THE SPEED OF PHOTONS IN A VACUUM AND EXPERIMENTS TO MEASURE IT

S. B. Abduvasiyev
Jizzakh State Pedagogical Institute,
Sh. Rashidov-4, 100130, Jizzakh, Uzbekistan

Abstract
This article presents the experiments conducted by various scientists to determine the speed of light, along with the results obtained from these experiments.

Keywords: Interferometer, Speed of light, Physio experience, The speed of light depends on the medium.

Introduction

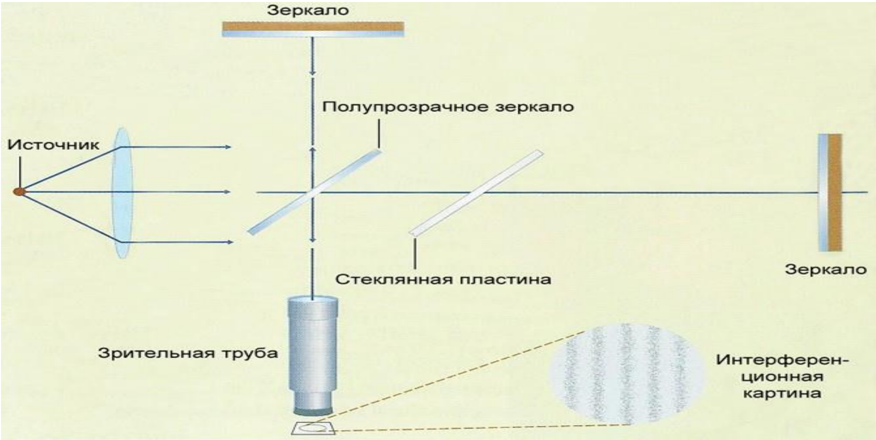
It is difficult to imagine absolute emptiness—a complete vacuum containing nothing at all. Human consciousness strives to fill it with something material, and throughout the long centuries of human history, it was believed that the universe was filled with ether. The idea was that interstellar space was occupied by some invisible and intangible fine substance.

When Maxwell's system of equations was developed, predicting that light propagates through space at a finite speed, even the author of this theory himself assumed that electromagnetic waves propagate in a medium, similar to how acoustic waves travel through air and water waves through the sea.

In the first half of the 19th century, scientists meticulously worked on a theoretical model of ether and the mechanics of light propagation, including all sorts of levers and axes, which were thought to facilitate the transmission of oscillatory light waves in ether.

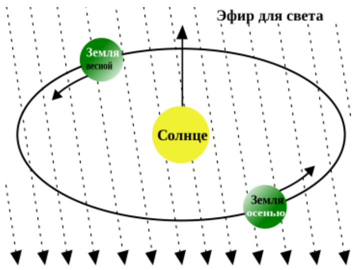
In 1887, two American physicists—Albert Michelson and Henry Morley—decided to conduct an experiment aimed at once and for all proving to skeptics that the luminiferous ether truly exists, fills the universe, and serves as the medium through which light and other electromagnetic waves propagate. Michelson was renowned as an authoritative designer of optical instruments, while Morley was celebrated as a tireless and meticulous experimental physicist. The experiment they devised was easier to describe than to execute.

Michelson and Morley used an interferometer (Fig. 1)—an optical measuring device in which a beam of light is split into two by a semi-transparent mirror. This glass plate was silvered on one side just enough to partially transmit incoming light rays while reflecting the rest. A similar technology is used today in single-lens reflex cameras.



Interferometer structure of Micelson

As a result, the light beam splits, and the two coherent beams diverge at a right angle to each other. They then reflect off two mirrors positioned equidistantly from the semi-transparent mirror and return to it. The resulting light beam recombines at the semi-transparent mirror, producing an interference pattern. This pattern enables the detection of even the slightest desynchronization between the two beams. The Michelson-Morley experiment was fundamentally designed to confirm (or refute) the existence of the universal ether by detecting the presence of an "ether wind" (or its absence). Indeed, as Earth moves along its orbit around the Sun, it travels relative to the hypothetical ether, moving in one direction for half the year and in the opposite direction for the other half.



