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MICHELSON'S RECENT RESEARCHES ON LIGHT.*

By JOSEPH LOVERING, President.

For many generations it was assumed that no sensible time was taken by light in moving over the largest distances. The velocity of sound was found by noting the time which elapsed between seeing the flash and hearing the report of an explosion. It was only in the vast spaces of astronomy that distances existed large enough to unmask the finite velocity of light, and, in extreme cases, to make it seem even to loiter on its way.

The satellites of Jupiter were discovered by Galileo in 1610; and the eclipses of these satellites by the shadow of Jupiter became an interesting subject of observation. It was soon noticed that the interval between successive eclipses of the same satellite was shorter when the earth was approaching Jupiter, and longer when the earth was receding from Jupiter. The change of pitch in the whistle of a locomotive, under similar motions, would suggest to the modern mind an easy explanation. A Danish astronomer, Römer, without the help of this analogy, deciphered the problem in astronomy. The eclipse was telegraphed to the observer by a ray of light, and the news was hastened or delayed in proportion to the distance from which it came. In this way it was discovered that light took about eighteen minutes to run over the diameter of the earth's orbit. This discovery was published by Römer in the Memoirs of the French Academy in 1675. The mathematical astronomer Delambre, from a discussion of one thousand of these eclipses observed between 1662 and 1802, found for the velocity of light 193,350 miles a second.

Meanwhile Römer's method, after fifty years of waiting, had been substantially confirmed in an unexpected quarter. Dr. Bradley, of the Greenwich Observatory, the greatest astronomical observer of his day, was perplexed by certain periodical fluctuations, of small amount, in the position of the stars. Suddenly the explanation was flashed upon him by something he observed while yachting on the River Thames. He noticed that, whenever the boat turned about, the direction of the

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vane altered. He asked the sailors, Why? All they could say was, that it always did. Reflecting upon the matter, Bradley concluded that the motion of the boat was compounded with the velocity of the wind, and that the vane represented the resultant direction. He was not slow in seeing the application of this homely illustration of the parallelogram of motion to his astronomical puzzle. The velocity of light was compounded with the velocity of the earth in its orbit, so that its apparent direction differed by a small angle from its true direction, and the difference was called aberration. In spearing a fish or shooting a bird, the sportsman does not aim *at* them, but *ahead* of them. This inclination from the true direction is similiar, in angular measure, to what the astronomer calls aberration. Struve's measurement of aberration combined with the velocity of the earth in its orbit gave for the velocity of light 191,513 miles a second. Both of the two methods described for obtaining the velocity of light depend for their accuracy upon the assumed distance of the earth from the sun. The distance adopted was the one found by the transits of Venus in 1761 and 1769, viz. 95,360,000 miles.

During the last forty years, the opinion has been gaining ground among astronomers that the distance of the sun, as deduced from the transits of Venus in 1761 and 1769, was too large by 3 per cent. Expeditions have been sent to remote parts of the earth for observing the planet Mars in opposition. The ablest mathematical astronomers, as Laplace, Pontecoulant, Leverrier, Hansen, Lubbock, Airy, and Delaunay, have applied profound mathematical analysis to the numerous perturbations in planetary motions, and proved that the sun's distance must be diminished about 2,000,000 miles in order to reconcile observations with the law of gravitation. Airy reduced the distance of the sun by more than 2,000,000 miles, to satisfy the observations on the transit of Venus in 1874. Glasenapp derived from observed eclipses of Jupiter's satellites a distance for the sun of only 92,500,000 miles. From these and similar data, Delaunay concluded that the velocity of light is about 186,420 miles a second.

These triumphs of astronomical theory recall the witty remark of Fontenelle, that Newton, without getting out of his arm chair, calculated the figure of the earth more accurately than others had done by travelling and measuring to the ends of it. And Laplace, in contemplation of similar mathematical achievements, says: "It is wonderful that an astronomer, without going out of his observatory, should be able to determine exactly the size and figure of the earth, and its distance from the sun and moon, simply by comparing his observations with analysis; the knowledge of which formerly demanded long and laborious voyages into both hemispheres."

The ancients supposed that light came instantaneously from the stars; a consolation for those who believed that the heavens revolved around the earth in twenty-four hours. Galileo and the academicians of Florence obtained even negative results, While the number of physical sciences has received numerous additions during the last half-century, new affiliations and a more intimate correlation have been manifested. In this mutual helpfulness light has played an important part. The optical method of studying sound, and the many varieties of flame apparatus, have made acoustics as intelligible through the eye as through the ear.

Velocity being expressed by space divided by time, it is evident that in measuring an immense velocity we must have at our command an enormous distance, such as we find only in astronomy, or else possess the means of measuring fractions of time as small as one-millionth of a second. The first successful attempt to measure such a velocity was made by Wheatstone in 1834. Discharges from a Leyden jar were sent through a wire, having two breaks in it one-fourth of a mile apart. The wire was in the form of a loop, so as to bring the breaks into the same vertical line. The sparks seen at these breaks were reflected by a mirror at the distance of 10 feet, and revolving eight hundred times per second. The images of the two sparks were relatively displaced in a horizontal direction. As the displacement did not exceed one-half of an inch, the time taken by electricity to go from one break to the other was less than a millionth of a second. Since the distance was one-quarter of a mile, the electricity travelled *in that case* at the rate of 288,000 miles a second. If this experiment is interpreted to mean that electricity would go over 288,000 miles of similar wire in one second, as it probably often was at that time, the conclusion is fallacious. The velocity of electricity, unlike that of sound or light, diminishes when the length of wire increases.

In 1838, Wheatstone suggested a method for measuring the velocity of light, which he thought was adequate for giving not only the absolute velocity but the difference of velocity in different media.

