Morley experiment, but many other optical phenomena, some of them known long before the Michelson-Morley experiment was performed, contained clues to the solution of the problem. And in this chapter we shall review some of the important evidence relating to the propagation of light, both in empty space and in transparent material media.

JRE OF LIGHT

The propagation of light involves the transport of energy away from a source. The simplest picture of this process is in terms of a stream of particles emitted from the source; Pythagoras, back in the 6th century B.C., proposed this mechanism. It accounts, very directly, for the propagation of light in straight lines (as evidenced by the sharpness of shadows) and for the fact that light can travel with complete ease through a vacuum. In 1667 there appeared the first clear exposition of a different theory—that light is a vibration communicated through a medium of some kind. This was propounded by Robert Hooke in his famous book *Micrographia*. At about this time were observed some of the phenomena that could not easily be related to a particle theory of light—the brilliant colors of thin air films between glass surfaces, and the encroachment of light upon the region of the geometrical shadow. Huygens, in his *Treatise on Light*,[1] developed the wave theory explicitly, and showed how it could account for reflection and refraction.

The particle theory and the wave theory have been the only clearly defined models by which to describe light and its propagation. For a long time—until the 20th century in fact—the two theories were taken to be mutually exclusive; it seemed obvious that acceptance of the one must imply rejection of the other. From the vantage point of today, we see that both photon and wave aspects of the behavior of light must be accepted—that the facts cannot all be forced into the mold of one or other of the two theories. We have learned also (thanks largely to Einstein) that we should focus on the bare facts of observation, and should not, through our adherence to a particular theory, read more into them than is there. To be specific, the wave properties of light are undeniable—diffraction, interference, polarization, etc.

[1]C. Huygens, *Treatise on Light* (written in 1678, published in 1690), unabridged republication of the original English edition of 1912 translated and introduced by S. P. Thompson, Dover, New York.

But the waves of ordinary experience require a medium. What more natural, therefore, than to build up a detailed specification of the medium that carries waves of light, and then to seek to detect it? Yet it was a quest that led only to frustration. Einstein showed that the search for the medium—the *luminiferous ether*—was sterile and unnecessary. The ether was a red herring—something that diverted physicists into following a false scent. Perhaps in this present discussion we should not introduce the ether at all, knowing that we are going to bury it again in the end. Yet one cannot fully appreciate the emergence of special relativity without some feeling for the importance and the appearance of reality that the ether once enjoyed. In the next section, therefore, we shall briefly discuss this background.

THE LUMINIFEROUS ETHER

The story of 19th-century physics was, in large part, the story of the triumph of the wave theory of light. At the beginning of the century (1801–1804) Thomas Young made his quantitative studies of interference phenomena. Beginning in 1818, Fresnel published calculations that were able to account in detail for the facts of interference, diffraction, and polarization. Since, as Huygens had shown, a wave theory was as competent as a particle theory to describe the ray properties of light—rectilinear propagation and the laws of reflection and refraction—the picture of light as a vibration in a medium, analogous to transverse waves on a string, seemed unassailable. But what could one say about the properties of the medium—which came to be called the *luminiferous ether*—in which these vibrations were presumed to take place?

Until about 1850 the propagation of light was envisaged in purely mechanical terms. This, however, posed very considerable difficulties, because it was hard to understand how the speed of light could be so very great. (The first quantitative measurement was due to the Danish astronomer Roemer in 1675. He noted systematic variations in the times, as recorded by clocks on earth, at which the moons of Jupiter moved into the planet's shadow, and was astute enough to recognize that these variations were linked to the position of the earth in its orbit and to the associated transit time of the light over a variable distance.) A wave speed of more than a hundred thousand miles per second was many orders of magnitude greater than the speed of any other mechanical disturbance, and demanded a medium which, although so tenuous that the planets could travel through it year after year with no detectable loss of speed, must nevertheless develop very strong restoring forces when displaced from equilibrium—since the speed of propagation of a wave depends on this restorative property of the medium. It was unsatisfying, too, that the only clue to the properties of the medium was the measured value of c itself; nothing was known a priori.

