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SIGNIFICANCE OF THE ETHER-DRIFT EXPERIMENTS OF 1925 AT MOUNT WILSON[1]

THE general acceptance of the theory that light consists of wave motion in a luminiferous ether made it necessary to determine the essential properties of the ether which will enable it to transmit the waves of light and to account for optical phenomena in general. The ether was at first presumed to fill all space, even that occupied by material bodies, and yet to allow all bodies to move through it with apparent perfect freedom. The question of whether the ether is carried along by the earth's motion has been considered from the early days of the wave theory. Theories of the ether are intimately associated with theories of the structure of matter, and these are among the most fundamental in the whole domain of physical science.

The discovery of the aberration of light, in 1728, was soon followed by an explanation according to the then accepted corpuscular theory of light. The effect was attributed to a simple composition of the velocity of light with the velocity of the earth in its orbit. A second explanation was proposed, based on the wave theory, which seemed almost as simple as the former, but it failed to account for the fact, later proved by experiment, that the aberration is unchanged when observations are made with a telescope filled with water. Fresnel developed the theory which has been generally accepted, first, that the ether is at rest in free space and in opaque bodies, while, second, in the interior of moving transparent bodies it is supposed to move with a velocity less than the velocity of the body in the ratio $\frac{n^2-1}{n^2}$, where n is the index of refraction. These two hypotheses give a complete and satisfactory explanation of aberration; the second is considered to have been proved by the experiments of Fizeau and of Michelson and Morley on the velocity of light in moving media; the first hypothesis, that of an ether at rest in space and in opaque bodies, has always been in doubt.

Several physicists have sought to prove the existence of the stationary ether by direct experiment. The most fundamental of such proposals was that of Professor A. A. Michelson, made in 1881, based upon the idea that the ether as a whole is at rest and that light waves are propagated in the free ether in any direction and always with the same velocity with re-

[1] Address of the president of the American Physical Society, read at Kansas City, December 29, 1925.

spect to the ether. It was also assumed that the earth in its orbital motion around the sun passes freely through this ether as though the latter were absolutely stationary in space. The experiment proposed to detect a relative motion between the earth and the ether, and it is this relative motion which is often referred to as "ether-drift." The experiment is based upon the argument that the apparent velocity of light would vary according to whether the observer is carried by the earth in the line in which the light is traveling or at right angles to this line. The velocity of light is three hundred thousand kilometers per second, while the velocity of the earth in its orbit is one ten thousandth part of this, thirty kilometers per second. The actual motion of the earth is at all times the resultant of the motion of the earth in its orbit, varying in direction and having a velocity of thirty kilometers per second, and of the constant motion of the sun (including the whole solar system), in an unknown direction and with an unknown velocity. Therefore, the actual relative motion of the earth and ether is unknown, and it may be less than thirty kilometers per second or very much greater. If it is assumed that the relative motion is equal to that of the earth in its orbit, and if it were possible to measure the direct effect of this motion on the *apparent* velocity of light, then the velocity measured in the line of motion should differ from the apparent velocity at right angles to this line, by thirty kilometers per second, or by one part in ten thousand. This is what is called a "first order effect"; but, unfortunately, there is no known method of measuring the velocities under such simple conditions. All methods require the ray of light to travel to a distant station and back again to the starting point, and a positive effect of the earth's motion on the ray going outward would be neutralized by a negative effect on the returning ray. But, for a moving observer, it was shown that the neutralization would not be quite complete; the apparent velocity of the ray going and coming in the line of the earth's motion would differ from the apparent velocity of the ray going and coming at right angles, in the ratio of the square of the velocity of the earth to the velocity of light, that is, by an amount equal to one part in $(10{,}000)^2$ or to one part in 100,000,000. The only effect which can be experimentally determined, therefore, is exceedingly minute; it is a "second order effect."

A remarkable instrument known as the "interferometer," which had been invented by Professor Michelson, is capable of detecting a change in the velocity of light of the small amount involved in ether drift. In this experiment a beam of light is literally split in two by a thin film of silver, on what is called the "half-silvered mirror"; the coating of silver is thin enough to allow about half of the light to pass straight through, while the other half is reflected in the usual manner. These two beams of light may thus be made to travel paths at right angles to each other. At the end of the desired path each beam is reflected back upon itself and the two come together where they first separated. If the two paths are optically equal, that is, if there are exactly the same number of wavelengths of light in each, the reunited portions will blend with the waves in concordance. If, however, one path is a half-wave longer than the other, the waves will come together in "opposite phase," the crest of one coinciding with the trough of the other. These and other phase relations between the two rays produce effects called "interference fringes," observation of which enables one to detect slight changes in the velocity of light in the two paths.

In the year 1887, at Case School of Applied Science, in Cleveland, Professor Michelson, in collaboration with the late Professor Edward W. Morley, of Western Reserve University, made certain important developments of method and apparatus and used the interferometer in the now famous "Michelson-Morley experiment," in an effort to determine whether the motion of the earth through space produces the effect upon the velocity of light as predicted by theory. Unfortunately we do not know in what absolute direction the earth is going and so it is not possible to place the interferometer certainly in this direction. Therefore, the whole apparatus is mounted on a base which floats on mercury so that it can be turned to all azimuths of the horizontal plane of observation in the effort to find the direction of the drift. The rotation of the earth on its axis causes the plane of the interferometer to move as though it were on the surface of a rotating cone, the axis of which coincides with that of the earth and thus to take many different space orientations. It is only that component of the actual drift which lies in the plane of the interferometer at the moment of observation which can be observed. Therefore, the apparent azimuth and magnitude of the drift should change with the time of observation.

The full significance of the ether-drift experiments of 1925 can be presented only by considering the interpretations given to the experiments made previously. For this reason a historical summary of all the experiments will be given.

