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Pioneering applications in such diverse fields as astronomy, atomic spectra and mensuration followed the initial disappointment over the failure to detect a luminiferous ether.

Robert S. Shankland

Albert Abraham Michelson was the first American scientist to win the Nobel Prize, and his career is one of the most fascinating in the entire history of physics. His earliest work was firmly based on the classical physics of geometrical optics—in a precise determination of the velocity of light by an improved Foucault method. But then he mastered wave optics and invented his interferometer, and from that point on he proceeded to dazzle the scientific world with a display of the applications he found for his invention during a career that exhibited throughout a unique pattern of originality and dedication to physics.

The interferometer came into being for the specific purpose of measuring the Earth's motion through the luminiferous ether, a project familiar to generations of physics students as the "Michelson–Morley experiment." Although this single undertaking has proved important enough to guarantee Michelson's place in history, the unexpected negative result caused response at the time to be lukewarm, and this is not the work for which the Nobel Prize was awarded in 1907. He was honored instead for the other applications of his invention—particularly for his work on the determination of the length of the International Standard Meter in terms of the wavelength of light, but also for such diverse and pioneering achievements as the discovery of fine and hyperfine structure in atomic spectra and the first application of interference measurements in astronomy.

The birth of a concept

Michelson's invention of this remarkable instrument, the interferometer—which to the present day plays important roles in Fourier spectroscopy, laser-beam interferometers and the ring-laser gyro—came suddenly with but little relationship to his earlier researches on the speed of light.

He had been born in 1852 at Strzelno in the Prussian province of Posen and travelled with his parents to frontier towns of California and Nevada. Then he made his way with the greatest determination to the Naval Academy at Annapolis, where he excelled in science and made his first precise measurement of the speed of light. One will search in vain in his Annapolis textbook[1] and in his papers and correspondence for clues as to what inspired his great invention. At Annapolis, and later, when Simon Newcomb invited him to collaborate with him at the Naval Observatory in Washington, Michelson's velocity-of-light determinations employed exclusively the methods of ray or geometrical optics, with heliostats, mirrors and lenses to produce intense beams of light; there is no indication in this period of his concern or interest in the wave properties of light or in optical interference.

But in a few weeks in 1880 between his last velocity of light determinations with Simon Newcomb in Washington and his first work in Helmholtz's laboratory at Berlin (where he had gone on leave from the Navy for special study and research), he clearly had mastered the basic principles of the wave nature of light and then invented his interferometer, which is one of the most powerful and elegant applications of the characteristic interaction between light waves.

However, two events had occurred in Washington that bear closely on the invention of his interferometer. The first was a letter, dated 19 March 1879, which James Clerk Maxwell[2] had written to David Peck Todd at the Nautical Almanac Office inquiring about astronomical observations on Jupiter's satellites suitable for a determination of the speed of light but which more importantly, might reveal the Earth's motion through the ether of space. In this letter, which was also studied by Newcomb and Michelson, Maxwell had asserted that no terrestrial method was capable of measuring the speed of light to the one part in a hundred million that would be necessary in any laboratory experiment to detect the Earth's motion through the ether. Maxwell's statement appears clearly to have been the challenge that the young Michelson accepted for developing his interferometer specifically to carry out a laboratory ether-drift experiment, which he first conducted in Germany and later in its final form with Edward W. Morley at Cleveland.

A second clue showing Michelson's shift in interest from ray optics to wave optics after his study of Maxwell's letter is suggested by a short paper he presented to the Philosophical Society of Washington on 24 April 1880. It is entitled "The Modifications Suffered by Light in Passing Through a Very Narrow Slit."[3] This report gives a brief but accurate account of his observations on the already well known diffraction phenomena produced by a narrow slit. However, the subject seems to have been new to Michelson, and he reported his keen observations on the color and polarization of the light as he narrowed the slit width while using sunlight for the source. This early paper is certainly not one of his major contributions, but it does reveal his remarkable observational ability as he describes precisely the colors, polarization, and diffraction patterns produced. This paper strongly suggests he had already appreciated that the key to meeting Maxwell's challenge for precision optics was essentially to find a method of measurement that would directly employ the extremely short wavelengths of light and not depend on the macroscopic length and time measurements of ray optics that he had employed exclusively in his earlier work.

