PERPLEXITIES IN THE PROPOGATION OF LIGHT

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In this project, the historical background of the light theories, which are the particle theory and the wave theory will be given briefly. Also, ether as a the theoretical result of the wave theory will be explained and the nonexistence of ether will be prooved by the experiments.

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I. INTRODUCTION

It is known that velocity of the motion depends on the reference frame, that is it is different in different reference frames. Therefore, a universal velocity of light seems to make a contradiction to this statement. However, Einstein has resolved this contradiction. In this project, we will try to explain the propagation of light together with the experiments that are evidences to the theory.

II. THE NATURE OF LIGHT

The propagation of light can be defined as "the transport of energy away from the source."[1] In the most simplistic model introduced by Phythagoras, light is considered as particle. According to this theory, light propogates in straight lines and travels through vacuum. This model was good enough to explain phenomena such as the sharpness of the shadows. However, in 17^{th} century, in order to explain the phenomena such as brilliant colors of thin air film between glass surfaces and encroachment of light upon the region of the geometrical shadow, Robert Hooke proposed light as a vibration communicated through a medium.[1] Later on, Huygens developed the wavetheory of light and his theory was good enough to expain reflection and refraction. However, these two were considered as separate theories until Einstein. In the wave theory, it was thought that a medium was needed to for the propagation of light, just like in other natural waves. Hence, physicists tried to find ether in their experiments.

III. THE LUMINIFEROUS ETHER

The wavetheory of light was developed in the 19^{th} century. Some of the most important studies are Thomas Young's interference experiments, Fresnel's calculations on interference, diffraction, and polarization, and Huygens' studies on rectilinear propagation of light. A Danish astronomer, Roemer, observed the moons of Jupiter and the variation in their time to move into planet's shadow. He recognized that they were related to the earth's orbit and the time light travels this variable distances. The mechanical interpretation of light made it difficult to understand its huge speed. This lead to the need of a medium in which planets could travel through without any loss in their speed, and which produced very strong restoring forces when displaced from the equilibrium, because the speed of the propagation of light, c, depended on these restoring forces. The problem was that there was no evidence of such a field, but only a measured value of c.

In his electromagnetic theory of light, James Clerk Maxwell predicted c in terms of medium. The speed of light must be defined with respect to its medium whose magnitude can be a function of the wavelength and is uniquely defined for an isotropic medium. According to the particle theory, c is relative to the source. However, in electromagnetic theory, it is independent of the source. This leads to a conclusion that the velocity of the source of light has no contact with the radiation it emits.

IV. STELLAR ABERRATION

As the earth moves in its orbit around the sun, the position of a star changes. This effect is called parallax. James Bradley aimed to measure the distances of stars using this change. However, he discovered that it depended not on earth's position, but instead on its motion around the sun. If the earth were stationary, the telescope had to be aimed directly to the attitude of the star. However, as the earth moves, the telescope must be tilted in order to be able to observe the star. The difference between these two angles is called aberration. It can also be visualized thinking of a raindrop falling vertically on earth observed from a car with velocity horizontal to the ground. Then the drops are observed as inclined. The figure below shows a similar thing with a telescope pointed at a star with attitute θ_0 moving to the left and attitute of the star for the observation is θ.

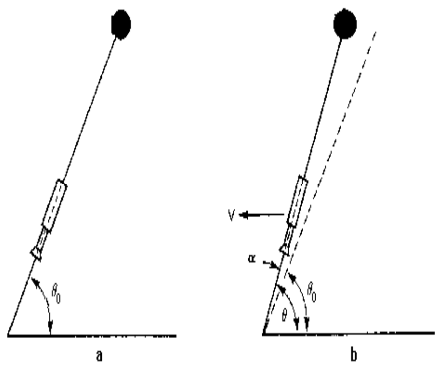

FIG. 1: The observation of a star from the moving earth.[2]

Let us consider now a system similar to the one above. The true attitute of the star is α this time and the telescope moving to the right must be pointed with an angle of α'. The relation between these angles can be calculated as follows:[3]

$$u'_x = \frac{u_x - v}{1 - u_x v/c} \tag{1}$$

$$u'_y = \frac{u_y}{\gamma(u)(1 - u_x v/c^2)} \tag{2}$$

where u is the velocity of the photon and is

$$u = (-c\cos\alpha, -c\sin\alpha) \tag{3}$$

in the coordinate system S and

$$u' = (-c\cos\alpha', -c\sin\alpha') \tag{4}$$

in the coordinate system S'. Then one can get the reations.

