The Michelson-Morley experiment

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(Dated: April 21, 2020)

In the present article, we study the Michelson-Morley experiment which was performed in 1887 to establish the existence of ether. In section I, we discuss some key points on the history of light followed by the ether hypothesis. Then, in section III, we study the details of Michelson-Morley experiment, observations and its consequence.

I. THROWING SOME LIGHT ON THE HISTORY OF LIGHT

- Newton(1642-1727) was the developer of the corpuscular theory of light (1672). This theory fails to explain the phenomena of diffraction, interference, and polarization. In 20th century, after the discovery of photoelectric effect, his corpuscular theory again came into light.

- Christian Huygens (1629-1695) proposed the wave picture of light (1690). He assumed that light is the longitudinal wave which propagate through the medium ether.

- In the past (starting from Aristotelian era), people tried to obtain the speed of light using various methods (using hypothetical/theoretical argument (or calculation) or experimental observations). Some of them were very close to the current accepted value of the speed of light. In 1862, L. Foucault obtained a value of the speed of light about 298000 km/s. He had done some modification of H. Fizeau method for measuring the speed of light who obtained (in 1849) its value 315000 km/s.

- Thomas Young(1773-1829) performed his double slit experiment in 1802. He shown, experimentally, that light has a wave nature which contradicted Newton's corpuscular theory but supported Huygens theory of light, however, at the time of Young, his experimental observations were not given much attention by the people at that time.

- The experimental work (1815) of Augustin Jean Fresnel (1788-1827) on diffraction of light and two year later his work on polarization of light indicated that *light is a transverse wave.*

- In 1865, J.C. Maxwell unified the electricity and magnetism and *proposed that light is an electromagnetic wave* and propagate transverse to electric and magnetic field.

II. LUMINIFEROUS ETHER CONCEPT

- In 19th century, physicist believed that light needs a medium to propagate like other waves need, e.g., sound wave, water wave.

- People proposed that all of space is filled with an elusive matter which was named as the *luminiferous (light-bearing) ether.*

- Proposed properties of ether on the basis of its undetectability–**zero density, perfect transparency**.

- Now assuming the ether medium, and using concept of Newtonian relativity, an observer moving through the ether with velocity u would compute the light velocity $c+u$, where c is the light velocity in the ether frame which is assumed to be inertial.

- The above argument, thus, claims that velocity of light is not invariant under Galilean transformation. But the Maxwell's electromagnetic theory states that speed of light is constant in free space and equal to the fixed value $c = 1/\sqrt{\epsilon_0 \mu_0}$. But this does not mean that this disagreed the ether hypothesis. The light (which Maxwell proposed to be electromagnetic wave) was assumed to propagate through ether medium.

III. THE EXPERIMENTAL SETUP AND OBSERVATIONS

Here we describe the basic experimental setup of Michelson-Morley experiment. In this experimental setup, one can measure the speed of light in different inertial frames/different directions and see whether light speed in different inertial systems/different directions varies