When Michelson arrived at Helm-

Albert A. Michelson in 1927 at his desk in the Ryerson Physical Laboratory, University of Chicago. This is one of two photographs, taken by H. P. Burch, that Michelson often said he liked better than any others. (Courtesy of the Michelson Museum). Figure 1

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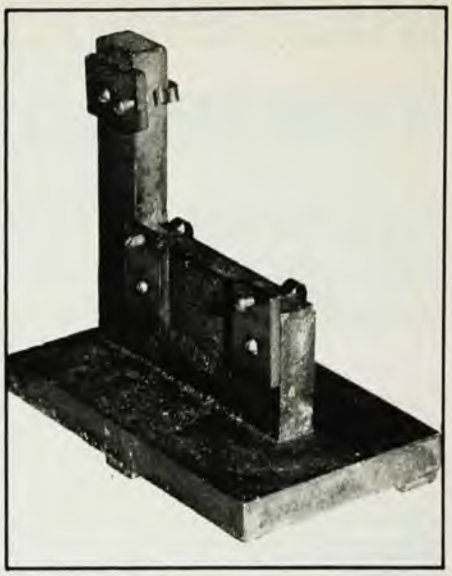
The Michelson–Morley experiment as used in Cleveland in 1887, with its optical parts mounted on a five-foot-square sandstone slab. This photograph was found in 1968 by D. T. McAllister in a Michelson notebook at Mount Wilson Observatory. (Courtesy of the Michelson Museum and the Hale Observatories.) Figure 2



Holder for optical-flat "beam-splitter" of the Michelson–Morley interferometer used in 1886–87 at what is now Case Western Reserve University. Figure 3

holtz's laboratory in Berlin in the fall of 1880, he experienced for the first time the thrill of a well equipped and active research center, for at that time this was probably the outstanding laboratory in Europe for physics research. There also he was suddenly brought in touch with the best apparatus available for experiments in optics, for Helmholtz himself was already world famous for his researches in physiological optics. The questions that had been raised in Michelson's mind by the phenomena of his narrow-slit experiment in Washington had "sensitized" him to react strongly and appreciate fully the many new stimuli of Helmholtz's laboratory. In any event, soon after his arrival in Berlin his pondering and search for an optical method that would meet the severe requirements posed by an ether-drift experiment aroused his natural creative instincts and he invented the Michelson interferometer. (But it is possible that he had already conceived the essential elements of the instrument while still in Washington, where Newcomb had introduced him to Alexander Graham Bell who later, on Newcomb's recommendation, supplied the necessary funds to have the first interferometer built by Schmidt and Haensch in Berlin.)

In later years he always stated that the interferometer was devised specifically for the ether-drift experiment. It is, of course, impossible to trace precise paths in the creative thinking of a scientist and conclusively demonstrate how he finally arrived at his goal, and there are discontinuities in the process that even the man, himself, cannot explain. But it seems clear that Maxwell's letter and the narrow-slit experiment in Washington were essential spurs to Michelson's genius for his invention of the interferometer.

This instrument is a classic example of symmetry, and apparent simplicity. He dispensed with the narrow slits that physicists had employed since the days of Thomas Young to produce interference between coherent light beams, and instead used a large glass optical flat silvered just enough on one face to half reflect and half transmit the entire wavefront of the light impinging on it, thus giving much greater intensity and permitting a wide range of experiments that had been impossible with all earlier optical apparatus. Once the two coherent light beams were produced at the optical "beam splitter," they could then each be directed by mirrors and lenses in a variety of ways (through moving water for example) and then be reunited to add and subtract their vibrations to produce the beautiful patterns of bright and dark interference fringes that Michelson studied in one experiment after another for the rest of his life. He spent the last forty years at the University of Chicago (figure 1 is a photograph dating from this period).

Ether drift

We will note here only a few of the great experiments he carried out with his interferometer. As already stated, it was specifically devised to measure the motion of the Earth through the ether, a medium that in those days was universally believed to be essential for the propagation of light. In this experiment, first tried unsuccessfully at Potsdam in 1881, and then after Michelson became the first professor of physics at Case School of Applied Science, it was conducted in its definitive form (see figures 2 and 3) by Michelson and Morley at Cleveland in 1887.

