As the azimuth of the effect in the interferometer, which corresponds to the azimuth of the apex, oscillates across the meridian, it reaches a maximum displacement, first to the east and then to the west in each sidereal day. When $\delta \geqq \phi$, this maximum azimuth may be treated as the azimuth of a circumpolar star at its eastern or western elongation. It is shown in treatises on spherical and practical astronomy that the azimuth of elongation depends in a very simple way upon the declination of the star and upon the latitude of the observatory. The relation is:

$$\sin A_{\max} = \cos \delta / \cos \phi,$$

whence

$$\cos \delta = \sin A_{\max} \cos \phi.$$

When $\delta \leqq \phi$, the azimuth of the apex swings completely around the horizon in a sidereal day. If θ_E is the sidereal time when the azimuth is due east, then

$$\tan \delta = \tan \phi \cos (\theta_E - \alpha).$$

Presuming that the orbital velocity of the earth is known, the formulae now provided are sufficient for the determination in general of the apex and velocity of the absolute motion of the earth, from observations of the relative motion of the earth and ether as made with the interferometer. These observations, giving simply the maximum displacement of the interference fringes as the apparatus turns on its axis, together with the azimuth at which this maximum displacement occurs, must adequately cover the period of one sidereal day for a given epoch. A complete set of such observations gives one determination of the velocity of the absolute motion and two independent determinations of the apex of the motion.

The determination of the direction of the earth's absolute 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 width or zero position. 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. The two effects, magnitude and azimuth of observed relative motion, are quite independent of each other.

Harmonic analysis of the fringe displacements

The records of the actual interferometer observations for the Mount Wilson cycle consist of three hundred and sixteen pages of readings of the positions of the interference fringes, of the form shown in Fig. 8. Each set contains readings for twenty or more turns of the interferometer. The twenty or more readings for each of the sixteen observed azimuths are averaged and the averages are compensated for the slow linear shift of the whole interference system during the period of observation, as explained previously in connection with Fig. 9. The average readings for each set are then plotted on coordinate paper, to a large scale, for the purpose of harmonic analysis. The graphs, I, II, III, and IV, Fig. 21, show the readings for four successive sets of observations made on April 2, 1925. The plotted points are positions of the central black fringe of the interference pattern with respect to the fiducial point, as the interferometer makes one complete turn. The unit for the scale of ordinates is one-hundredth of a fringe width, while the abscissae correspond to azimuth intervals of $22\frac{1}{2}°$, beginning at the north point and proceeding clockwise around the horizon. A chart of this kind is plotted for each set of observations. These charted "curves" of the actual observations contain not only the second-order, half-period ether-drift effect, but also a first-order, full-period effect, any possible effects of higher orders, together with all instrumental and accidental errors of observation. The present ether-drift investigation is based entirely upon the second order effect, which is periodic in each half revolution of the interferometer. This second-order effect is completely represented by the second term of the Fourier harmonic analysis of the given curve. In order to evaluate precisely the ether-drift effect, each curve of observations has been analyzed with the Henrici harmonic analyzer for the first five terms of the Fourier series. The first-order effect in the observation is shown by the fundamental component, which is drawn under the corresponding curve of observations in Fig. 21; the second-order effect is shown by the curve next below; while the fourth curve in each instance shows the sum of the third, fourth, and fifth components. It is evident that the observed curves contain very little trace of any effects of any higher orders. The residual curves are of very small amplitude and are evidence of the fact that the incidental and random errors are small. The harmonic analysis and synthesis has been performed by methods which have been completely described elsewhere by the writer.[12]

The harmonic analysis of the observations gives directly the amplitude in hundredths of a fringe width and the phase as referred to the north point of the second harmonic of the curve, which is the ether-drift effect. The observed amplitude of the movement of the fringes is at once converted into the equivalent velocity of the relative motion of the earth and ether, as observed in the plane of the interferometer, by means of the relation developed in the elementary theory of the experiment:

$$d = 2D(v^2/c^2)$$

and

$$v = (dc^2/2D)^{\frac{1}{2}},$$

d being the observed half-period displacement of the fringes and D the length of the arm of the interferometer, that is the distance from the half-silvered mirror by means of multiple reflections to the end mirror, No. 8, both being expressed in terms of the effective wave-length of the light used for the interferences; v is the relative motion of the earth and the ether in the plane of the interferometer and c is the velocity of light, both being expressed in kilometers per second. The nomograph, Fig. 20, consists of a parabolic curve which shows the relative velocity corresponding

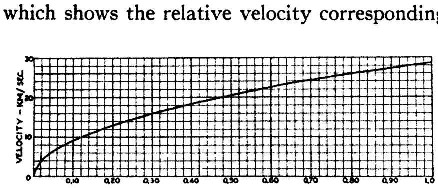

FIG. 20. Relation of fringe displacement to velocity of ether-drift for $2D = 112{,}000{,}000\lambda$ and $\lambda = 5700$A.

[12] D. C. Miller, *The Science of Musical Sounds*, 123 (1916); J. Frank. Inst. **181**, 51 (1916); **182**, 285 (1916).

to a fringe displacement as observed in the interferometer used in these experiments. It is for light of wave-length $\lambda = 5700$A, and for a total light-path of $2D = 112{,}000{,}000\lambda$. The azimuth of the ether-drift effect is the direction in which the telescope points when the half-period displacement of the fringes is a positive maximum. This azimuth, A, is obtained from the phase, P, of the second harmonic component of the observations as determined by the analyzer, from the following relation:

$$A = (1/2)(P - 90°).$$

The point thus located is the crest of the curve representing the second component, expressed in degrees, measured from the north point; the x-axis of the curves shown in Fig. 21 begins at the

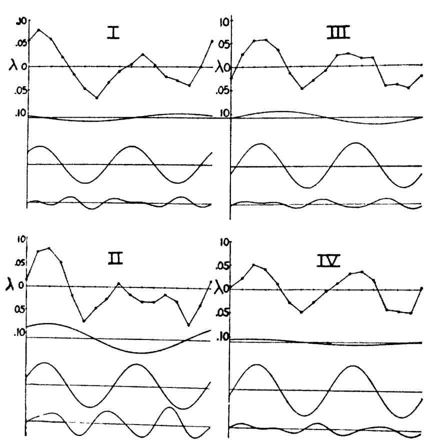

FIG. 21. Harmonic analysis of ether-drift observations.

north point and extends for one turn of 360°, through the east, south and west points of azimuth back to the north point. The figure shows, in the graphs of the second components, what has already been mentioned, that, within 360° of azimuth for one complete turn, there are *two* crests of the second component, corresponding to two azimuths 180° apart, between which the interferometer is incompetent to distinguish. The dispersion of the azimuth readings is much less than 90° and the necessity for continuity of azimuth indications for successive observations removes the ambiguity as to which zone of azimuth a reading belongs but it does not, in the end determine whether the direction in the line of motion is plus or minus. The magnitude and direction of the earth's orbital motion are known and since its direction is reversed at epochs six months apart, its combination with a constant cosmical motion gives the resultant motions which are different for the two epochs. The combination of the orbital and cosmical motions will lead to results consistent with the observed effects only when the cosmic motion is taken with the correct sign and thus the ambiguity is removed.

