History of the Speed of Light

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Honors University Physics II

The speed of light is an important constant that is used for many scientific measurements; however, the value for the speed of light is a value that took numerous scientists and philosophers hundreds of years to obtain. The experiments ranged from thought experiments to innovative studies using tools as simple as lanterns and as complex as turntables, mirrors, and lasers in complex arrangements with the end result being a very precise calculation and understanding of the velocity of light.

The first experimentations concerning the velocity of light are found as far back as 300 BC in Greece. Before the 1600's, "light was thought to propagate instantaneously through the ether, which was the hypothetical mass-less medium distributed throughout the universe" (Deaton and Payton 2). At this time, scholars believed that light traveled in straight lines, and they knew certain properties of light refraction. Claudius Ptolemy, an Alexandrian mathematician and astronomer, "compiled tables of measured angles of incidence and refraction" even though the law of refraction wasn't discovered until 1621 (Jaffe 22). Aristotle postulated that the speed of light was infinite while in another part of the world, the Islamic scientist Avicenna reasoned that the speed of light, while very fast, must be finite (Jaffe 23).

The next road-mark in the study of the speed of light was performed by the Italian Galileo Galilei. In 1638, Galileo proposed an experiment where two individuals stood a measured distance away with two lanterns (Británica Online). The first lantern was uncovered and then when the individual by the second lantern saw the change, he also uncovered his lantern.

By comparing the data collected with the control, each individual standing right beside the other and determining the human error and delay in removing the cover, Galileo determined that their was no difference in time from the control to that of the measurements taken up to a mile apart. Since the human error measurement was 0.2 seconds it was determined that the speed of light could not be calculated from this experiment within any range of accuracy (Deaton and Payton 4). This lead Galileo to conclude that if light wasn't infinite then it must be at least "ten times (faster) than the speed of sound" (Británica Online). This experiment was repeated by numerous other scientists who came to the same conclusion: although no time difference was shown, all that this experiment proved was light moves at a very rapid pace and that its' speed was faster than the speed of sound.

The first measured experimental value to be taken for the velocity of light was calculated by a Danish astronomer named Ole Rømer while working at the Paris Observatory. Rømer was studying Io, one of the moons of Jupiter that orbits and is eclipsed by Jupiter at a regular rate. By watching the moon Io for an extended period of time, Rømer realized that the moon's eclipses were lagging more and more each month but then after a certain period of time, they began to pick back up. He was even able to predict the exact delay time between the expected viewing of the Io eclipse and the actual time at which it appeared (Fowler).

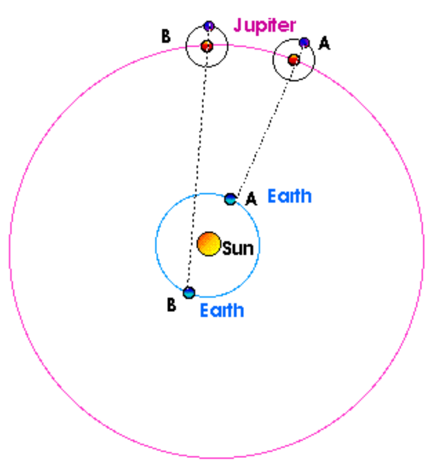
Rømer explained that "as the Earth and Jupiter moved in their orbits, the distance between them varied" (Fowler). The light from Io, which was actually reflected sunlight, took time to reach the earth and took the longest time when the earth was farthest away. "When the Earth was furthest from Jupiter, there was an extra distance for light to travel equal to the diameter of the Earth's orbit compared with the point of closest approach"

(Fowler). The eclipses observed were furthest behind the predicted times when the Earth was the farthest away from Jupiter.

From these values Rømer concluded that it took twenty-two minutes for the light to cross the Earth's orbit. For his calculations, Rømer also needed to determine the distance between the Earth and the Sun. From his basic calculations, he determined the distance between the Earth and the Sun was between forty million miles and ninety million miles.

