European J of Physics Education Volume 5 Issue 1 2014 Shivalingaswamy & Rashimi

# I am the speed of light c, you 'see' …..!

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*(Received: 13.10. 2013, Accepted: 20.10.2013)*

**Abstract**

The accurate measurement of speed of light is of great importance in understanding various concepts in Physics in particular and science in general. In Physics we come across various concepts and applications in which high degree of accuracy of speed of light becomes important. In this article we discuss the various attempts made to determine the speed of light in a chronological order and then significant roles played by speed of light in physical theories has been discussed.
**Key words:** Speed of light; time of flight techniques; theories of relativity; global positioning system.

## Introduction

For thousands of years humans have been aware of the fact that light is essential to see objects around them. Even though the nature and properties of light were not known, people were able to develop light sources for their convenience. Early scientists believed that light travelled at infinite speed. On philosophical grounds, scientists like Bacon felt that light had a finite velocity, though extremely large. Today we know that the velocity of light plays a very important role in nature and its value has been determined to a great accuracy. The speed of light plays a very important role in the dynamics of moving objects. It provides an important link between matter and energy as signified in the most famous equation in physics: $E = m c^2$ .The velocity of light sets an upper limit on the signal velocity between any two bodies. Hence, the interactions between bodies are linked to the speed of light directly or indirectly. The speed of light has been found to be independent of the velocity of the source and the detector, very contrary to our common notion of material velocities. Speed of light is one among three fundamental constants that represents the three dimensions of so-called 'cube of physical theories', a construction that structures the state of modern physics. Hence, attempts are going on to determine its value with ever greater accuracy.

In this short article, I present an account of various attempts to determine the speed of light and the significant role it plays in physical theories.

**Milestones in the Measurement of speed of light**

Speed of light is now universally represented by symbol 'c'. This symbol originated from the initial letter of the Latin word "celerity" meaning "swift" or "quick". This symbol was used by Weber and Kohlrausch in their papers in 1856. For some years this symbol was regarded as Weber's constant. In 1894 Paul Drude, with certain modifications, introduced the symbol 'c' for the speed of light. It is to be noted that upper case 'C' represents coulomb, the unit of electric charge. Later this symbol was picked up by other scientists and has become universally accepted.

Scientists have been trying measure the speed of light accurately for over three hundred years. They have used different ingenious techniques like time of flight methods, spectroscopic methods, electromagnetic methods and resonance methods etc. to determine the speed of light. In this section, we briefly discuss some of the milestones in measurement of speed of light.

The first significant attempt to measure speed of light was made by Galileo in 1638. Galileo's method was similar to the one that is used to measure speed of sound wherein reciprocal gun firing by two observers stationed at two different locations is employed. Galileo used powerful lamps in his attempt to determine the speed of light. But Galileo failed in his attempt because the time interval between uncovering his lamp and the light seen from the lamp of his assistant was so very small and could not be measured accurately due to unavailability of high precision clocks during his time. Galileo somehow was able to declare that the light travels at least ten times the speed of sound. Even though Galileo was unable to measure accurately the speed of light, his experiment was a remarkable one as it made a breakthrough regarding the common belief that the speed of light was infinite.

A truly exceptional attempt to determine speed of light was made by Ole Rømer, a Danish astronomer in 1676. He estimated speed of light by observing times of eclipses of the moons of Jupiter which seemed to depend on relative positions of the earth and Jupiter (A.A Michelson, 1995). Rømer noticed that there was a delay in the appearance of moons of Jupiter when the distance between earth and Jupiter was far. He correctly guessed that this delay was due to the extra time required for light to travel when earth was at a greater distance from Jupiter. Since this method involved the diameter of the earth's orbit which was not known accurately during that time, Rømer estimated the speed of light as214000 $kms^{-1}$.

