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ETHER-DRIFT EXPERIMENTS AT MOUNT WILSON[1]

AFTER the wave theory of light was established, it became necessary to assume the existence of an all-pervading medium in which the waves could be developed and transmitted; this hypothetical medium was called the "ether." It was endowed with such properties as were necessary for the explanation of observed phenomena. Several physicists sought to prove the existence of the 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 respect 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 300,000 kilometers per second, while the velocity of the earth in its orbit is 1/10,000th part of this, 30 kilometers per second. If the earth's orbital velocity were directly effective, the two apparent velocities should differ by 30 kilometers per second or by one part in 10,000. However, 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.

[1] Read before the National Academy of Sciences, Washington, April 28, 1925.

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 wave-lengths 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, in Cleveland, Professor Michelson, then professor of physics at Case School of Applied Science, in collaboration with Professor Edward W. Morley, of Western Reserve University, made certain important developments of method and apparatus and used the interferometer in an effort to determine whether the motion of the earth through space produces the effect upon the velocity of light predicted by theory. Unfortunately we do not know in what absolute direction the earth is going through space 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 presumed ether 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 cone whose axis 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 horizontal 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. A drift perpendicular to the plane of the interferometer will produce no effect whatever; it is quite possible that this condition may occur at certain times of the year.

It is not possible at this time to explain the details of the principles involved. The observations are made by looking through a telescope at the system of interference fringes formed by the two beams of light. As the interferometer is rotated on its axis, an ether drift would cause the whole system of fringes to oscillate, moving first to one side and then to the other, this effect being periodic in each *half* revolution of the interferometer about its vertical axis. For a relative motion of the earth and the ether equal to the orbital velocity of the earth, that is 30 km/sec, the displacement in the original Michelson-Morley experiment would have been 4/10th of a fringe.

In November, 1887, Michelson and Morley announced the conclusions drawn from their observations made in July of that year 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." (That is, it is less than 7½ 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. There is a significant "Supplement" to this report which begins with the following sentence: "But it is not impossible that at even moderate distances above the level of the sea, at the top of an isolated mountain peak, for instance, the relative motion might be perceptible in an apparatus like that used in these experiments."[2]

At the International Congress of Physics, held in Paris in 1900, Lord Kelvin gave an address in which he considered theories of the ether. He remarked that "the only cloud in the clear sky of the theory was the null result of the Michelson-Morley experiment." Professor Morley and the writer were present, and in conversation with Lord Kelvin he 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 experiment, 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 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

[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).

of wood was used in 1902 and 1903, but the changes in the wooden frame due to the variations in humidity and temperature made accurate observations impossible. 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 constructed of structural steel, and was erected in a basement room in the Physical Laboratory of Case School of Applied Science in Cleveland, and observations were made in 1904 and 1905. The results of these observations were published in *The Philosophical Magazine* for May, 1905. They were stated 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."[3]

It was at this time that Einstein became interested; and later in the year, 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, tending to show that for an observer on the moving earth, the measured velocity of light would 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 had given a definite and exact null result. This interpretation of the experiment was not acceptable to the writer, and further observations were undertaken to determine this particular question.

In the autumn of 1905, Morley and Miller removed the interferometer from the laboratory basement to a site on Euclid Heights, Cleveland, at an altitude of about 300 feet above Lake Erie, and free from obstruction of buildings. Five sets of observations were made in 1905–1906, which give 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.

Professor Morley retired from active work in 1906 and it devolved upon the present writer to continue the experiments. It seemed desirable that further observations should be carried out at a much higher altitude, but numerous causes prevented the resumption of observations. The publication of reports on the solar eclipse of 1919, which were interpreted as confirming the theory of relativity, revived the interest in the ether-drift experiments. A generous friend provided ample funds to cover the considerable expense involved. The site of the Mount Wilson Observatory near Pasadena, California, at an elevation of about 6,000 feet, seemed to be a suitable place for further trials. Through the kindness of President Merriam, of the Carnegie Institution at Washington, and of Directors Hale and Adams, the experiments were resumed by the writer in March and April, 1921, at the Mount Wilson Observatory. The apparatus was substantially the same as that used by Morley and Miller in 1904, 1905 and 1906. Observations were also made in the latter part of the year 1921 and again in 1924 and 1925.

At the Mount Wilson station, about 5,000 single measures of the ether-drift have been made at various times of the 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; September 5, 1924, 10 sets; and April 1, 1925, 35 sets.