The situation was transformed when James Clerk Maxwell, in 1861, produced his electromagnetic theory of light. It now became possible to *predict* the numerical value of the speed of light for any given medium, in terms of measurable electric and magnetic properties of the medium. There was no longer such a gulf between ether and ordinary matter, although the intangibility of the ether might still seem mysterious. The wave theory seemed to have achieved its ultimate justification, and the ether a reality that could not be gainsaid.

Granted the existence of the ether, it was of course quite clear what was meant by "the speed of light." Any wave has a definite velocity with respect to the medium through which it moves. The magnitude of this velocity may be a function of wavelength (the phenomenon of dispersion) but is otherwise uniquely defined, at least for an isotropic medium (i.e., one containing no preferred directions). In particular, the speed of light through a medium should be quite independent of any motion of the source, in direct contrast to a particle-emission mechanism, in which one would expect the speed *relative to the source* to be the unique quantity. Acceptance of the wave theory did not wait upon an experimental proof that the measured value of c is indeed independent of the source velocity. If this had been known to Huygens, he would no doubt have used it as one more proof that a particle model of light was inadmissible. In fact, however, the wave theory appeared to be adequately supported by other lines of evidence, and the effect of source motion was not explored until the wave theory, in its turn, had run into severe difficulties. In Chapters 3 and 5 we shall have more to say about experiments on radiation from moving sources; for the present we shall merely state the result—that the velocity of a source of light is *not* communicated to the radiation it emits.

Let us, then, put ourselves in the position of a physicist of, say, 1900, and look at some striking optical phenomena from the standpoint of a wave theory.

STELLAR ABERRATION

In 1725 the British astronomer James Bradley tried to measure the distances of some stars by looking for an apparent change in their positions as the earth moved around the sun. He hoped to use the diameter of the earth's orbit as a base line, and to determine stellar distances in essentially the same way as a surveyor measures distances by triangulation. He did observe an effect, but he discovered that it was not parallax; it depended not on the earth's position, but on its *motion* at a given point in the orbit. (The true parallax effect is unobservably small for most stars.)

Consider Fig. 2–1, which depicts the orbit of the earth around the sun, and a star viewed from four positions of the earth, at 3-month intervals. The true altitude of the star with respect to the plane of the earth's orbit (the ecliptic) is the angle θ_0. Because of the earth's changes of position, one would expect the altitude to be greatest when the earth is at position 2 and

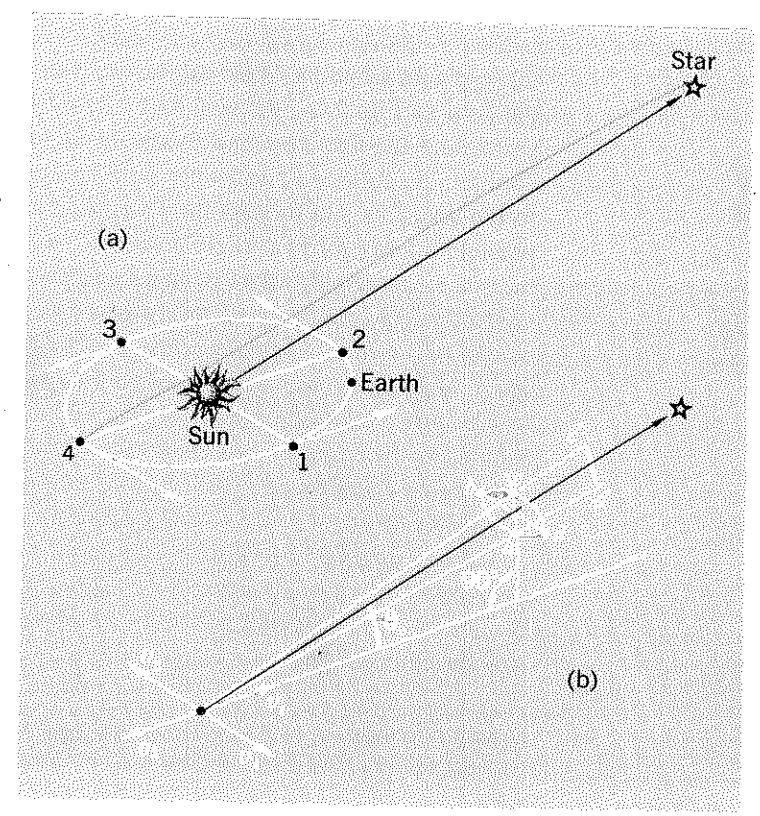


Fig. 2–1 Stellar aberration. (a) A distant star is viewed from the succession of positions 1-2-3-4 as the earth moves around the sun. (b) In a coordinate system attached to the earth (but with the direction of the axes fixed in space), the apparent position of the star follows the elliptical path a-b-c-d. The effect depends on the changes in the direction of the earth's velocity, not on the changes in its position as such.