In July, 1887, Michelson and Morley made six sets of observations for the ether-drift effect, one at noon and one at six o'clock in the evening, on each of three days, July 8, 9 and 11. This constitutes the whole of the observations made by Michelson and Morley. In November, 1887, they announced their conclusions as follows: "Considering the motion of the earth in its orbit only . . . the observations show that the relative motion of the earth and the ether is probably less than one sixth of the earth's orbital velocity and certainly less than one fourth."[2] (That is, it is less than seven and one half kilometers per second.) It is to be noted that this experiment was designed and carried out solely to detect the influence of the earth's orbital motion, which should have different values at the two times of day chosen for observation, and that the smallest quantity which could be measured with certainty was one fourth of the expected effect.

In 1895, Lorentz and FitzGerald suggested that the motion of translation of a solid through the ether might produce a contraction in the direction of the motion, with extension transversely, the amount of which is proportional to the square of the ratio of the velocities of translation and of light, and which might have a magnitude such as to annul the effect of the ether-drift in the Michelson-Morley interferometer. The optical dimensions of this instrument were determined by the base of sandstone on which the mirrors were supported. If the contraction depends upon the physical properties of the solid, it was suggested that pine timber would suffer greater compression than sandstone, while steel might be compressed in a lesser degree. If the compression annuls the expected effect in one apparatus, it might in another apparatus give place to an effect other than zero, perhaps with the contrary sign.

The writer, in collaboration with Professor Morley, constructed an interferometer about four times as sensitive as the one used in the first experiment, having a light path of 214 feet, equal to about 130,000,000 wave-lengths. In this instrument a relative velocity of the earth and ether equal to the earth's orbital velocity would be indicated by a displacement of the interference fringes equal to 1.1 fringes. This is the size of the instrument which has been used ever since. The optical parts were all new and nothing was used from the original apparatus excepting the mercury tank and its wooden float.

Such an instrument with a base made of planks of pine wood was used at Cleveland, in 1902, 1903 and 1904, for the purpose of directly testing the Lorentz-FitzGerald effect, but the changes in the wooden frame due to the variations in humidity and temperature made it difficult to obtain accurate observations. A new supporting frame was designed by Professor F. H. Neff, of the Department of Civil Engineering of Case School of Applied Science, the purpose being to secure both symmetry and rigidity. This frame, or base, was made of structural steel and was so arranged that the optical dimensions could be made to depend upon distance-pieces of wood, or upon the steel frame itself. Observations were made with this apparatus in 1904. The procedure was based upon the effect to be expected from the combination of the diurnal and annual motions of the earth together with the presumed motion of the solar system towards the constellation *Hercules* with a velocity of 17.7 kilometers per second. On the dates chosen for the observations there were two times of the day when the resultant of these motions would lie in the plane of the interferometer, about 11:30 o'clock, A. M., and 9:00 o'clock, P. M. The calculated azimuths of the motion would be different for these two times. The observations at these two times were, therefore, combined in such a way that the presumed azimuth for the morning observations coincided with that for the evening. The observations for the two times of day gave results having positive magnitudes but having nearly opposite phases; when these were combined, the result was nearly zero. The result, therefore, was opposed to the theory then under consideration; but according to the ideas which will be set forth later in this address it now seems that the superposition of the two sets of observations of different phases was based upon an erroneous hypothesis and that the positive results then obtained are in accordance with a new hypothesis as to the solar motion. Our report of these experiments published in the *Philosophical Magazine* for May, 1905, concludes with the following statement: "Some have thought that this experiment only proves that the ether in a certain basement room is carried along with it. We desire therefore to place the apparatus on a hill to see if an effect can be there detected."[3]

In the autumn of 1905, Morley and Miller removed the interferometer from the laboratory basement to a site on Euclid Heights, Cleveland, free from obstruction by buildings, and having an altitude of about three hundred feet above Lake Erie and about eight hundred and seventy feet above sea-level. Five sets of observations were made in 1905–1906, which give a definite positive effect of about one tenth of the then "expected" drift. There was a suspicion that this might be due to a temperature effect, though there was no direct evidence of this. A plan was made for putting this surmise to the test after a summer's vacation. We had erected the interferometer on land owned by a friend; during our vacation absence, the land was sold and the new owner ordered the immediate removal of the interferometer. Professor Morley retired from active work in 1906 and it devolved upon the present writer to continue the experiments.

[2] Michelson and Morley, "Relative Motion of the Earth and the Luminiferous Ether," *Am. Jl. of Sci.*, 34, 333 (1887); *Phil. Mag.*, 24, 449 (1887); *Jl. de Phys.*, 7, 444 (1888).

[3] Morley and Miller, "An Experiment to detect the Fitz-Gerald-Lorentz Effect," *Phil. Mag.*, 9, 680 (1905); Proc. Am. Acad. Arts and Sci., 41, 321 (1905); "On the Theory of Experiments to detect Aberrations of the Second Degree," *Phil. Mag.*, 9, 669 (1905).

It seemed desirable that further observations should be carried out at a much higher altitude, but numerous causes prevented the resumption of observations.

It was at this time that Einstein became interested; and in November, 1905, he published a paper on "The Electrodynamics of Moving Bodies."[4] This paper was the first of a long series of papers and treatises by Einstein and others, which has developed into the present theory of relativity. In this first paper, Einstein states the principle of the constancy of the velocity of light, postulating that for an observer on the moving earth, the measured velocity of light must be constant, regardless of the direction or amount of the earth's motion. The whole theory was related to physical phenomena, largely on the assumption that the ether-drift experiments of Michelson, Morley and Miller had given a definite and exact null result.

The deflection of light from the stars by the sun, as predicted by the theory of relativity, was put to the test at the time of the solar eclipse of 1919. The results were widely accepted as confirming the theory. This revived the writer's interest in the ether-drift experiments, the interpretation of which had never been acceptable to him.

The site of the Mount Wilson Observatory, near Pasadena, California, at an elevation of about six thousand feet, appeared to be a suitable place for further trials. An elaborate program of experimentation was prepared, and ample funds to cover the very considerable expense involved were very generously provided by Mr. Eckstein Case, of Cleveland. The president and trustees of Case School of Applied Science gave every possible assistance by allowing leave of absence to the writer at such times as were desirable for making the experiments and by providing an assistant for carrying on the very laborious work of calculating and analyzing the observations. Through the kindness of President Merriam, of the Carnegie Institution of Washington, and of Directors Hale and Adams, the ether-drift experiments have been carried on at the Mount Wilson Observatory during the past five years.

