Comparisons are dangerous, but I greatly doubt whether Michelson has ever been equaled in his chosen field. Most of his researches demanded refinements that other physicists, however talented, could hardly dare to hope for, still less attain. I think of him as a master artist, conceiving new visions, terrestrial and celestial, and giving them precise and enduring form.

It was characteristic of such an artist to select light, in all its varied hues, not only as the subject but also as the chief agent of his investigations. In the first of the Lowell Lectures incorporated in Light Waves and Their Uses, Michelson spoke as follows of his subject:

This, to my mind, is one of the most fascinating, not only of the departments of science, but of human knowledge. If a poet could at the same time be a physicist, he might convey to others the pleasure, the satisfaction, almost the reverence, which the subject inspires. The aesthetic side of the subject is, I confess, by no means the least attractive to me. Especially is its fascination felt in the branch which deals with light, and I hope the day may be near when a Ruskin will be found equal to the description of the beauties of coloring, the exquisite gradations of light and shade, and the intricate wonders of symmetrical forms and combinations of forms which are encountered at every turn.

After predicting the rise in the near future of "a color art analogous to the art of sound—a color music," since then partially realized, he continues:

These beauties of form and color, so constantly recurring in the varied phenomena of refraction, diffraction, and interference, are, however, only incidentals; and, though a never-failing source of aesthetic delight, must be resolutely ignored if we would perceive the still higher beauties which appeal to the mind, not directly through the senses, but through the rea-
Albert Abraham Michelson, 1852–1931

Copyright E. Willard Spurr, Pasadena, Cal.
soning faculty; for what can surpass in beauty the wonderful adaptation
of Nature's means to her ends, and the never-failing rule of law and order
which governs even the most apparently irregular and complicated of her
manifestations? These laws it is the object of the scientific investigator
to discover and apply. In such successful investigation consists at once
his keenest delight as well as his highest reward.

As it is hopeless in the space at my disposal to do justice to
even a fraction of Michelson's work, I shall confine myself to a
few of its phases with which I was fortunate enough to have per-
sonal contact. I met him first at Cleveland in 1888 when, in my
student days, I attended a meeting of the American Association
for the Advancement of Science and listened with delight to his
vice-presidential address before Section B. I had worked since
boyhood in spectroscopy and was thus partially prepared to ap-
preciate some of the limitless possibilities of the interferometer
he described. Little did I realize, however, to what a point he
would carry them in future years.

Michelson's life-long passion for accuracy of measurement
was illustrated in this Cleveland address. The spectroscope had
attained high resolving power in Rowland's hands, but the inter-
ferometer provided another means of fine resolution, the extreme
value of which Michelson proved. The beauty of this instrument
in its many types could not fail to impress everyone who appre-
ciated in any degree the value to science of such new and power-
ful methods of research. In one of its forms, for example, the
interferometer surpasses the microscope for measuring very
minute displacements, while in another it transcends the telescope
in measuring extremely small angles. The gain is not a minor
one, as the results are from twenty to fifty times as accurate as
those obtainable with the microscope or the telescope.

In 1892, when the first buildings of the University of Chicago
were being erected, I was working about two miles away at the
Kenwood Observatory. As a young and inexperienced member
of the original faculty of the University, I heard with surprise
and delight of Michelson's acceptance of the professorship of
physics. His superb work at the Ryerson Physical Laboratory
forms a brilliant chapter in the history of science. It was a rare
privilege to see him in action and to watch the development of
his successive discoveries. I recall especially his uncanny precision in estimating the visibility of interference fringes, which he read off in quick sequence as though from a printed table while he rapidly shifted, step by step, the position of his interferometer mirror. In fact, his skill as an observer matched his power of conceiving new methods and embodying them in instrumental form.

Before 1892 Michelson had measured the velocity of light, performed with Morley the famous experiment that served as the foundation stone of Einstein's theory of relativity, and applied the interferometer to a great variety of purposes. One of these showed that light-waves, presumably invariable throughout the universe, could be employed as a constant and indestructible standard of length. It was therefore not surprising that he was invited by the International Bureau of Weights and Measures to measure the standard meter at Sèvres. This delicate operation, which took nearly a year to complete, fixed the length of the meter bar with an absolute accuracy of about one part in two million and a relative accuracy of about one part in twenty million. Slow change or even complete destruction of the standard meter would therefore no longer be a serious calamity, as it could easily be replaced from Michelson's measures, subsequently beautifully confirmed by Benoit, Fabry, and Pérot.