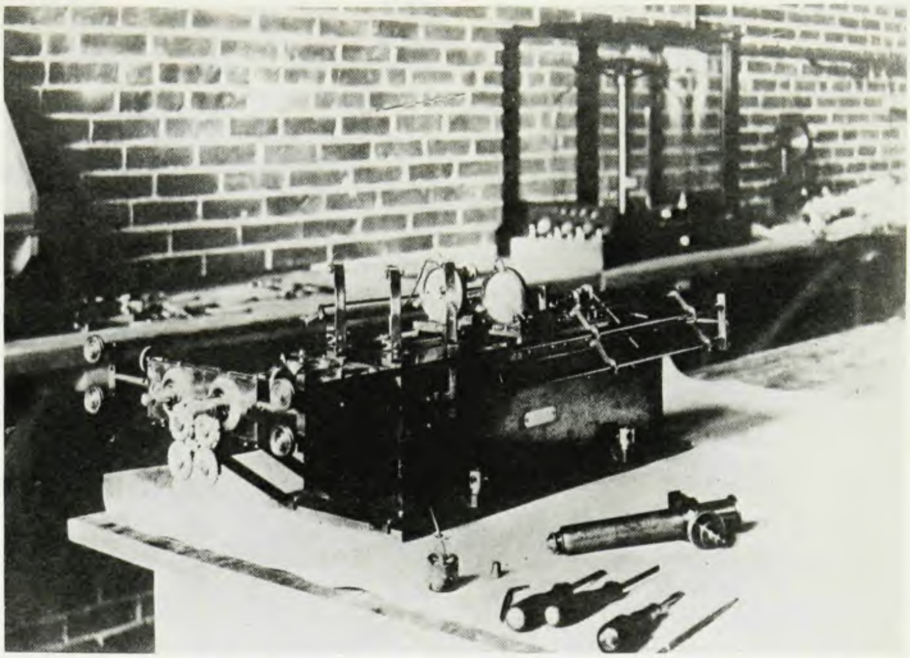
One of the two coherent light beams produced in the interferometer was caused to traverse a to-and-fro path along the direction of the Earth's motion, while the other light beam travelled along a path of exactly equal length in a perpendicular direction. On their return the two light beams were recombined to produce white-light interference fringes, so that the central white fringe could serve as a reference. Michelson had confidently expected from calculations that, when the apparatus was rotated so as to interchange the positions of the two light beams, the pattern of interference fringes would shift and thus reveal the Earth's motion through the ether. This procedure, in effect, compares with great precision the speed of light in the two arms of the interferometer. The ether theory predicted that this speed should be altered unequally by the Earth's motion, to a degree proportional to the square of the ratio of the Earth's speed to that of light. The apparatus was sensitive enough to have shown this extremely small effect discussed by Maxwell, but no significant shift of the interference fringes was observed. The scientific world generally, and Michelson in particular, were greatly disappointed by this result, which was in direct conflict with accepted theory at that time. It was many years before the work of George Fitzgerald, H. Antoon Lorentz, Joseph Larmor, Henri Poincaré and, finally, Albert Einstein carried theoretical physics to the point where Michelson and Morley's result could not only be explained, but served as an essential basis for our modern concepts of space and time.

It is a curious fact that for many years Michelson seldom mentioned this result. It did not appear in his Vice-Presidential Address to the American Association for the Advancement of Science, delivered at Cleveland in 1888; his students at Case School of Applied Science never heard of it in his physics classes there, and it is absent from his Nobel Prize lecture in 1907. After many years Michelson did discuss it in his optics courses at the University of Chicago, but only after the relativity theory was fully established; even then it was described primarily in its relation to the ether theory of Augustin Fresnel and Lorentz, rather than for its importance to relativity.[4] But, in Einstein's words, Michelson had "led the physicists into new paths, and through his marvelous experimental work paved the way for the development of the theory of relativity. He uncovered an insidious defect in the aether theory of light as it then existed, and stimulated the ideas of H. A. Lorentz and Fitzgerald out of which the special theory of relativity developed. This in turn pointed the way to the general theory of relativity, and to the theory of gravitation."[5] As Robert A. Millikan emphasized in 1948 at the dedication of the Michelson Laboratory in California, the ether-drift trial has long been regarded as one of the two greatest physics experiments performed in the nineteenth century (the other being the Faraday-Henry discovery of electromagnetic induction).