In that year Arago communicated to the French Academy the details of an experiment which he thought would give the velocity of light in air or a vacuum. As his own health was broken down (he died in 1853) he appealed to two young French physicists to undertake the experiment. On July 23, 1849, Fizeau, by a method wholly his own, made a successful experiment. A disk cut at its circumference into 720 teeth and intervals, and made by Breguet, was rapidly rotated by a train of wheels and weights. A concentrated beam of light was sent out through one of the intervals between two teeth of the disk, which was mounted in a house in Suresne, near Paris, and was sent back by a mirror placed on Montmartre, at a distance of about 5 miles. The light, on its return, was cut off from the eye or entered it, according as it encountered a tooth or an interval of the disk. If the disk turned 12.6 times in a second the light encountered the tooth adjacent to the interval through which the light went out. With twice as many rotations in the disk the light could enter the eye through the adjacent interval. With three times the original velocity, it was cut off by the next tooth but one, and so on. From the number of teeth and the number of rotations in a second the time taken by the light in going and returning was easily calculated. In this way the velocity of light was found to be 195,741 miles per second. In 1856, the Institute of France awarded to Fizeau the Imperial prize of 30,000 francs in recognition of this capital experiment.

In 1862, Foucault succeeded in measuring the velocity of light by a wholly different method, all parts of the apparatus for it being embraced within the limits of his laboratory. The light emanated from a fine reticule, ruled on glass and strongly illuminated by the sun. It then fell upon a plane mirror revolving four hundred times a second, by which it was reflected successively to five other mirrors, the last of which was plane, and returned it back by the same path to the revolving mirror and reticule. The total distance traveled was only about 66 feet. As the revolving mirror had moved while the light was making this short journey, the image of the reticule was displaced in reference to the reticule itself; and this displacement was the subject of measurement. Although the time involved was only about one fifteen-millionth of a second, this brief interval was translated by the method of the experiment into a measurable space, and gave 185,177 miles per second for the velocity of light, differing from the best results of astronomical methods by only 1,243 miles. Foucault was prompted to this experiment by Leverrier, director of the observatory. Arago was the first to propose the experiment. To obtain greater accuracy he placed the moving mirror in a vacuum, but without any advantage. He said, "Le mieux est l'ennemi du bien." His modest claim was that he had suggested to Foucault the problem and indicated certain means of resolving it. Babinet thought that the experiment admitted of ten times greater accuracy. With three times only it might correct Struve's value of aberration.

In 1873, Cornu, another French physicist, repeated the experiments of Fizeau with a toothed wheel, the work extending over three years. The observer was stationed at the École Polytechnique. The reflecting mirror and collimating telescope were placed on Mont Valerian, at a distance of about 33,816 feet. Three different wheels were tried, having 104, 116, and 140 teeth respectively, and rotating between seven and eight hundred times a second, the velocity being registered by electricity. Cornu used at times all the eclipses from the first to the seventh order. Calcium and petroleum light were tried, as well as sunlight. A chronograph with three pens recorded automatically seconds, the rotations of the toothed wheel, and the time of the eclipse. More than a thousand experiments were made, six hundred of which were reduced. The velocity of light as published by Cornu in 1873, was 185,425.6 miles per second. The probable error was 1 per cent. In 1874, Cornu gave the result of a new set of experiments made by him in conjunction with Fizeau over a distance of more than 14 miles between the Observatory and Montlhéry. The experiments were repeated more than five hundred times, mostly at night with the lime light. The light was sent through a 12 inch telescope and returned through a 7-inch telescope. The toothed wheel which produced the eclipse was capable of rotating sixteen hundred times a second. From these experiments the velocity of light was placed at 186,618 miles. The probable error did not exceed 187 miles. The time was recorded accurately within a thousandth of a second.

I come now to that which most interests us to-night, viz, the part taken in this country for the measurement of these great velocities. About 1854, Dr. Bache, chief of the U. S. Coast Survey, appropriated $1,000 for the construction of apparatus to be used in repeating Wheatstone's experiment on the velocity of electricity. But those who were expected to take part in the investigation were called to other duties, and the money was never drawn.

In 1867, Professor Newcomb recommended a repetition of Foucault's experiment, in the interest of astronomy, to confirm or correct the received value of the solar parallax. In August, 1879, Mr. Albert A. Michelson, then a master in the United States Navy, presented a paper to the meeting of the American Association for the Advancement of Science, on the measurement of the velocity of light. This paper attracted great attention. Mr. Michelson adopted Foucault's method with important modifications. In Foucault's experiment the deflection of the light produced by the revolving mirror was too small for the most accurate measurement. Mr. Michelson placed the revolving mirror 500 feet from the slit (which was ten times the distance in Foucault's experiment) and obtained a deflection twenty times as great, although the mirror made only one hundred and twenty-eight turns in a second. With apparatus comparatively crude, he obtained for the velocity of light 186,500, with a probable error of 300 miles. This preliminary experiment, made in the laboratory of the Naval Academy in May, 1878, indicated the directions in which improvements must be made in order to insure greater accuracy. The distance from the slit to the revolving mirror must be increased, the mirror must revolve at least two hundred and fifty times a second, and the lens for economizing the light must have a large surface and a focal length of about 150 feet. With the aid of $2,000 from a private source Mr. Michelson was able to carry out his ideas on a liberal scale.

His new experiments were made in the summer of 1879. The revolving mirror, made by Alvan Clark & Sons, was moved by a turbine wheel. Its rapidity of revolution was measured by optical comparison with an electric fork which made about one hundred and twenty-eight vibrations a second, the precise value being accurately measured by reference to one of König's standard forks. The velocity generally given to the mirror was about two hundred and fifty-six turns a second. The distance between the revolving and the fixed mirror was 1,986.26 feet.