The measurement of the standard meter was a formidable task, involving a great variety of difficult operations. Hundreds of radiations had to be analyzed in order to find one of sufficient homogeneity. Finally the red line of cadmium vapor at a certain temperature and pressure was selected. Its visibility curve under the chosen conditions is of such a character that the interference fringes would be measurable over a difference of path of 220 millimeters, corresponding to about 350,000 light-waves. As the counting of hundreds of thousands of fringes would be an extremely troublesome and uncertain task, Michelson divided the distance to be measured into smaller parts, and used a set of intermediate standards of the highest optical precision. He could then count the fringes without difficulty, and combine the results so as to give the total length of the meter with the accuracy stated.
Every one of Michelson's researches is so interesting that it is difficult to confine attention to a few. To astronomers, however, his work on the velocity of light, the Michelson-Morley experiment, and the measurement of the diameters of stars probably stand first. Just as he made the exact wave-length of the cadmium line the fundamental unit of terrestrial measurement so he fixed the exactly determined velocity of light as the fundamental unit of celestial measurement. The many critical parts played by the velocity of light in modern physics raises its significance to a level attained by few other constants of nature.

All three of these investigations, though initiated in the early years of his career, have reached their final stages in California. Indeed, Michelson's first use of interference methods for celestial measurements was made at the Lick Observatory in August, 1891. Two parallel slits, adjustable in distance apart, were placed over the objective of the 12-inch refractor, which was directed to a satellite of Jupiter. For a uniformly illuminated disk the fringes due to the superposition at the focus of the light-pencils passing through the two slits should vanish when its angular diameter equals the wave-length of the light multiplied by 1.22 and divided by the distance between the centers of the slits. This method gave excellent values for the four satellites, which are approximately a second of arc in diameter. But the possibility of utilizing it to reveal the extremely minute angular diameters of stars seemed very remote. If the same device were employed, a telescope of enormous aperture would be required. Moreover, it appeared very doubtful whether sufficiently good atmospheric conditions could be found for the purpose.

However, Michelson often discussed the method with me, and before the war I asked him to try it at Mount Wilson. In 1918 the invitation was renewed. After first ascertaining with a pair of slits separated by the full aperture of the 40-inch Yerkes telescope that the fringes from a star could be clearly seen, he came to California and repeated the test with the 60-inch reflector on September 18, 1919. The fringes were very distinct, so a further test was made with the 100-inch reflector, this time

using a small screen with two apertures near the eyepiece, where their distance and orientation could be very readily controlled. As the fringes corresponding to the full aperture of 100 inches were clear and steady under magnifications ranging from 2,000 to 10,000 diameters, it was evident that the method could be used even with seeing 2 on a scale of 10. I recall with pleasure the intense satisfaction of all those who saw the fringes on that occasion.

As the aperture of the 100-inch reflector is not great enough for the measurement of the diameter of a star, the first move was to apply the method to the spectroscopic binary Capella. The components of this close double star, about 0'05 apart, are not directly visible in telescopes. Each component, however, produces its own set of fringes, and on rotating the disk carrying the slits (a valuable method proposed by Anderson), the visibility of the fringes is seen to vary with the position angle. When the line joining the slits corresponds with the line joining the stars, the slits are separated until the fringes of one set fall exactly between those of the other, causing minimum visibility, or complete disappearance of the fringes if the two components are of equal brightness. The distance between the slits then permits the angular distance between the two stars to be computed with an accuracy far greater than that attained in the micro-metric measurement of wide binaries. For example, in Anderson's early measurements of Capella, the separation was determined within considerably less than one per cent. The 100-inch reflector might be used for much work of this character, as its theoretical limit of resolution with the interferometer is 0'025, and double stars down to about the eleventh magnitude should be within its range. Smaller telescopes could also be used to advantage in this way, as results of high precision can be obtained with ordinary seeing, and the apparatus required is extremely simple.²

As Michelson's tests in 1919 were so satisfactory, an interferometer with movable mirrors on a base 20 feet in length was at once constructed for use with the 100-inch telescope. Eddington has explained in a popular way in his book *Stars and Atoms*, as he had previously done more technically, the method of selecting the most promising stars for measurement. *Sirius*, because of its intense radiation per unit area of surface, need not be of great angular diameter to account for its brilliancy. What we need is a star which is extremely bright in spite of feeble surface radiation. *Betelgeuse*, a low-temperature red star, must have a great angular diameter in order to explain its brightness. Eddington had calculated its angular diameter and found it to be 0\(^\circ\)051. Here, then, was an object which should be measurable with a 20-foot interferometer, which is equal in theoretical resolving power to a telescope of about 40 feet aperture.