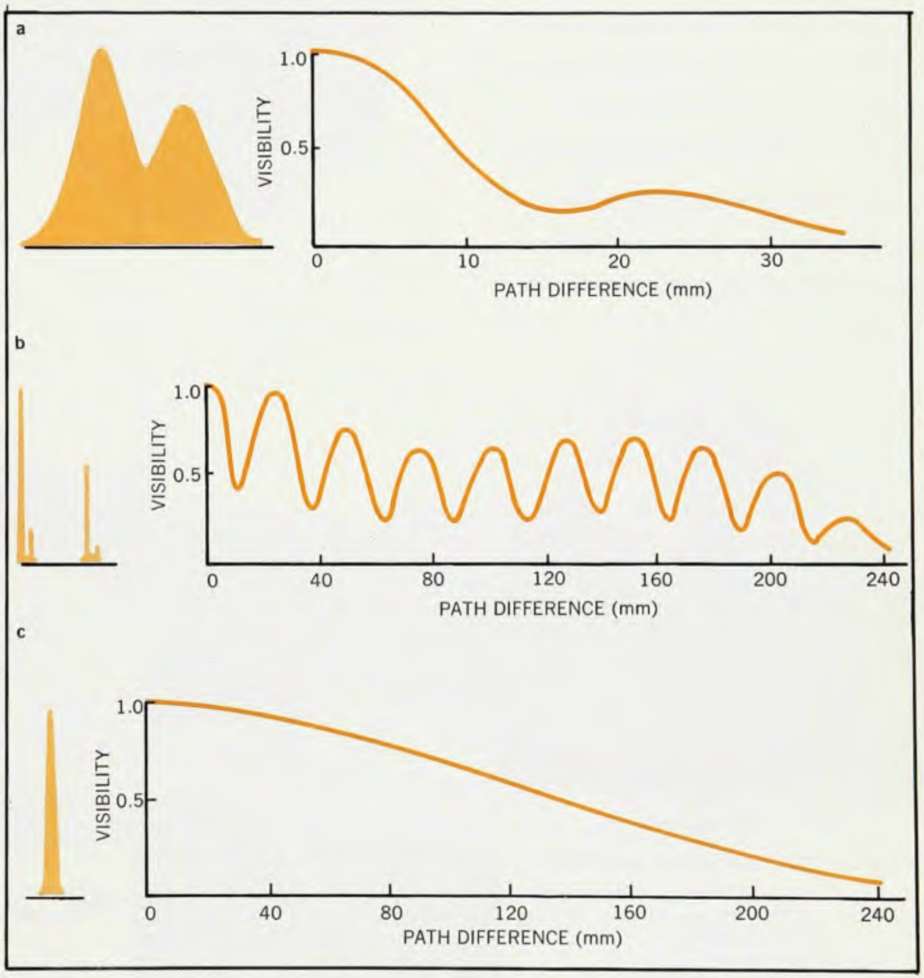
Measuring the meter

But strangely enough this was not the work for which Michelson was awarded a Nobel Prize, the first such award to an American. Rather, the Prize was given primarily in recognition with Morley in Cleveland, and in 1887 they abruptly abandoned the search for the ether to prove the feasibility of their optical method for standardization of the meter.[6] An early form of interferometer built for this purpose is now at Clark University and is shown in figure 4. Michelson alone com-Paris which was jealously guarded against damage or loss. Clearly a reproducible standard of length was highly desirable—one that could be duplicated at any major laboratory in the world.

The solution of the problem was first undertaken by Michelson in collabora-tion with Morley in Cleveland, and in 1887 they abruptly abandoned the search for the ether to prove the feasibility of their optical method for standardization of the meter.[6] An early form of interferometer built for this purpose is now at Clark University and is shown in figure 4. Michelson alone com-



Early interferometer of the type developed by Michelson and Edward W. Morley and used by Michelson in Paris for measuring the standard meter in wavelengths of cadmium light, 1892–93. (Courtesy of the Michelson Museum and Clark University.) Figure 4



