

# More

## The Michelson-Morley Experiment

In Michelson's interferometer, shown schematically in Figure 1-9a, light beams are the analogy of the boats in Example 1-3, with Earth corresponding to the ground. The field of view seen by the observer consists of parallel alternately bright and dark interference fringes (Figure 1-9b.) As you recall, interference between the two recombining light waves at  $A$  is the result of the difference  $\Delta n$  in the number of waves  $n_1$  and  $n_2$  in the two paths, which results in the waves differing in phase on returning to  $A$ . The number of waves  $n$  in either path is given by

$$n = \frac{L}{\lambda} \quad \mathbf{1-9}$$

where  $\lambda$  = wavelength of the light and  $L$  = length of the path. For  $\Delta n = 0$  or integer, constructive interference (i.e., phase difference =  $0, 2\pi, 4\pi, \dots$ ) results in maximum brightness. If  $\Delta n = \frac{1}{2}$  integer (i.e., an integer  $\pm \frac{1}{2}$ ), destructive interference (i.e., phase difference =  $\pi, 3\pi, 5\pi, \dots$ ) results in darkness or minimum intensity. Intermediate values for  $\Delta n$  result in intermediate intensities. While the absolute value of  $\Delta n$  for any specific fringe is difficult to determine, it is clear that for successive bright (or dark) fringes, the values of  $\Delta n$  differ by  $\pm 1$ . The distance between successive maxima or minima is called the *width* of the fringe.<sup>7</sup> (See Figure 1-9b.)

Notice in Equation 1-9 that a change in either  $L$  or  $\lambda$  (or both) will cause a change in  $n$ . A change in  $L$  for light path 2 across the field of view due to the air wedge between  $M'_2$  and  $M_1$  is what causes the parallel fringes shown in Figure 1-9b. The change in the speed of light due to Earth's motion that Michelson and Morley were looking for would result in a change in  $\lambda$ , since the speed  $c$  of a wave is related to the wavelength  $\lambda$  by

$$c = f\lambda \quad \mathbf{1-10}$$

where  $f$  = frequency of the wave.<sup>8</sup> Changing  $c$  to  $c'$  thus changes  $\lambda$  to  $\lambda'$ , and this would in turn result in a change in  $n$ .

With the interferometer at rest in the laboratory as Earth moves to the left through the ether with speed  $v$ , the two light beams in Figure 1-9a correspond to the boats in Figure 1-7a, the points labeled  $A$ ,  $B$ , and  $C$  on the interferometer are analogues of the labeled marks on the shore, and the ether replaces the river. (In Figure 1-7a the shore "moves" to the left relative to the "stationary" river.) Thus, Michelson derived an

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expression for the difference  $\Delta t$  in the travel times for the two light beams produced by the beam splitter at  $A$  along paths 1 and 2 that was identical to Equation 1-8:

$$\Delta t = t_2 - t_1 \approx \frac{L v^2}{c^2} \tag{1-8}$$

with the speed in path 1 greater than that in path 2 because  $t_2 > t_1$ . The greater speed in path 1 means that  $\lambda_1 > \lambda_2$  (by Equation 1-10) and, hence, there would be a difference in the number of waves  $\Delta n$  in the two paths (by Equation 1-9), *in addition* to the  $\Delta n$  caused by the air wedge. The observed interference fringes would, of course, be the result of the sum of the two  $\Delta n$  values.

Michelson's interest was in that part of the total  $\Delta n$  associated with the expected difference in the speed of light in the two paths, and he devised an ingeniously simple way of separating its effect from the total while coincidentally making knowledge of the actual direction of  $\mathbf{v}$  unnecessary. By rotating the entire experimental apparatus  $90^\circ$  about an axis perpendicular to the plane formed by the light rays so that path 2 became parallel to the assumed direction of  $\mathbf{v}$ , the values of the relative light speeds in the two paths were interchanged. In this configuration  $\Delta t$  now becomes

$$\Delta t = t_2 - t_1 \approx -\frac{L v^2}{c^2}$$

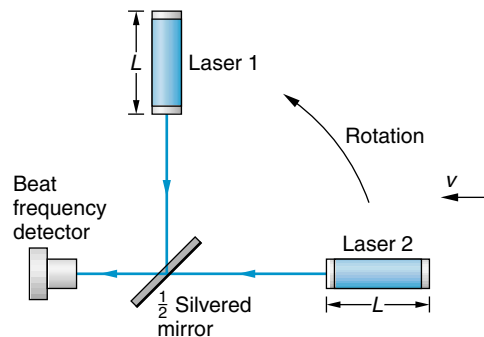
and the magnitude of the total time difference during a  $90^\circ$  rotation  $\Delta t_{\text{total}}$  is equal to

$$\Delta t_{\text{total}} = \frac{2L v^2}{c^2} \tag{1-11}$$

As the interferometer rotates, there is then a corresponding change  $\Delta N$  in the number of light waves in the two paths given by

$$\Delta N = \frac{c}{\lambda} \cdot \Delta t_{\text{total}} = \frac{2L v^2}{\lambda c^2} \tag{1-12}$$

Equation 1-12 is also equal to the expected change, or shift, in the position of the fringes in the field of view of the interferometer. To see that this is true, recall that each point across the field of view of the interferometer in Figure 1-9b corresponds to a particular phase difference between the recombining beams—e.g., the phase difference between successive bright fringes is  $2\pi$ . Rotating the interferometer causes