The Ether-Drift Observations Made at Mount Wilson in 1925–1926

General program of observation

The ether-drift observations, made by the writer previous to 1925, consist of twenty-five sets of 995 turns made in collaboration with Professor Morley in 1902–1905, eighty-six sets of 1146 turns made in Cleveland in 1922–1924 and one hundred and sixty-six sets of 1181 turns made at Mount Wilson in 1921 and 1924. These experiments had given conclusive evidence of a real effect which was systematic but which was small in magnitude and was inexplicable as to its azimuth. A program was adopted involving an extensive series of observations for the solution of the general problem of ether-drift without any presumed effects. In order to justify general conclusions, it is necessary to have observations extending throughout the twenty-four hours of the day to show the effects of the rotation of the earth on its axis and at several different times of the year to show the effects of the earth's orbital motion. Since the orbital motion is always tangent to the orbit, it will have different directions at different seasons, producing a resultant absolute motion peculiar to each epoch. Such observations were made at Mount Wilson for four epochs, April 1, August 1 and September 15, 1925, and February 8, 1926; the number of sets of observations for these epochs is thirty-six, ninety-six, eighty-three and one hundred and one, respectively, giving a total of 6402 turns. The model shown in Fig. 24 indicates the relative positions of the earth in its orbit for these four epochs. The results obtained from the complete analysis and reduction of these observations will be given in detail.

It may be noted that these observations have involved the taking of over 200,000 readings of the positions of the interference fringes, requiring that the observer should walk in a small circle, in the dark, while making the readings, a distance of about 160 miles. More than half of these readings were made in the Mount Wilson observations of 1925 and 1926. The latter observations lead to 12,800 single measures of the velocity of the ether-drift and to 25,600 single determinations of the apex of this motion.

Data of observation

In the manner described there are obtained from each set of observations, corresponding to a given sidereal time: first, the magnitude of the relative motion of the earth and ether as projected on the plane of the interferometer, expressed as a velocity in kilometers per second; and second, the azimuth, measured from the north point, of the line in which this projected motion takes place. These observed quantities for the four epochs are shown graphically in four charts, Fig. 22. Each dot on the upper curve of each chart represents a velocity and directly under it on the lower curve is the corresponding azimuth of a single observation. The solution is based upon the average curve of the observations; as there is considerable dispersion among the single observations, and to eliminate all bias, the average curves have been obtained by simple arbitrary running average for determining twenty equally spaced points on each curve. The observations for April, the first series taken, were not sufficiently numerous at two times of day and for these curves only a smaller number of points are available. The average points are shown by the larger dots with circles and the eight heavy line curves, one for magnitudes and one for azimuths for each of the four epochs constitute the material for further consideration.

There are four curves showing the average observed magnitude of the ether-drift effect throughout the sidereal day for the four epochs; each of these curves leads to a determination of the velocity in kilometers per second of the relative motion of the earth and ether and also of the right ascension and declination of the apex

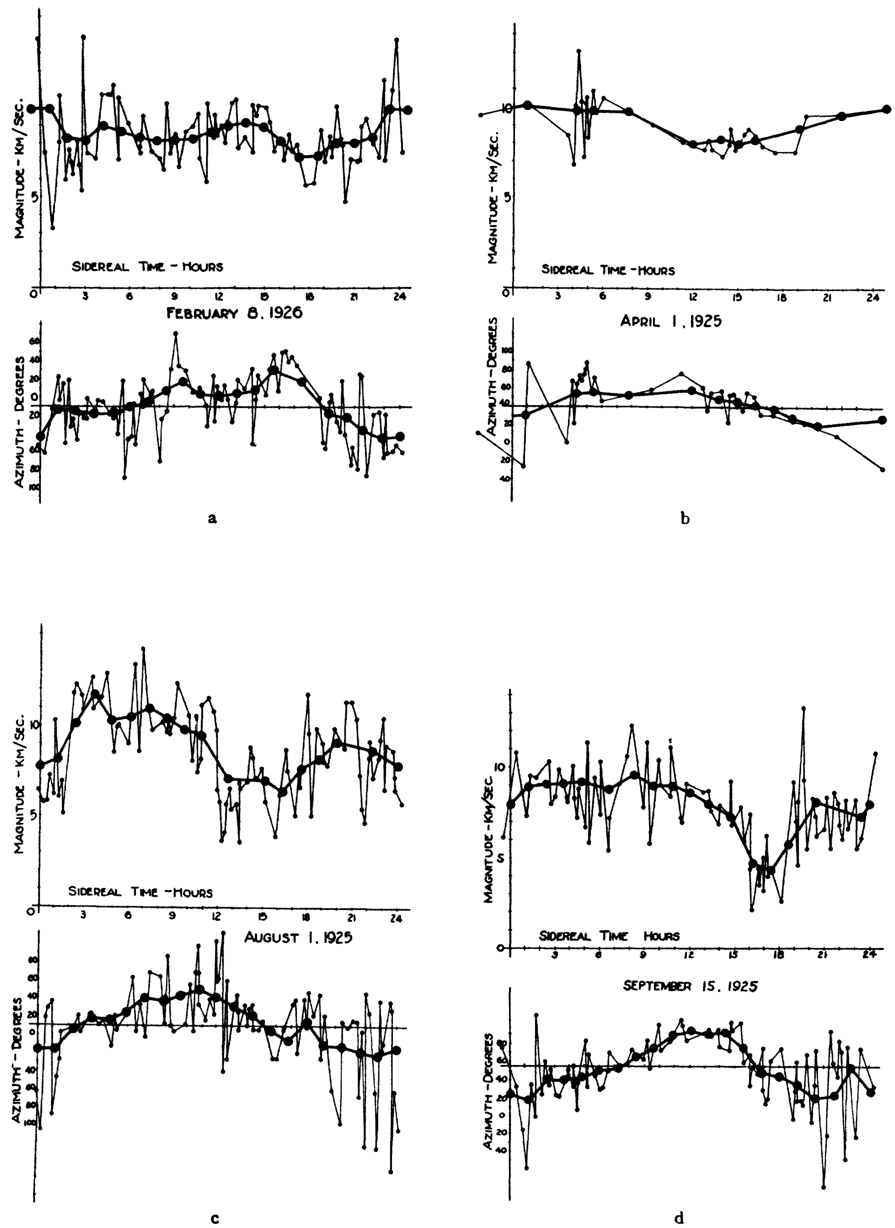

FIG. 22. Single observations and average curves for the ether-drift effect at Mount Wilson in 1925–1926.

of the earth's absolute motion, characteristic of the particular epoch. There are four curves showing the average azimuth of the ether-drift effect throughout a sidereal day, for the four epochs; each of these curves determines the right ascension and declination of the apex of the earth's absolute motion. In all, there are four determinations of the velocity of motion as projected on the plane of the interferometer, one for each epoch, and eight independent determinations of the apex of the motion, two for each epoch.

These observations are to be reduced according to the principles explained in the preceding sections, to determine the positions of the apexes of the resultant motions for the four epochs. From each curve for the magnitude of the effect are to be obtained the numerical values of the maximum and minimum ordinates and the sidereal time of the minimum; from each curve for the azimuth of the effect are to be obtained the maximum oscillation of the azimuth and the two sidereal times when the curve crosses its axis.

The reduction of the observations involves the latitude of the location of the interferometer. The observations here recorded were made at the Mount Wilson Observatory in latitude +34° 13′.

It is at once evident from the character of the curves of observation, Fig. 22, that the declination of the apex is *greater* than the complement of the latitude of the observatory; this is indicated by the fact that the departure of the azimuth curve from its axis is always less than 90° and by the fact that the magnitude curve shows only a single maximum and a single minimum. This determines the choice of the alternate formulae of calculation. The study of the conditions with the models leads to the same conclusion. Furthermore, the earlier calculations of these observations included the consideration of an apex with a declination smaller than the complement of the latitude, always leading to inconsistent results. Thus the apex is known to be circumpolar in its astronomical relations.

It may be noted that both the direction and the velocity of the ether drift should change from epoch to epoch because the effect is the resultant of the constant cosmic motion of the earth and of the changing orbital motion and these changes should be systematic and characteristic of the epoch, as will be explained later.

Final results of observation

Tables I and II give the right ascensions and declinations of the apexes of the observed motion of the earth for the four epochs and for the two alternative directions. In the tables α-Mag and δ-Mag indicate the values obtained from the magnitude curves, while α-Az and δ-Az are obtained from the azimuth curves.