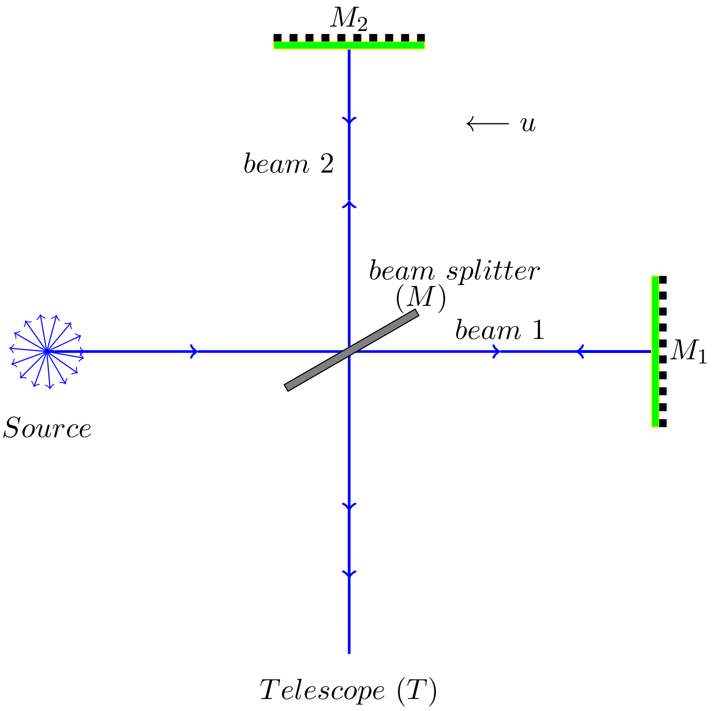

FIG. 1: Michelson Interferometer. u denotes the velocity of ether with respect to the Interferometer. M denotes the partially silvered mirror which is used to split the beam coming from source into two beams. The beams are reflected back from mirrors M_1 and M_2. The reflected beams transmitted to the telescope where one obtains the fringe patterns due to interference of beams.

or remains same. The very basic idea of this experiment was to measure the speed of light in different directions and try to establish the ether hypothesis.

Next, we consider the following points of experiment (the Interferometer is described in Fig. (1)):

- Interferometer is fixed on the Earth.
- People assume that ether is fixed with respect to sun and the Earth moves through it with a speed of 30 km/s.
- Beam of light emitted from the source is split by the beam splitter (partially silvered mirror which is inclined at 45^0 to the beam directions) into two waves which have constant phase difference between them.
- Beam 1 reflects back from mirror M_1 to splitter M where it again partially reflected

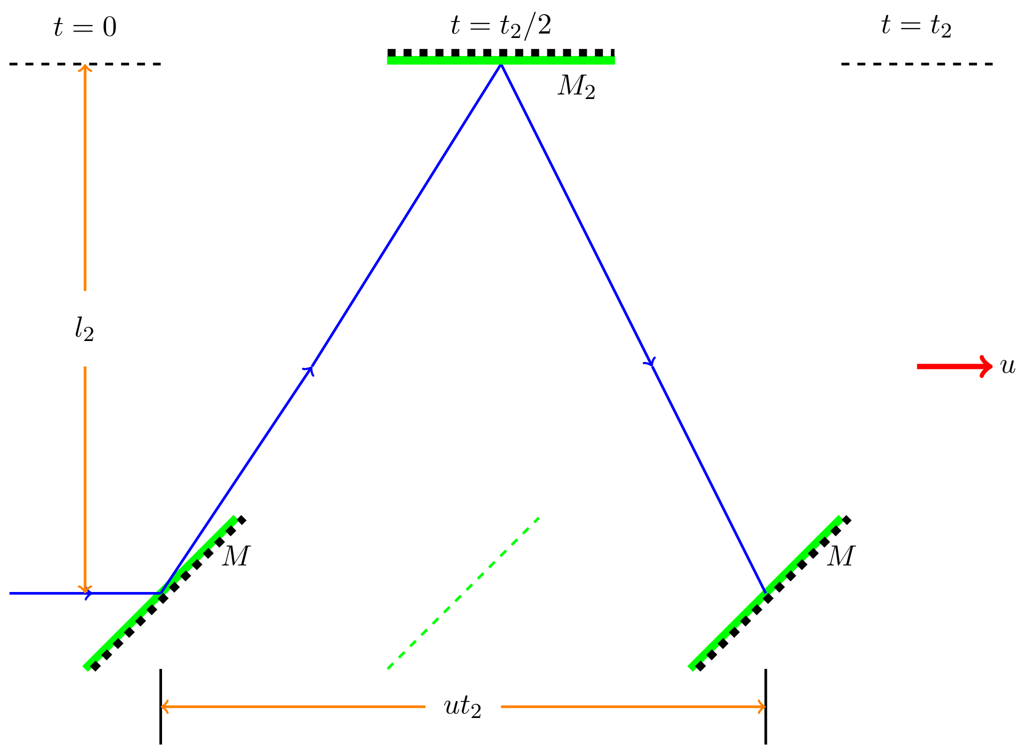

FIG. 2: Figure demonstrates the cross stream path of beam 2. Here mirrors move with velocity u with respect to ether, also u is the velocity of Interferometer with respect to ether.

by M and goes to telescope T.