With these numbers, he calculated the speed of light to be 48,203 leagues per second (or about 214,000 km/sec). This value is "too small because of his inaccurate knowledge of the relative velocity of the Earth and Jupiter" (Sanders 3). The actual time it takes the light to cross the Earth's orbit is sixteen minutes and the actual distance between the Earth and the Sun is ninety three million miles. Despite the error in Rømer's calculations, his greatest contribution was not his value for the speed of light but that he provided definitive proof that light took time to travel, no matter how small the distance it was covering. Even with the evidence provided by Rømer concerning the speed of light, the true value of his work was not accepted until 1727.

Ole Rømer



Jupiter and Io Experiment

The next influential scientist in determining a value for the speed of light was an English astronomer named James Bradley in January 1729. Bradley found an innovative way of calculating the speed of light by accident when attempting to calculate the parallax of stars with the start *Gamma Draconis* (Davidson). A parallax of stars is a change in the stars positions that mirrored the change in the Earth's position in its orbit around the sun. While using a friend’s observatory to make his calculations, Bradley made an important discovery. Bradley found that “*Gamma Draconis* did indeed shift in its location, but in the opposite direction from what was expected” (Davidson).

Bradley determined from this information that stellar variation in position was brought about by the aberration of light which was brought about by the speed of light and the forward movement of earth in its’ orbit (Fowler). Bradley’s studies were of interest to the Royal Society since it provided for an alternative technique for calculating the speed of light. “By analyzing measurements of stellar aberration angle and applying that data to the orbital speed of the Earth, Bradley was able to arrive at the remarkably accurate estimate of 183,000 miles (295,000 kilometers) per second” (Davidson).

The problem with all of the calculations for the speed of light up to this point was that each one had been calculated with variables from space and scientists at the time had no way of knowing if the values previously calculated pertained to Earth, yet for the lantern experiment to work, the lanterns would have to be ten miles apart to even measure a one-ten thousandth of a second difference in time. Since one-ten thousandth of a second is not a variable that can be measured by the naked eye, another more compact and accurate means of Earth bound measurement was necessary to calculate the speed of light within a narrow margin of error. It took two hundred years for this problem to be solved by two French rivals named Fizeau and Foulcault.

In 1849, a wealthy French physicist named Armand Hippolyte Fizeau made an apparatus that would provide a way to shrink the distance between the “lanterns” and provide a more accurate way to measure time to a smaller degree. Fizeau’s apparatus consisted of a turn table with close teeth which a beam of light passed through at such a rapid rate (so that the lantern is constantly being covered and uncovered). The idea was that the blip of light which went out through one gap between teeth would only make it back through the same gap if the teeth had not had time to move over significantly during the round trip time to the far away mirror. The wheel consisted of seven hundred and twenty teeth and the wheel was rotated hundreds of times a second so that the time it took for a tooth to move over would be a fraction of one-ten thousandth of a second. Fizeau determined the value for the velocity of light to be 315,300 km/sec (Jaffe 31).

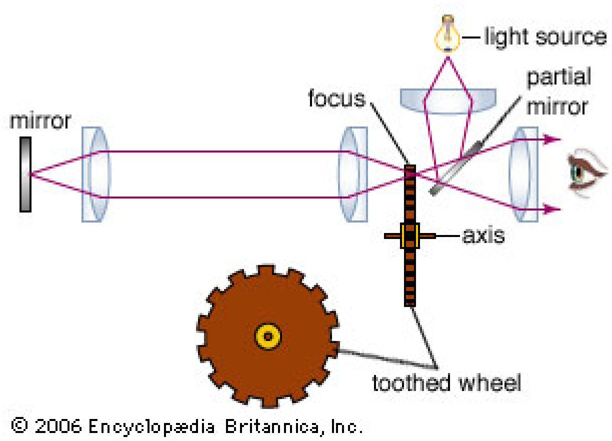


Diagram of Fizeau’s experimental set-up

In 1862, thirteen years after Fizeau’s experiment, a French medical student named Jean Foulcaust created a very similar apparatus to that of Fizeau’s with one important improvement. The innovative addition by Foulcaust was to replace the multi-pronged wheel with a rotating mirror that catches the light from the primary light source (Jaffe 31). At one point in the new mirror's rotation, the light reflected off of a distant mirror which reflected the light back to the rotating mirror after only a fractional change in distance. The position of the beam was recorded from where it went into the mirror and where it returned and the displacement angle was recorded. From these measurements he determined the speed of light to be 298,000 km/sec (Sanders 6).