"Visibility curves" of interference fringes as a function of light-path differences in the two interferometer arms (solid color curves on right), with the analyzed structure of the spectrum lines (colored peaks on left). Part a: Fine-structure doublet of H-alpha line of hydrogen. Part b: Hyperfine structure in a line of thallium. Part c: The narrow red line of cadmium used to standardize the meter. (From A. A. Michelson, "Light Waves and Their Uses," University of Chicago Press, 1903.) Figure 5

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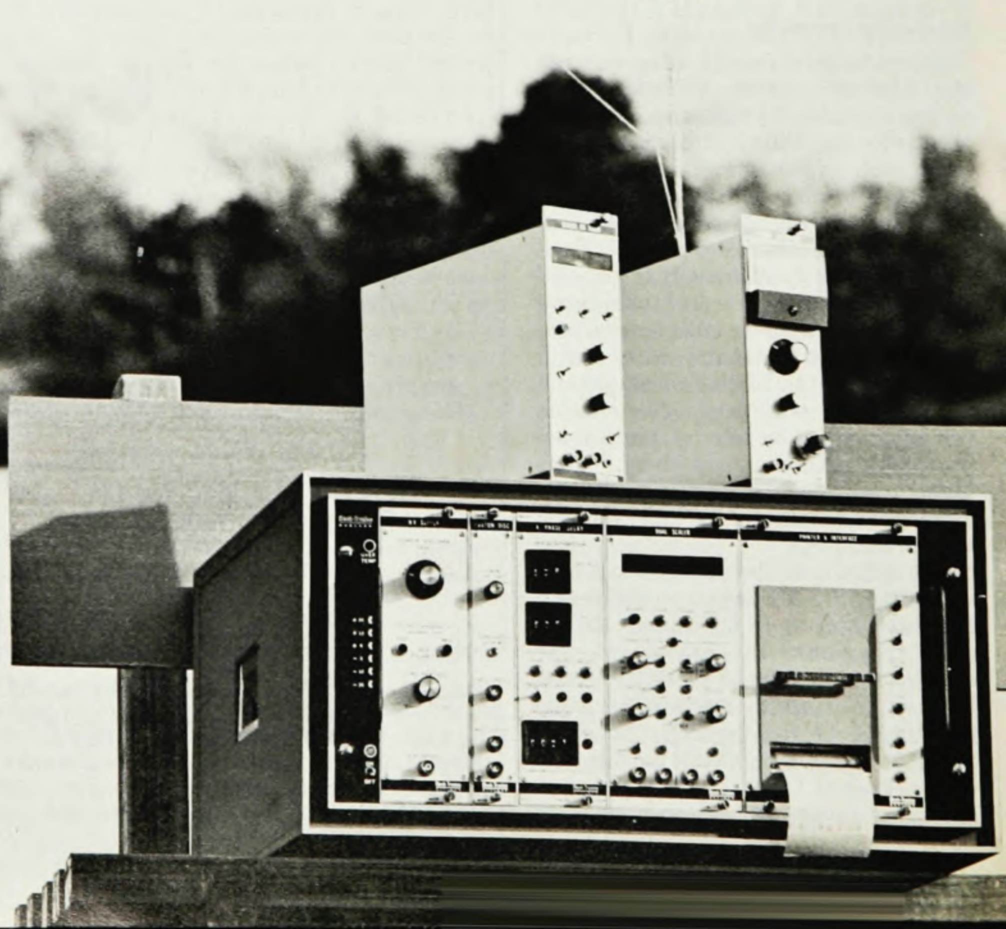

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pleted the determination in Paris, and since that time it has been a matter of little concern whether or not the standard meter bar continues to exist, for thanks to Michelson and the later development of the orange-red line of krypton[7] as a new primary standard, the length of a light wave is now the official standard of length.

Two major discoveries were made by Michelson and Morley in the course of their standard meter work in Cleveland.[8] To measure the meter in terms of light waves it was essential that the interference fringes in their special interferometer should be produced by light of an extremely narrow spectrum line, so that interference between light beams with a large difference in path was possible. In the course of their search for such a light source they analyzed many spectrum lines with the interferometer by observing the changes in the "visibility" of the fringes as the path difference was increased. Today this process is the basis of the large activity in Fourier spectroscopy.[9] They were surprised to find that nearly all spectrum lines are complex and thus discovered what is now known as "fine-structure" in the spectrum of hydrogen, and "hyperfine structure" in the spectra of mercury and thallium (see figure 5). It was many years before the full significance of these findings for atomic and nuclear physics was understood, and it is interesting to note that the detailed explanation of fine structure requires the relativity theory that owed so much to Michelson's other experiments. The discovery of fine structure and hyperfine structure will always ensure their work an important place among those experiments that were basic for the development of quantum mechanics and nuclear physics. They also were the stimuli that led Michelson to his invention of the echelon spectroscope, his harmonic analyzer for more accurate Fourier spectroscopy, and his long program at the University of Chicago in the ruling of diffraction gratings.

