Mr. Simon and I have taken about 750 stereoscopic cloud expansion photographs, using apparatus such as that shown diagrammatically in figure 2. Our chief difficulty has been to eliminate stray X-rays, which give rise to meaningless tracks often indistinguishable from those due to scattered quanta. The results of the last 350 plates, in which these rays were reduced to a relatively low intensity, are shown in figure 3. Here I have plotted the deviation Δ of the observed tracks from the theoretical angle. On the spreading wave theory, the values of Δ should be nearly uniformly distributed between 0 and 180 degrees. On the quantum theory they should be concentrated near 0, as is obviously the case. The occurrence of tracks at other angles is explicable as due in part to stray X-rays and in part to the method of plotting the results.

A more detailed account of the work will be published when further experiments, which are now in progress have been completed. The results already obtained, however, permit us to state, with very little uncertainty, that the direction in which a quantum of scattered X-rays can produce an effect is determined at the moment it is scattered, and can be predicted from the direction of motion of the recoil electrons. In other words, *scattered X-rays proceed in directed quanta.*

It is possible to clothe this statement in the language of the wave-theory, if we keep in mind that a wave with a single quantum of energy can produce an effect in only one direction.[2]

[1] W. Bothe and H. Geiger, *Zeitschr. Physik.*, **26** (1924) 44.

[2] Since this paper was read before the Academy, I have received a letter from Dr. Bothe informing me that H. Geiger and he have also observed the coincidences demanded by the quantum theory but contrary to the theory of Bohr, Kramers and Slater. Their work will be described soon in *die Naturwissens haften.*

ETHER-DRIFT EXPERIMENTS AT MOUNT WILSON

By Dayton C. Miller

Case School of Applied Science

Read before the Academy April 28, 1925

The Michelson-Morley Experiment to determine the relative motion of the earth and the luminiferous ether, "ether drift," was first performed in Cleveland, Ohio, in the year 1887.[1] The experiment is based upon the argument that the apparent velocity of light should be slightly different according to whether the observer is carried by the earth in the line in which the light is travelling, or at right angles to this line. The interferometer devised by Michelson is capable of showing very minute changes in the relative velocities of two beams of light. Simple theory shows that if the velocity of the earth's motion were directly effective in observations made with the interferometer, the apparent velocities of the light going in the direction of the earth's motion, and of that at right angles to this direction, would differ in the ratio of the square of the velocity of the earth to the velocity of light. The actual motion of the earth in space is the resultant of its oribital motion and of the motion of translation of the solar system as a whole. The latter component motion being unknown, it is impossible to predict any "expected" relative motion of the earth and ether. The interferometer is affected only by that component of the earth's total motion which lies in the horizontal plane of the apparatus. This plane is perpendicular to the radius of the earth at the location of the observatory, and because of the diurnal rotation and the annual revolution of the earth, this plane is continually changing with respect to space in general.

Michelson and Morley floated the interferometer on mercury, so that the instrument could be turned to all azimuths of the horizontal plane of observation in the effort to find the direction of the presumed ether-drift. A drift perpendicular to the plane of the interferometer would produce no effect whatever. The rotation of the earth on its axis would cause the plane of the interferometer to move as around the surface of a cone, and thus to take many different space orientations. Therefore the apparent azimuth of the drift should change with the time of observation. In November 1887, Michelson and Morley announced their conclusion 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 the earth's orbital velocity and certainly less than one-fourth." (That is, it is less than $7^1/_2$ kilometers per second.) This result was considered by many as a null result, often called a negative result, and by some was thought to throw grave doubts upon the validity of the hypothesis of the luminiferous ether.

At the International Congress of Physics, held in Paris in 1900, Lord Kelvin expressed the conviction that the experiment should be repeated with a more sensitive apparatus. The writer in collaboration with Professor Morley constructed an interferometer about four times as sensitive as the one used in the first experiments, having a light path of 224 feet, equal to about 150,000,000 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 1.5 fringes. This apparatus was used in the basement of the Physical Laboratory of Case School of Applied Science in Cleveland, observations being made in 1904 and 1905.[2] The result of these observations was published as follows: "We may therefore declare that the experiment shows that if the ether near the apparatus did not move with it, the difference in velocity was less than 3.5 kilometers per second, unless the effect on the materials annulled the effect sought. 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."