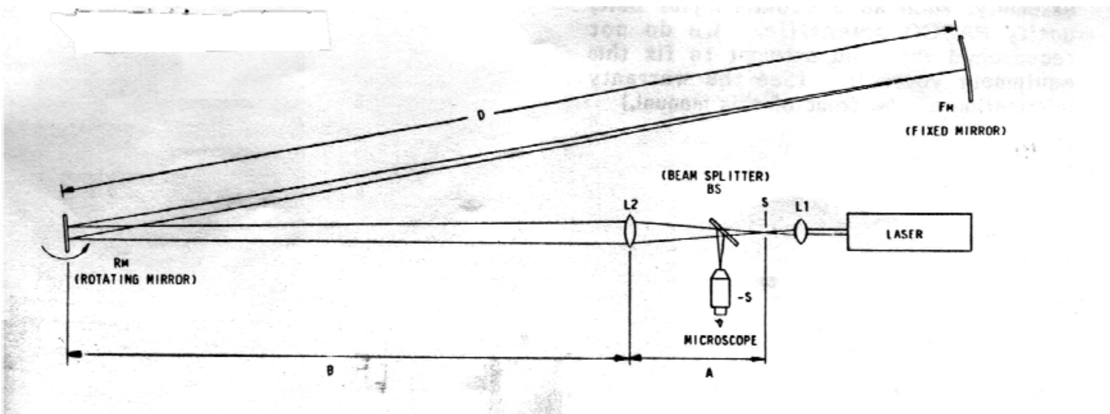


Diagram of Foulcaust's experiment

The next major advance was made by Albert Abraham Michelson, the first American Winner of the Nobel Prize. Michelson was the designer a number of experiments to prove that a substance called ether existed and that the Earth was traveling through this substance.

To understand Michelson's experiments and their significance, it's first important to know about Maxwell's equations. Maxwell's equations were discovered and complied in 1861 by James Maxwell and were used to understand the laws of electromagnetism. From these equations, a theoretical equation for the speed of light (c) was determined to be $c = 1/\sqrt{\mu_o \varepsilon_o}$. This equation allowed Maxwell to calculate the speed of light to be $3x10^{10}$ cm/s (Venkataraman 22). The problem now was, what is it that light in propagated through that allows it to have the speed predicted above? At this time, the common scientific opinion was that there was a substance called ether that filled all space and that light's speed was calculated at the value $3x10^8$ m/s through stationary ether (Venkataraman 23). This mentality is what lead to Michelson's experiments and in turn lead to his discovery of a more accurate method for calculating the speed of light.

Michelson's first experiment in 1878 was basically the same as Fizeau and Foucault experiments in that is was composed of a measurement of the time elapsed as light travels from a source out to a reflection mirror and returns to the place of origin (Hughes 4). This experiment was called Michelson's Potsdam Experiment and was intended to prove that ether existed and was the substance through which light was propagated. In 1924, Michelson employed the best aspects of each scientist's experiments into his own innovation. From Foucault's experiment he took the used of a mirror for greater accuracy and he used a multifaceted octagonal year. Michelson explained: "the advantage of the octagonal revolving mirror that lies in the possibility of receiving the return light on a succeeding face, thus eliminating the measurement of the angular deflection of the returned beam…" (Elsevier Publishing Company).

