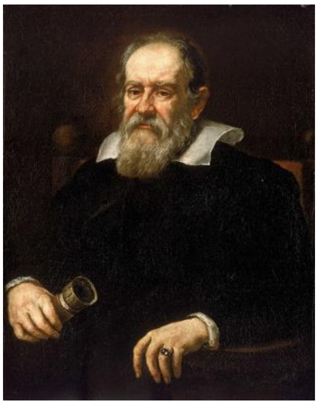
Velocity of Light

2.1 Introduction

Determination of the velocity of light is of great importance. Einstein has shown that the energy released by the nucleus of an atom or otherwise is given by $E = mc^2$; where m is the decrease in mass and c is the velocity of light.

But, before the 17th century, it was thought that the velocity of light is infinite. The fact that the flash of lightning is seen instantaneously and the sound is heard after some time shows that the velocity of light is greater than the velocity of sound. The first attempt to find the velocity of light was made by Galileo in 1600.

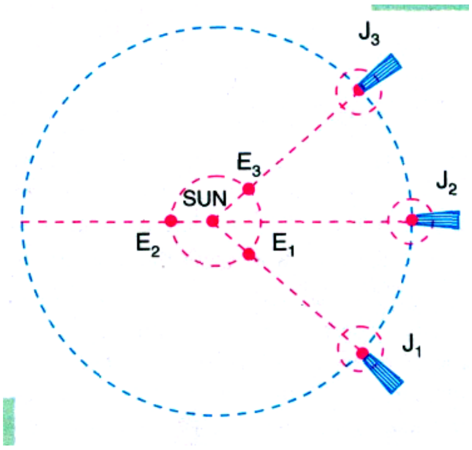
2.2 Galileo's Experiment



Two observers were stationed at a distance of a few kilometers. One observer uncovered his lamp and the second observer uncovered his lamp after seeing light from the lamp of the first observer. The first observer tried to measure the time interval between the uncovering of his lamp and the light seen from the lamp of the second observer. If the distance between the two observers = x, $2x$ then $c = 2x/t$. But Galileo failed to find the velocity of light as the time interval t was very small and could not be measured accurately. The first successful attempt was made by Romer, a Danish astronomer in 1676.

2.3 Romer's Astronomical Method

Romer observed the eclipses of Jupiter's satellites at times when the earth was at different positions with respect to Jupiter. He found that while the earth, in its orbital motion round the sun, receding from Jupiter, the mean period between two successive eclipses of a particular satellite is longer than that when the earth is moving nearer Jupiter. This anomaly formed the basis for the calculation of the velocity of light. He explained when the earth is receding from Jupiter; light has to travel a greater distance at each successive disappearance of the satellite whereas when the earth is approaching Jupiter, light has to travel a shorter distance at each successive disappearance of the satellite. Jupiter has a number of satellites or moons revolving around it. Jupiter makes a complete revolution around the sun in 11.86 years whereas the earth completes one revolution in one year. It is assumed for the sake of simplicity that the orbit of the earth and Jupiter are circular. The satellites which revolve around Jupiter have their periods lying between 11 hours 58 minutes for the satellite nearest the planet and 16 days, 16 hours, 32 minutes and 11 seconds for the most remote satellite.



The velocity of light measured by Romer was nearly 186,000 miles/second

This method is not very accurate due to the following reasons:

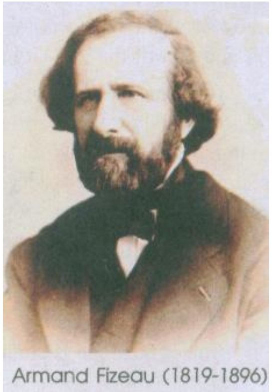
(i) Orbits are not circular but they are elliptical.

(ii) Correct value of the diameter of the earth is not known.