The light from the moving mirror was concentrated on the fixed mirror by a lens 8 inches in diameter, with a focal length of 150 feet. These improvements on Foucault's arrangement were so advantageous that Mr. Michelson obtained, even with a smaller speed in the revolving mirror, an angle of separation between the outgoing and returning rays of light so great that the inclined plate of glass in front of the micrometer was not necessary; the head of the observer not shutting off the light. The mean result of one hundred observations taken on eighteen different days made the velocity of light 186,313 miles per second, with a probable error of 30 miles.

In 1882, at the request of Professor Newcomb, Mr. Michelson made a redetermination of the velocity of light at the Case Institute, in Cleveland, Ohio, by the method already described, with some modifications. The space traversed by the light in going and returning between the two mirrors was 4,099 feet. Two slight errors in the reduction of his former work were corrected in this. The velocity deduced from five hundred and sixty-three new observations was 186,278 miles, with a probable error of 37 miles.

In March, 1879, Congress had voted an appropriation of $5,000 for experiments on the velocity of light, to be made under the direction of Professor Newcomb. All the delicacy of instrumental construction, all the skill of scientific observation, and all the resources of mathematical discussion were enlisted in this service. The method adopted was that of the revolving mirror. The movable mirror was mounted at Fort Myer. Two different locations were selected for the fixed mirror, viz, the Naval Observatory and the Washington Monument. In one case the distance was 2,550.95 meters, or about 8,367.12 feet; in the second case, 3,721 meters, or about 12,205.57 feet. Mr. Michelson assisted in the observations until his removal to Cleveland, in the autumn of 1880. The observations began in the summer of 1880, and were continued into the autumn of 1882, the most favorable days in spring, summer, and autumn, being selected. In all five hundred and four sets of measurements were made, viz, two hundred and seventy-six by Professor Newcomb, one hundred and forty by Professor Michelson, and eighty-eight by Mr. Holcombe. After a full discussion of all the observations and the possible sources of error, Professor Newcomb decided to rest the final result on the one hundred and thirty-two sets of observations made in 1882 over the long distance between Fort Myer and the Washington Monument. The velocity then obtained was 186,282 miles. The velocity deduced from the three sets of observations was 186,251 miles. The probable error of the first result was about 19 miles.

For some future attack upon this problem Professor Newcomb suggested a prism for the reflector with a pentagonal section, and placed at such a distance that it could revolve through an arc of 36° while the light was going and returning; five hundred turns a second and a distance of 19 miles would fulfill this condition. In the Rocky Mountains, or the Sierra Nevada, stations from 20 to 30 miles distant could be found, and with no greater loss of light from absorption than is produced by 2 or 3 miles of common air.

The first experiments made in Great Britain for the measurement of the velocity of light were published by James Young and Prof. G. Forbes in the Philosophical Transactions of 1882. They adopted the method of Fizeau. In 1878, between six and seven hundred observations were made; but the number of teeth in the rotating wheel was insufficient. New experiments were made in 1880–'81 across the river Clyde. Two reflectors were used at unequal distances, and the time was noted when an electric light after the two reflections was at its maximum. The corrected distances for the two mirrors were 18,212.2 and 16,835 feet. After an elaborate mathematical discussion of the theory of this method, the velocity of light was placed at 187,221 miles. This value exceeded those obtained by Cornu or Michelson; but this might be explained by the color of the light used in the different experiments. Mr. Young and Professor Forbes made some experiments with lights of different colors, in confirmation of this view. But Professor Michelson compared his three hundred and eighteen observations with sunlight and two hundred and sixty-seven observations with electric light, and found that the difference was in the opposite direction; and in a differential experiment, when half the slit was covered with red glass, he found no displacement. Young and Forbes were attracted to their experiments on the velocity of light by Maxwell's speculations on the electro-magnetic theory of light, and also as promising the most accurate method of obtaining the parallax and distance of the sun. Their velocity of light combined with Struve's constant of aberration made the sun's parallax 20″.445, and its distance 93,223,000 miles.

When Arago, in 1838, suggested to the French Academy an experiment on the velocity of light, and explained his method of making it, which was essentially the one afterwards adopted by Foucault, he had in view the settlement of the long controversy between the advocates of the corpuscular and undulatory theories. Almost all of the different classes of phenomena in geometrical optics can be explained by either one of these theories, though even here the undulatory has the advantage of greater simplicity. But in one respect the two theories are antagonistic. According to the corpuscular theory, light should move faster in glass or water than in air, for example. The undulatory theory reversed this proposition. Here was an *experimentum crucis*. In 1850, Fizeau and Foucault made the experiment, each in his own way, and in both experiments the result was in favor of the theory of undulations. It has been shown that in the case of air alone lengths of many thousand feet are practicable. But the absorbing power of water prevents the use of greater lengths than about 10 feet. Light would pass through 10 feet of air in less time than one eighteen-thousandth of a second;

and the difference of time for air and water would be only a fraction of that small fraction. Hence the exceeding delicacy of the experiment.

In 1883, Mr. Michelson, at the request of Professor Newcomb, repeated Foucault's experiments for finding the difference of velocity of light in air and water. Foucault did not aspire to quantitative precision in his results. The experiments of Michelson proved that the ratio of the velocities was inversely as the indices of refraction. The velocity with sunlight was a little greater than with the electric light; which opposes the conclusion of Young and Forbes. When Mr. Michelson covered half of the slit with red glass, the two halves of the image were exactly in line. Experiments were also made on the velocity of light in carbon disulphide, which led to the inference that its index of refraction was 1.77, and that orange-red light traveled from one to two per cent. faster than greenish blue light. Mr. Michelson was enabled to make this investigation by a grant from the trustees of the Bache Fund.