His initial set-up consisted of a multifaceted rotating mirror created by Elmer Sperry, an arc lamp that cast a beam through a narrow slit, reflecting mirrors to direct the beam of light along a desired path, a reflecting concave mirror, and a prism to direct the beam of light into the observing eyepiece. Michelson felt that if the light was traveling through an ether medium, then the light that moved between the mirrors in a parallel fashion would have to travel with the current of the ether and then against it to return to the mirror where the mirrors that aimed the light in a perpendicular fashion would only have to go with the ether current and then parallel to the ether (Hughes 2 and 5). That meant that if the time it took for the light to return from the parallel set-up was slower than the time it took for the light to return from the perpendicular set-up there would have been solid proof of ether. The figure below demonstrates the initial set-up for Michelson's first experiment (Fowler).

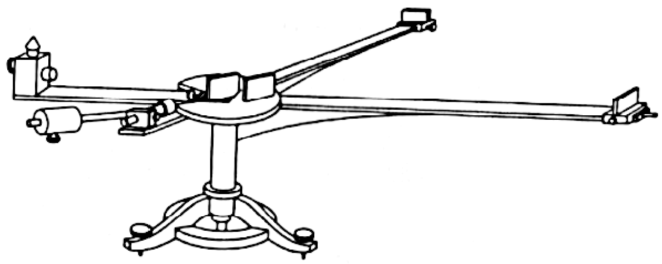


Diagram of Michelson's first experiment

At the time of the experiment, the common scientific opinion was that these experiments would provide a 0.04 fringe shift based on the difference in passage time from the parallel to the perpendicular arrangement. In the first experiment, Michelson calculated a fringe shift on 0.02 which was surprising to Michelson. Upon receiving criticism about his data, Michelson even commented that, "I have never been fully satisfied with the results of my Potsdam experiment…" (Venkataraman 41).

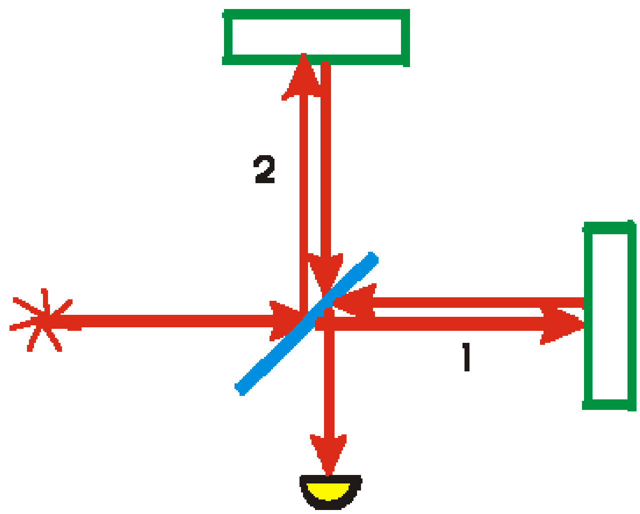
The second and more significant of the Michelson experiments was in collaboration with an American scientist named Edward Williams Morley and was in response to criticisms from the scientific community concerning the accuracy in his previous experiment. The following experiment became known as the Michelson-Morley Experiment and proved to be an extremely useful tool to determining the speed of light.

Albert Abraham Michelson

Edward Morley

The changes to the new apparatus where in an attempt to correct the error in the previous experiments preformed by Michelson. First, the new experiment was conducted in the basement of a cement stone laboratory building so all measurements would be calculated at a relatively constant temperature. Second, the entire apparatus was mounted on either concrete or brick base to mineralize motion not pertaining to the experiment (Venkataraman 41). After all of the precautionary corrections had been made, Morley and Michelson repeated the previous experiment and this time where about to report an expected fringe of less than 0.01 (Davidson).