The very first observations made in March, 1921, 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 the ether drift. The causes suggested were magnetic deformation of the steel frame of the interferometer and the effects of radiant heat. In order to eliminate the effects of radiant heat the metal parts of the interferometer were completly covered by cork about one inch thick. Fifty sets of observations were made under these conditions, showing the periodic displacement of the fringes due to the drift agreeing with the first observations.[5]

[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).

[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).

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 of aluminum or brass, thus the entire apparatus was on the mercury float. All the metal parts were made free from magnetic effects and the possible effects due to heat were much reduced. In December, 1921, 42 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.

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 extended investigation in the laboratory demonstrated that the full-period effect mentioned in the preliminary report on the Mount Wilson observations is a necessary geometrical result 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 definite positive effect corresponding to the observations previously made at Mount Wilson. The observations on Mount Wilson were resumed in March, 1925, and continued until about the middle of April, during which time 1,600 measures of the drift in 35 sets were made. Again many variations in detail of arrangement of parts and in methods of observing were made without in any way altering the result. Throughout the latter epoch of observations, the conditions were exceptionally good. Some of the time there was a fog which rendered the temperature very uniform. Four precision thermometers were hung on the outside of the house. On several occasions the extreme variation of temperature was not more than 0.1 degree and usually it was less than 0.4 degree. Such variations did not at all affect the periodic displacement of the interference fringes. The observations of April, 1925, give results almost identical with those of April, 1921, notwithstanding that the interferometer had been rebuilt and that a different system of illumination and different methods of observation were employed and that it was mounted on a new site in a house differently oriented.

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 result, 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 observations. Observations at different sidereal times should show different azimuths and all observations at the same sidereal time should show the same azimuth for a given epoch. A preliminary graphical solution of the observations indicates that these conditions are fulfilled.

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. Professor 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 positive displacement of the interference fringes, such as would be produced by a relative motion of the earth and the ether at this observatory, of approximately ten 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 and probably never has given a true zero result. A complete calculation of experiments, to be made in the immediate future, should give definite indications regarding the absolute motion of the solar system in space.

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RISKS INCURRED IN THE INTRODUCTION OF ALIEN GAME BIRDS

WITH the decrease in the supply of game animals which has inevitably accompanied the close settling of our country by Europeans, it has commonly occurred to those interested to remedy the situation by importing and planting non-native species which it is thought might be more prolific or hardier than the native species. This idea at first thought is appealing, and it has seemed so reasonable to many game administrators that it has been tried over and over again both in our own state (I am writing from California) and in other states, at great public expense. Experiments of this sort within the state of California alone have entailed the expenditure of upwards of fifty thousand dollars, as shown by the printed reports of our California Fish and Game Commission. But, not one non-native game species has become established here to a degree of success warranting the declaration of an "open season" upon it.

It has just been announced through the public press that our state fish and game commission, apparently forgetting all these past and unsuccessful experiments, has again under serious consideration a plan for raising in captivity and liberating certain non-native game birds; and the kind specifically mentioned is the Hungarian partridge. This announcement must bring dismay to every student of nature whose concern (as is my own) extends to include the welfare and usefulness to man of California's wild life generally and is not restricted to objects of sport alone.

In the first place, it is believed by some thinking naturalists that the chances are decidedly against the success of this project—success as bringing the beneficent results expected of it by the gunner. To repeat, such experiments have already been tried,[1] and these have involved no less than twelve non-native game species and an aggregate of at least 13,000 individual birds, by record, liberated. No success has been achieved. Are chances of success now, with further depletion of natural food and cover, any better than before?

Howsoever, *if* the introduction now proposed *should* prove successful from the sportsman's standpoint and, say, the Hungarian partridge become fully established, what would be the possible, even probable, results? One result, about which there is no question whatsoever in my own mind, would be the crowding out, the supplanting, in partial measure if not altogether, of our native California quail.

An axiom which I think all close students of natural history would accept without reservation is as follows: No two species of identical or even closely similar biological predilections can long occupy the same niche or ecologic space at the same time. If the same food supply, in kind and amount, if the same type of shelter for roosting or resting, or if the same sort of breeding places be resorted to by two species, there will be inevitable conflict. One or the other species will give way, because bound to be at less advantage in some respect as to structural equipment or instinctive manner of reacting to the conditions about it. The Hungarian partridge and the California quail belong to two genera of gallinaceous birds within the same family. While there are undoubtedly some differences between these two birds in their ecological requirements, the general similarities are exceedingly close. More or less keen competition would be bound to operate sooner or later to the disadvantage of one of them. I, for one, hereby protest against any act that will likely jeopardize the existence of our native Califor-

[1] See Grinnell, Bryant and Storer, "Game Birds of California," 1918, pp. 29 to 44.