Various other methods of measuring the velocity of light have been proposed. About 1850, Laborde suggested, in a letter to Arago, a mechanical method of measuring the velocity of light. He supposes two disks, with many holes at the outside, connected by a very long axis and rotating rapidly. The light which was sent out through a hole in one wheel would be transmitted or arrested by the second wheel, behind which an observer was stationed. The distance between the wheels, the time of rotation, and the order of the eclipse, would be sufficient for calculating the velocity of light. Laborde imagined an enormous axis more than 200,000 miles long. Moigno recommended the substitution of a mirror for the observer and the second wheel, which would double the distance travelled by the light. A distance of 1,640 feet, a disk 25 feet in radius, with 1,000 holes, and turning 360 times a second, would be more than sufficient to surprise the reflected ray and stop it.

In 1874, Burgue suggested a new way of finding the velocity of light by experiment. If a white disk, with a black radius, is rotated rapidly, and at each turn is illuminated by an instantaneous flash, this radius will appear immovable. If this flash is reflected on the disk from a distant mirror, the black radius will be displaced. No details of the arrangement of apparatus and no experiments were published.

In 1885, Wolf proposed the following arrangements: Two mirrors were placed 5 meters apart and facing each other. The radius of curvature of each mirror was 5 meters. The first mirror was 0.20 of a meter in diameter; the other, 0.05 meter, revolved rapidly (two hundred turns a second). A slit was made in the center of the large mirror through which light was sent to the small mirror, forming an image on the surface of the large mirror; this image became an object for the small mirror, forming another image on the larger mirror, at a distance from the first mirror depending on the velocity of rotation. These images could be sent out laterally by an inclined plate of thin glass, and their distance measured by a micrometer. Wolf expected advantages from the proximity of the two mirrors which would more than balance those of the long distances used by Foucault and Michelson.

The greatest difficulty which the undulatory theory of light has encountered is found in the attempted reconciliation between the requirements of the refraction of light and the aberration of light. To explain refraction, the density of the luminiferous æther must be greater when the index of refraction is greater. If a body moves, it must carry its inclosed æther with it, as its refractive power does not change. On the other hand, to explain the aberration of light, it must be supposed that the æther in the telescope does not move with the telescope; that the æther sifts through the telescope, the æther in front taking the place of the æther left behind; or, as Young expressed it, that the æther flows through the air and solid earth as easily as the wind blows through the trees of a forest.

The difficulty can be eluded by supposing that a refracting body carries along with it as much of the æther as it possesses in excess of what would exist in a vacuum of the same bulk. This, added to what is always sifting through it, would maintain its æther at a constant density. What this fraction is which must travel with the body was calculated by Fresnel. But while the refracting power has been protected, how is it with aberration? That would be increased to a small extent. But as the aberration is very small, only about $20\frac{1}{2}''$ at its maximum, the required change in its value might be masked by ordinary errors of observation. Boscovich suggested to Lalande, in 1766, that a telescope filled with water instead of air would test the theory; but he made no experiment. Wilson, of Glasgow, also proposed a water telescope in 1782. In the course of time it appeared that not only was the effect of the earth's motion on refraction and aberration under trial, but also the solar parallax, the motion of the solar system, and that of other stars.

The case is clearly stated by Lodge in this way: Sound travels quicker with the wind than against it. Is it the same with light? Does light travel quicker with the wind? Well, that depends altogether on whether the æther is blowing along as well as the air. If it is, then its motion must help the light on a little; but if the æther is at rest, no motion of the air, or of matter of any kind, can make any difference. According to Fresnel, the free æther is at rest, the bound is in motion. Therefore the speed of light will be changed by the motion of the medium; but only by a fraction, depending on its index of refraction,—infinitesimal for air, but sensible for water.

At an early day Arago investigated the effect which a change in the velocity of light would produce on aberration and refraction. He saw that a change of 5 per cent. in the velocity of light would alter the aberration by only one second, whereas the refraction in a prism of 45° would be affected to the extent of two minutes. He observed the zenith distances of stars with and without the prism; and also the deviation of stars which passed the meridian at 6 A. M. and 6 P. M. The observations were made with a mural circle and a repeating circle. Arago expected to find a difference of ten or fifteen seconds, but found none. He thought that a difference no greater than one ten-thousandth would have been manifested by his observations had it existed. Arago attempted to explain his negative results by assumptions based upon the corpuscular theory of light. But Lloyd thought that the change in the length of the wave would balance the change in the direction of the ray. Arago's observations were communicated to the Institute on December 10, 1816, and excited great interest. They were quoted by Laplace and Biot. But the manuscript was mislaid and not found until 1853, when it was published. Mascart thinks that this experiment of Arago owes its reputation to Fresnel's explanation of it by his fraction.

In regard to the wave-motion involved in the transmission of light, Maxwell says: "It may be a displacement, or a rotation, or an electrical disturbance, or indeed any physical quantity which is capable o assuming negative as well as positive values. But the æther is loosely connected with the particles of gross matter; otherwise they would reflect more light." Then he asks the question, "Does the æther pass through bodies as water through the meshes of a net which is towed by a boat?" It is difficult to obtain the relative motion of the earth and æther by experiment, as the light must move forward and then back again. One way is to compare the velocities of light obtained from the eclipses of Jupiter's satellites when Jupiter is in opposite points of the ecliptic. Cornu referred, in 1883, to the difficulty of observing these eclipses, especially when Jupiter is in conjunction with the sun. On account of this difficulty observations have been neglected for the last fifty years. Observations must be made near quadratures. Cornu suggests a proper arrangement for this purpose.

At various times between 1864 and 1868, Maxwell repeated Arago's experiment in a more perfect form. A spectroscope was used, having three prisms of 60° each. A plane miror was substituted for the slit of the collimator. The cross-wires of the observing telescope were illuminated by light reflected by a plate of thin glass placed at an angle of 45°. Light went to the mirror and was sent back to the wires from which it started after passing through six prisms. The experiment was tried when the light started in the direction of the earth's motion, and when in the opposite; also, at different seasons of the year. In all cases the image of the wires coalesced with the wires.