TABLE I. *Right ascension of apex.*

Epoch	α-Mag	α-Az	Mean North	Mean South
Feb. 8	18^h 0^m	18^h 0^m	18^h 0^m	6^h 0^m
Apr. 1	15 15	16 10	15 42	3 42
Aug. 1	15 45	16 10	15 57	3 57
Sep. 15	17 5	17 0	17 3	5 5

TABLE II. *Declination of apex.*

Epoch	δ-Mag	δ-Az	Mean
Feb. 8	±79° 35′	±75° 19′	±77° 27′
Apr. 1	±78 25	±75 12	±76 48
Aug. 1	±67 30	±62 4	±64 47
Sep. 15	±61 40	±62 28	±62 4

TABLE III. *Velocities and displacements.*

Epoch	Velocity	$\lambda = 5700$A
Feb. 8	9.3 km/sec.	0.104λ
Apr. 1	10.1	0.123
Aug. 1	11.2	0.152
Sep. 15	9.6	0.110

The curves of observation, Fig. 22, give directly the values of the maximum velocity of relative motion of the earth and ether, as observed in the plane of the interferometer, for the four epochs; these velocities are given in Table III. The table also shows the displacements of the interference fringes, in terms of a fringe-width, which would be produced in the interferometer used in these experiments, by the observed velocities of ether drift.

The three tables contain all of the data provided by the three hundred and sixteen sets of observations made at Mount Wilson in 1925 and 1926, for the solution of the ether-drift problem.

In this work the calculations proceed directly from the actual observations, without any presumptions as to the result. All of the original observations have been included in the calculation, without any omissions and without the assignment of weights. No corrections of any kind have been applied to the observed quantities. This procedure has been adopted as the only safe one in the first search for a hitherto unidentified effect. The present results strikingly illustrate the correctness of this method, as it now appears that the forty-six years of delay in finding the effect of the orbital motion of the earth in the ether-drift observations has been due to the efforts to verify certain predictions of the so-called classical theories and to the influence of traditional points of view.

Absolute Motion of the Solar System and The Earth's Orbital Motion Determined

Northern apex of the solar motion rejected

As already explained, the interferometer determines the line in which the motion of the earth with respect to the ether takes place but does not determine the direction of motion in this line. The results of the observations given in Tables I and II indicate either an apex located near the north pole of the ecliptic or one diametrically opposite, near the south pole of the ecliptic. The choice between the two possible directions of motion is determined by the consistency of the results in satisfying the original observations taken as a whole and in connection with known phenomena. The studies of the proper motions and of the motions in the line of sight of stars in our own cluster have shown that the solar system is moving with respect to the nearby stars towards an apex located in the constellation Hercules, about 42° from the northern one of the two apexes indicated by the interferometer observations, the velocity of this motion being about nineteen kilometers per second. This circumstance seemed confirmatory of an absolute motion towards the north and the northern apex was chosen for further study of the problem.

Upon the completion of the observations for three epochs at Mount Wilson, corresponding to April 1, August 1, and September 15, 1925, a study of the results was made upon the presumption of a northern apex. Various trial solutions were checked with the parallelogram apparatus, Fig. 18, and finally by a partial least squares solution, for the determination of the velocity of the cosmic motion. The effects which should be characteristic of the several epochs because of the varying direction of the orbital motion could not be identified in the corresponding curves of observation, indicating that the orbital component is probably much smaller than the cosmic component. The curves for the three epochs were simply averaged and it was found that when plotted in relation to *local civil time*, the curves are in such phase relations that they nearly neutralize each other; the average effect for the three epochs thus plotted is very small and unsystematic. The curves of observation were then plotted with respect to *sidereal time* and a very striking consistency of their principal characteristics was shown to exist, not only among the three curves for azimuth and those for magnitude, but, what was more impressive, there was a consistency between the two sets of curves, as though they were related to a common cause. The average of the curves, on sidereal time, showed conclusively that the observed effect is dependent upon sidereal time and is independent of diurnal and seasonal changes of temperature and other terrestrial causes and that it is a cosmical phenomenon. The results of this study were presented as the address of the President of the American Physical Society at the meeting in Kansas City, on December 29, 1925.[13] The conclusion stated that there is a positive, systematic ether-drift effect, corresponding to a constant relative motion of the earth and the ether, which at Mount Wilson has an apparent velocity of ten kilometers per second; and that the variations in the direction and magnitude of indicated motion are exactly such as would be produced by a constant motion of the solar system in space towards an apex, near the north pole of the ecliptic, having a right ascension of $17\frac{1}{2}$ hours and a declination of $+65°$. On the hypothesis of the Stokes ether concept, that the ether is partially entrained by matter moving through it, it was suggested that the observed velocity of ten kilometers per second might be only a fraction of the absolute velocity;

[13] D. C. Miller, Science **63**, 433 (1926).

and further, assuming that the earth's orbital velocity of thirty kilometers per second, similarly reduced, would be so small as to be near the limit of perceptibility in these observations, it was suggested that the actual velocity of the cosmical motion might be two hundred kilometers or more, per second. It was also reported that, for some unexpected reason, all the azimuths were displaced to the westward.

A fourth series of observations was made at Mount Wilson, corresponding to the epoch, February 8, 1926, and a reëxamination of all the observations for the four epochs was made, as before, on the presumption of an apex near the north pole of the ecliptic and, because no consistent effect of the orbital motion could be found, the four series of observations were simply averaged for the determination of the cosmical motion of the solar system. The results of this elaborate study were reported at the Pasadena Ether-Drift Conference of February 4 and 5, 1927,[14] indicating that there is a constant cosmical motion, of the same general characteristics as were reported at Kansas City, the apex having a right ascension of 17 hours and a declination of +68°. It was understood at this time that the process of averaging the observations for the four epochs eliminated the orbital effect, since two of the positions of the earth in its orbit were nearly diametrically opposite the other two, as is shown in Fig. 24. It was announced at the Pasadena Conference that the orbital effect, if it existed, was certainly small and though the search so far had failed to demonstrate its influence, yet the writer was confident that it would be found and that further study and observation would be carried on for this purpose. It may be added that an adequate analysis and calculation of the observations of the four epochs, upon any one set of assumed conditions, requires the time of an expert computer for perhaps a full year. This and other considerations, such as the making of further observations in Cleveland in 1927 and 1929, have delayed the plan for the restudy of the Mount Wilson observations until the autumn of 1932.

As explained in the next section, the new study of the problem, based upon the presumption of a solar motion directed to the southward, has given consistent results for both the cosmic motion of the solar system and for the orbital motion of the earth. For this reason the northern apex of the solar motion is rejected in favor of the southern apex.

Southern apex of the solar motion adopted

Beginning in the autumn of 1932, a reanalysis of the ether-drift problem, and a recalculation of the observations made at Mount Wilson in 1925 and 1926 have now been completed. By adopting the alternative possibility that the motion of the solar system is in the cosmic line previously determined but is in the *opposite direction*, being directed to the apex near the south pole of the ecliptic, a wholly consistent solution has been obtained. This gives *for the first time* a quantitative determination of the absolute motion of the solar system and a positive detection of the effect of the orbital motion of the earth, by means of the ether-drift interferometer.