Observations were begun in March, 1921, using the apparatus and methods employed by Morley and Miller in 1904, 1905 and 1906, with certain modifications and developments in details. The very first observation gave a positive effect such as would be produced by a real ether-drift, corresponding to a relative motion of the earth and ether of about ten kilometers per second. But before announcing such a result it seemed necessary to study every possible cause which might produce a displacement of fringes similar to that caused by ether-drift; among the causes suggested were magneto-striction and radiant heat. In order to test the latter the metal parts of the interferometer were completely covered with cork about one inch thick, and fifty sets of observations were made showing a periodic displacement of the fringes, as in the first observations, thus showing that radiant heat is not the cause of the observed effect.

In the summer of 1921 the steel frame of the interferometer was dismounted and a base of one piece of concrete, reinforced with brass, was cast in place on the mercury float. All the metal parts were made of aluminum or brass, thus the entire apparatus was free from magnetic effects and the possible effects due to heat were much reduced. In December, 1921, forty-two sets of observations were made with the non-magnetic interferometer. These show a positive effect as of an ether drift, which is entirely consistent with the observations of April, 1921. Many variations of incidental conditions were tried at this epoch. Observations were made with rotations of the interferometer clockwise and counter-clockwise, with a rapid rotation and a very slow rotation, with the interferometer extremely out of level, due to the loading of the float on one side. Many variations of procedure in observing and recording were tried. The results of the observations were not affected by any of these changes.[5]

The entire apparatus was returned to the laboratory in Cleveland. During the years 1922 and 1923 many trials were made under various conditions which could be controlled and with many modifications of the arrangements of parts in the apparatus. An arrangement of prisms and mirrors was made so that the source of light could be placed outside of the observing room, and a further complication of mirrors was tried for observing the fringes from a stationary telescope. Methods of photographic registration by means of a motion picture camera were tried. Various sources of light were employed, including sunlight and the electric arc. Finally an arrangement was perfected for making observations with an astronomical telescope having an objective of five inches aperture and a magnification of fifty diameters. The source of light adopted was a large acetylene lamp of the kind commonly used for automobile headlights. An extended series of experiments was made to determine the influence of inequality of temperature and of radiant heat, and various insulating covers were provided for the base of the interferometer and for the light path. These experiments proved that under the conditions of actual observation the periodic displacement could not possibly be produced by temperature effects. An ex-

4 Einstein, "Zur electrodynamik bewegter Körper, *Ann. der Physik*, 17, 891 (1905).

5 Miller, "Ether-drift Experiments at Mount Wilson Observatory," *Phys. Rev.*, 19, 407 (1922); SCIENCE, 55, 496 (1922).

tended investigation in the laboratory demonstrated that the full-period effect mentioned in the preliminary report of the Mount Wilson observations is a necessary geometrical consequence of the adjustment of mirrors when fringes of finite width are used and that the effect vanishes only for fringes of infinite width, as is presumed in the simple theory of the experiment.

In July, 1924, the interferometer was taken again to Mount Wilson and mounted on a new site where the temperature conditions were more favorable than those of 1921. The interferometer house was also mounted with a different orientation. Again the observations showed a real periodic displacement of the fringes, as in all the observations previously made at Mount Wilson and at Cleveland.

In spite of long-continued efforts it was impossible to account for these effects as being due to terrestrial causes or to experimental errors. Very extended calculations were made in the effort to reconcile the observed effects with the accepted theories of the ether and of the presumed motions of the earth in space. The observations were repeated at certain epochs to tests one after another of the hypotheses which were suggested. At the end of the year 1924, when a solution seemed impossible, a complete calculation of the then expected effects, for each month of the year, was made for the first time. This indicated that the effect should be a maximum about April first, and further that the direction of the effect should, in the course of the twenty-four hours of the day, rotate completely around the horizon. Observations were made for verifying these predictions in March and April, 1925. The effect was equal in magnitude to the largest so far observed; but it did not point successively to all points of the compass, that is, it did not point in directions 90° apart at intervals of six hours, nor point in opposite directions at intervals of twelve hours. Instead of this, the direction merely oscillated back and forth through an angle of about 60°, having, in general, a northwesterly direction.

Previous to 1925, the Michelson-Morley experiment has always been applied to test a specific hypothesis. The only theory of the ether which has been put to the test is that of the absolutely stationary ether through which the earth moves without in any way disturbing it. To this hypothesis the experiment gave a negative answer. The experiment was applied to test the question only in connection with specific assumed motions of the earth, namely, the axial and orbital motions combined with a constant motion of the solar system towards the constellation Hercules with the velocity of about nineteen kilometers per second. The results of the experiment did not agree with these presumed motions. The experiment was applied to test the Lorentz-FitzGerald hypothesis that the dimensions of bodies are changed by their motions through the ether; it was applied to test the effects of magneto-striction, of radiant heat and of gravitational deformation of the frame of the interferometer. Throughout all these observations, extending over a period of years, while the answers to the various questions have been "no," there has persisted a constant and consistent small effect which has not been explained.

The ether-drift interferometer is an instrument which is generally admitted to be suitable for determining the relative motion of the earth and the ether, that is, it is capable of indicating the direction and the magnitude of the absolute motion of the earth and the solar system in space. If observations were made for the determination of such an absolute motion, what would be the result, independent of any "expected" result? For the purpose of answering this general question, it was decided to make more extended observations at other epochs in 1925, and this was done in the months of July, August and September.