Lodge states the case clearly thus: "If all the æther were free there would have been a displacement of the image of the wires. If all the æther were bound to the glass there would have been a difference on the other side. But, according to Fresnel's hypothesis there should be no difference either way. According to his hypothesis, the free æther, which is the portion in relative motion, has nothing to do with the refraction. It is the addition of the bound æther which causes the refraction, and this part is stationary relatively to the glass, and is not streaming through it at all. Hence the refraction is the same whether the prism be at rest or in motion through space." Maxwell is more guarded in his own statement of the case. He says: "We can not conclude certainly that the æther moves with the earth, for Stokes has shown from Fresnel's hypothesis that the relative velocities of the æther in the prism and that outside are inversely as the square of the index of refraction, and the deviation in this case would not be sensibly altered, the velocity of the earth being only one ten-thousandth of the velocity of light."

In 1879, Maxwell wrote to Prof. D. P. Todd, then at the Nautical Almanac Office in Washington, asking him if he had observed an apparent retardation of the eclipses of Jupiter's satellites depending on the geocentric position of the planet. Such observations, he thought, would furnish the only method he knew of finding the direction and velocity of the sun's motion through the surrounding medium. In terrestrial methods of measuring the velocity of light, it returns on its path, and the velocity of the earth in relation to the æther would alter the whole time of passage by a quantity depending on the square of the ratio of the velocities of the earth and light, and this is quite too small to be observed.

In 1839, Babinet made a very delicate experiment on the relation of the luminiferous æther to the motion of the earth. He found that when two pieces of glass of equal thickness were placed across two beams of light which interfered so as to produce fringes, one of them moving in the direction of the earth's motion and the other contrary to it, the fringes were not displaced. The experiment was made three times by Babinet, with new apparatus each time. He concludes that here is a new condition to be fulfilled by all theories in regard to the propagation of light in refracting media. According to all the theories admitted or proposed, the displacement of the fringes should have been equal to many lengths of a fringe—that is, many millimeters—while by observation it was nothing. Stokes has calculated the result according to Fresnel's theory, or his own modification of it, and found that the retardation expressed in time was the same as if the earth were at rest. Fizeau has pointed out a compensation in the effect of Babinet's experiment. He says: "When two rays have a certain difference of march, this difference is altered by the reflection from the turning mirror." By calculating the two effects in Babinet's experiment, Fizeau finds that they have sensibly equal values, and of opposite sign.

In 1860, Angström communicated to the Royal Society of Upsala a method of determining the motion of the solar system by observations on the bands of interference produced by a glass grating. In 1863, he published the results which he had obtained. After allowing for Babinet's correction on account of the motion of the grating, Angström finds that a difference in the direction of the observing telescope with reference to the earth's motion might produce a displacement of the fringes amounting to 49″.8. Selecting the line D in the fourth spectrum, he thought that the influence of the earth's annual motion was verified, but that of the motion of the solar system was less decided. The observations were more consistent with the assumption that the solar system moved with a velocity equal to one-third of that in its orbit, than with an equal velocity, or none at all. In 1862–'63, Babinet presented to the Academy of Paris a paper on the influence of the motion of the earth on the phenomena produced by gratings, which depend not on reflection, refraction, or diffraction, but on interference. His principal object was a study of the motion of the solar system. He calculated the effects to be expected, but published no observations. In 1867, Van der Willigen measured the length of waves of light by means of a grating. When a slit was used, no effect was produced by the motion of the earth, the slit partaking of that motion. With a star, a movement of the earth in the direction of the light had an effect. This is the theoretical result, and agrees with Babinet's experiment, but is not applicable to solar light when reflected by a mirror. That behaves as light from a terrestrial source. In 1873, he rejects the proposition that the refraction of light is modified by the motion of its source or of the prism. In 1874, he seems to doubt the reality of the effect produced on diffraction.

In 1867, Klinkerfues used a transit instrument having a focal length of 18 inches. In the tube was a column of water 8 inches long, and a prism. He observed transits of the sun and of certain stars whose north polar distance was equal to the sun's, and which passed the meridian at midnight. The difference of right ascension is affected by double the coefficient of aberration. He computed that the column of water and the prism would increase the aberration by 8″. The amount observed was 7″.1. In 1868–'69, Hoek of Amsterdam discussed the influence of the earth's motion on aberration. Delambre had calculated from the eclipses of Jupiter's satellites that light must take 493^s.2 in coming from the sun. Hence the aberration must be 20″.255. Struve's observed aberration made the time 497^s.8. Hoek decided in favor of Struve; but he thought that it was desirable that a new set of observations should be made on the eclipses. Klinkerfues espoused the side of Delambre. Hoek said that, if the earth's motion was taken into account, according to Fresnel's fraction, different results would be harmonized. In 1868, he made experiments on a divided beam of light, the two parts going in opposite directions through tubes filled with water. There was no interference attributable to the effect of the earth's motion. As to any influence to be expected from the motion of the solar system, he thinks that motion must be insignificant compared with the initial motion of the comets, and with the cometary orbits, which are parabolas with few hyperbolas.

In 1872, and on several previous occasions, one of the grand prizes of the Academy of Paris was offered for an investigation of the effect produced by the motion of the luminary or of the observer. This prize, consisting of a gold medal or 3,000 francs, was awarded in 1874 to Mascart. He maintained that in Arago's experiment the change in refraction produced by the fraction of the earth's motion was compensated by the displacement of the observing telescope. Mascart repeated Babinet's experiment with gratings, where the effects of the motion of the telescope and of the grating would be additive, and found the sum small compared with Babinet's calculation. He thinks that the change in the length of the wave caused by the motion is compensated by the displacement of the measuring apparatus. He concludes that reflection, diffraction, double refraction, and circular polarization are powerless to show the motion of the earth, either with solar light or that from a terrestrial source.