- Beam 2 reflects back from mirror M_2 to splitter M and partially transmits through M and goes to T.
- Both the beams interfere at T after returning from mirrors M_1 and M_2.

Phase difference between beams 1 and 2: Let l_1 and l_2 be the path length of beams 1 and 2, u be the velocity of ether wind and c be the speed of light in ether. Now time taken by beam 1 (denoted by t_1 in apparatus frame) to travel distance from M to M_1 and returning back from M_1 to M is obtained as

$$\begin{aligned} t_1 &= \frac{l_1}{c-u} + \frac{l_1}{c+u} \\ &= \frac{2l_1}{c}\left[\frac{1}{1-u^2/c^2}\right]. \end{aligned} \tag{1}$$

The path of beam 2 is shown in Fig. (2) which enables us to write

$$ct_2 = 2\left[l_2^2 + (ut_2/2)^2\right]^{1/2}.$$

We obtain the time t_2 (in ether frame) given as

$$t_2 = \frac{2l_2}{c}\left[\frac{1}{1-u^2/c^2}\right]^{1/2}. \tag{2}$$

Next, the time difference $t_2 - t_1 = \Delta t$ is given by Eqs. (1) and (2) as

$$\Delta t = \frac{2}{c}\left(\frac{l_2}{\sqrt{1-u^2/c^2}} - \frac{l_1}{1-u^2/c^2}\right). \tag{3}$$

Rotating the apparatus by angle 90^0, l_1 becomes the corresponding cross-stream length and using similar analysis we obtain the time difference $\tau_2 - \tau_1 = \Delta\tau$, where subscript 1 and 2 represents time corresponding to beam 1 and 2 respectively, as

$$\Delta \tau = \frac{2}{c}\left(\frac{l_2}{1-u^2/c^2} - \frac{l_1}{\sqrt{1-u^2/c^2}}\right). \tag{4}$$

Now using (3) and (4), we obtain the change in differences due to rotation

$$\begin{aligned}\Delta\tau - \Delta t &= \frac{2}{c}\left(\frac{l_2}{1-u^2/c^2} - \frac{l_1}{\sqrt{1-u^2/c^2}}\right) - \frac{2}{c}\left(\frac{l_2}{\sqrt{1-u^2/c^2}} - \frac{l_1}{1-u^2/c^2}\right)\\ &= \frac{2(l_1+l_2)}{c}\left(\frac{1}{1-u^2/c^2} - \frac{1}{\sqrt{1-u^2/c^2}}\right).\end{aligned}$$

Next, we use binomial expansion and ignore the terms higher than the second order and obtain

$$\Delta\tau - \Delta t \approx \frac{2(l_1+l_2)}{c}\left(1 + u^2/c^2 - 1 - u^2/(2c^2)\right).$$

Or

$$\Delta\tau - \Delta t = \frac{(l_1+l_2)}{c}\left[\frac{u^2}{c^2}\right], \tag{5}$$

which indicates that there is shift in fringe pattern due to rotation. Thus, shift in number of fringes (say ΔS)is obtained as

$$\Delta S = \nu(\Delta\tau - \Delta t) = \frac{(l_1+l_2)}{\lambda}\left[\frac{u}{c}\right]^2, \tag{6}$$

where λ is the wavelength of light and $\nu = c/\lambda$. For $l_1 = l_2 = l$ we obtain,

$$\Delta S = \frac{2l}{\lambda}\left[\frac{u}{c}\right]^2. \tag{7}$$

For $u = 30km/s$ (which gives $u/c \approx 10^-4$), length $l = 11m$ and $\lambda = 5500A^0$, we obtain

$$\Delta S = 0.4\ . \tag{8}$$

Thus, the calculation shows that there is a shift of four tenth of a fringe. Michelson-Morley taken many observations but *couldn't verify the fringe shift experimentally.* The physicist at the time couldn't reject the ether hypothesis but suggested that there should be some alternate theory which could explain both the result of experiment and the ether hypothesis. After two decades of the Michelson-Morley experiment, Einstein's relativity theory (1905) resolved the mystery of the existence of ether. In the next study material, we will discuss the Einstein relativity theory.

[1] R. Resnick, *Introduction to Special Relativity*, Wiley-VCH, (1968) .