Anyone who has learned from laboratory experience the extreme sensitiveness of small and massive interferometers will appreciate the many difficulties involved in building, adjusting, and operating an interferometer 20 feet long, weighing 800 pounds, mounted at the upper end of a long telescope tube. The final adjustment required to produce equality in path to a ten-thousandth of an inch was accomplished, not by the comparatively coarse method of moving the mirrors, but with the aid of an adjustable double wedge of glass, devised by Michelson for the purpose. A trial of this method on *Vega* by Michelson, Pease, and others in August, 1920, showed that fringes could be observed in white light with mirror separations ranging from 7 to 18 feet. It was then only necessary to wait for an opportunity to observe *Betelgeuse* under favorable conditions. This occurred on December 13, 1920, after Professor Michelson had returned to Chicago for the winter. Dr. Pease, who had acquired great skill in the manipulation of the interferometer, found that the visibility of the fringes steadily decreased as the mirrors were separated, finally disappearing when they were 10 feet apart. If the mean wave-length of the light of *Betelgeuse* is assumed to be 5,750 angstroms, the angular diameter comes out 0\(^\circ\)047 (corresponding to about 240,000,000 miles), a value in good agreement with Eddington's prediction. Subsequently
Pease measured Arcturus, Antares, Mira Ceti, and other stars, which range in diameter from about 21,000,000 to 400,000,000 miles. Recently an interferometer permitting a mirror separation of 50 feet has been erected at Mount Wilson on its own equatorial mounting, and preliminary measures made by Pease show that its performance is satisfactory. I have mentioned this work in some detail because it illustrates how Michelson's conception, fully developed and described by him in 1890, has opened a new department of astrophysical research. For while it is true that star diameters can be computed by other means, they all involve theoretical considerations which call for confirmation by actual measurement.

A similar account of his extensive work on the velocity of light and on the Michelson-Morley experiment would reveal the same desire for extreme accuracy, the same power of invention, and the same skill in overcoming the many difficulties encountered as his demand for perfection became more and more insistent. I remember particularly a discussion regarding the velocity of light during his first visit to Pasadena. He was sure his old work could be materially surpassed, but was still pondering upon methods. The next morning he described an improved scheme evolved during the night. At that time the uncertainty in the value of the velocity of light was about 30 kilometers per second, or 1 part in 10,000. When determined by the revolving-mirror method of Foucault the result depends upon the measurement of the distance between the stations, the speed of the revolving mirror, and the angular displacement of the returned beam. The chief uncertainty lay in the determination of this angular displacement. In Foucault's experiments, made to ascertain the relative velocities of light in air and water, the greatest distance between the mirrors (obtained in his laboratory by five reflections) was 20 meters. With a speed of rotation of 500 turns per second the angle of deflection was only 160" and the uncertainty about 1 part in 160. This sufficed to show that the velocity in water is less than in air, thus favoring the undulatory theory of light as opposed to the corpuscular theory. Michelson, who wished for greater precision, had subsequently found that the ratio of the velocities in air and water, after applying a cor-
rection developed by Rayleigh, is equal to the index of refraction of the liquid. As for the velocity in air, he had reduced the uncertainty to 1 part in 10,000. But he knew he could do better.

By means of an interference method of testing, he obtained square and octagonal mirrors in which the average error of the angles between the faces was of the order of 1 part in 1,000,000. These were to be given a speed sufficient to make the returning light fall on the next succeeding face. With a speed of 1,000 revolutions per second and a rotation of 90°, the distance between stations required to give the desired accuracy is about 37.5 kilometers, somewhat less than the distance between Mount Wilson and Mount San Antonio.

After some preliminary experiments in 1920 by Pease and Ellerman, it became evident that more light was necessary. Michelson thereupon devised an improved optical system, which gave much brighter images. A station was established on the San Antonio ridge, at an elevation of 6,800 feet and a distance from Mount Wilson of 22 miles. Measurements were made by Michelson in 1924 and, with a number of polygonal mirrors, in 1926. The final results are given here to illustrate the remarkable agreement of five sets of measures:

<table>
<thead>
<tr>
<th>Turns per Second</th>
<th>Mirror</th>
<th>Number of Observations</th>
<th>Velocity of Light in Vacuo</th>
</tr>
</thead>
<tbody>
<tr>
<td>528</td>
<td>Glass octagonal</td>
<td>576</td>
<td>299,797</td>
</tr>
<tr>
<td>528</td>
<td>Steel octagonal</td>
<td>195</td>
<td>299,795</td>
</tr>
<tr>
<td>352</td>
<td>Glass 12</td>
<td>270</td>
<td>299,796</td>
</tr>
<tr>
<td>352</td>
<td>Steel 12</td>
<td>218</td>
<td>299,796</td>
</tr>
<tr>
<td>264</td>
<td>Glass 16</td>
<td>504</td>
<td>299,796</td>
</tr>
</tbody>
</table>