In 1871, Airy used a vertical telescope, and measured the meridional zenith distance of γ Draconis, the star by which Bradley discovered aberration. It is about 100″ north of the zenith. The tube of the telescope, which was 35.3 inches long, was filled with water. The days of observation included the seasons of the equinoxes, when the star is most affected in opposite directions by aberration. The observations were repeated in the spring and autumn of 1872. No increase was produced in the aberration by the water in the telescope.

In 1873, Ketteler, in the preface to the "Laws of the Aberration of Light," enumerates thirty-nine persons who have investigated the effect of motion on the pheuomena of sound and light. From his own analysis he concludes: (1) that a motion of the prism and telescope perpendicular to the direction of a star produces no effect on the refraction; (2) that when the motion is in the direction of the star, the velocity of the light is changed according to Fresnel's fraction of that motion; and (3) that for any intermediate direction it is changed to the extent of that fractional part of the motion multiplied by the cosine of the angle between the direction of the motion and the direction of the star.

In 1859, Fizeau proposed an experiment for ascertaining if the azimuth of the plane of polarization of a refracted ray is influenced by the motion of the refracting medium. When a ray of polarized light passes through an inclined plate of glass, the plane of polarization is changed, according to certain laws investigated by Malus, Biot, and Brewster. The degree of change depends upon the inclination of the ray, the azimuth of the plane of primitive polarization, and the index of refraction of the glass. The incidence and azimuth being constant, this rotation of the plane of polarization increases with the index of refraction. This index being inversely as the velocity of light, the rotation is smaller the greater this velocity. Fizeau used two bundles of glass, four plates in each, and slightly prismatic, inclined to one another. One bundle was made of common glass; the other of flint glass. The angle of incidence for the ray was 58° 49′. When the azimuth of the primitive plane of polarization was 20°, the rotation of the plane of polarization was 18° 40′ and 24° 58′ for the two bundles. By Fresnel's hypothesis the change in the velocity of light from the motion of the medium is $\pm\left(\frac{\mu^2-1}{\mu^2}\right)v$. The greatest available velocity for the medium is that of the earth in its orbit, viz, 101,708 feet per second (31,000 meters). At the time of the solstices this motion is horizontal, and from east to west at noon. If the incident light comes from the west, the velocity of light is diminished by Fresnel's fraction of the velocity of the earth. If the light comes from the east, its velocity is increased by the same amount. The change in the index of refraction $\left(\text{or}\frac{\delta\mu}{\mu}\right)$ is equal to $\frac{v'}{v}(\mu^2-1)$; this for an index of 1.513 amounts to $\frac{1}{11740}$. Measurements show that in glass, the index increasing by a certain fraction, the rotation increases by a fraction four and one-half times greater, and the consequent change in the plane of polarization would be $\frac{1}{2500}$. The total change on reversing the direction from which the light came would be $\frac{1}{1250}$. If the incidence is 70°, and allowance is made for the change of direction inside of the glass, the fraction becomes $\frac{1}{1500}$. When a ray of light falls on a single plate of glass at an angle of 70°, if its plane of primitive polarization makes an angle of 20° with the plane of refraction, this plane is changed by 6° 40′. This multiplied by $\frac{1}{1500}$ gives sixteen seconds for the probable effect of the earth's motion. With forty such plates the effect would be increased to ten and two-third minutes. Two mirrors were used, one to the east and the other to the west, and light could be sent by a heliostat upon either one. The apparatus was easily turned through 180° so as to receive successively the light which travelled with or against the earth's motion.

With a single pile of plates highly inclined and a second pile less inclined, of more highly tempered glass and in the opposite azimuth, a rotation of 50° could be produced, while the tendencies to elliptical polarization were exactly balanced. The motion of the earth could modify this result to the extent of only two minutes; which is too small for accurate observation. Fizeau then resorted to a device already indicated by Botzenhart for amplifying this effect. A small variation in the primitive plane of polarization produces a greater effect the smaller the azimuth of this plane. If the original azimuth is only 5°, a small change in the azimuth trebles the value of the rotation. A large rotation is first produced on a ray whose azimuth is large, and then this rotation is largely changed by another pile so placed that the ray enters it under a small azimuth. More than two thousand measurements were made under various conditions. For noon observations at the time of solstice the rotation was always greater when the light came from the west, and was less at other times of day. The excess in the value of the rotation when the light came from the west varied between 30′ and 155′, according to the different ways in which the piles of plates were combined. The difference in the values of the rotation according as the light came from the west or east was consistent with a change in the index of refraction corresponding to Fresnel's hypothesis. Fizeau indicated his intention of renewing the research with improved apparatus, but no further publication on the subject by him can be found.

Faye has criticised this investigation of Fizeau, on the ground that he has taken no account of the motion of the solar system towards the constellation Hercules. This motion, recognized by astronomers on substantial evidence, amounts to 25,889 feet per second (7,894 meters) at its maximum. Its influence is almost zero at noon of the solstices. But it increases after noonday. Faye examines Fizeau's observations at 4 P. M., and finds discrepancies of 12′ or 15′ between the results of theory and observation. By neglecting the term which corresponds to the motion of the solar system, Fizeau's observations accord better at all hours of the day. Must the inference be, Faye asks, that the solar system does not move? Tessan, in reply to Faye, says that the sun, from which Fizeau derived the light used in his experiments, moves with the rest of the solar system; and that therefore Fizeau was justified in neglecting the term which expresses this motion, as of no effect on his calculations. Fizeau's theory depends only on the relative velocity between the source of light and the body which receives it; that is, the velocity of revolution and rotation of the earth.