In 1728, James Bradley, an English Physicist determined speed of light by using stellar aberration. He measured the apparent shift in the position of a fixed star due to rotation of earth. Stellar aberration angle is related to the ratio of orbital speed of earth around sun and speed of light. Bradley was able to measure the small stellar aberration angle. Hence he was able to estimate speed of light by knowing orbital speed of earth. He concluded that the speed of light was around 301000 $kms^{-1}$. But even this method involved the value of the diameter of the earth's orbit which was not known accurately during that time.

Attempts to determine the accurate value of speed of light continued. The first efficacious experiment for the measurement of speed of light was carried out by Arnold Fizeau, a French Physicist in 1849. His method involved shining of light from a source which was kept at a distance of about 7 km on a rotating wheel consisting of 720 teeth and rotating at about 12.6 rotations per second. He calculated the speed of light on the basis of appearance and disappearance of image with respect to the speed of wheel. He estimated the speed of light in free space as 313000 $kms^{-1}$. Although this experiment was straight forward and did not include any assumptions, the experiment suffered from many disadvantages such as non-uniform speed of rotation of the wheel, poor image quality etc.

In 1856, Weber and Kohlrausch measured the ratio of electromagnetic and electrostatic units of charge by discharging Leyden jar and found that the ratio is very close to the speed of light as measured by Fizeau. It was a very interesting coincidence that puzzled many scientists at that time. For some years this ratio was regarded as Weber's constant.

In 1862, Leon Foucault a French Physicist used the method suggested by Wheatstone in 1834. It required much shorter distances than Fizeau's method and was based on a modification of Fizeau's method. This method involved reflection of light from a remote mirror to the rotating mirror. As the mirror was rotating, the light from such a mirror bounced back in a direction which was slightly different from the direction of incidence (Ajoy K Ghatak, 2009). By measuring this extremely small deviation angle Foucault estimated the speed of light in free space as 299796kms$^{-1}$.

After the formulation of electromagnetic theory by James Clerk Maxwell in the early 1860's, it became clear that light is a form of electromagnetic radiation whose speed in free space is given by $c = 1/\sqrt{\mu_0 \in_0}$, here $\mu_0$ represents magnetic permeability of free space and $\in_0$ represents electric permittivity of free space. This equation not only predicted the theoretical value of speed of light, but also unified electricity, magnetism and optics in some sense. This quest for unification of different forces has now been carried forward to electromagnetic, weak and strong forces. Later, Maxwell theoretically proved that electric signal in a resistanceless wire travels at this speed. Thus with this theory, all other electromagnetic waves such as gamma rays, x-rays, Ultra-Violet rays, Infra-Red waves, Radio and microwaves along with visible light were categorised to one family.

In 1907, Rosa and Dorsey estimated speed of light as $2.99788\times10^8$ms$^{-1}$ by determining the values of $\mu_0$ and $\in_0$ . The vacuum permittivity was estimated by measuring capacitance and dimensions of a capacitor, whereas the value of vacuum permeability is fixed at exactly $4\pi\times10^{-7}Hm^{-1}$ using the definition of ampere.

In 1926, Albert Michelson, an American Physicist measured the speed of light using an octagonal rotating mirror. The experiment was carried out between two hill stations namely Mt. Antonio and Mt. Wilson observatory. This experiment is regarded as one of the most accurate methods to determine the speed of light. It also known as a 'null method' since it does not involve any error due to measurement. Michelson estimated the speed of light as $2.99797\times10^8$ms$^{-1}$.

In 1941, W.C Anderson measured the speed of light by Kerr cell arrangement. He obtained the value of 'c' as 299776±6 kms$^{-1}$. In 1958, Froome improved this method by using microwave interferometer and Kerr cell shutter to obtain the value of 'c' as 299792.5±0.1 kms$^{-1}$.