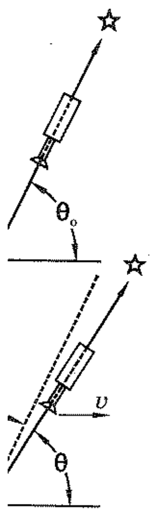


Fig. 2–2 Basis of stellar aberration. (a) A stationary telescope aligned on a star. (b) A moving telescope aligned on the same star.

least when it is at position 4. Instead, Bradley found that the altitude was greatest at position 3 and least at position 1.

The phenomenon can be understood in terms of Fig. 2–2. A telescope on a stationary earth (a) would have to be pointed at the true altitude θ_0 in order that the rays of light from the star should travel along the axis of the instrument and form an image at the center of the field of view. But on a moving earth (b) the telescope would have to be tilted at a slightly different angle, θ. The difference of angles is the aberration, α. We can observe a comparable phenomenon when it rains. If raindrops are falling vertically at speed w, but we are in a vehicle moving at speed v, we see the drops moving along straight lines inclined to the vertical at an angle $\tan^{-1}(v/w)$.

The aberration effect would never be detectable if the earth moved always with the same velocity, but the *changes* in the direction of motion during the year lead to a systematic change in the apparent position. This can be analyzed quantitatively with the help of Fig. 2–1. At positions 1 and 3 the earth's velocity vector and the line from sun to star make an angle θ_0 with one another. At positions 2 and 4 the earth's velocity is at right angles to the line from sun to star; the aberration angle has its greatest possible values ($\pm v/c$) at these positions. At positions 1 and 3 we have a situation like that depicted in Fig. 2–2, in which the aberration angle is only of magnitude $v \sin \theta_0/c$. Thus in the course of a year the star appears to describe an elliptical path which has a major axis (measured as an angle 2β) equal to $2v/c$ and a minor axis of $2\beta \sin \theta_0$. The length of the major axis should be the same for all stars; the length of the minor axis depends on the altitude θ_0 of a star with respect to the plane of the earth's orbit.

What Bradley observed corresponded exactly to the above description. Figure 2–3 is a graph of some of his observations on the star γ Draconis; it shows how the apparent position of the star varied in the north-south direction over a 12-month period.[1]

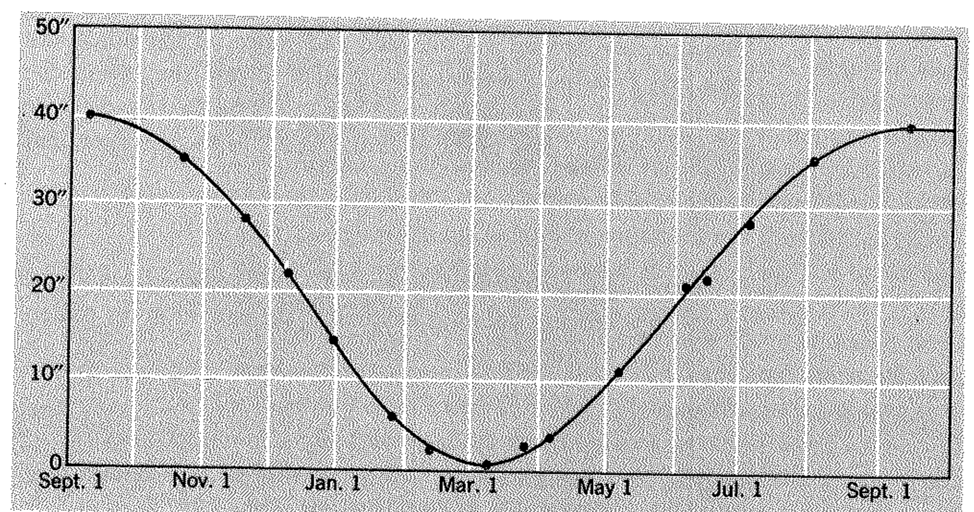
[1]Data taken from J. Bradley, *Phil. Trans. Roy. Soc.*, **35**, 637 (1729). For an interesting account of Bradley's work, with many details, see A. Stewart, "The Discovery of Stellar Aberration," *Sci. Am.* **210**(3), 100 (1964).