It may be asked: why was not such a procedure adopted before? The answer is, in part, that we were concerned with the verification of certain predictions of the so-called classical theories; and in part that it is not easy to develop a new hypothesis, however simple, in the absence of direct indication. Probably a considerable reason for the failure is the great difficulty involved in making the observations at all times of day at any one epoch. I think I am not egotistical, but am merely stating a fact when it is remarked that the ether-drift observations are the most trying and fatiguing, as regards physical, mental and nervous strain, of any scientific work with which I am acquainted. The mere adjustment of an interferometer for white-light fringes and the keeping of it in adjustment, when the light path is 214 feet, made up of sixteen different parts, and when it is in effect in the open air, requires patience as well as a steady "nerve" and a steady hand. Professor Morley once said, "Patience is a possession without which no one is likely to begin observation of this kind." The observations must be made in the dark; in the daytime, the interferometer house is darkened with black paper shades; the observations must be made in a temperature which is exactly that of the out-of-door air; the observer has to walk around a circle about twenty feet in diameter, keeping his eye at the moving eyepiece of the telescope attached to the interferometer which is floating on mercury and is turning on its axis steadily, at the rate of about one turn a minute; the observer must not touch the interferometer in any way, and yet he must never lose sight of the interference fringes, which are seen only through the small aperture of the eyepiece of the telescope, about a quarter of an inch in diameter; the observer makes sixteen readings of the position of the interference fringes in each turn, at times indicated by an electrical clicker; these operations must be continued without a break through a set of observations, which usually lasts for about fifteen or twenty minutes, and this is repeated continuously during the several hours of the working period.

When observations are in progress the interferometer to which the observing telescope is attached is caused to rotate on the mercury float so that the telescope points successively to all points of the compass, that is, it points to all azimuths. A relative motion of the earth and the ether should cause a periodic displacement of the interference fringes, the fringes moving first to one side and then to the other as referred to a fiducial point in the field of view, with two complete periods in each rotation of the instrument. Beginning when the telescope points north, the position of the fringes is noted at sixteen equidistant points around the horizon. The azimuth of the line of sight when the displacement is a maximum having been noted at two different times of day, it is a simple operation to calculate the right ascension and declination, or the "apex" of the presumed "absolute" motion of the earth in space. The determination of the direction of the earth's motion is dependent only upon the direction in which the telescope points when the observed displacement of the fringes is a maximum; it is in no way dependent upon the amount of this displacement nor upon the adjustment of the fringes to any particular zero position. As the readings are taken at intervals of about three seconds, the position of the maximum is dependent upon observations covering an interval of less than ten seconds. A whole period of the displacement extends over only about twenty-five seconds. Thus the observations for the direction of the absolute motion are largely independent of ordinary temperature disturbances. The observation is a differential one and can be made with considerable certainty under all conditions. A set of readings usually consists of twenty turns of the interferometer made in about fifteen minutes' time; this gives forty determinations of the periodic effect. The forty values are simply averaged to give one "observation." Any temperature effect, or other disturbing cause, which is not regularly periodic in each twenty seconds over an interval of fifteen minutes would largely be cancelled out in the process of averaging. The periodic effect remaining in the final average must be real.

The position of the fringe system is noted in units of a tenth of a fringe width. The actual velocity of the earth's motion is determined by the amplitude of the periodic displacement, which is proportional to the square of the relative velocity of the earth and the ether and to the length of the light path in the interferometer. A relative motion of thirty kilometers per second, equal to the velocity of the earth in its orbit, would produce a displacement of the fringes from one extreme to the other, of 1.1 fringes. Disturbances due to temperature or other causes lasting for a few seconds or for a few minutes might affect the actual amount of the observed displacement and thus give less certain values for the velocity of relative motion, while at the same time the position of maximum displacement is not disturbed. Thus it is to be expected that the observations for the velocity of motion will not be as precise as the observations for the direction of motion. The two things, magnitude and azimuth of observed relative motion, are quite independent of each other.

It is desirable to have observations equally distributed over the twenty-four hours of the day; since one set requires about fifteen minutes of time, ninety-six sets, properly distributed, will suffice. The making of such a series usually occupies a period of ten days. The observations are finally reduced to one group and the mean date is considered the date of the epoch. The observations made at Mount Wilson in 1925 correspond to the three epochs, April 1, August 1 and September 15, and are more than twice as numerous as all the other ether-drift observations made since 1881. The total number of observations made at Cleveland represent about 1,000 turns of the interferometer, while all the observations made at Mount Wilson previous to 1925 correspond to 1,200 turns. The 1925 observations consist of 4,400 turns of the interferometer, in which over 100,000 readings were made. A group of eight readings gives a value for the magnitude and direction of the ether-drift function, so that 12,500 single measures of the drift were obtained. This required that the observer should walk, in the dark, in a small circle, for a total distance of 100 miles, while making the readings. Throughout these observations the conditions were exceptionally good. At times there was a fog which rendered the temperature very uniform. Four precision thermometers were hung on the outside walls of the house; often the extreme variation of temperature was not more than one tenth of a degree, and usually it was less than four tenths of a degree. Such variations did not at all affect the periodic displacement of the fringes. It may be added that while the readings are being taken, neither the observer nor the recorder can form the slightest opinion as to whether any periodicity is present, much less as to the amount or direction of any periodic effect.

The hundred thousand readings are added in groups of twenty, are averaged and then are plotted in curves. These curves are subjected to mechanical harmonic analysis for the purpose of determining the azimuth and magnitude of the drift. In this work all the original observations have been used, without any omissions and without the assignment of weights; furthermore, there are no corrections of any kind to be applied to the observed values. The results of the analyses are finally charted in such a way as to show the variation in the azimuth of the drift throughout the day of twenty-four hours for each epoch, and the variation in magnitude is similarly charted. The observations of 1925 thus provide six curves, three showing the variation in azimuth for the different epochs and three showing the variation in magnitude. The curves are shown in Figs. 1 and 2. The dots,

