LETTERS TO THE EDITOR

PHYSICAL SCIENCES

Improved Limit on the Absence of Dispersion of the Velocity of Light

LABORATORY measurements have duly verified that the velocity of light is independent of the velocity of the source to an accuracy of 1.3 in 10^4 for γ -rays from π^0 meson decay at 6 GeV (ref. 1) and is also isotropic to better than 6 in 10^8 (ref. 2), 2 in 10^8 (ref. 3) and 2 in 10^{10} (ref. 4) in a frame of reference attached to the Earth. The best evidence that the velocity of light is independent of frequency probably depends on astronomical observations of Cepheids in the nearest galaxies, and makes it possible to set a limit of 1 in 10^8 on dispersion. Somewhat poorer limits over a much wider range of frequencies, from the visible to the radio-frequency region, have been provided by observations of flare stars⁵.

Very recently⁶, optical pulses of width of 1.5×10^{-3} s were detected in the direction of the Crab nebula pulsar⁷. If this object is identified with the supernova remnant at an estimated distance of $1,700$ pc (ref. 8), the pulse width allows a limit of $|(\Delta c/c)| = |(\Delta t/t)| = 10^{-14}$ to be put on any dispersion over the frequency range of 5 to 8×10^{14} Hz. More refined measurements using a beam splitter and suitably gated photomultiplier tubes looking simultaneously at the red and blue parts of the spectrum in conjunction with large reflectors (compare ref. 9) could improve the sensitivity—to the extent that it is limited by shot noise—by at least three orders of magnitude with integration times of a few hours.

Observations in higher frequency regions of the spectrum suggest themselves, particularly if the recent observations^{10,11} should prove that pulsars emit high energy γ -rays. Radio frequencies show large dispersion¹² because of the finite electron density in space and are unsuitable for this purpose. It is conceivable that optically (and even higher frequency) active pulsars may be associated with the more recent supernovae of Tycho Brahe (1572) and of Kepler (1604) located at comparable distances⁸. Should these younger objects have even shorter periods, an even greater improvement in the sensitivity may become possible.

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Below is the referee's report on Dr Isaak's MS, published by arrangement with the author and the referee—Editor, *Nature*.

I DO not wish to cast any doubt on the validity of the results stated, but I am wondering just what those results are. Experimentalists do not report their results in the raw form; they express them in terms of certain concepts, and that is a correct procedure, provided their concepts are correct. As the measurement of time becomes more accurate, Newtonian or quasi-Newtonian concepts become less applicable. It is imperative that results be stated in relativistic terms, preferably the general theory rather than the special theory.

One asks then: What is a frame of reference? What is the velocity of light (I do not mean the value, I mean the concept)? In Newtonian physics, one considers a rigid body with two marks on it (A and B). One measures the distance AB with a rigid scale. One arranges to have a light signal pass from A to B. One notes the times of departure and arrival (t_A and t_B). Then the velocity of light is $c = AB/(t_B - t_A)$. Very nice and simple. But when we pass to relativity, these concepts evaporate. There is no absolute time and no rigid bodies, at least none with Newtonian simplicity (compare Born, 1909). Out of this debacle, one thing emerges—proper time as recorded by a standard (or atomic) clock—and that is why the accurate time measurements become so fundamental. The measurement of proper time seems to me the most basic measurement in physics. It must then be treated with due respect.

Imagine now a physicist on the Earth engaged on optical experiments of such accuracy that he cannot afford to muddle his thoughts with Newtonian concepts. Let W_A be the world line of his source and W_B the world line of some object. He sends a light signal from source to object, and it is sent back. The (proper) time interval $T(ABA)$ is recorded by a clock carried along W_A . In this experiment, where is a velocity and where is a distance? Neither is a basic concept any longer. The basic thing is $T(ABA)$. Assuming that the experiment has been made *in vacuo*, I would say boldly that the distance is $\frac{1}{2}T(ABA)$ —as we would if this were a radar signal bounced off the Moon or a planet. As for velocity, I would try to avoid this confusing word, or I might say that by definition it is unity. No frame of reference is involved here, unless you want to call the world line W_A by that name.

Turning now to the first sentence of Mr Isaak's article, I first notice reference to possible dependence of the velocity of light on the velocity of the source. I thought that the idea of such a dependence was dead many years ago—it does not make sense relativistically. With regard to isotropy, it is tautologous to verify it, for it is built into the definition of distance in terms of time, as indicated here. The question of what we can find out (without tautology) from refined optical experiments on the Earth has been dealt with in detail in my *Relativity: the General Theory* (North-Holland, 1964), p. 401. We can, of course, in principle measure the Earth's rotation (as Michelson did long ago using oil-pipes in the desert). We can also find the curvature of the observer's world line (which is the familiar g), and we can in principle find out something about the real gravitational field as incorporated in the Riemann tensor. But of course the effects are so small that one needs either a large apparatus or much more accurate clocks. The essential thing is to distinguish between what is relativistically real (physics) and the old outmoded ideas inherited from the Newtonian standpoint.

But the article is primarily concerned with dispersion—the dependence of velocity on frequency. Two photons with different frequencies start from a distant object and reach us within a certain short interval of time. Hence an estimate of a limit on dispersion. All I would say here is that it should be made clear that the "velocity" in question is the group-velocity relative to some postulated medium, not the phase-velocity.