In the autumn of 1905, Morley and Miller removed this interferometer from the laboratory basement to a site on Euclid Heights, Cleveland, at an altitude about 300 feet above Lake Erie, and free from obstruction of buildings. Five sets of observations were made in 1905 and 1906, which gave a definite positive effect of about $^1/_{10}$ 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.

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

Through the kindness of President Merriam of the Carnegie Institution of Washington and of Directors Hale and Adams the experiments were resumed by the writer in March and April 1921, at the Mount Wilson Observatory in California where the elevation above sea level is about 6000 feet. The apparatus was substantially the same as that used by Morley and Miller in 1904, 1905 and 1906.

At the Mount Wilson station, about 5000 single measures of the ether-drift have been made at various times of day and night. These have been reduced in 204 different sets, each set consisting of observations made within one hour's time. The observations correspond to four different epochs of the year, as follows: (I) April 15, 1921, 117 sets of observations; (II) December 8, 1921, 42 sets; (III) September 5, 1924, 10 sets; and (IV) April 1, 1925, 35 sets.

I. Between April 9 and April 21, 1921, over 1300 single measures of the ether-drift were made. These were recorded in 117 sets of measures. By combining the sets made at nearly the same hour on different days, the number was reduced to six principal observations. Each observation gives for a specified time the magnitude of the displacement of the interference fringes, together with the azimuth of the line of sight in which the displacement is a maximum. This is equivalent to saying that the observations give directly the apparent relative motion of the earth and ether in kilometers per second, together with the direction of the drift. Since the light in the interferometer travels along one arm and back again, the observation indicates only the line in which the drift occurs, but does not indicate whether it is in the positive or negative direction. The only criterion for determining the direction in the given line is the consistency of observations made at different epochs.

Figure 1 shows the observations of April 1921, in which the arrows indicate the observed direction and the magnitude of the drift, the arrows being located around a circle at points corresponding to the sidereal times of observation.

In order to eliminate any periodic effect of radiant heat, the metal parts of the interferometer were completely covered with large plates of cork about one inch thick. About fifty sets of observations were made under these conditions. The periodic displacement of the fringes due to the drift was the same with the cork in place, as it was without the cork.

II. In the summer of 1921, the steel frame of the interferometer was

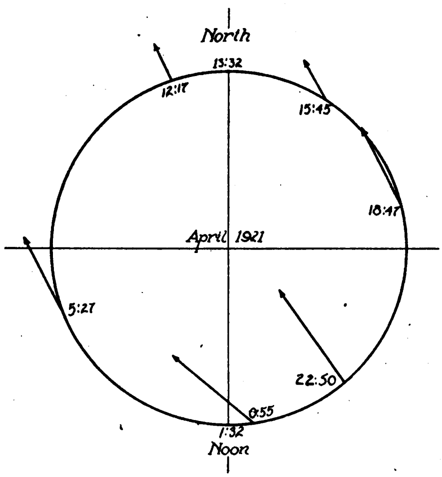

FIGURE 1

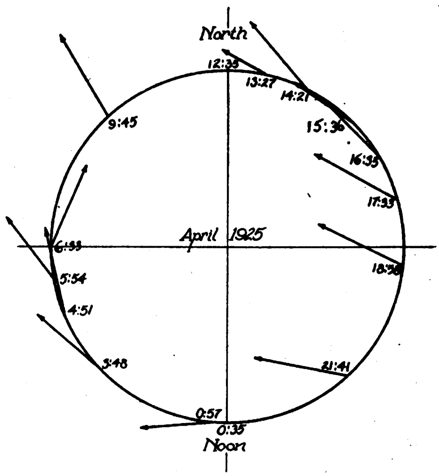

FIGURE 2

dismounted. A base of one piece of concrete, reinforced with brass rods, was cast in place on the mercury float. New supports of aluminum or brass were made for the optical parts. The entire apparatus was free from magnetic effects, and any possible effects of heat were much reduced.