$$\begin{aligned} -c\cos\alpha' &= \frac{-c\cos\alpha - v}{1+\frac{v}{c}\cos\alpha} && (5)\\ &= \frac{\cos\alpha + \frac{v}{c}}{1+\frac{v}{c}\cos\alpha} && (6)\end{aligned}$$

$$\begin{aligned} -c\sin\alpha' &= \frac{-c\sin\alpha}{\gamma(1+\frac{v}{c}\cos\alpha)} && (7)\\ &= \frac{\sin\alpha}{\gamma(1+\frac{v}{c}\cos\alpha)} && (8)\end{aligned}$$

Finally, using the trigonometric formula, one can join these relations.

$$\tan\alpha/2 = \frac{\sin\alpha}{1+\cos\alpha} \tag{9}$$

$$\tan\alpha'/2 = \frac{\sin\alpha'}{1+\cos\alpha'} \tag{10}$$

$$\tan\alpha'/2 = \frac{\frac{\sin\alpha}{\gamma(1+\frac{v}{c}\cos\alpha)}}{1+\frac{\cos\alpha+\frac{v}{c}}{1+\frac{v}{c}cos\alpha}} \tag{11}$$

$$\tan\alpha'/2 = \frac{\sin\alpha}{\gamma(1+\frac{v}{c}\cos\alpha+\cos\alpha+\frac{v}{c})} \tag{12}$$

$$\tan\alpha'/2 = \frac{\sin\alpha}{\gamma(1+\frac{v}{c})(1+\cos\alpha)} \tag{13}$$

$$\tan\alpha'/2 = \frac{1}{\gamma(1+\frac{v}{c})}\tan\alpha/2 \tag{14}$$

$$\tan\alpha'/2 = \frac{\sqrt{1-\frac{v^2}{c^2}}}{1+\frac{v}{c}}\tan\alpha/2 \tag{15}$$

$$\tan\alpha'/2 = \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}}\tan\alpha/2 \tag{16}$$

The changes in the earth's velocity makes it possible to observe aberration. When the earth's velocity is perpendicular to the line connecting the sun and the star, the aberration angle is the greatest. The magnitude of the aberration angle is $\frac{v \sin\alpha}{c}$. Hence, the star moves on an elliptical path with major axis $\frac{2v}{c}$, which is the same for all stars, and minor axis $\frac{2v\sin\alpha}{c}$, which changes with respect to the altitute of the star, α. Bradley used these observed aberration angles assuming that his first prediction putting the emphasis on the earth's movement is true. As the earth's velocity was well known at the time, 30km/h, he tried to calculate an improved value of the velocity of light, c. The particle theory of light gives a straightforward explanation to aberration. However, for the wave theory, in order to explain this, the earth must not carry ether with it as it moves around. Therefore, earth must not disturb ether during its motion.

V. A MODIFIED ABERRATION EXPERIMENT

Another experiment on the light dragged by the medium can be performed using a water filled telescope in the aberration experiment. When a telescope is directed towards a star which is perpendicular to the earth's orbit. Then the aberration angle will be α and the refrective index of the telescope is n. This will cause the light to spend more time in the telescope than before with a speed c/n. At this point one can directly think that the new aberration angle due to this, β, would be $\frac{nv}{c}$, v being the speed of telescope moving sideways. However, due to different medium on each side of the telescope, light will travel inside the telescope with an angle, δ:

$$n = \frac{\sin\beta}{\sin\delta} \approx \frac{\beta}{\delta} \tag{17}$$

$$\delta \approx \frac{v}{\frac{c}{n}} = \frac{nv}{c} \tag{18}$$

$$\beta \approx n\delta \approx \frac{n^2 v}{c} \tag{19}$$

$$\alpha \approx \frac{v}{c} \tag{20}$$

$$\beta - \alpha \approx \frac{(n^2-1)v}{c} \tag{21}$$

At this point β, α, n, and c can be measured and from here v can be calculated. However, when Sir George Airy made this experiment, the observed that the position of the star did not change, which means $\beta = \alpha$, hence $\delta = \alpha/n$. Before, J. A. Fresnel predicted this result, but in a wrong intuition of water partially dragging the light. Before him, Arago discovered that the refraction through the glass was as if the earth were not moving in the ether. The calculation leading to the fraction of water dragging light, f can be done, assuming that Fresnel is right. If the length of the telescope is l, then the time that light spends in telescope is

$$t = \frac{l}{c/n} = \frac{nl}{c} \tag{22}$$

At this time, the telescope travels a distance of vt. Then the light is displaced a distance of $l\delta$ by the refraction, and of fvt by the drag of the water. In order the result of the experiment to be null, the sum of these must be equal to the distance the telescope travels.

$$vt = l\delta + fvt \tag{23}$$

From eqn. (22) and eqn.(20) one can write,

$$l = \frac{ct}{n} \tag{24}$$

$$\delta = \frac{\alpha}{n} = \frac{v}{nc} \tag{25}$$

Then the drag fraction of water, which is also called Fresnel's drag coefficient, can be calculated as follows:

$$vt = \frac{ct}{n}\frac{v}{nc} + fvt \tag{26}$$

$$f = 1 - \frac{1}{n^2} \tag{27}$$

The magnitute of this coefficient gives the result that the earth is motionless in the ether, and it is a "null phenonemon".[1]

VI. FIZEAU'S MEASUREMENT OF THE DRAG COEFFICIENT

Fizeau set up an experiment aiming to observe the value of Fresnel's drag coefficinet. In his experiment he used an inclined glass with semitransparent metal coating to split the beams in two. One part of the beam passes directly and reaches a mirror, C, whereas the other part is perpendicularly reflected and reached another mirror, E. Then the beam reflected from both of these mirrors reach another mirror, D and are reflected again. In this way two of the beams travel the same distance but in different directions. Finally, they come to the telescope ao that the interference fringes are observed. A fringe corresponds to a difference in the optical paths of the beams. The optical path of a beam in a meduim with refractive index n, and travel distance d is nd.

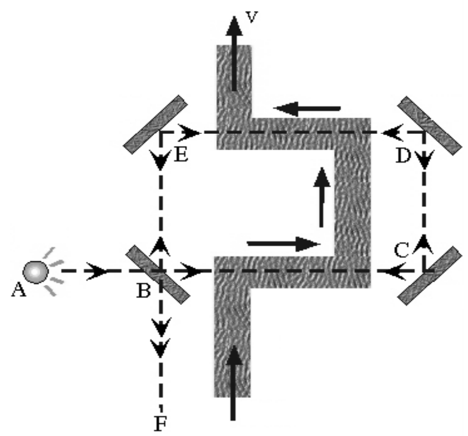

FIG. 2: Schematic view of Fizeau's Experiment.[9]

In order to observe the drag coefficient, he put one tube of length l in the path between the mirrors C and D, and another one of the same length between the mirrors E and D. Then he made water to flow through these tubes with velocity, v, which will drag the light. In the first tube, light will travel in the same direction with the flow of water, whereas in the other tube, it will be in the opposite direction. Outside the tubes, everything is identical, therefore the beams traveling in the opposite directions with respect to the flow of water, will lead to an optical path difference, which can be interpreted by observing the time difference.

$$\Delta t = \frac{2l}{\frac{c}{n} - fv} - \frac{2l}{\frac{c}{n} + fv} \approx \frac{4n^2 fvl}{c^2} \tag{28}$$

Then the optical path difference will be $c\Delta t$. The number of wavelengths in this path, δ is therefore,

$$\delta = \frac{c\Delta t}{\lambda} \tag{29}$$

$$\delta = \frac{4n^2 fvl}{\lambda c} \tag{30}$$

All the values except the value of f is known here, hence it can be calculated from this equation. The approximate values of the other parameters are; $l = 1.5m$, $v = 7m/s$, $\lambda = 5.3 \times 10^{-7}m$, the refractive index of water, $n = 1.33$, and change of optical path, $\delta = 0.23 fringe$. This leads to an observed value of $f_{obs} \approx 0.48$, whereas the calculated value is $f_{calc} = 0.43$.