In 1881, Professor Michelson published the results of his investigation on this delicate problem. He first calculates the probable difference of time taken by the light in going and returning over a given distance, according as that distance lies in the direction of the earth's motion or at right angles to it. If the distance were 1,200 millimeters, the difference of time translated into space would be equal to one-twenty-fifth of a wave-length of yellow light. The apparatus was ingeniously devised so as to bring about fringes of interference between the two rays which have travelled on rectangular paths. The whole apparatus was then turned round bodily through 90°, so as to exchange the conditions of the two interfering rays. Special apparatus was made for this experiment by Schmidt and Haensch of Berlin, and was mounted on a stone pier at the Physical Institute of Berlin. It was so sensitive to accidental vibrations that it could not be used in the day-time, nor indeed earlier than midnight. To secure greater stability the apparatus was moved to the Astrophysikalisches Observatorium in Potsdam, in charge of Professor Vogel. But even here the stone piers did not give sufficient protection against vibration. The apparatus was then placed in the cellar, the walls of which formed the foundation for an equatorial. But stamping with the feet, though at a distance of 100 meters, made the fringes disappear.

The experiments were made in April, 1881. At this time of the year, the earth's motion in its orbit coincides roughly with the motion of the solar system, viz, towards the constellation Hercules. This direction is i clined about 26° to the plane of the earth's equator, and a tangent to the earth's motion in its orbit makes an angle of 23½° with the plane of the equator. The resultant would be within 25° from the equator. The nearer the components are in magnitude, the more nearly would the resultant coincide with the equator. If the apparatus is placed so that the arms point north and east *at noon*, the eastern arm would coincide with the resultant motion of the earth, and the northern arm would be at a right angle to it. The displacement produced by revolving the whole through 90° should amount to one-twenty-fifth of the interval between two fringes. If the proper motion of the solar system is small compared with the velocity of the earth in its orbit, the displacement would be less. Mr. Michelson drew from these experiments the conclusion that there was not a sufficient displacement of the fringes to support the theory of aberration, which supposes the æther to move with a certain fraction of the earth's velocity. The displacement however was so small that it easily might have been masked by errors of experiment. Mr. A. Graham Bell supplied Mr. Michelson with the money required for this investigation,

In 1886, Mr. Michelson and Mr. Morley published a paper on the influence of the motion of the medium traversed by the light on its velocity. Fizeau had made similar experiments. In both cases the interfering rays were changed in velocity in opposite ways by flowing air or water through which they were transmitted. With air having a velocity of about 82 feet (25 meters) a second, the effect was so small that it might easily be covered up by errors of experiment; but with water it was measurable, and the result corresponded with the assumption of Fresnel, that the æther in a moving body is stationary, except the portions which are condensed around its particles. In this sense, it may be said that the æther is not affected by the motion of the medium which it permeates. For this investigation, which was made possible by a grant from the Bache Fund of the National Academy, Mr. Michelson and Mr. Morley devised a new instrument, called the refractometer. Cornu writes of Michelson's experiments on moving media: "Leur travail conçu dans l'esprit le plus élevé éxecuté avec ces puissant moyens d'action que les savants des États-Unis aimant à déployer dans les grandes questions scientifiques fait le plus grand honneur à leurs auteurs."

In 1887, Professor Michelson published another investigation of the question whether the motion of the earth in its orbit carried its æther with it. In his previous experiment his apparatus was sensitive to the smallest jars, and it was difficult to revolve it without producing distortion of the fringes, and an effect amounting to only one-twentieth of the distance between the fringes might easily be hidden by accidental errors of experiment. In the new experiment the apparatus was placed on a massive rock, which rested on a wooden base. which floated upon mercury. The stone was 1.5 meters square and 0.3 of a meter thick, At each corner four mirrors were placed, by reflection from which the length of path traversed by the light was increased to ten times its former value. The width of the fringes of interference, which were the subject of observation, measured from forty to sixty divisions of the observing micrometer. The light came from an Argand burner sent through a lens. To prevent jars from stopping and starting, the float was kept constantly in slow circulation, revolving once in six minutes. Sixteen equidistant marks were made on the stationary frame-work within which the float moved. Observations were taken on the fringes whenever any one of these marks came in the range of the micrometer. The observations were made near noon and at 6 P. M. The noon and evening observations were plotted on separate curves. One division of the micrometer measured one fiftieth of a wave-length. Mr. Michelson was confident that there was no displacement of the fringes exceeding one-hundredth of a wave length. It should have been from twenty to forty times greater than this. Mr. Michelson concludes that this result is in opposition to Fresnel's theory of aberration.

As late as 1872, Le Verrier thought that a new measurement of the velocity of light by Fizeau very important in the interest of astronomy; and in 1871, Cornu wrote that the parallax of the sun, and hence the size of the earth's orbit, were not yet known with the desirable precision. In 1875, Villarceau made a communication to the Paris Academy on the theory of aberration. He says that the parallax of the sun by astronomical measurement is 8″.86. Foucault's velocity of light combined with Struve's aberration makes the sun's parallax 8″.86. Cornu's velocity of light gives the same result only when it is combined with Bradley's aberration, which differs from that of Struve by 0″.20. Villarceau thinks that there is an uncertainty about the value of aberration on account of the motion of the solar system. In 1883, M. O. Struve discussed seven series of observations made by his father, Nyrén, and others, with various instruments and by different methods, at the Observatory of Pulkowa. He was certain that the mean result for the value of aberration was 20″.492, with a probable error of less than $\frac{1}{100}$ of a second. This aberration, combined with the velocity of light as deduced from the experiments of Cornu and Michelson, made the parallax of the sun 8″.784; differing from the most exact results of the geometric method by only a few hundredths of a second. Villarceau proposed to get the solar motion by aberration; selecting two places on the earth in latitude 35° 16′ north and south, and after the example of Struve, observing the zenith distances of stars near the zenith. The tangents of these latitudes are $\pm \frac{1}{\sqrt{2}}$ so that they contain the best stations for obtaining the constant of aberration, and the three components of the motion of translation of the solar system. In 1887, Ubaghs, a Belgian astronomer, published his results on the determination of the direction and velocity of the movement of the solar system through space. For finding the direction he used the method of Folie. For calculating the velocity he combined the observations on three groups of stars, the brightest belonging probably to the solar nebula. The resulting velocity was only about 10,000,000 miles a year. Homann, working on the spectroscopic observations at Greenwich, had obtained a velocity of 527,000,000 of miles. As late as 1887, Fizeau studied the nature of the phenomena when light was reflected from a mirror moving with a great velocity, and inferred that aberration was the same in this case as when the light was taken directly from a star.