Part of the system of evacuated pipes used in the Michelson-Gale-Pearson experiment at Clearing, Illinois, 1924-25. This photograph shows, left to right; Charles Stein, Thomas J. O'Donnell, Fred Pearson, Henry G. Gale, J. H. Purdy and an unidentified worker. (Courtesy of the Michelson Museum and J. H. Purdy.) Figure 6

The Earth's rotation

Michelson's experiments on the ether continued from 1881 until 1929, and "to the end he hoped to empirically prove there was this medium known as *the ether*."[10] One of the most interesting applications of his interferometer for this search was in the Michelson-Gale-Pearson experiment conducted in 1924-25 on the Illinois Prairie at what is now the Clearing industrial area west of Chicago. As early as 1904 Michelson had proposed an interferometer experiment to reveal the Earth's rotation through the ether. During 1921-23 he had made preliminary trials at the Mount Wilson Observatory, for after Eddington's successful solar-eclipse expeditions in 1919 had found the deflection of starlight by the sun, as predicted by general relativity, there had been a great revival of interest in all related experiments.

Michelson was in ill-health at the time, but with the active collaboration of Henry G. Gale, Fred Pearson and Tom O'Donnell a large system of 12-inch-diameter pipes for the light beams was set up on a rectangle (300 meters by 600 meters) on level ground. Figure 6 shows part of the large rectangle of pipes employed. The two light beams from a Michelson interferometer were reflected, (one in each direction) around the circuit of evacuated pipes. The Earth's rotation affected the times of travel of the two beams unequally and thus would be revealed by the interference fringes when the two beams were re-united. A second system of fringes from light-beams travelling in a smaller rectangle of pipes established the fiduciary point of the interference pattern. Michelson's poor health and the excessive newspaper publicity that attended this experiment cooled his enthusiasm for the work, but it was carried through successfully. This experiment is the optical analogue of the Foucault pendulum, and as such "only shows that the Earth rotates on its axis," as Michelson caustically remarked. The results were definite, giving a shift of 0.25 fringe in the larger optical circuit.[11] However, since this result was in agreement not only with both the special and the general theories of relativity but also with Fresnel's old fixed-ether theory, it did not give the decisive test that had been hoped for.

The techniques of this experiment were of great interest to Einstein, and the following letter from him accurately describes its relation to relativity:

September 17, 1953

Dear Dr. Shankland:

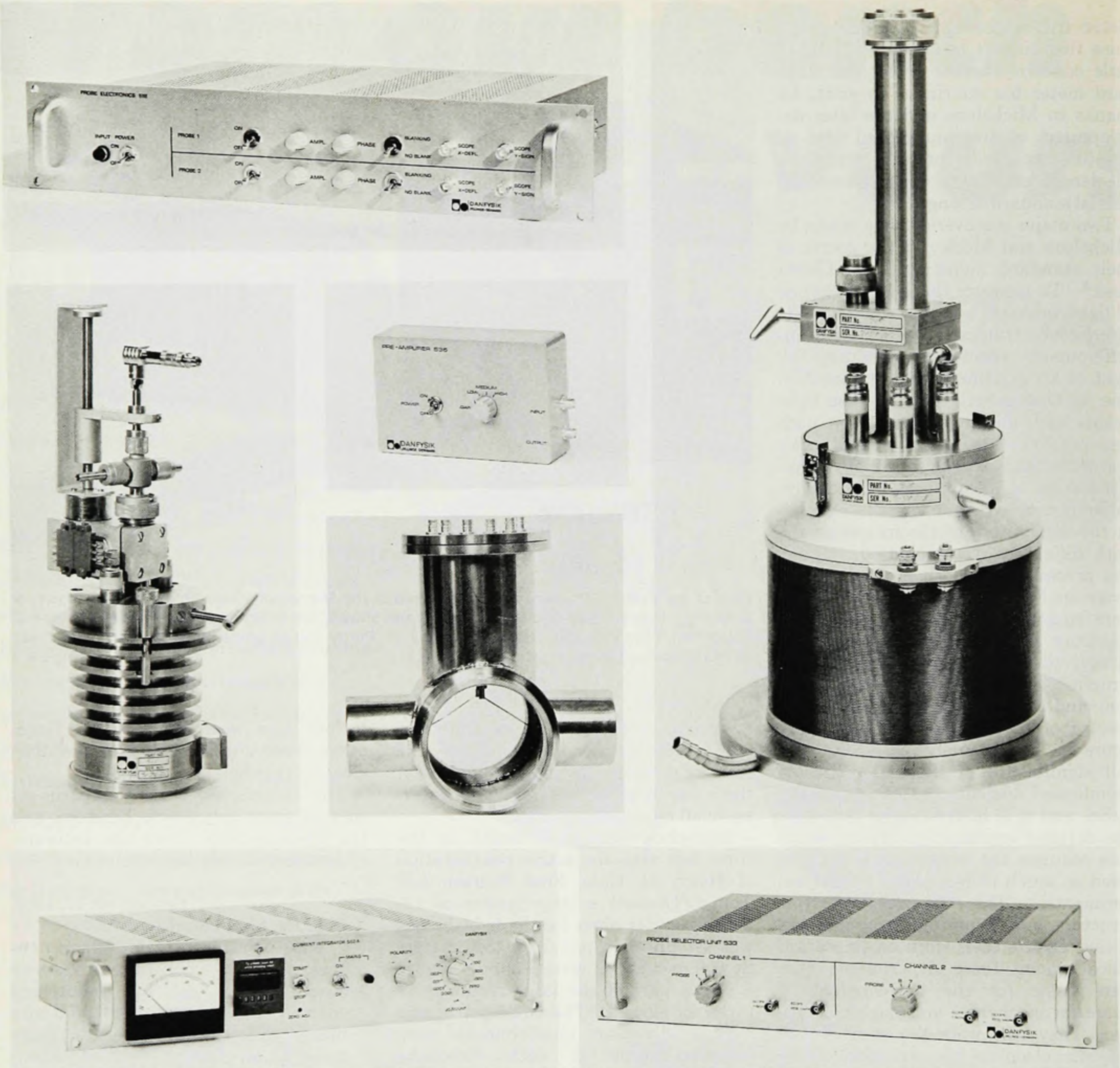
The Michelson-Gale experiment does, of course, concern the relativity question but, as you mentioned yourself, not insofar as relativity theory differs from Lorentz' theory based on an ether at rest. My admiration for Michelson's experiment is for the ingenious method to compare the location of the interference pattern with the location of the image of the light source. In this way he overcomes the difficulty that we are not able to change the direction of the earth's rotation.

Sincerely yours,
Albert Einstein (signed)

However, modern applications of this method in the ring-laser gyro have proved to be of great value for measuring and guiding rotations in the navigation of satellites, missiles, and aircraft.

The diameter of a star

One final application of the interferometer should be emphasized—in this case to astronomy. As shown in figure 7, Michelson adapted his instrument for use with large telescopes to mea-