From December 4 to December 11, 1921, about 900 single determinations of the drift were made, in 42 sets of observations. The results with this non-magnetic interferometer show a positive effect, as of an ether drift, of exactly the same magnitude and direction as was obtained at the first epoch in April 1921.

Many variations of incidental conditions were tried at this epoch. Observations were made with the centering pin tight in its socket, and then loose; with rotation of the interferometer clock-wise and counter clock-wise; with a rapid rotation of one turn in 40 seconds, and a slow rotation of one turn in 85 seconds; with a heavy weight added first to the telescope arm of the main frame and then to the lamp arm; with the float extremely out of level because loaded first in one quadrant and then in the next quadrant; with the recording assistant walking round in different quadrants, and standing in different portions of the house, near to and far from the apparatus. The results of the observations were not affected by any of these changes.

The entire apparatus was returned to the laboratory at Cleveland; during the years 1922 and 1923, many trials were made under various conditions which could be controlled, and with many modifications in the arrangement of parts of the apparatus. An arrangement of mirrors and prisms was made so that the source of light could be placed outside of the observing room, the light entering the rotating interferometer along the axis of rotation. This method has been used in the regular observations of epochs III and IV. A further arrangement of mirrors, rather complicated in practice, was tried, for observing the fringes from a stationary telescope; the necessity for frequent adjustment of the fringes in the field of view made this method impracticable. Experiments were made with devices for the photographic registration of the positions of the fringes, both from the fixed observing station, and by means of a motion-picture camera carried on the interferometer. Even with an arc light as the source, there was not sufficient illumination to produce a satisfactory photographic record, and the necessity for frequent adjustment of the fringes also made this method unsuitable. After abandoning the photographic method, an astronomical telescope having an objective of five inches aperture and a focal length of seventy-five inches was mounted on the interferometer. With a magnification of fifty diameters, the fringes were observable on a large scale and with ample illumination, so that direct reading with the eye was very satisfactory; this arrangement has been used ever since. Trials were made with various sources of light; with electric arc and incandescent lamps, the mercury arc, acetylene lamp, and also with sun light. The interchange between sun light and laboratory sources in no way altered the results. The final choice for the stationary source placed outside of the interferometer room (or house, on the mountain) was a large acetylene lamp of the kind commonly used for automobile head-lights.

An extended series of experiments was made to determine the influence of inequality of temperature in the interferometer room, and of radiant heat falling on the interferometer. Several electric heaters were used, of the type having a heated coil near the focus of a concave reflector. Inequalities in the temperature of the room caused a slow but steady drifting of the fringe system to one side, but caused no periodic displacement. Even when two of the heaters were placed at a distance of three feet from the interferometer as it rotated, and were turned to throw the heat directly on the uncovered steel frame, there was no periodic effect that was measureable. When the heaters were turned on to the light-path which had a covering of glass, a periodic effect could be obtained only when the glass was covered with opaque material in a very non-symmetrical manner, as when one arm of the interferometer was completely protected by a covering of corrugated paper-board while the other arms were unprotected. These experiments proved that under the conditions of actual observation, the periodic displacement could not possibly be produced by temperature effects.

As an indication of the reliability of the readings made with the interferometer, a series of observations are shown in figure 3, taken in the laboratory at Cleveland in July 1924. Two of these sets were made with sunlight as the source, the third and fourth lines from the top. The uncertainty of reading is less than 0.01 of a fringe, and the displacement is zero.

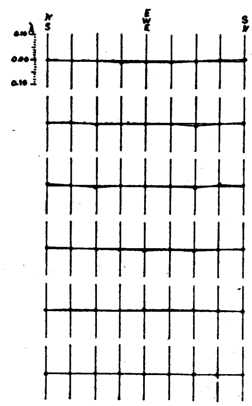
FIGURE 3

The investigation in the laboratory demonstrated that the full period effect mentioned in the preliminary report on the Mount Wilson observations,[3] is a necessary geometrical result of the adjustment of the mirrors in producing fringes of finite width. Under poor temperature conditions, such as existed at Mount Wilson in April 1921, it was necessary to use narrow fringes, in which case the full period effect is relatively large; as the width of fringes is increased, this effect decreases and vanishes only when fringes of infinite width are used, as is presumed is the simple theory of the experiment.

