, and doubling or tripling the number of reflections so that the displacement would be at least half a fringe.
>
> I shall look forward with great pleasure to your article on "Wave Theory" (hoping however, that you will not make it too difficult for me to follow).
>
> I can hardly say yet whether I shall cross the pond next summer. There is a possibility of it, and should it come to pass I shall certainly do myself the honour of paying you a visit.
>
> Present my kind regards to Lady Rayleigh and tell her how highly complimented I felt that she should remember me.
>
> Hoping soon to be able to renew our pleasant association, and thanking you for your kind and encouraging letter,
>
> I am,
> Faithfully yours,
> Albert A. Michelson

A definitive test of the Potsdam experiment had been the ultimate objective of Michelson and Morley for which their repetition of Fizeau's moving-water experiment had been only an

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[50] Sir Oliver Lodge, Nature **46**, 501 (1892); Phil. Trans. Roy. Soc. (London) **184**, 727 (1893); *Past Years* (Charles Scribner's Sons, New York, 1932), Chap. 15.

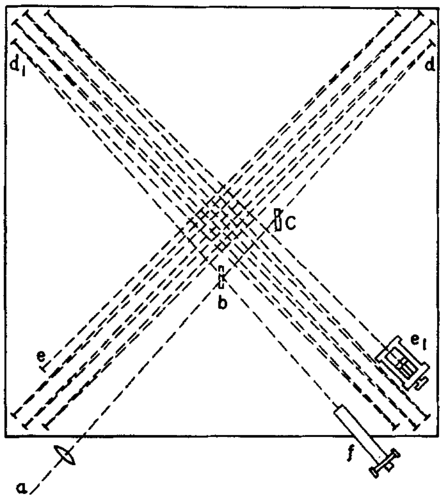

FIG. 6. Optical paths in the Michelson–Morley interferometer.

important preliminary. Their accurate result for the moving-water experiment was based on observed shifts in the interference pattern of about half the distance between fringes, and they were greatly encouraged by this positive result to devise an aether-drift apparatus of comparable sensitivity. Professor Morley's keen interest in the new experiment is evident in the following letter to his father:

> Cleveland, April 17, 1887
>
> "Michelson and I have begun a new experiment. It is to see if light travels with the same velocity in all directions. We have not got the apparatus done yet and shall not be likely to get done for a month or two. Then we shall have to make observations for a few minutes every month for a year. We have a stone on which the optical parts of the apparatus are to be fixed. The stone is five feet square, and about fourteen inches thick. This we shall have to support so that it can be turned around and used in different positions. Now since a strain of half a pound would make our observations useless, we have to support it so that its axis of rotation is rigorously vertical. My way to secure this was to float the stone on mercury. This we accomplished by having an annular trough full of mercury, with an annular float in it on which the stone is placed. A pivot in the center makes the float keep concentric with the trough. In this way, I have no doubt, we shall get decisive results."[51]

Michelson's Potsdam experiment had been greatly hampered by strains produced in the apparatus as it was turned in azimuth, and by vibrations transmitted to the optical parts which made the interference fringes unsteady, and often disappear entirely. The new Cleveland interferometer devised by Michelson and Morley overcame these difficulties as mentioned in Morley's letter by mounting the optical parts on a heavy sandstone slab 5 feet square and a foot thick and placing this on an annular wooden float supported by mercury contained in an annular cast-iron trough. An essential feature of the float design was that it permitted a comparatively small amount of mercury to support the heavy stone. This arrangement permitted the interferometer to be continuously rotated in the horizontal plane so that observations of the interference fringes could be made at all azimuths with respect to the earth's orbital velocity. When set in motion, it would rotate slowly (about once in 6 min) for hours at a time. No starting and stopping was necessary, and the motion was so slow that accurate readings of fringe positions could be made while the apparatus rotated.

