Is the Speed of Light Variable?

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Vic Stenger

In his 1905 theory of special relativity, Einstein hypothesized that the speed of light in a vacuum, *c*, is a universal constant that is independent of the motion of the source of light or observer. Since then, the predictions of the theory have stood up under the most stringent empirical tests. Indeed, modern physics rests on the solid foundation of relativity.

Nevertheless, we occasionally read in the media claims that "Einstein was wrong" and that *c* is a variable. After all, this is science and isn't every statement provisional?

Not in this case. By current international convention, *c* is a constant by definition. In physics, time and space are operationally defined and their deeper "meaning" left to philosophers and theologians. Time is what you measure on a clock. And, until recently, distance was what you measured with a meter stick.

The second is now defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine energy levels of the ground state of the Ce^{133} atom. Let me go back in history a bit and trace the development of the other basic unit, that of the meter as the unit of distance.

In 1793, the meter was introduced as 1/10,000,000 of the distance from the pole to the equator. In 1889 the standard meter became the length of a certain platinum-iridium bar stored under carefully controlled conditions in Paris. In 1906, the meter was redefined as 1,000,000 / 0.643 846 96 wavelengths in air of the red line of the cadmium spectrum. In 1960 it became 1,650,763.73 wavelengths in a vacuum of the electromagnetic radiation that results from the transition between two specific energy levels (2p10 and 5d5) of the krypton 86 atom. Finally, in 1983, the meter was defined to be the distance traveled by light in vacuum during 1/299,792,458 of a second.

Check what this last definition implies. Distance is no longer what you measure on a meter stick. As with time, it is what you measure on a clock. And, the speed of light in a vacuum *c* = 299,792,458 meters per second, *by definition.* Einstein's hypothesis is now built into our very definitions of time and space.

So, anyone claiming that *c* is not a constant is wrong. That's not opinion. That's inarguable fact. He might as well claim that a dollar is not a hundred cents. Now, perhaps someday it will turn out that defining distance this way was a bad move and some clock-independent operational definition of distance should be re-introduced. But, until then, without a redefinition of distance, any claim that *c* is variable is simply false.

Now, let me add a few elaborations. First, what we call "the speed of light in a vacuum" and label by *c* is technically not the speed of light at all but some limiting speed that an object initially traveling at less than *c* cannot be accelerated beyond. In principle, if the photon has some mass, no matter how tiny, then it is in fact not going at the speed *c* but something less. However, the mass, or rest energy, of the photon has a measured upper limit of $2x10^{-16}$ electron-volt, 22 orders of magnitude less than the mass of an electron. This implies that the speed of the lowest energy photon we know about, one in the 3K cosmic microwave background, with energy 1/4000 electron-volt, is moving at (1-

3.2×10^{-25})*c*. Furthermore, *gauge invariance*, a fundamental axiom of quantum electrodynamics, requires that the photon have exactly zero mass.

Second, there is no such thing as a perfect vacuum in the universe and so any observed light beam must travel through a medium and will have an effective speed c/n, where n is the index of refraction of the medium. While this usually yields speeds less than *c,* some media, such as highly ionized plasma, can have an index of refraction less than 1 over a limited light frequency range. In that case, the effective light speed can exceed *c*.

Third, when we have a localized pulse of light that contains photons of different energies or frequencies, the pulse will not move at *c* but at some "group velocity." This, too, is usually less than *c*.

Any one of these situations may be what people are talking about when they say the "speed of light is not constant." None of them mean that the limiting speed *c* is variable, which, as we have, seen, it cannot be as long as we maintain our current operational definitions of time and space. And none of these cases imply that Einstein was wrong or that we have to rewrite over a century of established physics.

Note that *c* is not just a constant but any old constant we want it to be--except zero. It is just a unit conversion factor we use to maintain the anachronism that distance and time should have different units. The "natural" unit system takes $c = 1$.

Similarly, Planck's constant *h,* and Newton's gravitational constant *G* are also arbitrary conversion factors whose values are governed by the unit system we choose to use. In so-called Planck units, $c = \hbar = G = 1$, where $\hbar = h/2\pi$. On the other hand, the dimensionless quantity $\alpha = e^2/\hbar c$, which is misleadingly called the "fine structure constant," where *e* is the unit electric charge, is not constant at all in the standard model of elementary particle and forces but depends on energy. Since $\hbar c$ is constant by definition, it follows that *e* is variable. Recent claims that α is varying with cosmological time do not imply that Einstein or anything else in conventional physics is wrong.

Vic Stenger is working on two new projects: *Where Do the Laws of Physics Come from?* and *The Godless Universe: The Scientific Case Against God*. For more details, so to his web site is at http://www.colorado.edu/philosophy/vstenger.