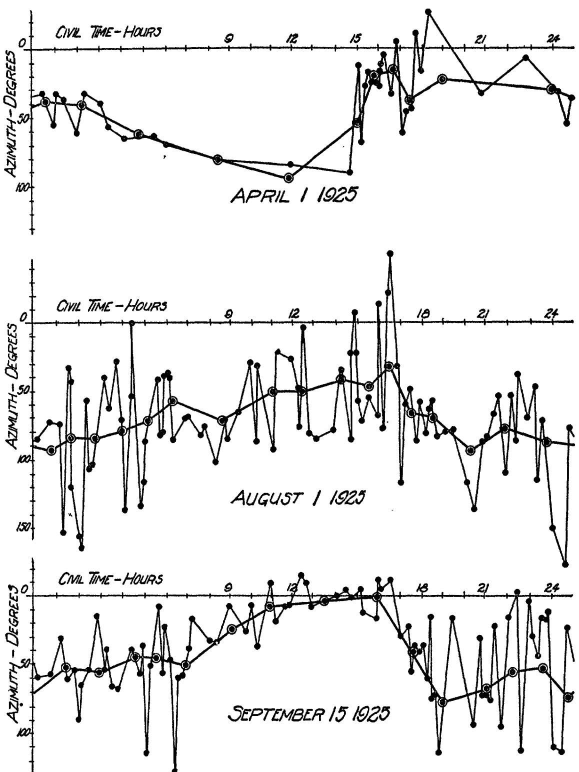

FIG. 1

connected by the light lines, represent single observations, each being the average of the readings from twenty turns of the interferometer during an interval of about fifteen minutes. The heavy line represents an arbitrary average of the single observations for the one epoch. In Fig. 1 the base line represents the twenty-four hours of the local civil day; a position on this line corresponds to a direction of motion to the north, while a point above the line indicates an easterly azimuth and one below the line, a westerly azimuth. In Fig. 2 the base again represents the hours of the civil day, while the magnitude of the ether drift, that is, the velocity of relative motion, throughout the day, is charted in kilometers per second. It is at once evident that there is something real in the observations; each curve has a definite and a characteristic form; certainly, the results are not zero, neither are they due to accidental errors of observation. The azimuth of the observed effect, Fig.

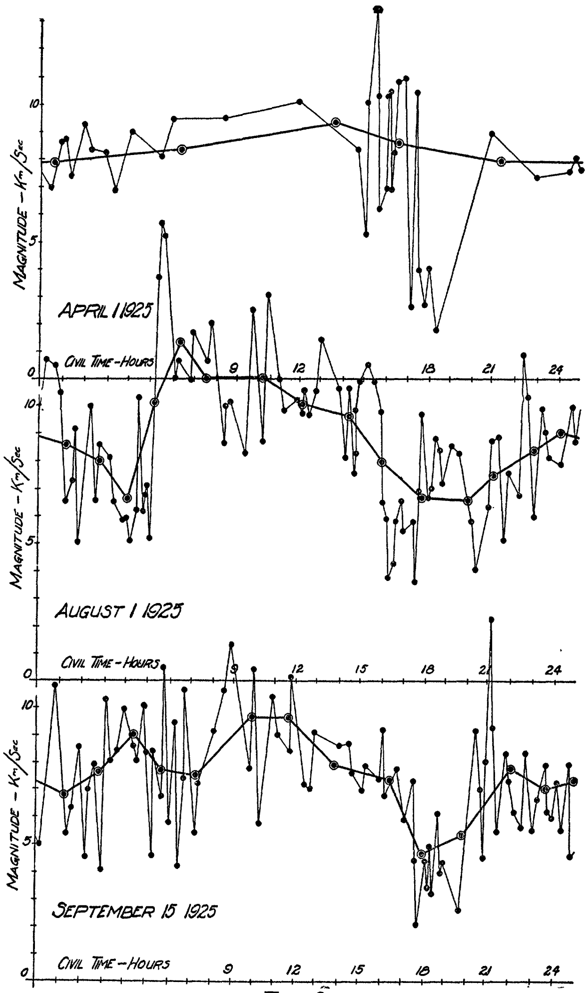

FIG. 2

1, varies in a periodic manner throughout the twenty-four hours of the day, the average being about 45° west of north, with the time of greatest westerly deviation varying with the time of year. Fig. 2 shows that the magnitude of the effect also varies periodically, with its maximum of about ten kilometers per second occurring at different times of day at different times of year.

It has been impossible to specify any effects of temperature, radiant heat, magnetism, gravitation or any other cause, which can produce the systematic variations indicated for the different epochs. The presumption was then made that the effects may be due to the motion of the earth and of the whole solar system through the ether, that is, to a real ether drift. Various graphic and numerical solutions were made for determining the apex and velocity of such a motion. These trial solutions were checked by means of a mechanical parallelogram apparatus, and finally by a partial least-squares solution. It was found that a direction towards a point in the constellation Draco, having the right ascension of 262° ($17\frac{1}{2}$ hours) and the declination of + 65°, when projected on the plane of the interferometer at all times of the day for the three epochs of observations, would have an azimuth which would vary as shown by the smooth, heavy-line curves of Fig. 3. The azimuth would, how-

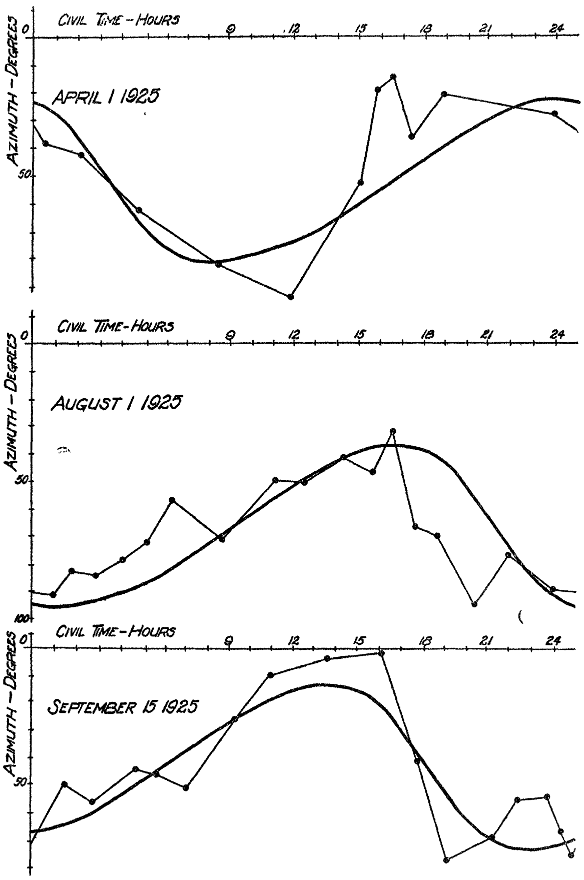

FIG. 3

ever, vary equally to the east and to the west of north; that is, the curve should be partly above and partly below the horizontal base line of the figure. As drawn, the curves have been arbitrarily displaced downward (westward) to match the broken line curves which show the actual results of observation, taken from Fig. 1.