The apexes derived from the observations for the four epochs, determined by the right ascensions and declinations given in Tables I and II, are shown on the chart, Fig. 23, which represents the south circumpolar region of the celestial sphere. The observed apexes derived from the azimuth curves are indicated by squares

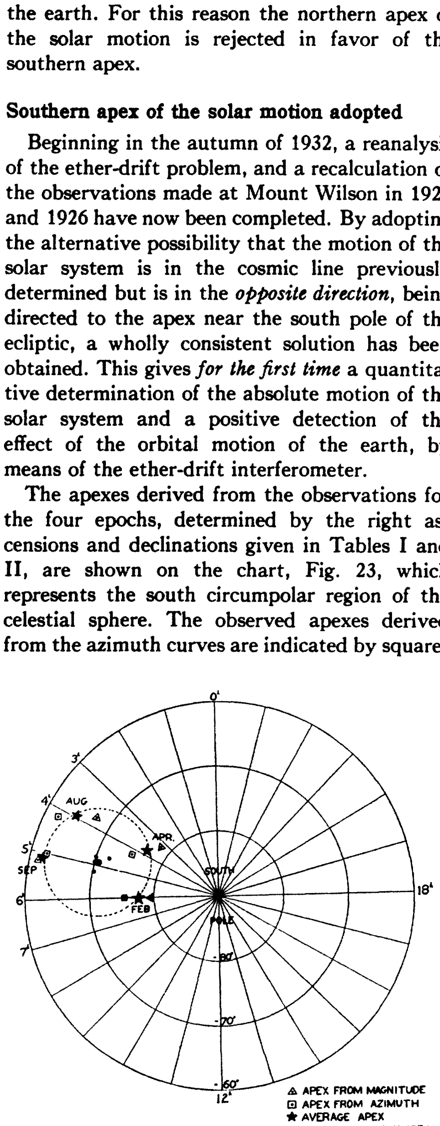

FIG. 23. Chart of the observed apexes of the resultant absolute motion of the earth.

[14] D. C. Miller, Astrophys. J. 68, 341 (1928); Contrib. Mt. Wilson Obs. No. 373, 12 (1928).

and those derived from the magnitude curves, by triangles; the means of the two positions for each epoch, indicated by the stars, are the final *observed* positions of the apexes of the earth's absolute motion for the respective epochs. The four apexes should lie on the earth's "aberration orbit," the center of which is the apex of the cosmic component of the earth's motion. This aberration orbit is the projection of the earth's orbit on the celestial sphere and, since the center is only 7° from the pole of the ecliptic, the projection, for the purposes of this study, is a circle. The center of the circle which most nearly fits the four observed apexes represented by the stars is found by graphic methods; this center is a *first approximation* to the apex of the earth's cosmic motion. The four apexes not only lie remarkably close to the circle but they are properly spaced to correspond to their epochs, as indicated by the model of the orbit, Fig. 24.

By means of the triangle law it is now possible to make an approximate solution for the velocity of the earth's cosmic motion. The explanation will be facilitated by means of the model, Fig. 24,

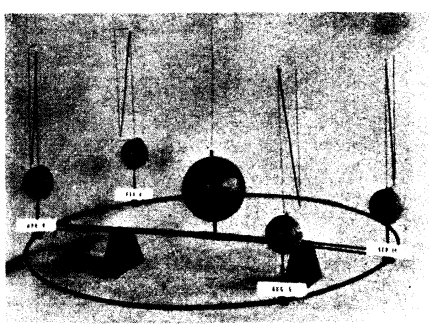

FIG. 24. Model illustrating the positions of the earth in its orbit at the four epochs of observation.

which shows the relative positions of the earth in its orbit for the four epochs; above each of the four globes is a wire parallelogram, approximately to scale, which illustrates the relations of the orbital and cosmic components of motion and their resultant; the cosmical component has a downward direction. The direction and magnitude of the orbital component are known, the direction of the resultant motion is given by the observations (its magnitude is not required), the direction of the cosmic component is towards the center of the aberration orbit as just found; thus there are given the directions of the three sides of a triangle, and the magnitude of one side, which determines the magnitudes of the other sides. In this manner, a first approximation to the velocity of the cosmic component of motion was found to be 200 kilometers per second.

Having obtained an approximate value for the velocity of the cosmic motion, it is used, by the application of the laws of spherical triangles, to find the apex of the cosmic component; this is done separately for each of the four epochs, by using the directions of the resultant motion given by the four observed resultant apexes and the velocity and directions of the earth's orbital motion appropriate to the four epochs. Thus there are obtained four approximate locations of the apex of the cosmic motion, based upon the assumed velocity; these should coincide with the center of the aberration orbit but probably will be scattered near the center.

Further trials were made, with assumed values for the velocity of the cosmic component of 205, 210, and 215 kilometers per second, leading to the conclusion that a velocity of 208 kilometers per second, for the cosmic component, gives the closest grouping of the four independently determined locations of the cosmic apex. Table IV gives the right ascensions and declinations of

TABLE IV. *Centers of aberration orbits from observed places.*

Epoch	α	δ
Feb. 8	$5^h\ 14^m$	−69° 54′
Apr. 1	4 46	−70 4
Aug. 1	4 40	−72 0
Sep. 15	4 54	−70 11
Mean apex	$4^h\ 54^m$	−70° 33′

the four points and, also, the mean values of the coordinates, which are adopted as locating the apex of the cosmic motion. The apexes, derived from the observations of each epoch separately, are shown by the four dots near the center of the circle in Fig. 23, while the average value of these positions is indicated by the dot in the circle. This is the final solution for the cosmic component of the motion of the earth and is the absolute motion of the solar system as a whole; this cosmic motion of the earth has a velocity of 208 kilometers per second and is directed to the apex having a right ascension of 4 hours and 54 minutes and a declination of $-70° 33'$.

The location of the apex thus determined is in the constellation Dorado, the Sword-Fish, and is about 20° south of the star Canopus, the second brightest star in the heavens. It is in the midst of the famous Great Magellanic Cloud of stars. The apex is only about 7° from the pole of the ecliptic and only 6° from the pole of the invariable plane of the solar system; thus the indicated motion of the solar system is almost perpendicular to the invariable plane. This suggests that the solar system might be thought of as a dynamic disk which is being pulled through a resisting medium, and which therefore sets itself perpendicular to the line of motion.

The fact that the sun is moving towards the southern apex with a velocity of 208 kilometers per second and at the same time is apparently moving, with respect to the near-by stars, in the opposite direction towards the constellation Hercules with a velocity of 19 kilometers per second, indicates that the group of stars as a whole is moving towards the southern apex with a velocity of 227 kilometers per second.

Reduced velocity and displaced azimuth are unexplained

The direction of the earth's motion in space has been determined by assuming that the motion is projected onto the plane of the interferometer and by observing the *variations* produced in the projected component by the rotation of the earth on its axis and by the revolution around the sun. The velocity of the motion has been obtained by comparison with effects presumed to be produced by the known orbital velocity of the earth. The evaluation of the observed effect is based on the presumption that it is a second order effect and that the ether is wholly stagnant and undisturbed by the motion of the earth through it. There are found to be two facts of observation which are wholly unexplained on this simple theory.

The displacement of the interference fringes has always been less than was expected, indicating a reduced velocity of relative motion, as though the ether through which the interferometer is being carried by the earth's motion were not absolutely at rest. When the values of the velocity of the earth's motion as calculated from the results of this investigation are compared with the velocities observed in the interferometer, there is obtained a quantitative measure of the factor of reduction which has so far remained inexplicable. Table V shows the maximum observed resultant velocities, from Table III, together with the calculated resultant velocities in the plane of the interferometer and the factor of reduction, k, for each epoch. The value of k which leads to results most concordant with the actual observations for all epochs is

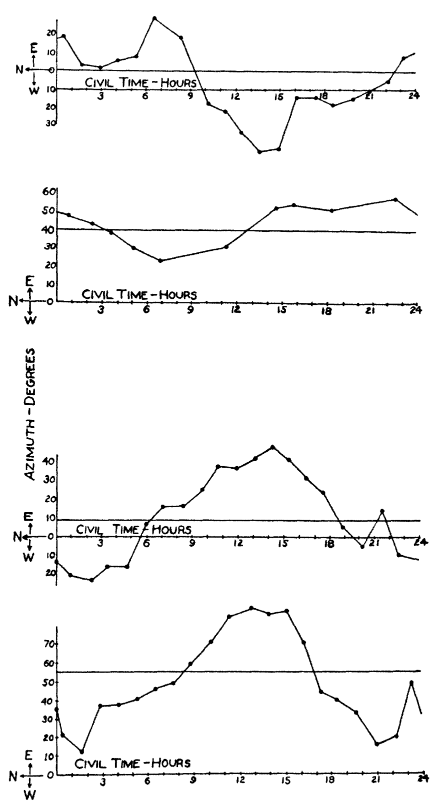

FIG. 25. Chart showing the observed displacement of the axis of azimuth of the ether-drift.