The solar parallax, calculated from Cornu's last experiment on the velocity of light and Delambre's equation of light (493″.2 being the time for passing over the radius of the earth's orbit)	=8″.878
From Struve's observed aberration	8″.797
From Bradley's observed aberration	8″.881
From Foucault's velocity with Struve's aberration	8″.860
From Le Verrier's latitudes of Venus by transits	8″.853
From meridian observations of Venus during 106 years	8″.859
From occultations of χ Aquarius in 1672	8″.866

Glasenapp calculated the time taken by the light in travelling the mean distance of the earth's orbit as equal to $500^s.85 \pm 1.02$. This time combined with Michelson's velocity of light makes the solar parallax 8″.76. Struve's constant of aberration with Michelson's velocity gives a parallax of 8″.81. From Gill's mean of the nine best modern determinations of aberration (=20″.496) the parallax comes out equal to 8″.78. If we regard the solar parallax as known, the eclipses give nearly the same velocity as aberration, though the former is a group-velocity and the latter a wave-velocity. Gill's parallax from observations of Mars (8″.78) agrees with Michelson's velocity of light and the mean constant of aberration.

In 1877–'78, Lord Rayleigh, in his profound treatise on the Theory of Sound, discussed the distinction between wave-velocity and group-velocity. In 1881, he recognized the same difference in the case of luminous waves. In the experiments of Young and Forbes, the wave-velocity might be nearly three per cent. less than the group-velocity. With toothed wheels and the revolving mirror, group-velocity was the subject of observation. Aberration gave wave-velocity; Jupiter's satellites, group-velocity; experiment however showed but little difference. Lord Rayleigh found formulæ for the relation between these two kinds of velocity, which involved the wave-length and the idex of refraction, and J. Willard Gibbs has compared them, and other formulæ proposed by Schuster and Gouy, with the experimental velocities of light. Michelson's experiment on the index of refraction of carbon disulphide agrees with the assumption that he was dealing with the group-velocity.

Although there is not a complete accordance between the results of different methods of investigation, astronomers and physicists will be slow to abandon the theory of undulations, and take up again the corpuscular theory of light. The latter theory has received fatal blows from which it cannot recover. The undulatory theory, which started with Huyghens more than two hundred years ago, and was elaborated by Fresnel sixty years ago, has survived many crises in its history, and is supported by a wonderful array of experiments. Some of the experiments of Mr. Michelson may require a modification in Fresnel's interpretation. Stokes and Challis have worked for many years upon it, and established it on mathematical principles differing from Fresnel's and from each other. Ketteler in his *Theoretische Optik*, published in 1885, builds upon the Sellmeier hypothesis, that ponderable particles are excited by the ætherial vibrations and then re-act upon them. There remains Maxwell's electro-magnetic theory of light, which has been elaborated by Glazebrook and Fitzgerald, and is supported, to say the least of it, by remarkable numerical coincidences.

Discrepancies between theory and experiment are always to be welcomed, as they contain the germs of future discoveries. We have learned in astronomy not to be alarmed by them. More than once the law of gravitation has been put on trial, resulting in a new discovery or in improved mathematical analysis. We may not expect in light such a brilliant discovery as that of the planet Neptune. The luminiferous æther is a mysterious substance, enough of a fluid for the planets to pass easily through it, but at the same time enough of a solid to admit of transverse vibrations. Stokes suggests water with a little glue dissolved in it as a coarse representation of what is required of the æther.

Mr. G. A. Hirn has written recently on the constitution of celestial space. He decides against the existence of an all-pervading medium. He thinks that matter exists in space only in the condition of distinct bodies, such as stars, planets, satellites, and meteorites. In nebulæ it is in a state of extreme diffusion; but elsewhere space is empty. But how would it be after the correction is applied for the equation of light? Humboldt said that the light of distant stars reaches us as a voice from the past. The astronomer is not seeing for the most part contemporaneous events. He is reading history; and often ancient history, and of very different dates. Stellar photography reveals millions of stars which cannot be seen in the largest telescopes, and new harvests of these blossoms of heaven (as they have been called) spring up like the grass in the night. Numbers fail to express their probable distances and the time taken by their light in coming to the earth. In the theogony of Hesiod, the brazen anvil took only nine days in falling from heaven to earth. On the other hand, the reduction of the sun's distance by three per cent. not only affects its mass and heat, but it changes the unit of measure for the universe. Such are the remote results of any change in the estimated velocity of light.

We may thank Professor Michelson not only for what he has established, but also for what he has unsettled. In his various researches, which I have hastily sketched, but which require diagrams or models to be clearly understood, he has displayed high intelligence, great experimental skill and ingenuity, and unflagging perseverance. With a full appreciation of his work, the Rumford Committee recommended, and the Academy voted, that the Rumford Premium be awarded to him.