It was most natural for Professor Morley to suggest the use of mercury to support the apparatus, as he had already used large quantities of mercury in his own work and in 1884 had obtained new apparatus of the type invented by Professor Wright of Yale for distilling mercury in vacuum, and which Morley himself had considerably improved. The sandstone slab used by Michelson and Morley was the one used later by Morley for the pier on which he supported his barometer and reading microscopes for his chemical researches.[52]

The optical paths in the Michelson–Morley interferometer are shown in plan in Fig. 6. Light from (a) is divided into two coherent beams at the half-reflecting, half-transmitting rear surface of the optical flat (b). These two beams travel at 90^0 to each other and are multiply reflected by two systems of mirrors $d-e$ and d_1-e_1. On returning to (b) part of the light from $e-d$ is reflected into the telescope at (f), and light from e_1-d_1 is also transmitted to (f). These two coherent beams produce interference

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[51] Letter in Biography of E. W. Morley by H. R. Williams, Ph.D. thesis, Western Reserve University (1942).

[52] E. W. Morley, "On the Densities of Oxygen and Hydrogen and on the Ratio of their Atomic Weights," Smithsonian Inst. Publ. (Contributions to Knowledge) No. 980 (1895), pp. 22–23 and Fig. 8.

fringes. These are formed in white light only when the optical paths in the two arms are exactly equal, a condition produced by moving the mirror at e_1 by a micrometer. (C) is the usual compensating plate. The effective optical length of each arm of the apparatus was thus increased to 1100 cm by the repeated reflections, as compared to the 120 cm optical paths of the Potsdam interferometer.

Figure 7 is a perspective drawing of the Michelson–Morley interferometer showing the optical system mounted on the sandstone slab. The slab is supported on the annular wooden float, which in turn fitted into the annular cast-iron trough containing the mercury. On the outside of this tank can be seen some of the numbers 1 to 16 used to locate the position of the stone in azimuth. The trough was mounted on a brick pier, which in turn was supported by a special concrete base. The height of the apparatus was such that the telescope was at eye level to permit convenient observation of the fringes when the instrument was rotating. While observations were being made, the optical parts were covered with a wooden box to reduce air currents and temperature fluctuations.

Figure 8 is a cross section through the sandstone slab and its supports. The wooden float, cast-iron trough, and brick pier are shown, and also the centering pin which prevented the float from bumping into the sides of the cast-iron trough. The pin was engaged only while the interferometer was being set into rotation, and, once started, the apparatus would continue to turn freely for hours at a time.

With this new interferometer, the magnitude of the expected shift of the white-light interference pattern was 0.4 of a fringe as the instrument was rotated through an angle of 90° in the horizontal plane. (The corresponding shift in the Potsdam interferometer had been 0.04 fringe.) From their recent experience with the Fizeau moving-water experiment, Michelson and Morley felt completely confident that fringe shifts of this order of magnitude could be determined with high precision.

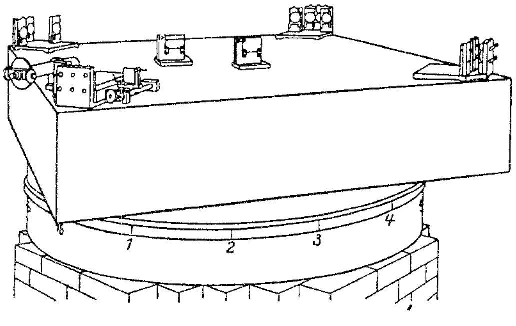

FIG. 7. Michelson–Morley interferometer used at Cleveland in 1887.

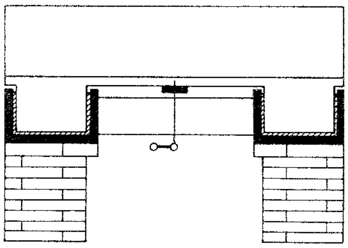

FIG. 8. Cross section of the Michelson–Morley interferometer.

The interferometer was set up in the southeast corner basement laboratory of the Case Main Building, a room having heavy stone walls and rather constant temperature conditions. Here, Michelson and Morley carried on the preliminary work of their experiment, but were prevented from making final observations for, on 27 October 1886, the Case Main Building suffered a disastrous fire.[53] A large part of all Michelson's physics equipment which he had purchased in Europe in 1881–1882, was destroyed in this fire, but the apparatus for the Michelson–Morley experiment was rescued by students living in the nearby Western Reserve University dormitory known as Adelbert Hall, a building later called Pierce Hall, which was razed in 1961. The Michelson–Morley equipment was moved to the southeast corner of the basement of Adelbert Hall.[54]

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[53] *The Cleveland Leader and Herald* (28 Oct. 1886).