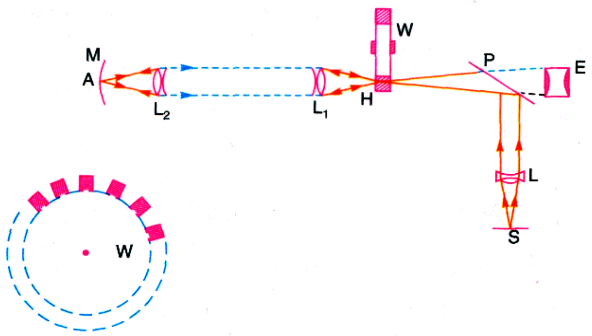
(iii) It may not be the exact time when the eclipse occurs.

2.4 FIZEAU'S METHOD

The first terrestrial method for determining the velocity of light was performed by Fizeau in 1849.



A bright source **S** emits light which after passing through a lens **L** and after reflection from the plane **P** is converged to a point **H**. Point **H** lies at the focus of the lens $\mathbf{L_1}$ and in a space between the two teeth of the wheel **W**. Therefore, the light after passing through $\mathbf{L_1}$ is rendered parallel and after traveling a distance of few miles is allowed to fall on the lens $\mathbf{L_2}$. The light after refraction through the lens $\mathbf{L_2}$ is brought-to focus at **A** which is also the pole of the concave mirror **M**. The radius of curvature of the mirror **M** is equal to twice the focal length of the lens **L₂**. Due to this, the rays are reflected along their original path. An image of **S** can thus be observed by the eye placed behind the eyepiece **E**.



The rim of the toothed wheel **W** is at **H** and the wheel is rotated about a horizontal axis. This is the important path of Fizeau's experiment. The teeth and spaces of the wheel are of equal width. Fizeau used a wheel with 720 teeth.

The velocity of light measured by Fizeau was nearly $3.14X10^8$ m/s

The main advantage of this method is that the principle involved is simple and Fizeau actually took the idea from the experiment attempted by Galileo (covering and uncovering the lamp).

It should be remembered that Fizeau's experiment is not free from criticism due to the following reasons:

(1) The complete eclipse or disappearance of light cannot be obtained due to the scattering of light from the teeth.

(2) The image of the source is very faint because the intensity of light is considerably decreased due to the refraction and reflection at various surfaces of the lenses and mirror.

(3) Uniform speed of rotation of the wheel cannot be attained.

(4) The appearance or disappearance is not abrupt but it takes place gradually from maximum to minimum and vice versa.

Improvement:

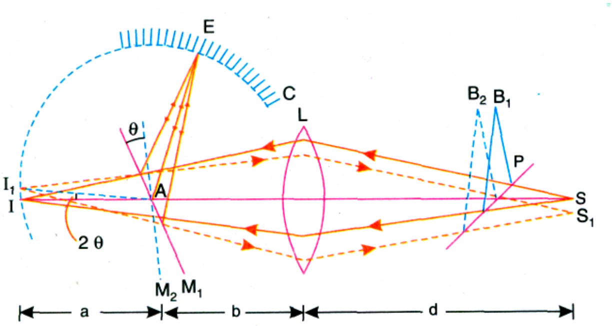
(1) Cornu in 1874 determined the velocity of light by Fizeau's method with improved apparatus. He used a distance of **23 kilometers** and instead of determining the velocity of rotation of the wheel for the disappearance of the image; he determined the velocity for which the brightness of the image, appears to become minimum and where the image begins to increase in brightness. His result for the velocity of light in air is **3.004×10^8m/s.**

(2) Young and Forbes in 1881 determined the velocity of light by Fizeau's method and **beveled the teeth** of the wheel so that light stopped by the teeth of the wheel was reflected to the sides. Moreover, they used the **silvered plates** having a small aperture for viewing the image instead of the glass plate **P**. They calculated the value of ***c*** as **3.013 x 10^8 m/s.**

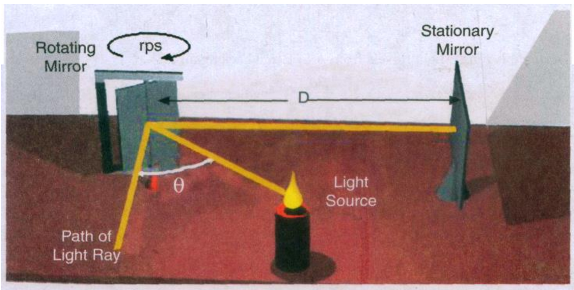
(3) Perrotin used Fizeau's method and kept the distance equal to **40 kilometers** and calculated the value of the velocity of light in the air as **2.999 x 10^8m/s**.