This leaves us with a reasult that the drag coefficient is confirmed by the experiment. The experiment was repeated by Michelson and Morley, and P. Zeeman. The result supports the stellar aberration observations, both resulting that a moving object has no contact with the ether. As the ether is stationary, the light gains a fraction of the material's velocity. However, the ether was still not detected.

VII. PRELUDE TO THE MICHELSON-MORLEY EXPERIMENT

The experiment was proposed by James Clerk Maxwell in 1879, but in a quite large scale. The aim of Maxwell's experiment is to measure the velocity of the solar system through the ether. He proposed the method as observing the eclipses of Jupiter's moon. In fact, this was not a new idea. Roemer, by detectiong the time differences, astablished to measure the speed of the light, using the aforementioned experimental technique.

Set up of the experiment is as follows:

Jupiter has a period of 12 terrestial years. Using this large difference between the periods of Earth and Jupiter, Maxwell proposed to observe the apparent time of the eclipses with earth at point A and at point B. Since Jupiter has a period of 12 terrestial years, it does not displace much from its position at A' when earth travels from point A to point B. Thus, it would be possible to measure the time that takes light to travel the radius of earth's orbit. Then the experimentalist will repeat the same process when jupiter comes to point B', which will take 6 terrestial years. But this experiment will have difficulties in the measurements. First difficulty is that it is not possible to obtain such accurate data to detect a difference between two measurements which are 6 years apart. Second one is that the theoretical value for the time difference comes out so small that Maxwell suspected the detection of such a value.

Theoretical value of the time difference is calculated as follows. We take the length of the path as l and earth's

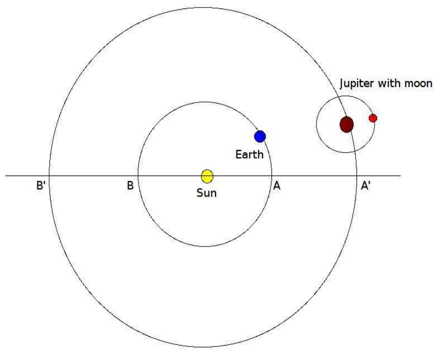

FIG. 3: Schematic view of the experiment proposed by Maxwell.

motion is along the direction of the path. Total time taken by light:

$$t = \frac{l}{c+v} + \frac{l}{c-v} = \frac{2lc}{c^2 - v^2} \approx \frac{2l}{c}(1 + \frac{v^2}{c^2}) \tag{31}$$

Thus the change of time due to the motion is:

$$\delta \approx \frac{2l}{c}\frac{v^2}{c^2} \tag{32}$$

If we were to take v as the orbital speed of earth, then $\frac{v}{c} = 10^{-4}$. Maxwell proposed his idea of the experiment in a letter to D. P. Todd from U. S. Nautical Almanac Office. This letter was also read by a young scientist, A. A. Michelson, who had conducted highly accurate experiment in determination of the speed of light. After reading this letter Michelson started to think about a way to conduct the experiment that is proposed by Maxwell. Indeed, he achieved this goal in 1881 which will be the end of the ether theory.

VIII. THE MICHELSON-MORLEY EXPERIMENT

Michelson-Morley experiment is based on the interference of two light beams. Interference is a consequence of wave theory of light which is the widely accepted theory during the 19^{th} century. The reason for interference is the phase of a light wave. There can be two types of interference:

1− Constructive interference: This case occurs when phases of two light beams is the same or differs by an integer multiple of wavelength, λ.

2− Destructive interference: This is the case when phase of one of the light beams is shifted by a factor of $\lambda/2$, from the phase of the second light beam.

Set-up of the experiment is known as Michelson interferometer. Roughly, an interferometer can be defined as an apparatus which makes the changes in the scale of λ, visible in macroscopic world.[4] Experimental apparatus of Michelson and Morley was consisting of a monochromatic light source, a beam splitter, two mirrors, a glass with the same thickness of beam splitter, and a telescope.