After 1970, due to the development of accurate caesium clocks and development of good quality light sources like Lasers, even better measurements became possible. By this time speed of light was known to within an error of ±1ms$^{-1}$. In the year 1973 Consultative Committee on Definition of Meter (CCDM) recommended speed of light in free space as $2.99792458\times10^8$ms$^{-1}$ and hence led to the redefinition of meter (the SI unit of length). In 1983, at 17$^{th}$ General Conference on Weights and Measurements 'meter' was redefined as the distance travelled by light in vacuum in $2.99792458\times10^8$ fraction of a second. This makes the speed of light in vacuum exactly $2.99792458\times10^8$ms$^{-1}$ (A.A Michelson, 1995).

The precise value of 'c' reduced the uncertainty in measuring wavelengths of light. This also led to a great accuracy in radio astronomy and astronomical units of lengths namely light year and parsec.. The precise value of 'c' has also helped the human kind as far as several useful applications are concerned. New technological applications like Light Detection And Ranging (LIDAR), Global Positioning System (GPS), Radio Frequency Identification (RFID) and many communication techniques became possible as a result of basic science research with regard to speed of light 'c'. The above technologies have occupied prominent place in defence, weather forecasting, measurement of pollutants in the atmosphere, wildlife monitoring, constructions, mapping etc. (Ajoy K Ghatak, 2009).

**Theories of Light**

As some physicists were engaged in the determination of accurate value of 'c', many others were interested in exploring the reasons for the special properties exhibited by light such as the constancy of speed of light as long as the refractive index is constant, refraction of light due to change in the speed of light whenever there was a discontinuity in the medium, interference, diffraction etc. Hence, it led scientists to formulate different theories about the nature of light.

In 1675, Newton sent to the Royal Society a paper in which he presented his corpuscular theory of light. Even though this theory was able to explain some of the observed properties of light such as rectilinear propagation, reflection etc. it failed to explain a few major characteristics of light. It was at best a mechanical model for light. No details about the corpuscles were provided or measured.

In 1679, Christian Huygens proposed his wave theory of light in which he postulated that, each point in a source of light sends out waves in all directions in a hypothetical medium called 'ether'. Ether was assumed to be continuous medium which pervades entire universe. In order to explain the tremendous speed of light, ether was assumed to be a medium with high elasticity and low density. This assumption was made since light was thought to be moving in ether just like sound waves propagating in a medium and hence light was expected to satisfy Newton's laws. Although Huygens' theory was able to explain reflection, refraction, dispersion etc., it is based on the assumption that there exists strange medium called ether pervading the universe. But the existence of ether with contradictory properties was simply assumed and was not been established by anyone. The landmark experiment carried out by Michelson and Morley in the year 1887 disproved the existence of ether. Recent resonance experiments have also confirmed the absence of ether.

James Clerk Maxwell in the early 1860's formulated the electromagnetic theory of light from which he proved that light is a wave consisting of time varying electric and magnetic fields which are mutually perpendicular to each other and perpendicular to direction of propagation. Using his equations for the electric and magnetic fields he derived a formula for the speed of light in vacuum as $c = 1/\sqrt{\mu_0 \in_0}$. He also deduced the expression for speed of light in a transparent material media as $= 1/\sqrt{\mu \in}$ . Where $\mu$ and $\in$ represent magnetic permeability and electric permittivity of the given medium respectively. This equation provided an answer for the reduction in speed of light when it is propagating in a medium. The ratio of speed of light in vacuum to the speed of light in material medium gives refractive index of that medium. This concept together with total internal reflection property of light led to the fabrication of optical fibres-the nerves of modern communication systems. Optic fibres not only made communication easy and fast but also made communication safe, more reliable and economical. Optic fibres also find many applications in endoscopy-a technique used to image internal parts of the body. Everything seemed to be alright with electromagnetic theory of light. But questions about black body radiation, photoelectric effect etc. demanded a radically new theory for light.