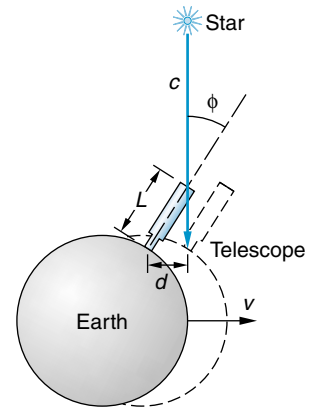


**Fig. 1-10** Experimental arrangement of Jaseja et al. for the laser version of the Michelson-Morley experiment.

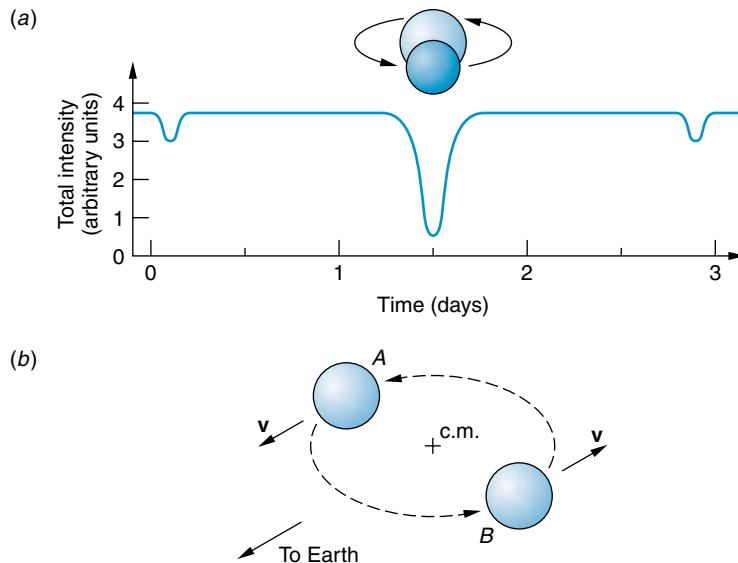
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an additional phase difference  $\Delta\phi = 2\pi \Delta N$  at each point, thus shifting the entire fringe pattern by an amount  $\Delta\phi/2\pi$ , which is, of course,  $\Delta N$ .

Recent searches for the relative velocity have utilized apparatus and techniques of higher precision than the Michelson-Morley experiment for making the crucial measurements of  $\Delta t$ . One of these, performed by T. S. Jaseja et al.<sup>9</sup> in 1964, replaced the mirrors and light beams in paths 1 and 2 in Figure 1-9a with identical lasers, as shown in Figure 1-10. As we will see in Chapter 9, the laser is a resonant cavity for light in which a standing wave is produced between two parallel mirrors. The frequency of the standing wave (= frequency of the emitted laser light) is proportional to the speed of light in the laser and inversely proportional to the distance between its parallel mirrors. With the lengths of the lasers equal, the difference in frequencies of the two laser beams (the “beat” frequency) is proportional to the difference in the speeds of light in the two lasers. As the system was rotated through  $360^\circ$ , any motion of Earth relative to the ether would cause the beat frequency to alternately increase and decrease, just as the fringes in Michelson’s interferometer were expected to shift when the apparatus was rotated. In the several laser experiments that have been performed, no change in the beat frequency within measurement accuracy has been detected. The most recent of these<sup>10</sup> has set an upper limit of 15 m/s for Earth’s speed relative to the ether. Many alternatives have been suggested to explain the Michelson-Morley experiment, such as a stationary layer of ether at the surface dragged along by Earth’s motion (see Figure 1-11) or a dependence of light speed on the relative motion of the source and observer (see Figure 1-12), but all have been ruled out by experimental observations. Thus, experimental evidence overwhelmingly supports the conclusion that the propagation of light is unaffected by the motion of Earth.



**Fig. 1-11** Stellar aberration. Light from a star, traveling at speed  $c$  in a straight line, enters the objective of the telescope. As the light moves down the tube, the telescope moves a distance  $d = vt$ , where  $v =$  orbital speed of Earth,  $L =$  length of the tube, and  $t =$  time for light to travel down the tube  $= L \cos \phi / c$ . Thus,  $\phi = \tan^{-1} (v/c) = 20.5$  s of arc. Observations of the star made 6 months later, when Earth’s velocity vector is in the opposite direction, require an aiming correction of 20.5 s in the opposite direction, or 41 s over the course of a year. This observation contradicts the proposal that a layer of ether dragged along by the moving Earth would explain the null result of the Michelson-Morley experiment.



**Fig. 1-12** Light curve of Algol, a bright eclipsing binary star in the constellation Perseus.

(a) One star of the binary is about 3 times as bright as the other. When the bright star is eclipsed by the dim star, as shown in the situation above the curve, the deep minimum in the intensity results. The eclipse of the dim star results in the more shallow minima. Each star in the pair rotates about the common center of mass once every 69 h at a speed of approximately 250 km/s. (b) On opposite sides of the orbit of either star its orbital velocity  $v$  points alternately toward and away from Earth. Classical theories of light would require that the speed of the star’s light with respect to Earth be  $c + v$  and  $c - v$ , respectively, leading to bizarre “ghost” stars. The fact that they have never been observed supports Einstein’s second postulate.