The east-west component of the aberration was not recorded. (You should consider the practical difficulties of measuring this component.) Thus Bradley's data span the minor axis of the aberration path.

Now the orbital speed of the earth is 30 km/sec, so that the value of $2v/c$ is 2×10^{-4} rad, or about 41 seconds of arc. A typical aberration path would resemble the outline of a football viewed from a distance of about 1 mile. The data shown in Fig. 2–3 span the minor axis of an aberration path for which $\theta_0 = 75°$, giving a calculated variation of 39.6″ between maximum and minimum altitudes, with a sinusoidal variation (why?) between these extremes. The observed range of variation corresponds extremely closely to this theoretical value. Actually, Bradley himself could not make a quantitative theoretical check of his result, because the speed of light was not well enough known. Instead, being sure that the basic interpretation of the phenomenon was correct, he used the observed aberration angles to obtain an improved value of c, the earth's orbital speed being at that time quite well known.

When we come to analyze the aberration phenomenon in terms of a theory of light, it is clear that a particle model provides a very ready explanation; it is just like the falling-rain analogy. However, one can also account for the effect in terms of waves

Fig. 2–3 Bradley's data on the north-south component of the aberration of γ-Draconis (1727–1728).



traveling through the ether, *provided* the ether remains completely undisturbed by the earth's motion. If, on the other hand, the ether near the earth were carried along with it, the aberration would not take place.[1] The notion of an ether completely undisturbed by the passage of the earth must have seemed a rather strained one to many physicists, but with the wave theory standing supreme it appeared unavoidable. And then it was natural to ask: Can one make any measurements that will disclose the magnitude of the velocity of the earth through the ether? We shall next describe some experiments bearing on this question.

MODIFIED ABERRATION EXPERIMENT

Suppose that a telescope has been aimed at a star whose true direction is at 90° to the plane of the earth's orbit. Let the unknown aberration angle be α [Fig. 2–4(a)] and let the unknown speed of the earth through the ether be v. Now imagine that the whole tube of the telescope is filled with water, of refractive index n. Since light travels more slowly in water than in air or vacuum, the time for the light to travel down the length of the telescope tube will be lengthened—by the factor n. One might expect, therefore, that to keep the star's image in the center of the field of view one would have to tilt the telescope further, to some new aberration angle β, and that the amount of this adjustment could be used to find the speed v. At first glance one might think that the angle β would be just nv/c, but in analyzing this experiment one must remember that, because the objective lens of the telescope now has air on one side and water on the other, the light rays entering the telescope are bent toward the axis of the instrument, as indicated in Fig. 2–4(b). Inside the telescope we would expect the rays to travel at an angle δ to the axis such that

$$n = \frac{\sin\beta}{\sin\delta} \approx \frac{\beta}{\delta}$$

Since the light is traveling downward with speed c/n, and the telescope is moving sideways at speed v, the condition for centering the star's image in the telescope is

$$\delta \approx \frac{v}{c/n} = \frac{nv}{c} \qquad (2\text{–}1)$$

[1]Actually, this conclusion is not inescapable, but one must postulate quite outlandish conditions to have "convected ether" *and* aberration.

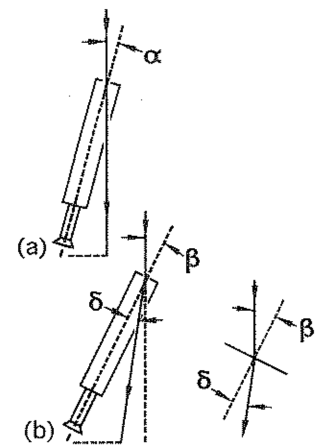


Fig. 2–4 Principle of Airy's experiment designed to reveal motion of the earth through the ether by sighting on a star with (a) a normal telescope; (b) the same telescope filled with water.