In order to explain black body radiation spectrum, Max Planck in 1900 proposed a revolutionary theory in which he said light consists of packets of energy called quanta. Each quantum is assumed to possess an energy which is an integral multiple of the product of Planck's constant (h) and frequency of radiation (f). Thus energy of a quantum of light is $E = nhf = \frac{nhc}{\square}$, where '$n$' is an integer. This theory was later employed by Einstein to explain photoelectric effect in 1905, for which he was awarded Nobel Prize in physics in the year 1921. The quantum nature of light was further reaffirmed by Compton effect and its explanation. The theory dealing with the absorption and emission of light from matter is now known as quantum electrodynamics (QED). It came into existence with the efforts of Feynman, Schwinger and Tomonaga. It is regarded as the most successful theory of light and matter. Light is now known to exhibit both particle and wave nature to different extent depending on physical conditions. It has further led to the unravelling of the dual nature of matter.

**Swift To 'c' From Theories Of Relativity**

An extraordinary position to the speed of light came from special theory of relativity (STR) proposed by Einstein in1905. Einstein formulated his theory on the basis of two important postulates that 'All laws of physics are the same in all inertial frames of reference which are moving with constant velocity relative to each other' and 'The speed of light in vacuum is the same in every inertial frame'. It is called Lorentz invariance of physical laws (David McMahon, 2006). This was a tremendous blow for the belief that speed of light depended on the velocity of the observer. His bold assumptions placed a maximum limit for the speed of light in particular and all matter and energy in general in free space. On the basis of these Einstein was able to deduce his famous mass-energy equation $E = mc^2$. The validity of STR was experimentally verified by Hughes and Drever independently in the early 1960's through their spectroscopic tests on isotropy of mass and space and hence the isotropy of 'c'. Even very recent experiments such as atomic frequency measurement carried out by Wolf et al. in 2006, the spin precession frequency in stored ultra-cold neutrons. Altarev et al. in 2009 have confirmed the Lorentz invariance and validity of another principle called the equivalence principle. STR predicted surprising results such as 'Length contraction', 'Time dilation', 'Variation of mass with velocity' etc**.** (Venkat Raman, 1999) . They have all been verified in several precision experiments. STR did not just affirm that the speed of light as an invariant physical parameter but radically changed our view of space and time. It led to the unified entity called space-time shattering the Newtonian view of absolute time. The speed of light has thus ushered in what we call 'modern physics'.

The Lorentz transformation equations used in STR show that both the time passage and length in the direction of traverse become zero at the speed of light (Gribbin, 1905). Thus time passage indeed stops. Inertial mass and time intervals have reciprocal relationship and are linked by Lorentz factor $\gamma = \sqrt{1 - \frac{v^2}{c^2}}$. So these things become infinite at light's speed. Infinite time intervals mean that a second last forever at light's speed. At speeds greater than speed of light, the Lorentz factor become imaginary, hence this puts a maximum limit for speed of material bodies. It is also the highest signal velocity of the interaction between particles. It also implies that all massless particles travel with the speed of light ((Gardner, 1962), (Einstein, A. 1961))

Suppose if we imagine that we travel with the speed close to speed of light, strange visual effects may appear. Relativistic aberration would cause objects to appear to bunch up and the Doppler shift would cause the colours of forward objects to shift towards blue, while the things behind shift towards red. These consequences were tested by Ives and Stilwell using hydrogen molecules.

STR holds good for inertial frames. For accelerated frames Einstein proposed a new theory called general theory of relativity (GTR) in 1916. This GTR predicts that quantum of light (Photon) has inertial mass although its rest mass is zero and hence could be affected by strong gravitational field. In 1919 a team of researchers led by Sir Arthur Eddington conducted a famous experiment to measure the precise location of stars surrounding the sun during an eclipse. Eddington's results confirmed the phenomenon that Albert Einstein had predicted four years earlier – that the light from stars would "bend" due to the gravitational effect of the sun, thus shifting the position of the stars slightly.

**Beating the Speed of Light**

But the STR does not rule out the presence of (hypothetical) particles that can only travel faster than light. These particles are named Tachyons by physicists in the 1960s.These subatomic particles would actually need an infinite amount of energy to slow down to the speed of light.