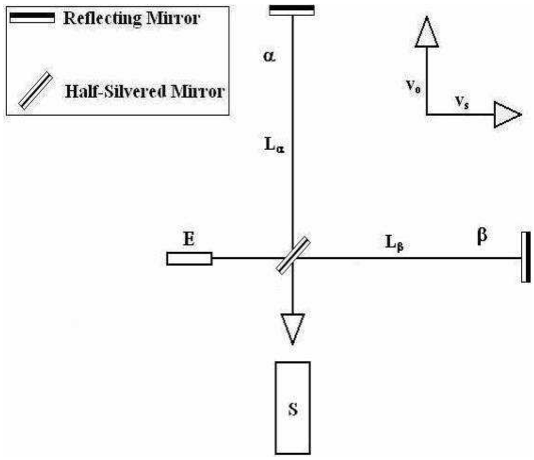

FIG. 4: The set-up of the Michelson-Morley experiment.

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Michelson interferometer stars operating by splitting the beam coming from the light source through the beam splitter. First, beam passes directly from the beam splitter and strikes on mirror M_1. Being reflected from the mirror, the beam goes back to beam splitter again and some of it is reflected to the telescope. On the other hand second beam follows a path which is perpendicular to the path of the first beam after it passes through the beam splitter. It joins to the first beam after being reflected from the mirror M_2, on the way to the telescope. As a result someone looking through the telescope will see the interference pattern of two light beams. Upto this point we have just considered what is intererence and interferometer, and how a Michelson interferometer operates. These concepts constitute crucial importance for Michelson-Morley Experiment. The original part of the experiment starts from this point on.

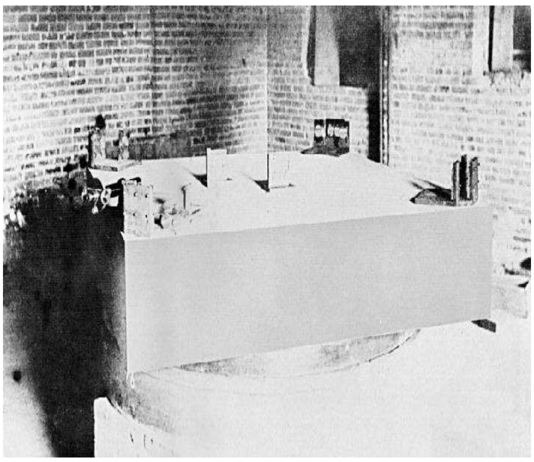

FIG. 5: The original set-up of the Michelson-Morley experiment.[6]

Michelson, proposed to move this apparatus with velocity v with respect to ether in the direction of the first beam. Therefore an ether wind would be blowing in the opposite direction of motion but also with velocity v. As a result velocity of the first beam would be $(c - v)$ on the way to the mirror, and $(c + v)$ on the way back to the beam splitter, from the Galilean velocity transformations. Thus, the time required for the first beam to travel mirror and back is given by:

$$t_1 = \frac{l_1}{c-v} + \frac{l_1}{c+v} = \frac{2l_1 c}{c^2 - v^2} = \frac{2l_1/c}{1 - v^2/c^2} \tag{33}$$

Similarly, second beam travels the distance between the beam splitter and the mirror with a speed of $\sqrt{c^2 - v^2}$. Time required for the second beam is:

$$t_2 = \frac{2l_2}{(c^2 - v^2)^{1/2}} = \frac{2l_2/c}{(1 - v^2/c^2)^{1/2}} \tag{34}$$

So the time difference between the journeys of the light beams can be written as:

$$\Delta = t_1 - t_2 \approx \frac{2l_1}{c}(1 + \frac{v^2}{c^2}) - \frac{2l_2}{c}(1 + \frac{v^2}{2c^2}) \tag{35}$$

$$\Delta \approx \frac{2(l_1 - l_2)}{c} + \frac{2l_1 v^2}{c^3} - \frac{l_2 v^2}{c^3} \tag{36}$$

Now we rotate the whole experimental setup by 90^o. As a result the path of the second beam points in the direction of motion. After modifying the Galilean velocity transformations according to the new configuration, time difference between the journeys of the light beams can be written as:

$$\Delta' = t_1' - t_2' \approx \frac{2l_1}{c}(1 + \frac{v^2}{2c^2}) - \frac{2l_2}{c}(1 + \frac{v^2}{c^2}) \tag{37}$$

$$\Delta' \approx \frac{2(l_1 - l_2)}{c} + \frac{l_1 v^2}{c^3} - \frac{2l_2 v^2}{c^3} \tag{38}$$