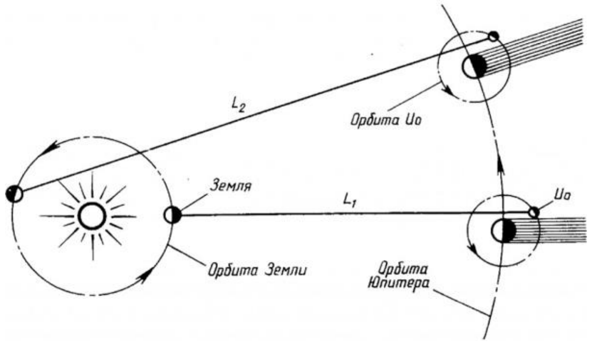
Thus, for half the year, the "ether wind" was expected to blow against the Earth, shifting the interferometer readings in one direction, and for the other half, in the opposite direction. However, after observing their setup over the course of a year, Michelson and Morley found no shifts in the interference pattern: complete ether calm! (Modern experiments of this kind, conducted with maximum precision, including those using laser interferometers, have produced similar results). Therefore, there is no ether wind, and consequently, no ether.

In the absence of an ether wind and ether itself, a fundamental conflict became evident between Newtonian classical mechanics (which assumes an absolute reference frame) and Maxwell's equations (which assert that the speed of light is a constant and independent of the reference frame). This conflict ultimately led to the development of the theory of relativity.

The Michelson-Morley experiment definitively demonstrated that there is no "absolute reference frame" in nature.

The 26-year-old Albert Einstein proposed an entirely new perspective on the nature of space and time, which contradicted contemporary views and, in particular, violated Galileo's principle of relativity. According to Einstein, the Michelson experiment yielded no positive results because space and time possess properties such that the speed of light is an absolute constant. This means that regardless of the reference frame of the observer, the speed of light relative to them is always 300,000 km/s. From this, it followed that the addition of velocities could not be applied to light: no matter the speed of the light source, the speed of light would remain unchanged (neither added to nor subtracted from).

Ancient scholars, for the most part, believed that light traveled at infinite speed. The first estimate of the speed of light was obtained as early as 1676.

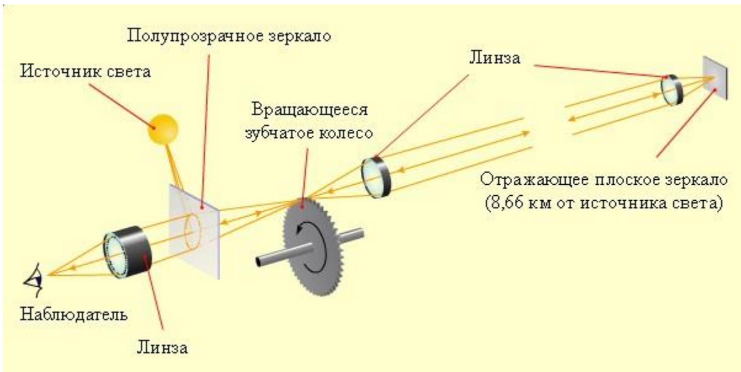


Observation diagram of Jupiter's moon Io

In 1727, the English astronomer James Bradley discovered the phenomenon of light aberration. This phenomenon occurs due to Earth's motion around the Sun and its own rotation. As a result, stars appear shifted in the night sky. Since both the Earth and the observer are constantly changing their direction relative to the observed star, the light emitted by the star travels different distances and strikes the observer at different angles over time (Fig. 4). The finite speed of light causes the stars in the sky to trace an elliptical path over the course of a year. This experiment allowed James Bradley to estimate the speed of light—308,000 km/s. In 1849, French physicist Louis Fizeau conducted a laboratory experiment to measure the speed of light. He placed a mirror in Paris at a distance of 8633 meters from the light source. However, according to Rømer's calculations, light would take only a hundred-thousandth of a second to travel this distance, a precision that was impossible to achieve with the clocks of that time. To overcome this limitation, Fizeau used a toothed wheel, which rotated along the path from the source to the mirror and from the mirror to the observer. The teeth of the wheel intermittently blocked the light. When the light beam passed between the teeth on its way to the mirror, but was blocked by the teeth on its return journey, Fizeau increased the wheel's rotation speed. As the rotation speed increased, the light barely disappeared, until the speed reached 12.67 rotations per second. At this point, the light reappeared. This observation indicated that the light was "hitting" the teeth and could not "pass" between them. Knowing the wheel's rotation speed, the number of teeth, and the doubled distance from the source to the mirror, Fizeau calculated the speed of light to be 315,000 km/s.