TABLE V. *Cosmical velocities.*

Epoch	Velocity-Obs.	Velocity-Calc.	k
Feb. 8	9.3 km/sec.	195.2 km/sec.	0.048
Apr. 1	10.1	198.2	0.051
Aug. 1	11.2	211.5	0.053
Sep. 15	9.6	207.5	0.046
Value adopted for calculations, $k=0.0514$			

$k=0.0514$ and this one value has been used in the calculations for the theoretical curves. However, until the physical nature of this reduction factor is understood, it need not be assumed that it should be constant for all epochs. It is assumed that the cosmic component and the orbital component are both reduced in the same proportion.

In accordance with the simple theory, the direction of the cosmic motion should swing back and forth across the north and south line once in each sidereal day, because of the rotation of the earth on its axis. When the observed azimuth of motion is charted, the resulting curve of directions crosses *its own axis* twice in each day, as shown in Fig. 25, but this axis is variously displaced from the meridian. For the February epoch the axis is displaced 10° to the west of north; for April the displacement is 40° east; for August 10° east, and for September 55° east.

Validity of the solution

Every suspected cause of disturbance having been eliminated, and an adequate method of

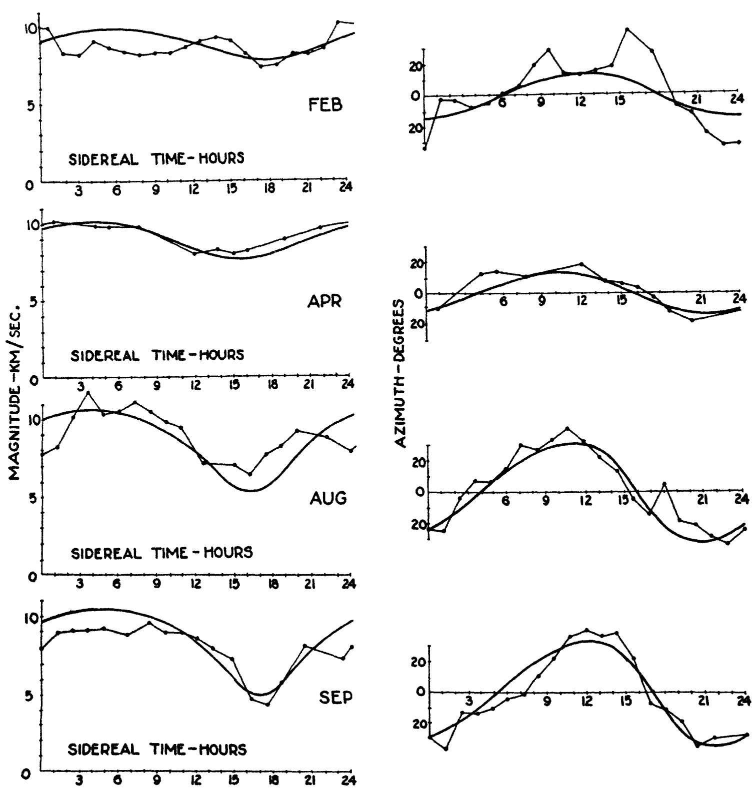

FIG. 26. The observed and calculated velocity and azimuth of ether-drift for the four epochs of observation, plotted with relation to sidereal time.

procedure having been developed, it is presumed that the persistently observed effects, which though small are systematic, are due to a real ether-drift. The observed displacement of the interference fringes, for some unexplained reason, corresponds to only a fraction of the velocity of the earth in space. The theoretical solution of the problem of absolute motion which has been presented involves only the *relative values* of the magnitudes of the observed effect and does not require a knowledge of the cause of the reduction in the apparent velocity of the motion nor of the amount of this reduction. The validity of the solution is shown by using the newly found velocity and direction of the cosmic motion together with the known velocity and direction of the orbital motion of the earth for the calculation of the resultant effects for each of the four epochs.

The magnitude and direction of the resultant motion, as projected on the plane of the interferometer, are computed for intervals of two hours throughout the sidereal day for each epoch. The magnitudes multiplied by the reduction factor k are shown in Fig. 26 by the four smooth-line curves at the left. The azimuths of the calculated directions, as referred to the axes of the curves, are shown by the smooth line curves at the right. Superposed on these eight curves are the average curves of the actual observations, taken from Fig. 22.

The calculated curves fit the observations remarkably well, considering the nature of the experiment. Since the cosmical component of motion is relatively large, its effect predominates so that the phases of the curves remain nearly constant when charted on sidereal time; that is, the minima all occur at about 17 hours. It is the orbital component which causes the flattening of the curves for February and April and causes an accentuated minimum six months later. The effect of the orbital component causes the apparent leaning forward in the azimuth curves for August and September.

The closeness with which the critical characteristics of the theoretical curves for the different epochs are followed by the observations is more strikingly shown when the curves are charted with respect to local civil time, as in Fig. 27. The predominating effect of the cosmic component while remaining constant in sidereal time, causes the minimum which occurs near sunrise in February to move progressively in civil time through the day, as the seasons change, so that in September it occurs near sunset; the time when the azimuth curve crosses its axis likewise shifts progressively in civil time.

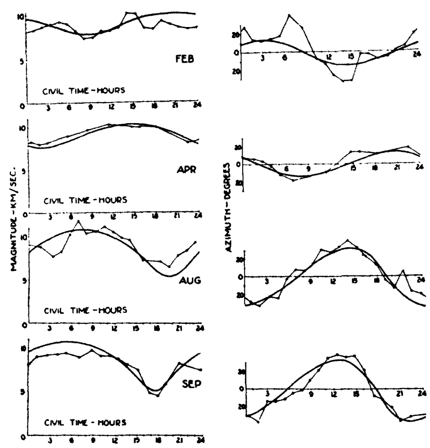

FIG. 27. The observed and calculated velocity and azimuth of ether-drift for the four epochs of observation, plotted with relation to civil time.

Continuing the astronomical description, having found the elements of the aberration orbit of the earth's absolute motion, these are used to compute the apparent places of the observations. The velocity and apex of the constant cosmic component of the earth's motion just found is combined with the known orbital velocity for the dates of the four epochs of observation, to find the four apexes of the resultant motions of the four epochs. The observed and calculated right ascensions and declinations of the apexes are given in Table VI.

TABLE VI. *Resultant apexes, observed and calculated.*

Epoch	α-Obs.	α-Calc.	δ-Obs.	δ-Calc.
Feb. 8	6^h 0^m	5^h 40^m	−77° 27′	−78° 25′
Apr. 1	3 42	4 0	−76 48	−77 50
Aug. 1	3 57	4 10	−64 47	−63 30
Sep. 15	5 5	5 0	−62 4	−62 15

The apex of the cosmic motion previously determined, given in Table IV, is shown by the large star in Fig. 28 and the four calculated apexes for the resultant motions at the four epochs are shown by the small circles, which necessarily lie on the circle representing the calculated aberration orbit. The observed apexes for the four epochs are represented by the small stars. The location of the pole of the ecliptic is also shown. The close agreement between the calculated and observed apparent apexes would seem to be conclusive evidence of the validity of the solution of the ether-drift observations for the absolute motion of the earth and also for the effect of the orbital motion of the earth, which hitherto has not been demonstrated.