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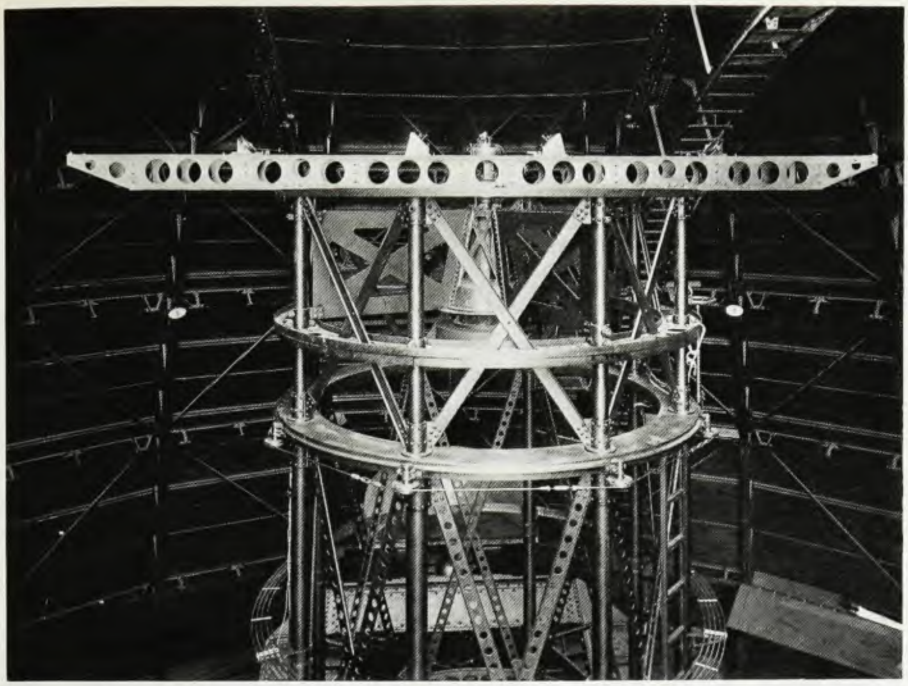

Michelson's twenty-foot stellar interferometer mounted on top of the 100-inch Hooker telescope at Mount Wilson Observatory in 1920, as used to measure the angular diameter of Betelgeuse. The outer two (movable) mirrors collect the starlight and the two inner ones direct it to the eyepiece. (Courtesy of the Hale Observatories.) Figure 7

sure the diameters of heavenly bodies. First, at the Lick Observatory in 1891, he determined the sizes of Jupiter's satellites;[12] later, in 1920 at the Mount Wilson Observatory, Michelson and Pease measured for the first time in history the angular diameter (0.047 seconds of arc) of a star (Betelgeuse).[13] This latter feat was one of the greatest triumphs of his life-long devotion to precision measurements with light waves, and extensions of his method are now an essential element for much work in long baseline radioastronomy. After explaining the technical details of the stellar measurement to a joint meeting of the American Physical Society and the AAAS, he then urged his children "to always remember the wonder of it."

In closing this account we should also realize that Michelson's other continuing scientific interest in addition to his interferometer was the measurement of the speed of light. He pursued this for over half a century from his first determination along the old sea-wall at Annapolis (1877–79), then across the Potomac in Washington, then along the railroad tracks in Cleveland (1882–84) and, finally, at Mount Wilson and at Santa Ana in California until the end of his days (1931).[14] The accuracy of his results improved steadily over the years and the continuing importance of this fundamental constant for science has fully justified the care that he lavished on its determination.

* * *

This article has been adapted from an address given 21 October 1973 at the New York University Hall of Fame Meeting at Town Hall, New York City.

References

1. A. Ganot, *Treatise on Physics*, (Atkinson's translation), New York (1873).
2. J. C. Maxwell, reprinted in Nature **21**, 314 (1880).
3. A. A. Michelson, Smithsonian Misc. Collections **20**, 119 and 148 (1881).
4. V. O. Knudsen, Notes of Michelson's University of Chicago Lectures made in 1917. Also correspondence with Michelson's students, Harvey Fletcher, Ralph D. Bennett and Richard L. Doan.
5. A. Einstein, Science **73**, 379 (1931).
6. A. A. Michelson, E. W. Morley, Amer. J. Sci. **34**, 427 (1887).
7. Natl. Bur. of Std. Publ. 232, April 1961.
8. A. A. Michelson, E. W. Morley, Amer. J. Sci. **38**, 181 (1889).
9. J. N. Howard, G. A. Vanasse, A. T. Stair, D. J. Baker, Aspen Conference on Fourier Spectroscopy, 1970.
10. Letter of T. J. O'Donnell (Michelson's instrument maker) to R. S. Shankland, 12 July 1973.
11. A. A. Michelson, H. G. Gale, F. Pearson, Astrophys. J. **61**, 137 (1925).
12. A. A. Michelson, Publ. Astron. Soc. Pacific **3**, 274 (1891).
13. A. A. Michelson, F. G. Pease, Astrophys. J. **53**, 249 (1921).
14. Dorothy Michelson Livingston, *The Master of Light*, Scribners, New York (1973). □