A year later, another French physicist, Léon Foucault, conducted a similar experiment, but instead of a toothed wheel, he used a rotating mirror. His result for the speed of light in air was

298,000 km/s. A century later, Fizeau's method was further refined. In 1950, an experiment by E. Bergstrand yielded a speed of 299,793.1 km/s.



Scheme of Louis Fizeau's experiment

This value deviates by only 1 km/s from the current measurement of the speed of light. With the advent of lasers and improved precision of measurement instruments, the error in measuring the speed of light was reduced to as little as 1 m/s.

In 1972, American scientists used lasers in their experiments. By measuring the frequency and wavelength of the laser beam, they determined the speed of light to be 299,792,458 m/s.

Interestingly, further improvement in the accuracy of light speed measurements in a vacuum was unachievable not due to the imperfection of the instruments, but because of the inherent error in the definition of the meter itself. For this reason, in 1983, the 17th General Conference on Weights and Measures defined the meter as the distance light travels in a vacuum in 1/299,792,458 seconds.

In any transparent medium, light travels more slowly than in a vacuum. Its speed vv depends on the refractive index nn of the medium:

n: $v = c/n$

where cc is the speed of light in a vacuum. The refractive index of air is 1.0003, water is 1.33, and various types of glass range from 1.5 to 1.8. Diamond has one of the highest refractive indices among transparent substances, at 2.42. Therefore, the speed of light in regular substances decreases by no more than 2.5 times.

In early 1999, a group of physicists from the Rowland Institute for Scientific Research at Harvard University (Massachusetts, USA) and Stanford University (California, USA) studied a macroscopic quantum effect known as **self-induced transparency**. This phenomenon was explored by passing laser pulses through an opaque medium under normal conditions. The medium consisted of sodium atoms in a special state called the Bose-Einstein condensate. When exposed to a laser pulse, the medium acquired optical properties that reduced the group velocity of the pulse by 20 million times compared to its speed in a vacuum. The researchers were able to slow the speed of light down to 17 m/s!

Self-induced transparency is a nonlinear optical effect that occurs when a very short and powerful light pulse passes through a medium that absorbs continuous radiation or long pulses. The medium becomes transparent to the light pulse. This effect is observed in rarefied gases when the pulse duration is on the order of 10^{-7} and 10^{-8} seconds, and in condensed media, it occurs with pulse durations of less than 10^{-11} seconds. As a result, a delay in the pulse occurs, and its group velocity decreases significantly.

This effect was first demonstrated by McCollum and Hahn in 1967 using ruby at a temperature of 4 K. In 1970, delays were observed in rubidium vapor, corresponding to pulse velocities 1000 times slower than the speed of light in a vacuum.

In the unique 1999 experiment, Len Westergaard Haeu, Zachary Datton, Cyrus Beruzi (Rowland Institute), and Steve Harris (Stanford University) cooled a dense cloud of sodium atoms held in a magnetic field to transition them into their ground state — the lowest energy level. They then selected only those atoms whose magnetic dipole moment was directed opposite to the magnetic field. The cloud was cooled to a temperature of less than 435 nK (nanokelvins, or 0.000000435 K, almost to absolute zero).

After this, the condensate was illuminated by a "linking" beam of linearly polarized laser light with a frequency corresponding to the energy of its weak excitation. The atoms transitioned to a higher energy state and ceased absorbing light, making the condensate transparent to the following laser radiation. At this point, very strange and unusual effects occurred. Measurements showed that, under specific conditions, the pulse passing through the Bose-Einstein condensate experienced a delay corresponding to a slowdown of the light by more than seven orders of magnitude — a 20 million times reduction. The speed of the light pulse slowed to 17 m/s, and its length was reduced several times — to 43 micrometers.

The experiment leader, Lene Westergaard Haeu, called this achievement a result "on the edge of possibility," but her team soon went even further. In 2001, they briefly "froze" the light inside a similar condensate and then released it to continue its movement. The delay was just one millisecond, but eight years later, Harvard physicists were able to hold the light for longer than a second.

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