2.5 Foucault's Rotating Mirror Method

In 1862, Foucault designed an apparatus for the measurement of the velocity of light. It requires a much shorter distance than Fizeau's method and it is a modification of Fizeau's method. Foucault used a rotating mirror instead of a toothed wheel.



Light from a strong source **S** falls on an achromatic lens **L**, after passing through the glass plate **P**. The light after passing through the lens **L** will converge at point **I**. The value of ***c*** found by Foucault was 2.96 x10^8 m/s.



Velocity of light demonstration by the foucault rotating mirror method. This is a simplified version of setup.

<u>**The main disadvantage** of the Foucault's method is that the image obtained is not very bright due to reflection and refraction of light at various surfaces.</u>

Foucault observed the velocity of light in water by placing a long cylindrical pipe of water between the concave mirror and the plane mirror. He found that the displacement *x* of the image when water was used, was greater for the same speed of rotation of the mirror than when the air was used.

Newton's corpuscular theory of light predicted that the velocity of light in water should be more than that in air. The result of Foucault gave a death blow to the corpuscular theory of light. The wave theory of light predicted that the velocity of light in water should be less than in air. Thus, Foucault's experiment justified the validity of the wave theory of light.

2.6 Michelson's Method

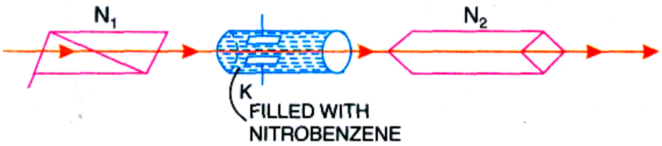
Michelson, an American Physicist, spent many years of his life in measuring the velocity of light. The method devised by him in the year 1926 at Mount Wilson observatory is considered accurate.

He obtained the value of $c = 2.99797 \times 10^{8}$ m /s.

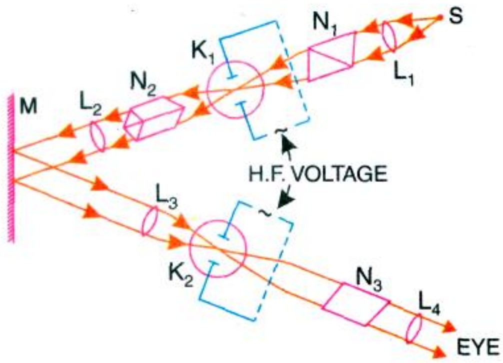
A.A. Michelson (America's first Nobel Prize winner in Physics)

2.7 Kerr Cell Method

Kerr cell method is an improvement "over the Fizeau's toothed wheel apparatus. It was first devised by Gaviola in 1925. In place of a toothed wheel, an electro-optic shutter is used which is capable of chopping a beam of light several hundred times more rapidly than can be done by the toothed wheel.



Electro-optic Shutter



It consists of a Kerr cell **K** placed between two crossed Nicol prisms N_1, and N_2 Kerr cell is a small glass container having two electrodes filled with nitrobenzene. *When a high voltage is applied to the electrodes of* **K**, *the light is transmitted through the system. On the other hand, when the field is switched off, light is stopped and not transmitted through the system.*

Thus, by using an electrical oscillator which supplies high-frequency voltage, the beam of light can be interrupted at the rate of many millions of times in one second.