[54] Letter from Sidney S. Wilson (Western Reserve Univ. Class of 1888) to Frank N. Shankland (Apr. 1949):

Twenty-Nine Palms, California
April, 1949

Dear Frank,

The night Case burned there were about ten of us Adelbert fellows living in the Old Dorm. We were the first to arrive . . . 15 minutes at least before the first fire engine (horse-drawn) . . . the building was all ablaze, the roof had fallen . . . the Morley-Michelson salvage from their apparatus was moved from the ruins to the Dorm basement and not into the Adelbert College basement as stated in your letter . . . their Lab. was then set up in the Southeast quarter of the basement directly under my room . . . Morley and Michelson were there much of the time . . . We were forbidden and threatened not to molest or even to inspect the Morley-Michelson apparatus. We didn't! . . . however, as words of caution turned to orders from Prexy Haydn for

In addition to the great efforts needed to reestablish, in Adelbert Hall, the Case physics laboratories and lectures for teaching, many weeks were required to set up the Michelson–Morley equipment for trial observations on the interferometer, improvements in the optics of the experiment, and mechanical refinements which would permit the stone to be rotated freely without introducing strains or vibrations. Finally, in July of 1887, Michelson and Morley were able to make their definitive observations. The experiments which gave their published data were conducted at noon and during the evening of the days of 8, 9, 11, and 12 July 1887. Instead of the expected shift of 0.4 of a fringe, they found "that if there is any displacement due to the relative motion of the earth and the luminiferous ether, this cannot be much greater than 0.01 of the distance between the fringes."[55]

Upon completion of the July 1887 experiments, Michelson sent a preliminary report of the work to Lord Rayleigh as follows:

> New York, August 17, 1887
>
> My dear Lord Rayleigh,
>
> The Experiments on the relative motion of the earth and ether have been completed and the result decidedly negative. The expected deviation of the interference fringes from the zero should have been 0.40 of a fringe—the maximum displacement was 0.02 and the average much less than 0.01—and then not in the right place.
>
> As displacement is proportional to squares of the relative velocities it follows that if the ether does slip past the relative velocity is less than one sixth of the earth's velocity.
>
> I enclose a poor photograph of the apparatus—which consists of a stone five feet square and one foot thick which floats on mercury and which holds the optical parts. Light from an argand lamp falls on *a*, part going to bcbcbcbaf and part to dedededaf.
>
> I hope to be able to send you a copy of the paper within a month.
>
> With kind regards to Lady Rayleigh,
>
> Very sincerely yours,
> Albert A. Michelson

No longer was it possible to believe that a positive result might be hidden in the errors of observation, and the doubts which had hung over Michelson's 1881 Potsdam experiment were now entirely removed by the Cleveland experiment. All explanations which had attempted to reconcile the Potsdam result with existing theories must now be abandoned, and new explanations for the behavior of moving optical and electrical systems had to be found.

At first, however, the full significance of this situation was not appreciated, and as late as 18 August 1892 Lorentz wrote to Lord Rayleigh:

> I have read your note with much interest and I gather from it that we agree completely as to the position of the case. Fresnel's hypothesis, taken conjointly with his coefficient $1-1/n^2$, would serve admirably to account for all the observed phenomena were it not for the interferential experiment of Mr. Michelson, which has, as you know, been repeated after I published my remarks on its original form, and which seems decidedly to contradict Fresnel's views. I am totally at a loss to clear away this contradiction, and yet I believe that if we were to abandon Fresnel's theory, we should have no adequate theory at all, the conditions which Mr. Stokes has imposed on the movement of the aether being irreconcilable to each other.
>
> Can there be some point in the theory of Mr. Michelson's experiment which has as yet been overlooked?