If the motion has a direction towards the constellation Draco with a velocity of ten kilometers per second, which remains constant throughout the year, its projection on the plane of the interferometer would vary in magnitude throughout the day, for the three epochs of observations, as shown by the smooth curves in Fig. 4. The broken-line curves show the variation in magnitude of the observed effect, being the averages from Fig. 2.

The curves so far considered have been plotted with respect to local civil time for Mount Wilson. If the

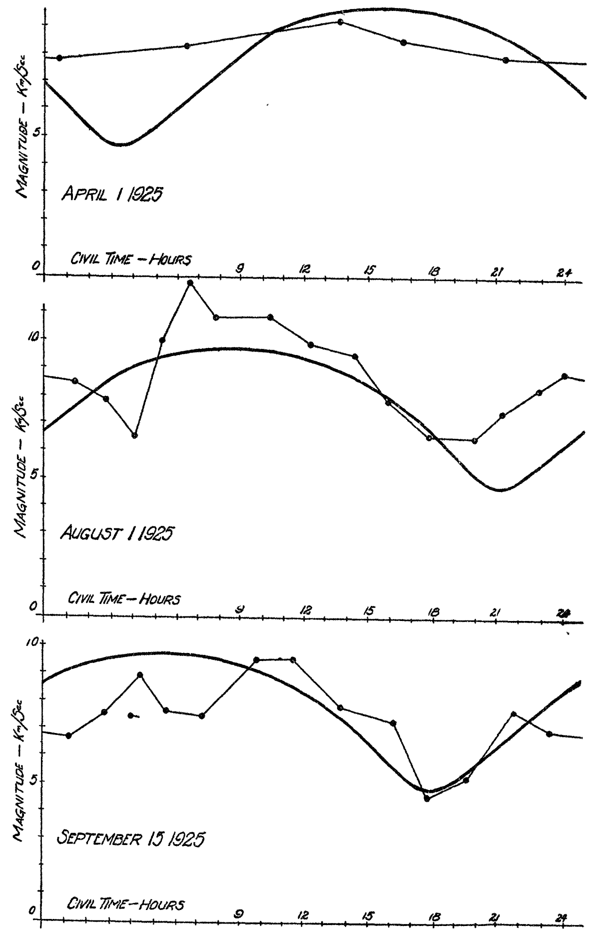

FIG. 4

direction and magnitude of the motion are constant throughout the year the curves of the variation are more appropriately plotted with respect to sidereal time; in Fig. 5 the curves are so plotted, the heavy line representing the averages of all observations for 1925. There is a remarkable agreement of the curves for the different times of year when plotted against sidereal time; the figure shows that the concordance of the curves for the direction of motion is better than for the magnitude. In Fig. 6 the final averages of Fig. 5 are shown by the broken-line curves, while the computed effects are shown by the smooth curves. For the azimuth the curves are drawn to a scale of displacement twice that of the preceding figures, the better to bring out the remarkable agreement between the curves.

As far as the observed quantities entering into these two curves are concerned, they are quite independent of each other; and each gives values of the