(Remember that the angles are grossly exaggerated in Fig. 2–4.) Now we do not know the true values of α, β, and δ, but we can surely measure the change of telescope direction, and we have

$$\beta \approx n\delta \approx \frac{n^2 v}{c} \qquad \alpha \approx \frac{v}{c}$$

Therefore,

$$\beta - \alpha \approx (n^2 - 1)v/c \qquad (2\text{–}2)$$

Everything is directly measurable except v, the value of which we should therefore be able to discover. This very experiment was carried out by Sir George Airy in 1871. The result? There was absolutely no change in the apparent position of the star!

How can we explain this null result? As a matter of fact, it had been predicted by the brilliant J. A. Fresnel, who had suggested this experiment many years earlier. Fresnel's expectations were based, however, not on the fundamental impossibility of detecting absolute motion, but on the assumption of a partial drag of the light by the medium. He had postulated this in 1818, after his fellow-countryman Arago had found that the refraction of starlight through glass appeared to take place just as though the earth were at rest in the ether.

Sir George Airy's experiment can be easily analyzed in these terms. For suppose that the water drags the light sideways with a fraction f of its own velocity v. The experiment has shown that the angle β is equal to the original aberration angle α $(= v/c)$ and hence that the angle δ is equal to α/n. Let the length of the telescope be l; then the time t for the light to pass down it when water-filled is nl/c. In time t the telescope moves through the distance vt; if the light is to emerge at the center of the eyepiece, its sideways displacement must be equal to this. But, as measured from the position of the eyepiece when the light enters the top of the telescope, the displacement of the light is the sum of $l\delta$, due to refraction, and fvt, due to dragging by the water. Hence we have

$$vt = l\delta + fvt$$

But

$$l = ct/n \qquad \text{and} \qquad \delta = \alpha/n = v/nc$$

Therefore,

$$vt = \frac{ct}{n}\frac{v}{nc} + fvt$$

whence

$$f = 1 - 1/n^2 \tag{2-3}$$

The quantity f is known as Fresnel's *drag coefficient*.

It may seem curious indeed that nature should provide a drag coefficient of just such a size that Airy's experiment, and others like it, should yield just the same result as if the earth were motionless with respect to the ether. Is there some way of exhibiting this drag as a *positive* effect, rather than as a null phenomenon? H. L. Fizeau had answered this in the affirmative in a famous experiment he performed in 1851.

[FIZ]EAU'S MEASUREMENT OF THE DRAG COEFFICIENT

Fizeau set up the apparatus shown diagrammatically in Fig. 2–5. A beam of light from a source S falls on an inclined glass plate P that has a semitransparent metal coating such that the beam is split into two parts. One part travels straight on until it strikes a mirror M_1. The other part is reflected through 90° and strikes M_3. With a third mirror M_2 in place, the two beams travel around the same rectangular path but in opposite directions. When they arrive back at P, part of the first beam is reflected and part of the second is transmitted, and the light thus emerging from the system enters a telescope T.

This arrangement constitutes a type of optical interferom-

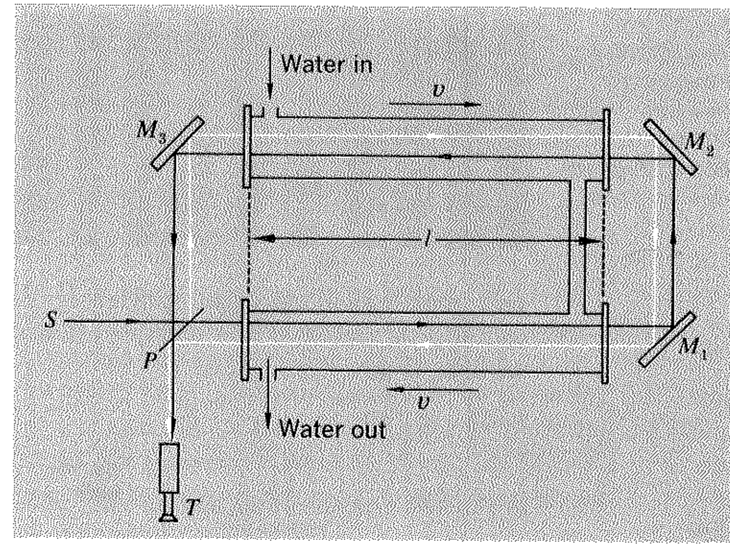


Fig. 2–5 Schematic diagram of Fizeau's "ether-drag" apparatus.