And Lord Kelvin, as late as 1900, in a lecture at the Royal Institution on 27 April of that year still referred to the Michelson–Morley experiment as one of the two "19th century clouds" (the other being the Maxwell–Boltzmann doctrine regarding the partition of energy) which dimmed the otherwise brilliant sky of the new scientific century. Kelvin had never fully accepted either the Maxwell electromagnetic theory or its extensions by Lorentz, and, as time passed, the older aether school which he represented fell farther and farther behind the new advances. Kelvin hoped to the end that the aether concepts could be saved, and in the preface to his Baltimore Lectures when reprinted in revised form in 1904 he would say ". . . that two of ourselves, Michelson and Morley, have by their great experimental work on the motion

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less noise and cause for jarring the basement stairs, our prejudice turned into a feeling of partnership and sympathy, later of pride. . . .

Yours,
Sid.

Also, letters from W. W. Coblentz (Case, Inst. Technol., Class of 1900) to R. S. Shankland (31 Oct. 1952) (quotes D. C. Miller); Comfort A. Adams (Case Inst. Technol., Class of 1890) to R. S. Shankland (3 Nov. 1952); and conversations with William Koehler (Case Inst. Technol., Class of 1889) (10 Dec. 1950; 11 Nov. 1952); and discussions with Prof. Hippolyte Gruener (17 Feb. 1950; 21 Dec. 1950; 28 Nov. 1952).

[55] A. A. Michelson and E. W. Morley, Am. J. Si. **34**,c 333 (1887); Phil. Mag. **24**, 449 (1887); J. Phys. (Paris) **1**, 444 (1888); Sidereal Messenger **6**, 306 (1887).

of ether relatively to the earth, raised the one and only serious objection against our dynamical explanations;. . . ." And at the 1900 International Congress of Physics in Paris, Kelvin had urged Morley and D. C. Miller (Michelson had left Case in 1889) to make another trial of the experiment, which they did with an even more conclusive null result than that obtained by Michelson and Morley.[56]

It is of interest to note that, although Michelson and Morley had planned to repeat their observations at regular intervals throughout the calendar year so that all epochs related to the earth's motion through space would be encompassed, they in fact made no further trials of this experiment after July 1887. The reason for this is probably the following.

The laboratory quarters in the basement of Adelbert Hall had been only temporary, and, at the beginning of the autumn term in September 1887, Michelson and Morley transfered their research activities to a basement laboratory in the Main Building of Adelbert College. Had they again set up the Michelson–Morley aether-drift interferometer there, it would have been a simple matter to repeat their observations at regular intervals during the year. Instead, they soon became involved in new lines of research that absorbed all their interests and efforts for the remaining two years that Michelson was a member of the Case faculty. In fact, Michelson, in his address on optical research as vice-president of section B of the A.A.A.S. in Cleveland in August 1888, failed to mention the Michelson–Morley experiment![57]

It was at this time that they developed the method which proved the feasibility of using light waves as the standard of length.[58] The files of the Warner and Swasey Company of Cleveland (for whom Professor Morley acted as consultant) still have a number of working shop drawings of the "Metre Subdividing Machine" which was built for Morley and Michelson in 1888. This machine was a highly engineered double-screw interferometer and has all of the essential features of the apparatus later used by Michelson in Paris to determine the length of the standard meter in light waves.

One of the most notable features of this work was their discovery of fine structure in the spectrum of hydrogen and hyperfine structure in the spectra of mercury and thallium. These optical multiplets were established with the Michelson interferometer by using the new Warner and Swasey instrument with optical arms of variable length and observing the changes in the visibility of the interference fringes as a function of optical-path difference between the two arms. This method was the natural outgrowth of their technique of moving the mirror e_1 (see Fig. 6) by a micrometer screw in order to improve the visibility of sodium-light fringes, as an aid in finding the white-light fringes in their aether-drift interferometer. The fine structure of the red hydrogen line was measured accurately in this way and shown to have a "doublet" structure.[58] Their early measurements of this "doublet" separation was the standard determination for many years and is in close agreement with the presently accepted value. The correct theoretical explanation of fine structure and hyperfine structure in spectrum lines, of course, had to wait many years until the development of quantum mechanics showed their relationship to electron spin and nuclear spin.

VII. CONCLUSION

It has already been emphasized that the Michelson–Morley experiment of 1887 could never be lightly considered, as had been the Potsdam result, as being due to some experimental inadequacy. Their result has always been accepted as definitive and formed an essential base for the long train of theoretical developments that finally culminated in the special theory of relativity.