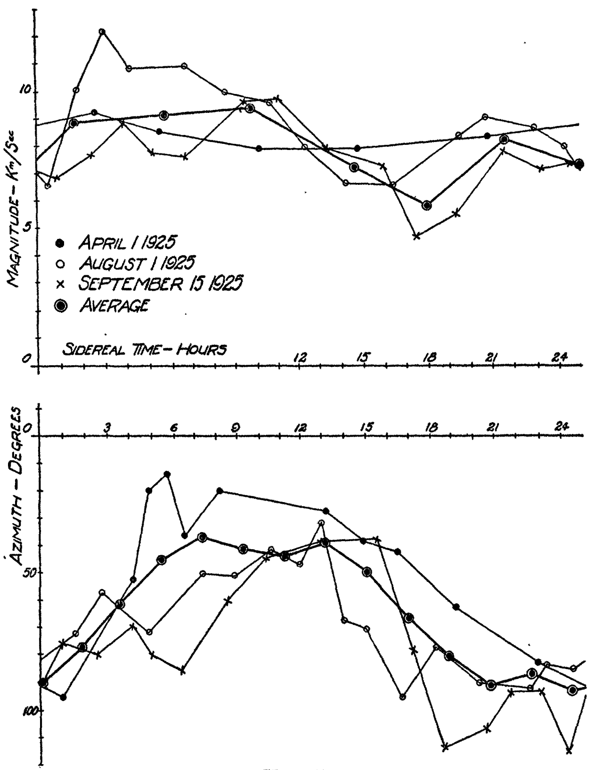

Fig. 5

right ascension and declination of the earth's absolute motion. The right ascension is the sidereal time at which the azimuth (in the simple case) passes from east to west of north; this corresponds to the place where the curve crosses its true axis when passing from a maximum to a minimum. The dotted lines in the lower part of Fig. 6 show that this occurs at $17\frac{1}{2}$ hours, which is the right ascension of the apex; or being expressed in degrees it is equal to 262°. The declination of the apex may be determined from the amplitude of the curve taken in connection with the latitude of the observatory; the value thus obtained is a declination of +65°. The observed velocity of the earth's motion, projected on the plane of the interferometer, should show a daily variation in magnitude as a result of the rotation of the earth on its axis; this magnitude should drop to its minimum value at a sidereal time which is the right ascension of the apex; and should reach its maximum twelve hours from this time. Considering the latitude of Mount Wilson, 31° 14′, and the declination of the apex as just determined from the azimuth of observations, it appears that at the time of maximum the plane of the interferometer makes an angle of less than 8° with the direction of the earth's motion; thus the projection of the velocity at this time does not differ appreciably from its full value, which is then shown to be equal to ten kilometers per second. The declination of the apex may be determined from the magnitude observations, as well as from those for azimuth, since it determines the ratio of maximum and minimum values of velocity for a given latitude. The agreement of the two right ascensions derived from these independent curves, indicated by dotted lines in Fig. 6, together with an equal concordance of the declinations, is a further very strong confirmation of the argument that the observed effects and the presumed motion are directly related.

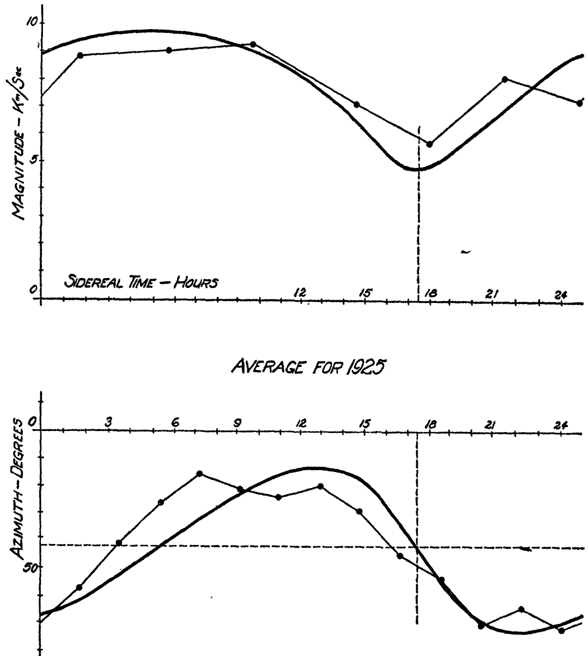

Fig. 6

A study of the numerical results shows that the probable error in the determination of the azimuth of the effect is ± 2°, while the probable error of the observed velocity on the supposition of a maximum value of ten kilometers per second is ± 0.6 kilometers per second.

The argument that the direction and magnitude of the observed ether drift is independent of local time and is constant with respect to sidereal time implies that the effect of the earth's orbital motion is imperceptible in the observations. No effect of this orbital motion has been found in these observations of 1925; this is strictly in accordance with the results obtained by Michelson and Morley in 1887 and by Morley and Miller in 1905. In order to account for this fact it is assumed that the constant motion of the earth in space is more than two hundred kilometers per second, but that for some unexplained reason the relative motion of the earth and the ether in the interferometer at Mount Wilson is reduced to ten kilometers per second; under these conditions a component motion equal to the earth's orbital motion would produce an effect on the resultant which is just below the limit of the smallest quantity which can be measured by the present interferometer. It is for this reason that it is concluded that the velocity of the motion of the solar system is at least two hundred kilometers per second and it may be much greater. The fact that the observed effect is dependent upon sidereal time and is independent of diurnal and seasonal changes of temperature and other terrestrial causes shows that it is a cosmical phenomenon.

The previous observations made at Mount Wilson, while not sufficiently extended to determine curves of the kind just indicated, should, nevertheless, be consistent with these observations. In Fig. 7 the results of the observations for April 15, 1921, are compared with the curves calculated from the observations of 1925, showing a very good agreement.

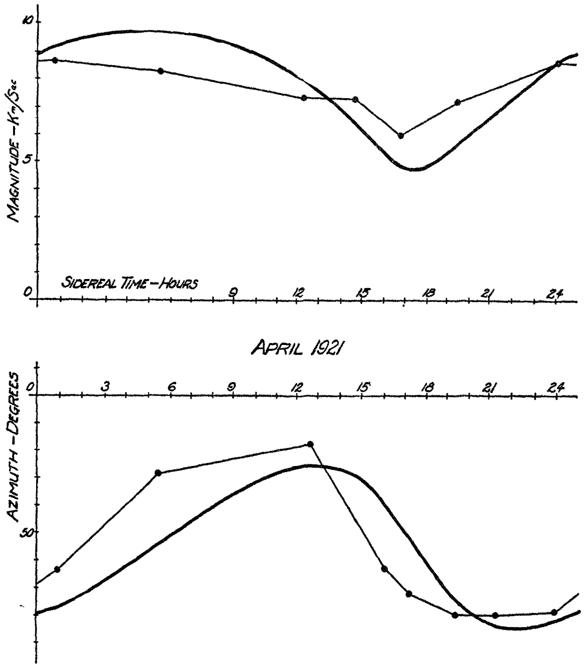

FIG. 7

The complete study of the ether-drift experiments of 1925, at Mount Wilson, leads to the conclusion that there is a systematic displacement of the interference fringes of the interferometer corresponding to a constant relative motion of the earth and the ether at this observatory of ten kilometers per second; and that the variations in the direction and magnitude of the indicated motion are exactly such as would be produced by a constant motion of the solar system in space, with a velocity of two hundred kilometers, or more, per second, towards an apex in the constellation Draco, near the pole of the elliptic, which has a right ascension of 262° and a declination of +65°. In order to account for these effects as the result of an ether drift, it seems necessary to assume that, in effect, the earth drags the ether so that the apparent relative motion at the point of observation is reduced from two hundred, or more, to ten kilometers per second, and further that this drag also displaces the apparent azimuth of the motion about 45° to the west of north.