III. After the conclusion of the experiments just described, the interferometer was taken again to Mount Wilson. In 1921, the apparatus had been located on the very edge of a deep canyon; it was feared that the air currents up and down the face of the canyon might produce a disturbance, and also that the unsymmetrical distribution of the rock of the mountain itself might be undesirable. In August 1924, a new site was chosen, on a very slightly rounded knoll, removed from the canyons. The interferometer house was erected with its orientation, as regards the ridge of the roof and the location of the door, changed by 90° from that of 1921. In every detail, the interferometer was the same as had been used in Cleveland in July 1924. On September 4, 5 and 6, 1924, 275 measures of the drift were made, in 10 sets of observations. The actual observations are plotted in Fig. 4. This shows a positive displacement of the fringes, in contrast with the small result obtained in Cleveland, shown in Fig. 3. The corresponding ether-drift is consistent in direction and magnitude with that previously obtained at Mount Wilson. Part of these observations were made with the glass case over the light path, covered with corrugated paper which had been found in the Cleveland experiments to exclude all effects of radiant heat. This covering produced no effect whatever, showing that there was no disturbance of this kind.

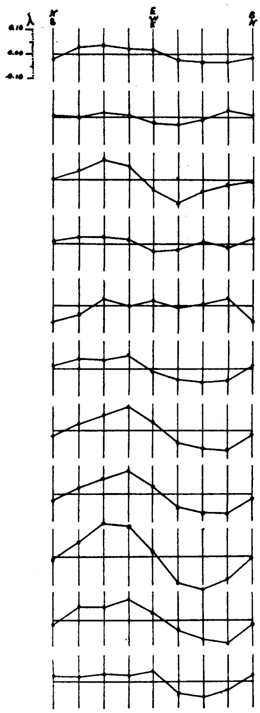

FIGURE 4

IV. Observations on Mount Wilson were resumed on March 27, 1925, and continued until April 9, during which time 1600 measures of the drift, in 35 sets, were made. The interferometer was as used in September 1924, excepting that new mirrors were provided for bringing in the acetylene light. During the first half of the observations for this epoch, the acetylene lamp was stationary and outside of the house; during the last half of the series, the lamp was placed on the cover of the interferometer, near the axis of rotation, which simplified some of the adjustments. There was not the slightest difference in the results obtained with the two positions of the light. The position of the assistant in the house was changed by a quadrant, with no effect on the result.

Throughout epoch IV the conditions of observation were exceptionally gocd; some of the time there was a fog, which rendered the temperature very uniform. Four precision thermometers were hung on the outside walls of the house; on numerous occasions the extreme variation of temperature was not more than 0.1°, and usually it was less than 0.4°; however, a variation of several degrees, while causing a constant drift of the fringe system, did not change the periodic displacement either in azimuth or magnitude.

The observations made at about the same time of day (or night) being combined, the 35 sets have been averaged in thirteen groups, and the resulting ether-drifts are shown in figure 2. The agreement between the results for 1921 and 1925 is striking, especially when it is recalled that the interferometer has been rebuilt as to its details, has a different system of illumination and observation, and has been changed to a new site, in a house differently oriented, and that many variations in observational procedure have been tried.

The interferometer readings being plotted, give directly, by harmonic analysis (carried out with the mechanical harmonic analyzer) the azimuth and magnitude of the ether-drift. There are no corrections of any kind to be applied to the observed values. In the work so far, every reading of the drift made at Mount Wilson has been included at its full value. No observation has been omitted because it seemed to be poor, and no "weights" have been applied to reduce the influence on the results, since no assumption has been made as to the expected result. It may be added that while the readings are being made, neither the observer nor the recorder can form the slightest idea as to whether any periodicity is present, much less as to the direction or amount of such periodicity.