Weighted mean, 299,796 ± 1

But in spite of this extraordinary internal agreement, Michelson desired independent confirmation. After testing greater distances through air, he decided to build a vacuum tube a mile long and 3 feet in diameter. The tube, of corrugated steel pipe in lengths of about 60 feet, and the other parts of the equipment were designed and erected on the Irvine Ranch by the Mount Wilson Observatory. A section 1,140 feet long was first
set up and satisfactorily tested by Pease and Pearson, after which the entire length of one mile was completed. In spite of the length and diameter of the tube, the air can be exhausted to a very low pressure. For the first time, therefore, the velocity of light has been accurately measured on earth in a vacuum, under conditions very nearly the same as those under which it travels through remote space.

By the aid of mirrors, the light from a brilliant source is reflected back and forth through the tube, giving a total path 8 or 10 miles in length. Thanks to the continued co-operation of the United States Coast and Geodetic Survey, the length of the tube has been measured with an accuracy of 1 part in 1,000,000. With the apparatus developed to the highest pitch of refinement and all uncertainties regarding the state of the intervening air removed, the last degree of precision might be expected. This result was attained by Michelson in a series of measures made just before his death. The value obtained was in close agreement with the mean of his San Antonio measures, while the probable error was not more than half as great and may be considerably less. The investigation will be completed by Pease and Pearson, who made all the preliminary adjustments and tests and have worked with Michelson for years. This final project in Michelson's long career was conducted under the joint auspices of the University of Chicago and the Mount Wilson Observatory, with funds provided jointly by the Carnegie Institution of Washington and the Rockefeller Foundation.

But of all Michelson's investigations, the celebrated Michelson-Morley experiment is perhaps the most significant. More than fifty years ago Michelson had become interested in the effects of motion of the transmitting medium on the velocity of light. In order to explain astronomical aberration Fresnel had assumed the ether to be at rest except in the interior of transparent media, where he supposed it to be moving with a velocity less than that of the medium. This second supposition, as already stated, had been confirmed by Michelson before the Michelson-Morley experiment was made. The object of this experiment was therefore to test Fresnel's first assumption by the method tried by Michelson in 1881, adopting, however, an inter-
ferometer capable of giving decisive results. No displacement of the fringes was detected, and the conclusion of Michelson and Morley was that "the relative velocity of the earth and the luminiferous ether was certainly not one-fourth and probably not one-sixth of the orbital velocity of the earth." Subsequent experiments, confirmed later by Morley and Miller, also gave a negative result. Later Lorentz took up the problem both theoretically and experimentally and reached the conclusion that it is impossible to detect a relative motion between the Earth and the ether. Recent experiments here and in Europe fully support this conclusion, though it has been questioned by Miller.

The explanation of the null-effect proposed by Lorentz and Fitzgerald ascribes it to a contraction of the interferometer support precisely sufficient to compensate for the theoretical difference of path. This phenomenon, as is well known, was the basis of Einstein's restricted theory of relativity, which led to the generalized theory of relativity and revolutionized physical science.

In spite of its importance, it is unnecessary to dwell upon the Michelson-Morley experiment, which is so familiar to all students of modern physics. Michelson's open mind is beautifully illustrated, however, by his attitude during the rise of Einstein's theories. At first cautious, as his scientific beliefs compelled him to be, he fully accepted Einstein's views as soon as he considered the evidence conclusive. Here he displayed, as always, that supreme honesty which Millikan has rightly described as his outstanding characteristic. He never deviated from an unflinching search for the truth, regardless of personal considerations or life-long convictions. Of such are the kingdom of science.

In another field Michelson, like Einstein and almost every other deeply original thinker, belied the strange and widespread public belief in an antagonism between art and science. Similar qualities of imagination are obviously needed in both fields, and it is hard to understand how a creative man of science can fail to find pleasure in literature, history, music, and art. Michelson's love for California, which led him to settle in Pasadena after retiring from the University of Chicago, was due not merely to exceptional opportunities for research, but also to his fondness
for painting and the ease with which he could find favorable conditions for practicing his art. The quotation I have given from his first Lowell Lecture describes his delight in color and reveals the spirit behind his brush. His personal charm, also suggested by those enthusiastic words, was felt by all his friends. As for the inspiration of his example, the Ryerson Laboratory, with its host of brilliant graduate students, is a sufficient indication. We in Pasadena who have profited so greatly by his presence realize the full extent of our loss, which will be profoundly felt throughout the scientific world.