It is evident that the present experiments are no more consistent with the old theories of a stagnant ether than were those of Michelson and Morley of 1887, and of Morley and Miller of 1905; the present work is in no way a contradiction of the earlier results, but is rather a confirmation and extension of them. That a set of six characteristic curves obtained from observations which are wholly independent of each other, and which were made at times of year with extreme differences of weather conditions, so consistently fit curves depending upon the assumed motion, as shown in Figs. 5 and 6, leads irresistibly to the conclusion that the observed effects are related to the presumed cause. One is compelled therefore to consider whether there can be a possible readjustment of the theories of the ether that will account for the reduced velocity and other experimental results.

The values of the quantities defining the absolute motion of the solar system as obtained from these ether-drift observations are in general agreement with the results obtained by other methods. The recent study of proper motions of stars by Ralph Wilson, of the Dudley Observatory, and of the radial motions of the stars by Campbell and Moore, of the Lick Observatory, give the apex of the sun's way in the constellation Hercules with a right ascension of 270° and a declination of about +30°, with a velocity of about nineteen kilometers per second. Dr. G. Strömberg, of the Mount Wilson Observatory, from a study of globular clusters and spiral nebulae, finds evidence of a motion of the solar system towards a point having a right ascension of 307° and a declination of +56°, with a velocity of three hundred kilometers per second. Lundmark, studying the spiral nebulae, finds evidence of a motion having a velocity of four hundred kilometers per second. The various determinations of the motion of the solar system are all in the same general direction and lie within a circle having a radius of 20°. Our assumed velocity of two hundred kilometers per second is simply a lower limit; it might equally well be three hundred or four hundred kilometers per second. The first assumption therefore seems to offer no difficulty. The location of the apex in the constellation Draco, at right ascension 262° and declination +65°, is within 6° of the pole of the ecliptic, that is, the indicated motion of the solar system is almost perpendicular to the plane of the ecliptic. The sun's axis of rotation points to within 12° of this apex. One can not help wondering whether there may be some dynamic significance in these facts.

The assumption that there is a drag of the ether by the earth involves a considerable readjustment of the theories of the ether, inasmuch as it requires a modification of the accepted explanation of aberration. In commenting on the preliminary report of this work presented to the National Academy of Sciences in April, 1925, Dr. L. Silberstein said: "From the point of view of an ether theory, this set of results, as well as all others previously discovered, are easily explicable by means of the Stokes ether concept, as modified by Planck and Lorentz, and discussed by the writer (Silberstein) in the *Philosophical Magazine*."[6]

The theory of Stokes may be described by means of the following sentences selected from Sir Joseph Larmor's treatise on "Aether and Matter," pages 10, 13, 35 and 36:

As Sir George Stokes was not disposed to admit that the aether could pass freely through the interstices of material bodies in the manner required by Fresnel's views, and as any other theory of its motion which could be consistent with the fact of astronomical aberration required irrotational flow, an explanation of the limitation to that flow had, he considered, to be found. This chain of argument, that motion of bodies disturbs the aether, that aberration requires the disturbance to be differentially irrotational, that this can only be explained by the dispersion of incipient rotational disturbance by transverse waves, and further that radiation itself involves transverse undulation, he regards as mutually consistent and self supporting, and therefore, as forming distinct evidence in favor of this view of the constitution of the aether. . . . The question then arises how far this explanation will extend to the case in which the aether is entrained by the matter that is moving through it. Attention has already been drawn to Sir George Stokes's considerations which would make the luminiferous property itself prevent the initiation of any rotational motion in the aether. It is in fact not difficult to prove that the energy of strain of a rigid incompressible medium of the type of ordinary matter may be expressed as a volume integral involving only the differential rotation, together with surface integrals extended over boundaries; and it follows that any local beginnings of rotational motion in an aether of elastic-solid type would be immediately carried off and distributed by transverse waves, so that if the rigidity is great enough no trace of rotational motion of the medium in bulk can ever accumulate.

There are systematic differences in the so-called constant of aberration and in standard star places as determined at different observatories, which might be explained on the hypothesis of a variation in ether drift due to differences in the local coefficient of drag. The drag at any given station may depend more or less upon altitude, local contour and the distribution of large masses of land such as mountain ranges. The ether-drift experiments have never been made at sea-level, nor, in fact, at any place except Mount Wilson, with sufficient completeness to give accurate measures of the effects. The evidence now indicates that the drift at Mount Wilson does not differ greatly in magnitude from that at Cleveland and that at sea-level it would probably have about the same value.

The reduction of the indicated velocity of two hundred or more kilometers per second to the observed value of ten kilometers per second may be explained on the theory of the Lorentz-FitzGerald contraction without assuming a drag of the ether. This contraction may or may not depend upon the physical properties of the solid, and it may or may not be exactly proportional to the square of the relative velocities of the earth and the ether. A very slight departure of the contraction from the amount calculated by Lorentz would account for the observed effect. A reëxamination of the Morley-Miller experiments of 1902–1904 on the Lorentz-FitzGerald effect is now being made, with the indication that the interpretation may be modified when taken in connection with the large velocity of the solar system indicated by the observations of 1925.

It need hardly be said that the determination of the absolute motion of the solar system from such interferometer observations is one of considerable complexity. I am under obligation to Professor J. J. Nassau, of the Department of Mathematics and Astronomy of Case School of Applied Science, and to Dr. G. Strömberg, of the staff of the Mount Wilson Observatory, who have given very great assistance in the analysis and in the mathematical solutions of various parts of the problem.

Note.—Since this paper was prepared, a very complete series of observations involving 2,000 turns of the interferometer has been made at Mount Wilson, corresponding to the epoch February 8, 1926. The general indications are that the latest observations are entirely consistent with the report here made, though it is possible that there will be slight modifications in the numerical results when all observations are combined. A definitive numerical calculation will require several months of continuous work and is now in progress.

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EXISTING PRACTICES OF POLLUTING PUBLIC WATER COURSES

Is civilization in danger of "being stewed in its own juice," or even as a preliminary smothered in a film of oil, (cold, not hot!) after an introductory sensory torture by the numerous and abundant waste products of human activity? This does not hark back

[6] February, 1920, Vol. 39, page 161.