Tachyons are thought as possibilities in several important physical theories such as String theory. Physicists are searching for clues which support their origin. Since they were thought to be high energy particles, if they hit earth from space they would produce an effect similar to that produced by cosmic rays. But no tachyons have ever been detected so far.

In September 2011, the OPERA(The Oscillation Project with Emulsion -tRacking Apparatus) collaborative experiment which joins CERN(The European Organization for Nuclear Research) scientists with their counterparts located 730 km away at Italy's Laboratori Nazionali del Gran Sasso (LNGS), found that neutrinos sent from the former to the latter location appeared to reach their destination 60 nanoseconds sooner than photon light particles. In March 2012 the ICARUS (Imaging Cosmic And Rare Underground Signals) experiment reported the neutrino velocities to be consistent with the speed of light, In June 2012 new results from CERN confirmed that the results of OPERA experiment which appeared to suggest that neutrinos could travel faster than light were incorrect. A faulty element of the fibre optic timing system has been said to be the cause of error. Thus, no particles have been found to have velocities greater than that of light.

**Vacuum and the speed of light**

Vacuum is one of the most fascinating concepts in physics. James Clerk Maxwell first imagined that light-speed in a vacuum is a constant throughout the universe. However, at a quantum level, it doesn't stay a vacuum: pairs of particles and antiparticles (quarks and antiquarks, electron-positron) that arise spontaneously and annihilate each other, these are called vacuum fluctuations.

This quantum noise preserves Heisenberg's uncertainty principle, since even the coldest vacuum of space can't be perfectly described as being empty; and vacuum fluctuations can even interfere with the most sensitive physical instruments.

A study, by Marcel Urban of France's University of Paris-Sud in Orsay, suggests that the energy fluctuations in vacuum could also affect the speed of light, since there's a statistical chance that light will interact with these virtual particles (pairs of particles and antiparticles). The fluctuations of the photon propagation time are estimated to be of the order of 50 attoseconds ($50\times10^{-18}$ s) per square meter of crossed vacuum, which might be testable with the help of new ultra-fast lasers (GerdLeuchs and Luis L. Sánchez-Soto ,2013). But these ideas need to be tested for better understanding of vacuum.

**Refractive Index of a material and the Speed of light**

The refractive index of a medium is a measure of the speed of light in that medium. It is expressed as the ratio of the speed of light in vacuum to that in the medium in which light is propagating. The velocity at which light travels in vacuum is treated as a physical constant. However, light travels slower through any given material, or medium, that is not a vacuum. This means that the value of refractive Index of any material is greater than 1. A refractive index of less than 1 is impossible. This would mean that light in this medium was travelling at a speed faster than the speed of light in vacuum.

The possibility of negative refractive index materials (NIM) was first raised by the Russian physicist, Victor Veselago, in the 1960s. He thought that if any one of two quantities, the electric permittivity and the magnetic permeability, of a material, was negative, Maxwell's equations of electromagnetism would give a negative refractive index. The theoretical possibility of a material with negative refractive index was known about, but until recently it was assumed that no such material existed. In the year 2000, David R Smith's team of University of California researchers produced a new class of composite materials by depositing a structure onto a circuit-board substrate consisting of a series of thin copper split-rings and ordinary wire segments strung parallel to the rings. This material exhibited unusual physical properties such as negative RI. When first demonstrated in 2000, the composite material was limited to transmitting microwave radiation at frequencies of 4 to 7 GHz (4.28-4.49 cm wavelengths). This range is between the frequency of household microwave ovens (~2.45 GHz, 12.23 cm) and military radars (~10 GHz, 3 cm). In 2007 NIST( National Institute of Standards and Technology ) in collaboration with the Atwater Lab at Caltech created the first NIM active at optical frequencies. It may seem that, in a material with negative refractive index, light propagates backwards, meaning reversibility in its handedness (i.e. opposite to the incident direction). This contradiction is due to the important distinction between the phase velocity of light and its group velocity. The individual wave fronts that makeup the light beams (the phase) travel backwards, but the beam itself (the group) which carries energy travels forwards. Scientists are engaged in understanding such mysterious effects.