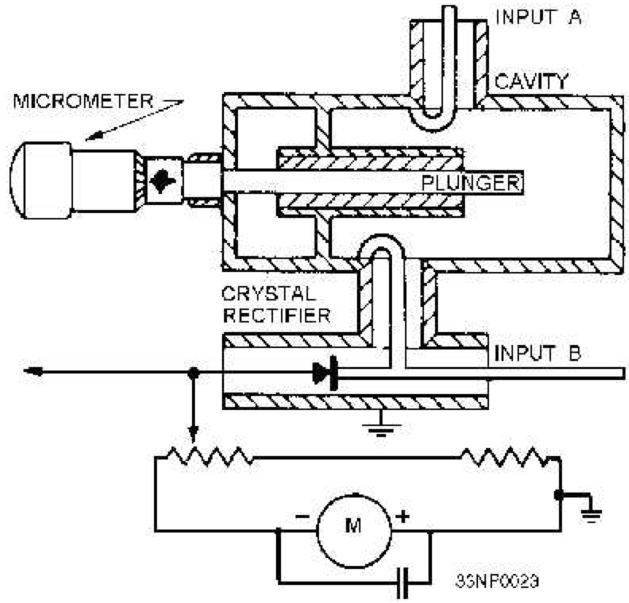
This was a confusing result since everyone believed the error in Michelson's previous experiment was that it was less than 0.04 fringe shift and thus they were expecting the more accurate study to increase to this value instead of decrease to a fringe shift of 0.01. That meant that the data from this experiment proved that ether could not, in fact, exist (Venkataraman 43). The reason for this data confused scientists for years until Einstein solved the problem with his theory of Special Relativity which accounted for the permeability of free space and the ability of a substance like light to travel in waves even if not through an ether-like substance.



The Interferometer created by Michelson and Morley

In addition to their discoveries concerning ether that won Michelson a Noble Prize, Michelson's and Morley's experiments also contributed to the calculations for the speed of light. They calculated a value of 299,910 (+ or -) 50 km/sec for the velocity of light which was a substantially greater value for the speed of light.

The next group of individuals to determine a value for the speed of light was a British physicist names Louis Essen. With the help of A.C. Gordon-Smith, he used a cavity resonance wavemeter to measure the velocity of light with unprecedented accuracy (Británica Online). With this machine, they calculated the speed of light to be 299,792 (+ or -) 3 km/s. Then in 1950 they calculated the value to even a greater degree of accuracy as 299,792 (+ or -) 1 km/s with an improved cavity resonator.



Model of the Cavity Resonance Wavemeter

Determining the speed of light today is a much simpler task than it once was. All that is required for this experiment is a few different household items: marshmallows, glass brownie dish, and a ruler. To start with, take the marshmallows and place them in the brownie pan with the wider sides facing up in a uniform fashion. Then, place the marshmallow pan into the microwave and put the microwave on the lowest heat setting offered.

As the marshmallows begin to heat, the microwave needs to be stopped when the marshmallows have begun melting in four or five different places. Once cooled, measure the distance between the melted spots and the measured value should be about the same distance. After all of the measurements have been taken, average them together to obtain a common value and then convert that value to meters.

Now, looking on the back of the microwave. There should be a sticker on the back of the microwave that tells what the energy output (in hertz) is for each particular microwave. With both the distance in meters and the energy output in hertz it is possible to calculate the speed of light.

[wavelength (meters)] x [frequency (Hertz)] = speed of light (meters/second)

$$\lambda f = c$$

Once the value for the speed of light has been calculated a percent error must be calculated using the actual value for the speed of light: c = 3.0×10^8 m/s.

(actual-theoretical)/actual x 100 = % error

Wavelength (λ)	Frequency (MHz)	Speed of Light (m/s)
12.6 cm	2450 MHz	3.09×10^8 m/s

Today the accepted value for the speed of light is 299,792,458 m/s; however, it is still considered a work in progress. Without the contributions of these earlier inventors, many of the scientific calculations today would be impossible, and without the contributions of Maxwell, Michelson, and Einstein, modern physics would still truly be a thing of the past. From thought experiments and astrological calculations to complex experimentation and mathematics, the calculation of the speed of light has come a long way to accelerate the scientific community forward into newer and more innovative creations.

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