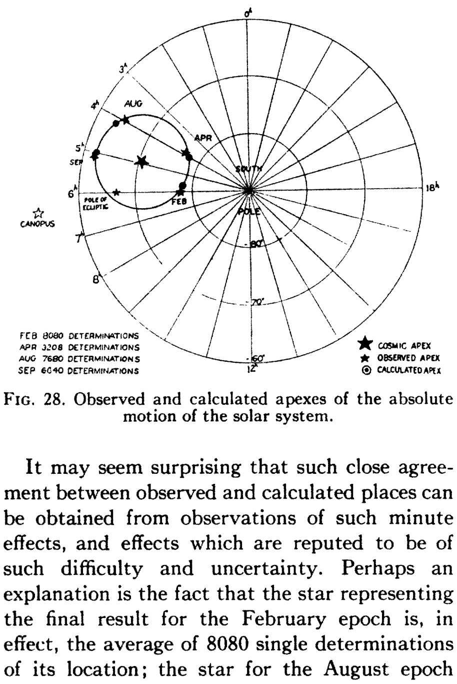

FIG. 28. Observed and calculated apexes of the absolute motion of the solar system.

It may seem surprising that such close agreement between observed and calculated places can be obtained from observations of such minute effects, and effects which are reputed to be of such difficulty and uncertainty. Perhaps an explanation is the fact that the star representing the final result for the February epoch is, in effect, the average of 8080 single determinations of its location; the star for the August epoch represents 7680 single determinations, that for September, 6640 and that for April, 3208 determinations.

Attention is called to the fact that the results here obtained are not opposed to the results originally announced by Michelson and Morley in 1887; in reality they are consistent with and confirm the earlier results. With additional observations, the interpretation has been revised and extended.

The model, Fig. 29, represents, to scale, the conclusions of this study of the absolute motion of the earth. The earth is represented by the ball near the top of the model and the plane of the ecliptic is the horizontal plane through the center of the earth. The cosmic component of the earth's motion, which is the absolute motion of

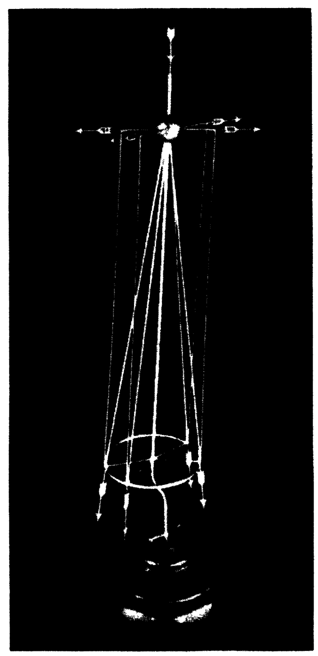

FIG. 29. Model illustrating the components of ether-drift.

the solar system, is directed to the apex near the south pole of the ecliptic and is represented by the arrow near the top of the model and by the rod in its prolongation below the earth. The orbital motions for the four epochs of these observations are represented by the four arrows in the horizontal plane. The four resultant motions are shown by the diagonals of the four parallelograms corresponding to the several epochs. The resultant motion in the course of a year traces on the celestial sphere the aberration orbit of the earth represented by the circle near the bottom of the model; the four epochal positions are marked by the arrows at the bottom. This part of the model corresponds to the orbital circle on the chart, Fig. 28, and to the model of the orbit with the four globes, Fig. 24.

Probable error

A study of the numerical results as plotted in Fig. 26 shows that the probable error of the observed velocity, which has a magnitude of from ten to eleven kilometers per second, is ± 0.33 kilometer per second, while the probable error in the determination of the azimuth is $\pm 2.5°$. The probable error in the right ascensions and declinations of the polar chart, Fig. 28, is $\pm 0.5°$.

FULL-PERIOD EFFECT

Throughout these experiments, while the attention has been given to the second-order, half-period effect, there has been present a full-period, first-order effect of comparable magnitude. The theory of the ether-drift experiment as usually given is exact but it is also abstract, being based upon simplified conditions of the apparatus which never exist in the actual experiment. What actually happens to the interference fringes depends not only upon the ether-drift effect but also upon the geometrical arrangement of the mirrors. The simple theory assumes that the mirrors at the ends of the two arms of the interferometer are perpendicular to the rays of light; this would produce fringes of infinite width, the whole field of view being uniformly illuminated, a critical condition never desired nor used in practice. In order to produce a series of straight fringes, suitable for the measurement of displacements, as shown in Fig. 7, it is necessary that one of the end mirrors be rotated about a vertical axis through a very small angle so that the two virtual interfering planes intersect. The width of the fringes and the number of fringes in the field of view are directly dependent upon this inclination of the end mirror. The angle of incidence of the light on the mirror, as used in these experiments, differs from 0° by about $\pm 4''$. The late Professor W. M. Hicks of University College, Sheffield, has given an elaborate discussion of the theory,[15] using methods which are not only rigorous but also general, applying to any adjustment whatever of the optical parts of the apparatus. In the theory of Hicks it is shown that when the periodic variation in the relative phases of the two beams of light in the interferometer takes place with the mirrors adjusted as in actual practice, there is introduced an additional effect which is periodic in a full turn of the instrument. The amplitude of this full-period effect, which varies inversely as the width of the fringes being used at the time of observation, is about equal to the amplitude of the ether-drift effect when there are eight fringes in the field of view; with the adjustment usually secured for six fringes in the field of view, the full-period effect is smaller than the half-period effect, as shown in Fig. 21.

The full-period effect, which has usually been overlooked, is present in all of the observations, including the original observations of Michelson and Morley. Hicks called attention to the latter fact and calculated its magnitude. Unfortunately, in none of the observations heretofore made have there been quantitative measurements of the width of the fringes which determines the angle of inclination of the mirror and it is not possible to use the full-period effect for a solution of the problem of ether-drift. However, the approximate number of fringes visible in the field of view has frequently been recorded. A comparison of the width of fringes thus indicated with the magnitude of the full-period effect shows a direct

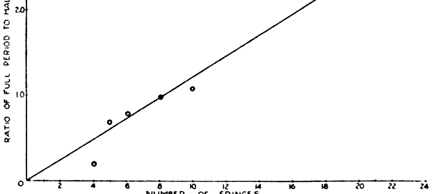

FIG. 30. The full-period effect; the relation of amplitude to width of fringes.

[15] W. M. Hicks, Phil. Mag. [6] **3**, 9, 256, 555 (1902); Nature **65**, 343 (1902); E. W. Morley and D. C. Miller, Phil. Mag. [6] **9**, 669 (1905).

linear relation as required by the theory of Hicks; this relation is shown in Fig. 30.

The Entrained Ether Hypothesis

In order to account for the results here presented, it seems necessary to accept the reality of a modified Lorentz-FitzGerald contraction, or to postulate a viscous or dragged ether. In commenting upon 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, is 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*."[16]

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 differently 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.

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. Sir Oliver Lodge in his autobiography says: "I still cling to the idea that the FitzGerald contraction is a reality which must be taken into consideration in any physical contemplation of the universe."[17]

One is compelled, therefore, to consider whether there are possible readjustments of the theories of the ether that will account for the reduction in the observed velocities of absolute motion and for the displaced azimuths. The difficulties presented by these anomalies are certainly not greater than those existing in many other fields of experimental research.

Other Recent Ether-Drift Experiments

Since the announcement of the evidence of absolute motion of the solar system made at Kansas City in 1925, several other experimenters have performed ether-drift experiments with interferometers of various designs and under various conditions, leading to results which are generally considered to be at variance with the conclusions of this paper. Brief reference to these experiments will be made but without extended analysis.

Dr. Roy J. Kennedy, at Pasadena, used an interferometer with an optical device of original design, giving great sensitivity.[18] The length of

[16] L. Silberstein, Phil. Mag. [6] 39, 161 (1920).

[17] O. J. Lodge, *Past Years*, 206 (1932).