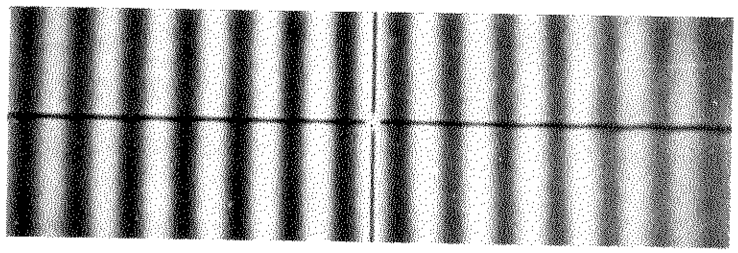
eter. If monochromatic or nearly monochromatic light is used, interference fringes are seen when one looks through the telescope. A particular fringe represents a particular optical path difference between the two interfering beams. (By *optical path* we mean the distance in vacuum equivalent to any actual path. A distance d through a medium of refractive index n represents an optical path nd; it is this that defines the number of wavelengths of the light that can be fitted into the distance.) The view through the telescope is like that shown in Fig. 2–6.

To provide a dragging effect, water is made to flow through two tubes with flat glass end plates as shown, so that one beam of light always travels with the water and the other beam always against it. Outside the water tubes the conditions are the same for both beams; thus to compute the optical path difference we need only consider what goes on inside the tubes. We can calculate this difference in terms of the difference of *times* for the two beams. If each tube is of length l and the speed of the water is v (with drag coefficient f), we have

$$\Delta t = \frac{2l}{(c/n) - fv} - \frac{2l}{(c/n) + fv}$$

which gives

$$\Delta t \approx \frac{4n^2 fvl}{c^2} \tag{2-4}$$



ig. 2–6 Interference fringes in apparatus of the Fizeau type. (Photo courtesy of G. C. Babcock, Michelson Laboratory China Lake, Calif.)

This implies an optical path difference $c\,\Delta t$. The change of optical path, expressed as a multiple (δ) of the wavelength λ of the light, is thus given by $c\,\Delta t/\lambda$:

$$\delta = \frac{4n^2 fvl}{\lambda c} \qquad (2\text{–}5)$$

In Fizeau's experiment the approximate values were

$l = 1.5$ m

$v = 7$ m/sec

$\lambda = 5.3 \times 10^{-7}$ m

$n = 1.33$ (refractive index of water)

$\delta = 0.23$ fringe

Substituting these values in Eq. (2–5) gives the observed value of f:

$$f_{\text{obs}} \approx 0.48$$

The value of f calculated from Eq. (2–3) is

$$f_{\text{calc}} = 0.43$$

This could be taken as confirmation of the drag hypothesis. The experiment was, however, repeated with greater precision by Michelson and Morley in 1886, and still later became the subject of a series of beautiful investigations by P. Zeeman and his associates in Holland during the years 1914–1922.

The result of Fizeau's experiment could be taken as reinforcing the observations on stellar aberration. Both could be interpreted by supposing that a moving object does not communicate any of its motion to the ether, either outside or inside it. Inside a moving transparent material (according to this view) the light is carried partly by the material and partly by the ether that permeates it. Since the ether remains at rest, the light behaves as if only a fraction of the velocity of the material were added to the light. The question therefore remained: Could the motion of the earth through the ether somehow be detected?

PRELUDE TO THE MICHELSON-MORLEY EXPERIMENT

In 1879 Clerk Maxwell, in England, wrote an acknowledgment of some astronomical tables he had received from D. P. Todd of the U.S. Nautical Almanac Office in Washington. These tables contained many observations of the planet Jupiter. Maxwell, in his letter, asked about the possibility of measuring the velocity of the solar system through the ether by observing the eclipses of Jupiter's moons. (We have mentioned earlier how Roemer was able to measure the speed of light by studying the time lag in detecting these eclipses.)