The first important suggestion advanced to explain the null result of Michelson and Morley was G. F. FitzGerald's hypothesis, made to Sir Oliver Lodge[59] in his study at Liverpool, that the length of the interferometer is contracted in the direction of its motion through the aether by the exact amount necessary to compensate

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[56] E. W. Morley and D. C. Miller, Phil. Mag. **8**, 753 (1904); **9**, 680 (1905).

[57] A. A. Michelson, Proc. AAAS **37**, 3 (1888).

[58] A. A. Michelson and E. W. Morley, J. Assn. Engrg. Soc. (May 1888); Am. J. Sci. **38**, 181 (1889).

[59] Sir Oliver Lodge, Nature **46**, 165 (1892); G. F. FitzGerald, *Scientific Writings* (Dublin University Press, Dublin, 1902), Vol. 34.

for the increased time needed by the light signal in its to and fro path. This contraction hypothesis was made quantitative by H. A. Lorentz in further development of his electron theory. In the original form of this theory used to deduce the Fresnel dragging coefficient, and other effects, Lorentz[60] had obtained equations for a moving electrical system by applying a transformation in which terms of higher order than (v/c) were neglected, and which showed that to this approximation the relative velocity of medium and observer had no influence on the phenomena. After Larmor[61] had shown how these transformations could be extended to include quantities of order $(v/c)^2$, Lorentz[62] gave the general solution, exact to all orders of (v/c), by introducing what has since been known as the "Lorentz transformation," under which Maxwell's equations for the electromagnetic field in empty space are covariant. This treatment provided a more general explanation for the null result of the Michelson–Morley experiment than that previously given by FitzGerald and Lorentz. In his development, Lorentz not only obtained new measures of length and mass, but also employed a new method of specifying time which he called "local time," needed for the description of the properties of moving systems.

During the same period, Poincaré[63] had contributed both to the philosophical and mathematical development of the subject. As early as 1899, he had asserted that the result of Michelson and Morley should be generalized to a doctrine that absolute motion is in principle not detectable by laboratory experiments of any kind, and, in lectures at international congresses held at Paris in 1900 and at St. Louis in 1904,[64] he gave to this generalization the name "The Principle of Relativity," whereby "the laws of physical phenomena must be the same for a 'fixed' observer as for an observer who has a uniform motion of translation relative to him: so that we have not, and cannot possibly have any means of discerning whether we are, or are not, carried along with such a motion." From the experimental evidence, Poincaré also concluded that "there must arise an entirely new kind of dynamics, which will be characterized above all by the rule, that no velocity can exceed the velocity of light."

In June 1905, Poincaré[65] again cited the result of the Michelson–Morley experiment and asserted that "it seems that this failure to demonstrate absolute motion must be a general law of nature." He then proceeded to complete the theory of Lorentz by obtaining the equations of transformation of the electric-charge density and the electric current when the time and space coordinates are changed by the Lorentz transformation (so named here by Poincaré). Poincaré put the Lorentz transformation into the symmetrical form now universally used in which they form a mathematical group, and also gave the relativistic formulation for the addition of velocities.

In September 1905, Einstein[66] published his famous paper on the "Electrodynamics of Moving Bodies," which developed the special theory of relativity from two postulates: (1) the principle of relativity was accepted as a postulate asserting the impossibility of detecting uniform motion as defined for an inertial system in Newtonian mechanics, and (2) the constancy of the speed of light as contained in Maxwell's equations was generalized to a postulate stating that light is always propagated in empty space with a velocity c which is independent of the state of motion of the emitting body. Both postulates could, of course, be considered as having a close relationship to the Michelson–Morley experiment, but actually Einstein arrived at his theory by a less direct route, becoming aware of the observational material principally through the writings of Lorentz which he began to study as a student in 1895. He was also keenly aware of the phenomena of stellar aberration and the experiment of Fizeau on the

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[60] H. A. Lorentz, Arch. Néerl. Sci. **25**, 363 (1892); *Versuch einer Theorie* . . . (E. J. Brill, Leiden, 1895); Proc. Amsterdam Acad. **1**, 427 (1899).