[18] R. J. Kennedy, Proc. Nat. Acad. Sci. **12**, 621 (1926); Astrophys. J. **68**, 367 (1928).

the light path, to the end mirror, represented by D in the formula previously given, was 200 centimeters. The apparatus was in a sealed metal case filled with helium. The conclusion was that any indicated ether-drift must be less than 2.5 kilometers per second; this limiting value was later reduced by Illingworth to 1 kilometer per second.

Professor A. Piccard and E. Stahel, of Brussels, thinking that the height above the earth's surface might influence the ether-drift effect, placed an interferometer in a balloon which ascended to an altitude of 2500 meters.[19] The balloon was rotated about a vertical axis by means of a propeller. The interferometer had a light path in which D was 280 centimeters; it had a self-recording device and a thermostatic control; it was enclosed in a metal case which was evacuated. The indicated velocity of ether-drift might have been as large as 7 kilometers per second, which was the limit of precision. This interferometer was later taken to the summit of the Rigi in Switzerland, at an altitude of 1800 meters, where the observations showed an upper limit to the possible ether-drift of 1.5 kilometers per second.[20]

The late Professor Michelson, together with F. G. Pease and F. Pearson, used an interferometer mounted in the laboratory of the Mount Wilson Observatory in Pasadena, having a light path, D, equal to 1616 centimeters, which was later increased to 2592 centimeters. The readings were made in the vertical axis of the interferometer, the observer being located in the room above the apparatus. "The results gave no displacement as great as one-fiftieth of that to be expected on the supposition of an effect due to a motion of the solar system of three hundred kilometers per second."[21]

Professor Georg Joos, working at Jena, used an interferometer mounted on a quartz base suspended in an evacuated metal housing and provided with photographic registration. The interferometer had a light path, D, equal to 2099 centimeters. The results indicated that any existing ether drift could not exceed 1 kilometer per second.[22]

In three of the four experiments, the interferometers have been enclosed in heavy, sealed metal housings and also have been located in basement rooms in the interior of heavy buildings and below the level of the ground; in the experiment of Piccard and Stahel, a metal vacuum chamber alone was used and in the experiment of Michelson, Pease and Pearson, the interferometer was in the constant temperature vault but did not have a vacuum case. If the question of an entrained ether is involved in the investigation, it would seem that such massive and opaque shielding is not justifiable. The experiment is designed to detect a very minute effect on the velocity of light, to be impressed upon the light through the ether itself, and it would seem to be essential that there should be the least possible obstruction between the free ether and the light path in the interferometer. It is planned to make a direct study of this factor of the problem.

In none of these other experiments have the observations been of such extent and of such continuity as to determine the exact nature of the diurnal and seasonal variations.

While the interferometer used by Kennedy is more sensitive than that of ordinary type, it is doubtful whether the precision of the result equals that obtained from the very large number of readings made under all conditions of temperature and season with the interferometer of the usual type which is much less sensitive to disturbing causes.

The limitations of the direct-reading method have been recognized but it has been adopted because of its simplicity and because it permits the accumulation of a large number of readings in the shortest time. It is believed that any lack of precision in making a single reading is fully compensated by the large number of readings and by the use of an interferometer of longer light-path and therefore of greater initial sensitivity. The interferometer used in the experiments here reported has a light-path, D, equal to 3203 centimeters.

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[19] A. Piccard and E. Stahel, Comptes Rendus **183**, 420 (1926); Naturwiss. **14**, 935 (1926).

[20] A. Piccard and E. Stahel, Comptes Rendus **185**, 1198 (1927); Naturwiss. **16**, 25 (1928).

[21] A. A. Michelson, F. G. Pease and F. Pearson, Nature **123**, 88 (1929); J. Opt. Soc. Am. **18**, 181 (1929).

[22] G. Joos, Ann. d. Physik [5] **7**, 385 (1930).

Other Evidences of Cosmic Motion

The various astronomical determinations of motion of the solar system in space, by the nature of the methods employed, indicate *relative* motion and do not directly give any information as to an absolute motion. However, several recent important experiments in diverse fields seem to give evidence of a cosmic motion. Dr. Esclangon, Director of the Paris Observatory, has made elaborate studies of earth tides (deformation of the earth's crust) and of ocean tides. In the latter work he considered 166,500 observations extending over a period of nineteen years.[23] There are component tidal effects which indicate a motion of the solar system in the plane which contains the sidereal time meridian of $4\frac{1}{2}^h$ and $16\frac{1}{2}^h$.[23]

By a study of the reflection of light, Esclangon finds strong evidence for what he calls an "optical dissymmetry of space" with its axis of symmetry in the meridian of 8 hours and 20 hours, sidereal time. This effect would be explained by an ether-drift and the results are in striking agreement with the ether-drift observations here reported.[24]

Many recent observations on cosmic rays show a very definite maximum of radiation in the direction indicated by the meridian of 5 hours and 17 hours, sidereal time. The very extensive observations of Kolhörster and von Salis, Büttner and Feld and of Steinke all show this effect.[25] Observations made on the nonmagnetic ship "Carnegie" show the same effect for the observations made between 30° north and 30° south latitude.[26]

Evidences of galactic motions which are related more or less directly to the absolute motion of the solar system have been found by Harlow Shapley studying interstellar matter, by J. S. Plaskett from investigation of the motion of *B*-type stars, and by G. Strömberg from researches on star clusters and nebulae.[27]

L. Courvoisier has made researches of several types to discover evidences of the absolute motion of the earth. His experiments relate to the reflection of light, the deformation of the earth, the elongations of Jupiter's satellites, and to the aberration constant. R. Tomaschek and W. Schaffernicht have made observations on related subjects.[28]

There are several anomalies in astronomical observations of less definite character, which, however, might be explained by the existence of an ether drift. Such anomalies occur in connection with the observed constant of aberration, standard star places and clock corrections determined at different times of day.

Karl G. Jansky of the Bell Telephone Laboratories has found evidences of a peculiar hissing sound in short wave radio reception, which comes from a definite cosmic direction lying in the meridian of 18 hours sidereal time.[29]

Acknowledgments

The experiments here presented have involved the taking of an enormous amount of observational material, by far the greater part of which was for the purpose of making adjustments and for preliminary trials of conditions; while only the smaller portion, which is still very large, has been used in the final calculations. The reduction of this mass of material has been exceedingly laborious. No other experiment comes to mind which has involved such an amount of detail and such extended study. This has required considerable attention from many different persons. The writer is under special obligation to Professor J. J. Nassau, of the Department of Astronomy of Case School of Applied Science, for very great assistance in the analysis and in the mathematical solution of the numerical and astronomical features of the work since the beginning of the Mount Wilson observations in 1921. Dr. G. Strömberg and other members of the staff of the Mount Wilson Observatory have given advice and assistance of

[23] E. Esclangon, Comptes Rendus **182**, 921 (1926); **183**, 116 (1926).

[24] E. Esclangon, Comptes Rendus **185**, 1593 (1927).

[25] Kohlhörster, Steinke and Büttner, Zeits. f. Physik **50**, 808 (1928).

[26] Report Carnegie Inst. **27**, 255 (1928).

[27] Harlow Shapley, Nature **122**, 482 (1928); J. S. Plaskett, Science **71**, 152 (1930); G. Strömberg, Astrophys. J. **61**, 353 (1925).

[28] L. Courvoisier, Astronomische Nachrichten, Nos. 5416, 5519, 5599, 5715, 5772, 5910. R. Tomaschek and W. Schaffernicht, Astronomische Nachrichten, Nos. 5844, 5929; Ann. d. Physik **15**, 787 (1932).