The essence of Maxwell's idea was very simple. Jupiter has a period of 12 terrestrial years, and so in half a terrestrial year, while the earth moves from A to B (Fig. 2–7), Jupiter does not travel very far in its orbit. Thus by observing the apparent times of eclipses with the earth successively at A and at B, we can infer the time taken for light to travel a distance equal to the diameter of the earth's orbit. This was Roemer's discovery, in fact. But if this time is measured when Jupiter is first at A', and then, 6 years or so later, at B', we can hope to discover whether the whole solar system is moving through the luminiferous ether with

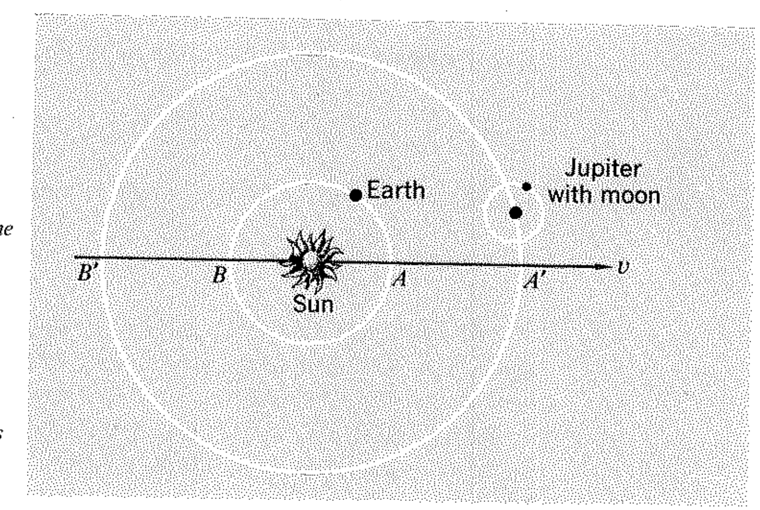


Fig. 2–7 Orbits of earth, Jupiter, and one of Jupiter's moons. Intervals betweeen moon's eclipses behind Jupiter, as observed at earth, depend on relative positions and motions of earth and Jupiter.

some speed v. For, if the diameter of the earth's orbit is l, we would expect to have

$$t_1 = \frac{l}{c + v} \qquad t_2 = \frac{l}{c - v}$$

and hence a time difference Δt given by

$$\Delta t = t_2 - t_1 \approx \frac{2lv}{c^2} = \frac{2v}{c} t_0 \tag{2-6}$$

where $t_0 = 16$ min approximately. If we could detect $\Delta t = 1$ sec, this would then correspond to v equal to about 150 km/sec. This is rather high compared with the known velocities of stars relative to the solar system (20 km/sec is a typical figure), but it is not excessive. Unfortunately, however, the difficulty of establishing any such difference through measurements made 6 years apart is great, and in fact the astronomical data available to Maxwell were not accurate enough for any such analysis, as Todd pointed out in his reply.

Maxwell, in proposing the above method, pointed to the feature that it was a first-order experiment—the effect would be proportional to the first power of the ratio v/c. And in his letter to Todd, Maxwell remarked that this distinguished it from terrestrial experiments on the speed of light, because these experiments necessarily used a beam of light that returned to its starting point. The time for any such round trip does in principle depend on the speed of the earth through the ether, but the effect is of the second order. Thus, if the length of the path (one way) is l, and if the earth's motion happens to be along the direction of the path at speed v, the total time taken by the light would be given by

$$t = \frac{l}{c + v} + \frac{l}{c - v} = \frac{2lc}{c^2 - v^2} \approx \frac{2l}{c}\left(1 + \frac{v^2}{c^2}\right)$$

The change of time due to the motion is thus given by

$$\Delta t \approx \frac{2l}{c}\frac{v^2}{c^2} \tag{2-7}$$

Maxwell remarked that this effect would be undetectably small. If v were taken as the orbital speed of the earth, we should have $v/c = 10^{-4}$, so that the fractional variation of flight time would be only 1 part in 10^8, which would surely be beyond the limits of observation. But Maxwell's letter was read by A. A. Michelson, who in the previous year (1878) at the young age of 25 had carried out a superb measurement of the speed of light.[1] And Michelson did not accept without question the impossibility of detecting motion via Eq. (2-7). Instead, he began thinking about a method to achieve it. Two years later, in 1881, he had some results. The next section describes his experiment, the most famous of all attempts to detect our motion through absolute space as defined by the ether.