**Arresting the 'speed of light'**

It is well known fact that light interacts with matter under certain conditions leading to abrupt transitions in the energy levels of atoms in the matter. The interaction of light with matter depends on frequency of light and its coherence. Thus lasers interact with matter strongly and lead to remarkable properties. Using the concept of 'coherent quantum superposition' it is possible to reduce speed of light to smallest value and it is even possible to halt it. If a light pulse is made to pass through a medium, it is effectively compressed by the ratio $\frac{c}{v_g}$ . Where

$v_g$ represent group velocity of the wave in that medium and $c$ is the speed of light in free space. Thus the pulse get delayed by a factor $\tau = \left(\frac{1}{v_g} - \frac{1}{c}\right)L,$ where $L$ is the length of the medium (Ziolkowski, R. W. , 2006) .

In 1999, Lene Hau et.al, at Harvard University could able to slow down a pulse of laser to a speed 30ms$^{-1}$ in ultra-cold sodium gas. In 2001, Lene Hau et. al were able to trap the laser pulse completely in a cloud of ultra-cold sodium atoms up to one millisecond. This kind of frozen light has promising applications in memory devices as one can use it as quantum information carrier once stability is achieved. Slowing down the light speed could have a number of practical consequences, including a great potential to send data, sound, and pictures in less space and with less power. The power to control light is seen as a key development for quantum information and communication. This may also bring a revolutionary enhancement in memory storage capacity of memory devices. It is the basic science which has sowed these dreams, now it is up to technology to realize these dreams.

## Concluding Remarks

The speed of light has fascinated the imagination of scientists for over two thousand years. Its measurements have been made right from the seventeenth century with ingenious methods with ever increasing precision. The speed of light was an important clue in the unification of electricity, magnetism and optics. It heralded the advent of modern physics, breaking the shackles of absolute time and mechanistic view of the physical world. Indirectly, it has led to the development of quantum electrodynamics, astrophysics and cosmology. Measurement of accurate value of speed of light with ever precision has brought up greater accuracy in modern communication and technologies, thus the speed of light has become an inherent aspect that should be understood by everyone who wish to pursue science or technology. Hence, we see that 'c' occupies a very important position among the alphabet of modern physical theories!.

**Acknowledgements**: We would like to thank Dr. B.A Kagali (Professor of Physics, Bangalore University, Bengaluru) for constructive discussions.

## References

Born, M. (1965). *Einstein's Theory of Relativity* U.S.A, Dover Publications.

Einstein, A. (1961). *Relativity: The Special and the General Theory - A clear explanation that can understand*, New York, NY: Random House.

Fayngold, M. (2002). *Special Relativity and Motions Faster than Light* Wiley VCH.

Gardner, M. (1962). *Relativity Simply Explained*. Mineola, NY: Dover Publications, Inc.

GerdLeuchs, B. and Sánchez-Soto L. L. (2013). A sum rule for charged elementary particles, *European Physical Journal D, DOI 10.1140/epjd/e2013-30577-8*

Gribbin, J., and Gribbin, M. (2005). *Albert Einstein, and the Theory of Relativity,* New York: Chamberlain Brothers.

McMahon, D. (2006). *Relativity Demystified* New Delhi, India, Tata McGraw - Hill Education.

Michelson, A.A. (1995). *Studies in Optics*, U.S.A, Dover Publications.Ajoy K Ghatak, (2009) *Optics,* New Delhi, India, Tata McGraw- Hill Publishing Co.

Venkatraman, G. (1999). *At the Speed of Light,* New Delhi, India, Vignettes in Physics Series, University Press.

Ziolkowski, R. W. (2006). *Metamaterials: Physics and Engineering Explorations.* Chapter 1. ISBN 978-0-471-76102-0. Wiley & Sons.