[61] J. Larmor, *Aether and Matter* (Cambridge University Press, Cambridge, England, 1900), Chap. 11.

[62] H. A. Lorentz, Proc. Amsterdam Acad. **6**, 809 (1904); Encykl. Math. Wiss. Leipzig (1904).

[63] H. Poincaré, *Électricité et Optique* (Carré et Naud, Paris, 1901).

[64] H. Poincaré, Bull. Sci. Math. **28**, 302 (1904).

[65] H. Poincaré, Compt. Rend. **140**, 1504 (1905); Circ. Mat. Palermo Rend. **21**, 129 (1906), presented 23 July 1905.

[66] A. Einstein, Ann. Physik **17**, 891 (1905) [also in English transl. (Dover Publications, Inc., New York)]; Poincaré and Einstein seem to have arrived at their results independently.

speed of light in moving water.[67] In his great paper, Einstein made the two postulates compatible by means of the Lorentz transformations for the conversion of coordinates and times of events between two inertial systems. He provided direct and convincing explanations for the classic experimental facts, including new treatments of aberration and the transverse Doppler effect. Einstein's approach led him to the relativity of the simultaneity of events, and so made the aether concept superfluous while also demonstrating that the "local time" of Lorentz is in fact the only meaningful time for the description of physical phenomena. His paper is generally considered as the definitive exposition of the special relativity principle and the climax of the century-long developments which had begun with Young and Fresnel to understand electrical and optical phenomena in moving media.

In the years following the acceptance of the theory of relativity, the Michelson–Morley experiment was subject to continual scrutiny, leading to a much deeper understanding of its significance. During the same period, the relativity theory was gradually presented on a more sophisticated basis, and, in more abstract form, less dependent on the special relationship with the optics and electromagnetism from which it had its origin.[68] The special theory in its turn led the way to the general theory of relativity and so to Einstein's theories of gravitation and cosmology.

In closing this account of the Michelson-Morley experiment, it may be appropriate to do so with the statement which Professor Einstein sent for a special meeting of the Cleveland Physics Society held on 19 December 1952 honoring the centenary of Michelson's birth.[69]

> "I always think of Michelson as the artist in Science. His greatest joy seemed to come from the beauty of the experiment itself, and the elegance of the method employed. But he has also shown an extraordinary understanding for the baffling fundamental questions of physics. This is evident from the keen interest he has shown from the beginning for the problem of the dependence of light on motion.
>
> The influence of the crucial Michelson–Morley experiment upon my own efforts has been rather indirect. I learned of it through H. A. Lorentz's decisive investigation of the electrodynamics of moving bodies (1895) with which I was acquainted before developing the special theory of relativity. Lorentz's basic assumption of an ether at rest seemed to me not convincing in itself and also for the reason that it was leading to an interpretation of the result of the Michelson–Morley experiment which seemed to me artificial. What led me more or less directly to the special theory of relativity was the conviction that the electromotive force acting on a body in motion in a magnetic field was nothing else but an electric field. But I was also guided by the result of the Fizeau-experiment and the phenomenon of aberration.
>
> There is, of course, no logical way leading to the establishment of a theory but only groping constructive attempts controlled by careful consideration of factual knowledge."[70]

ACKNOWLEDGMENTS

It is a pleasure to express my sincere thanks to Professor Sidney W. McCuskey, Professor Martin J. Klein, and Professor Leslie L. Foldy for constructive criticisms in the preparation of this paper.

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[67] R. S. Shankland, Am. J. Phys. **31**, 47 (1963).

[68] Especially through the work of H. Minkowski, who introduced the four-dimensional formulation of the theory in terms of the geometry of space–time, and also the use of tensor calculus; Gött. Nach. 53 (1908); Math. Ann. **68**, 526 (1910); H. A. Lorentz, A. Einstein, and Minkowski (*Das Relativätsprinzip* Leipzig, 1910) [also in English transl. (Dover Publications, Inc., New York)].

[69] R. S. Shankland, Nature **171**, 101 (1953).

[70] Professor Einstein also sent the German original, but as the English translation is his, it is given here.