Since the interference patterns depends on how much the phase of the beams shifted mutually, change in the time differeces will effect the interference patterns. The relation between the change in the time differences and shift in the fringes is given by the following relation:

$$\delta = \frac{c(\Delta - \Delta')}{\lambda} = \frac{v^2(l_1 + l_2)}{c^2 \lambda} \tag{39}$$

If lengths of two paths are equal to each other, above formula simplifies to:

$$\delta = \frac{2(v/c)^2}{\lambda/l} \tag{40}$$

Taking $v = 30km/s$, which is the velocity of earth in its orbit, and putting in the values of λ, l and c, gives a fringe shift of $\delta = 0.04$. But to everyone's suprise, when Michelson rotated his apparatus even for 360^o there were no shift in the fringes! Comment of this result can be made by two clear statements from Michelson himself:

1− "The interpretation of these results is that there is no displacement of the interference bands."[7]

2− "The result of the hypothesis of a stationary ether is thus shown to be incorrect."[7]

Michelson-Morley Experiment have been done many times during the following years after the first one. Below, there is a table which indicates different results of the experiment which are done by different scientists.[8]

Observer; year	l, cm	δ_{calc}	δ_{obs} (upper limit)	$Ratio$
Michelson; 1881	120	0.04	0.02	2
Michelson and Morley; 1887	1100	0.40	0.01	40
Morley and Miller; 1902-1904	3220	1.13	0.05	80
Miller; 1921	3220	1.12	0.08	15
Miller; 1923-1924	3220	1.12	0.03	40
Miller(sunlight); 1924	3220	1.12	0.014	80
Tomaschek(starlight); 1924	860	0.3	0.02	15
Miller; 1925-1926	3200	1.12	0.08	13
Kennedy; 1926	200	0.07	0.002	35
Illingworth; 1927	200	0.07	0.0004	175
Piccard and Stahel; 1927	280	0.13	0.006	20
Michelson et al; 1929	2590	0.9	0.01	90
Joos; 1930	2100	0.75	0.002	375

TABLE I:

IX. CONCLUDING REMARKS

All of the experiments explained so far results that either the motion through a medium does not exist or the medium did not exist. Ballistic model of light states that the "speed is uniquely defined with respect to the source not to the medium" and this gives an explanation both to the stellar aberration and Michelson-Morley experiment. This also agrees to Galileo who states that the relative velocity cannot give information about the velocity of the whole system. In 19^{th} century, the particle model was rejected by most of the physicist. However, the experiments giving results were the ones in which a relative velocity is defined. The velocity of the earth at one point in its orbit was defined with respect to the velocity at another point in the stellar aberration. Also, the velocity of the flowing water was defined with respect to the rest of the set-up in the Fzeau's experiment. The problem was particularly with the conflict between the stellar aberration and the result of the Michelson-Morley experiment.

When looking at the TABLE II, one can clearly see that different theories can explain different phenomena. On one hand the particle model cannot explain why the motion of the source has no effect on the velocity of light and why light travels slower in a dense medium than air. On the other hand, the wave theory cannot explain the conflict beetween the results of stellar aberation and Michelson-Morley Experiment. This remained a problem until Einstein discovered that the resolution is more radical than simply using one model in one problem and other in another

statement	Particle Model	Wave/ether model
light travels in straight lines.	OK	OK if wavelength≪beam width
Interference and diffraction effects	No convincing explanation	OK
Polarization of light	No convincing explanation	OK
Light velocity independent of source velocity	Definite disagreement	OK
Speed of light greater in air greater in air than in water	Definite disagreement	OK
Fizeau experiment and Airy	Requires partial drag of	Requires partial drag of
(water-filled telescope) experiment	light buy medium	light by medium
Stellar aberration (Bradley)	OK	OK if earth moves with repect to ether
Michelson-Morley experiment	OK	Implies that earth does not move with respect to ether

TABLE II:[1]

problem and creating a hybrid theory consisting of these two.

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