[29] Karl G. Jansky, Electronics **6**, 173 (1933).

the greatest value. Several research assistants have each, for considerable periods, been identified with the experimental work and the reduction and calculation of the observations; among these the following should be especially mentioned: R. F. Hovey (1920–1923), H. A. Pritchard (1923), Willard Samuelson (1924), G. Brooks Earnest (1925), F. W. Taylor (1925–1926), Donald H. Spicer (1926–1927) and James R. McKinney (1932–1933). Dr. R. M. Langer was a most efficient assistant throughout all the observations made at Mount Wilson in 1925 and 1926, which constitute the principal material for the conclusions of the present report. Professor Phillip M. Morse assisted very effectively in the first analysis of the general problem of the absolute motion of the solar system, and he made a considerable part of the calculations for the first solution of this problem in 1925–1926. The writer's research associates, Professor John R. Martin (1927–1931) and Mr. Robert S. Shankland (1932–1933), have been directly associated with the restudy of the problem which has resulted in the final determination of the absolute motion of the solar system and the orbital motion of the earth as presented in this report.

Case School of Applied Science has made possible the continuous prosecution of the study of the ether-drift problem. The Carnegie Institution of Washington and the Mount Wilson Observatory made available the exceptional facilities of Mount Wilson for observational work from 1921 to 1926. Mr. Eckstein Case provided funds for the very considerable expenses involved in making the elaborate series of experiments and tests.

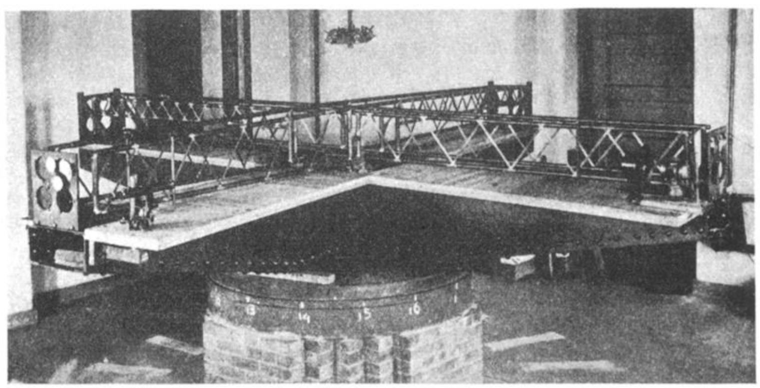

FIG. 10. The Morley-Miller ether-drift interferometer arranged for tests of the Lorentz-FitzGerald hypothesis, 1904.

FIG. 12. Interferometer house on "Ether Rocks," Mount Wilson.

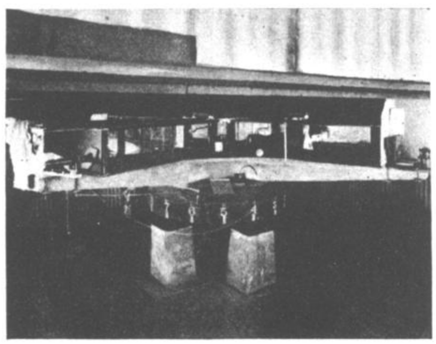

FIG. 13. Interferometer with base of concrete, 1921.

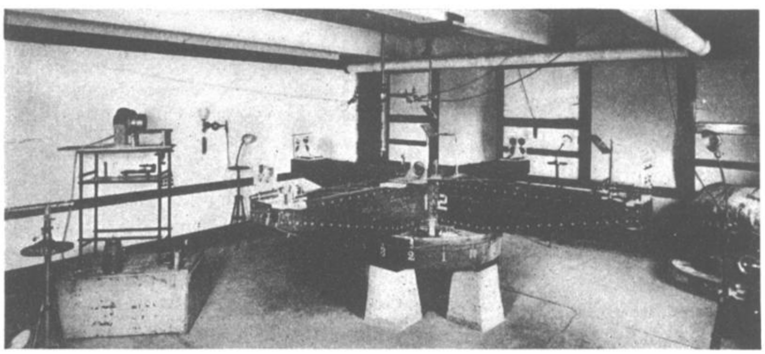

FIG. 14. The interferometer in the laboratory, 1923.

FIG. 15. Ether-drift house at Mount Wilson in 1924–1926.

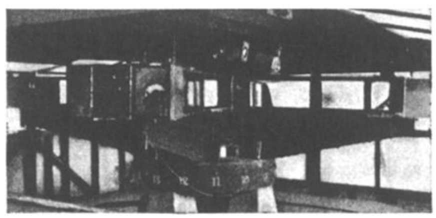

FIG. 16. The ether-drift interferometer as used at Mount Wilson in 1924–1926.

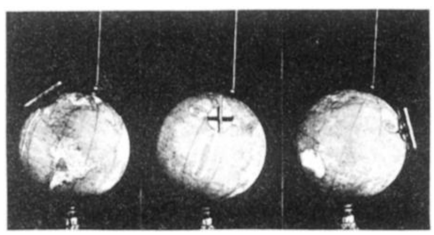

FIG. 17. Models illustrating the diurnal variation in the magnitude and direction of the ether-drift effect.

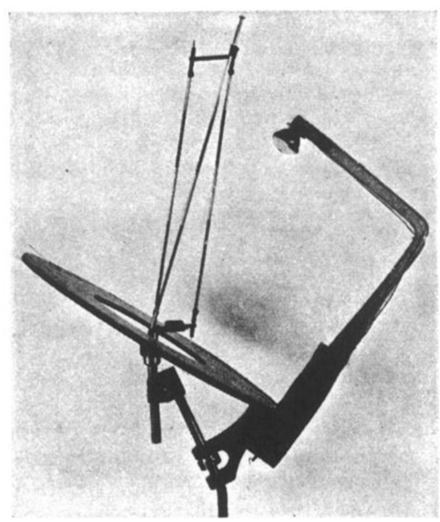

FIG. 18. Model for studying the components of ether-drift.

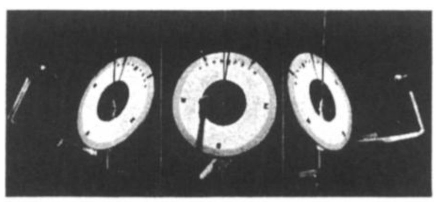

FIG. 19. Model illustrating the diurnal variation in the azimuth of the ether-drift.

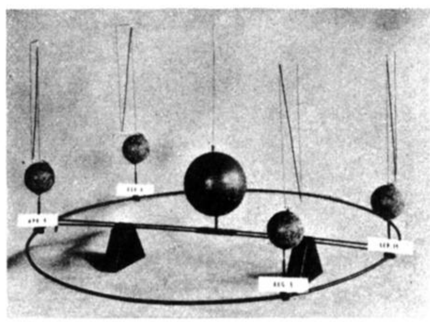

Fig. 24. Model illustrating the positions of the earth in its orbit at the four epochs of observation.

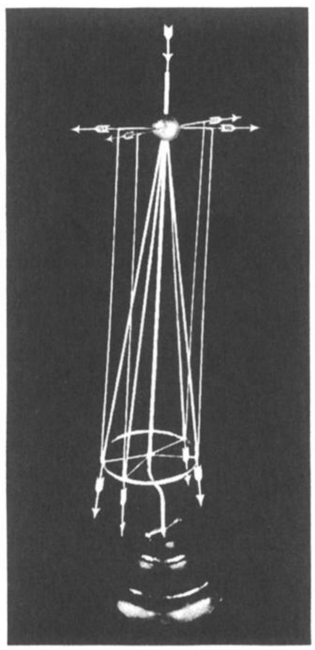

FIG. 29. Model illustrating the components of ether-drift.

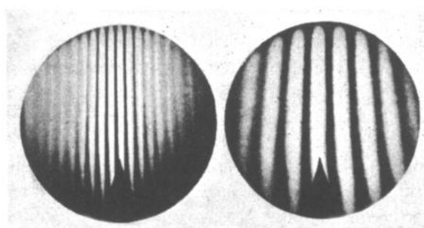

Fig. 7. The interference fringes as seen in the interferometer.