Advantages of Kerr Cell Method:

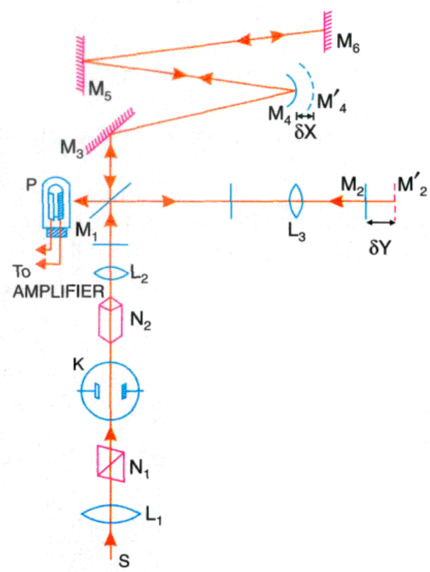
(1) As the frequency is very high, this device is capable of chopping a beam of light several hundred times more rapidly than can be done by the toothed wheel.

(2) The apparatus can be set up in a laboratory.

(3) The accurate frequency of the high-frequency oscillator is known.

2.8 Anderson's Method

In 1941, Anderson made use of one Kerr cell and divided the transmitted light pulses into two beams by means of a half-silvered glass plate. Light from a source S is allowed to pass through a modulated Kerr cell and is split up into two beams by the half-silvered glass plate M_1 One beam of the light goes towards M_2 and is reflected back, and the other beam goes along a longer path towards M_3, M_4, M_5 and M_6 and after reflection from M_6 retraces its path and finally, the two beams reach the photoelectric cell P.



The value of c found by Anderson by this method is **299,776 ± 6 km/s. This value is the mean of 2895 observations made by Anderson.**

<u>Advantages</u>:

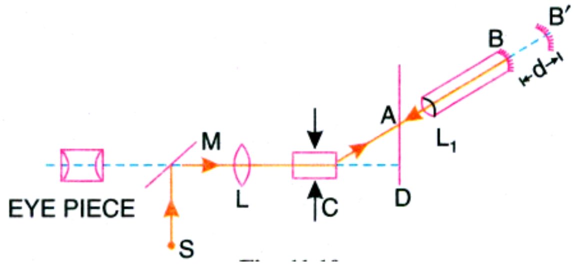
(1) The use of two Kerr cells is avoided in the method because it is practically difficult to match the characteristics of the two cells.

(2) The observations are taken by a photocell instead of the eye.

<u>Source of error</u>: The main source of error in this method is the difficulty in arranging for both beams to use the same position of the photoelectric cell.

2.9 Houston's Method

When a quartz crystal is subjected to a high-frequency electric field it is alternately compressed and extended and thus high-frequency oscillations are set up. This effect is known as the *piezoelectric effect*. When these high-frequency oscillations are set up in the form of pulses in a quartz crystal, it will be crossed by several parallel nodal planes. In such a case the intensity and refractive index at nodal planes are different from those at other planes and thus the crystal will act as a diffraction grating.



Monochromatic light from source S is allowed to fall on the quartz crystal C (whose faces are cut parallel) after reflection from the glass plate M. The lens L is used to make the beam parallel

The value of the velocity of light measured by Houston was 299,782 ± 9 km/s

QUESTIONS

1- Give a brief account of the methods for finding the velocity of light and give the details of the method which you consider most accurate.

2. Describe in detail Fizeau's method for finding the velocity of light. What are the chief difficulties met in carrying out this experiment?

3. Describe Foucault's method for finding the velocity of light. How does this method justify the correctness of the wave theory of light?

4. Describe the Kerr cell method for finding the velocity of light in the laboratory. What are the advantages of this method over other methods?

5. Describe a modern method for measuring the velocity of light.

6. Describe Anderson's method for determining the velocity of light. What are the merits and demerits of the method?

7. A certain monochromatic radiation has a wavelength of 5000 A in water. What is the wavelength in (i) vacuum and (ii) in carbon disulphide? (n for water is 1.333 and n for carbon disulphide = 1.628).