The test of these observations is whether they lead to a rational and wholly consistent indication of a constant motion of the solar system in space, combined with the orbital motion of the earth and the daily rotation on its axis. There is a specific relation for a given latitude between the observed azimuth of drift and the sidereal time of observation. Observations at different sidereal times should show different azimuths and all observations at the same sidereal time should show the same azimuth, for

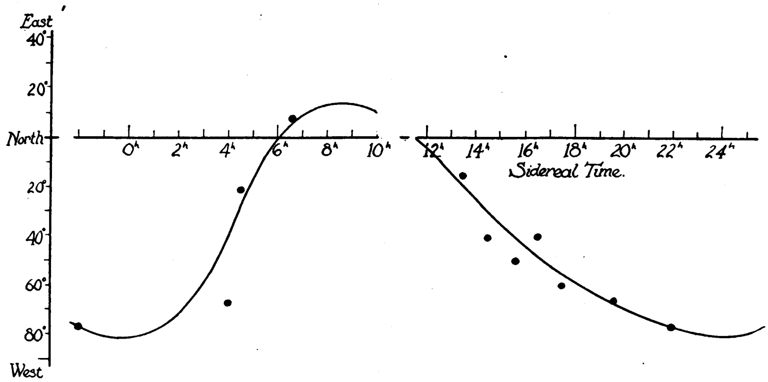

FIGURE 5

a given epoch. The 1600 observations of the ether-drift made in April 1925, consisting of 35 sets made on different days, have been combined into eleven sets at different sidereal times, and are charted in azimuth with respect to sidereal time in figure 5. The curve shown has been drawn arbitrarily to indicate that there is a definite relation. This curve is of the kind that would correspond to some definite direction and velocity of ether drift. The observations for the other three epochs, while not so numerous, give curves wholly consistent with this one.

It need hardly be said that the determination of the absolute motion of the solar system from such interferometer observations, is one of great complexity. Prof. J. J. Nassau of the Department of Mathematics and Astronomy of Case School of Applied Science, and Dr. G. Strömberg of the staff of the Mount Wilson Observatory, have given very great assistance in the mathematical analysis, and have developed solutions of various parts of the problem, and also a complete least-squares solution of the general problem. A definitive numerical calculation will require several months of continuous work, and is now in progress.

The ether-drift experiments at Mount Wilson during the last four years, 1921 to 1925, lead to the conclusion that there is a relative motion of the earth and the ether at this Observatory, of approximately nine kilometers per second, being about one-third of the orbital velocity of the earth. By comparison with the earlier Cleveland observations, this suggests a partial drag of the ether by the earth, which decreases with altitude. It is believed that a reconsideration of the Cleveland observations, from this point of view, will show that they are in accordance with this presumption and will lead to the conclusion that the Michelson-Morley Experiment does not give a true zero result. A complete calculation of the observations, now in progress, together with further experiments to be made in the immediate future, should give definite indications regarding the absolute motion of the solar system in space.

[1] Michelson and Morley, *Relative Motion or the Earth and the Luminiferous Ether, Amer. J. Sci.*, **34**, 333 (1887); *Phil. Mag.*, **24**, 449 (1887); *J. Physique*, **7**, 444 (1888).

[2] Morley and Miller, *An Experiment to Detect the FitzGerald-Lorentz Effect, Phil. Mag.*, **9**, 680 (1905); *On the Theory of Experiments to Detect Aberrations of the Second Degree, Phil. Mag.*, **9**, 669 (1905). *An Experiment to Detect the FitzGerald-Lorentz Effect, Proc. Amer. Acad. Arts Sci.*, **41**, 321 (1905).

[3] Miller, *Ether-Drift Experiments at Mount Wilson Observatory, Physic. Rev.*, **19**, 407 (1922); *Science*, **55**, 496 (1922).

THE INTENSITIES OF LINES IN MULTIPLETS. I. THEORY

By Henry Norris Russell

Mount Wilson Observatory, Carnegie Institution of Washington

Communicated May 8, 1925

It appears probable that the relative intensities of spectral lines belonging to the same multiplet group are determined by quantum conditions. This note presents formulae recently developed by the writer, which closely represent all the available data.

1. *Notation.*—From the standpoint of multiplet structure, a spectroscopic term may be completely specified by three integers, one of which defines the system to which the term belongs, the second the series, and the third distinguishes between the components of a multiple term. The most natural definition of these integers appears to be that which makes the first equal to the maximum number of components possessed by any term of the system: the second to the maximum number of components