Is the Speed of Light Independent of the Velocity of the Source?

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Recent observations of regularly pulsating x-ray sources in binary star systems are analyzed in the framework of the "emission" theory of light. Assuming that light emitted by a source moving at velocity v with respect to an observer has a speed $c' = c + kv$ in the observer's rest frame, we find that the arrival time of pulses from the binary x-ray sources implies $k < 2\times 10^{-9}$. This appears to be the most direct and sensitive demonstration that the speed of light is independent of the velocity of the source.

The special theory of relativity[1] is founded on two distinct postulates: (I) Any law of physics which holds in one coordinate system also holds in identical form in any other coordinate system moving uniformly with respect to the first—this is known as the principle of relativity; and (II) the velocity of electromagnetic radiation is independent of the velocity of the source. Taken together, these two postulates lead to a view of space and time with profound and disturbing consequences. Special relativity receives direct and indirect support from all of physics and, most stringently, through studies of the entire range of electromagnetic phenomena, from classical optics to quantum electrodynamics. However, despite numerous experimental verifications of the first postulate,[2] there have been very few direct demonstrations of the validity of the second postulate.[3-5] As Fox has emphasized,[6] some of the laboratory experiments may not provide unambiguous tests of (II) and have not been universally accepted. I therefore wish to present a more direct and sensitive extraterrestrial test of the second postulate.

Ritz[7] has proposed a version of electrodynamics which retained the two homogeneous Maxwell equations but changed the source equations in such a way that the speed of light would be c only relative to the source. In the "emission" or "ballistic" theories, electromagnetic radiation emitted by a source moving with velocity v with respect to a stationary observer would propagate with velocity $c' = c + v$ in the stationary observer's rest frame. To test the validity of the "emission" theory, it is convenient to hypothesize

$$c' = c + kv, \tag{1}$$

where k is a constant (1 for the Ritz theory; 0 for the Einstein theory) to be determined by experiment.

De Sitter[8] pointed out that if the velocity of light did depend on the velocity of the source, binary star systems would show peculiarities which has never been observed: The time order of events could be reversed, multiple images of a star could exist, and, he suggested, an apparent orbital eccentricity would appear. The absence of such effects has often been cited as evidence against the emission theories. However, it has been noted by Fox[6] that extraterrestrial observations at optical wavelengths may not bear on the validity of Eq. (1) at all. This is because the radiation from a distant star is scattered while propagating through the intervening circumstellar and interstellar matter. By the "extinction theorem"[9] of Ewald and Oseen, in a dispersive medium, the incident electromagnetic wave will be replaced by the reradiated fields produced by the dipoles of the medium. The resulting wave will propagate with a phase velocity characteristic of the medium. For radiation with free-space wavelength λ propagating in a medium with index of refraction n, the characteristic extinction length χ is $\chi = \lambda/2\pi|n-1|$. A plasma with electron density N has $\chi \cong (\lambda a_0 N)^{-1}$, where $a_0 = e^2/mc^2 \simeq 2.82 \times 10^{-13}$ cm. At an optical wavelength $\lambda = 5000$ Å, $\chi \simeq 0.75 N^{-1}$ light years. With $N \cong 0.04$ cm^{-3} (a typical value derived from pulsar dispersion measures) one has $\chi \simeq 2$ light years—less than the distance to the nearest star.

However, for 70-keV x rays (the highest energy at which the sources discussed below are known to pulse regularly) one has $\chi \simeq 20$ kpc ($\simeq 3 \times 10^{22}$ cm). Thus interstellar extinction will not invalidate observational tests made with Galactic hard-x-ray sources lying closer than the 10-kpc distance to the Galactic center or with extragalactic sources observed through the thin (~1 kpc) disk of our Galaxy. (If χ were less than the distance D from Earth to the source, in the following discussion one would have to use χ in place of D.) Furthermore, none of the systems considered below appears to contain sufficient circumstellar gas (which is not corotating with the x-ray source) to "extinguish" the initial wave and replace it by one propagating in a medium whose velocity is zero with respect to Earth.

To see what peculiar effects arise if $c' \neq c$, consider two stars in a binary system at a distance D from Earth and orbiting about their common center of mass in circular orbits with period $T = 2\pi/\omega$. Let one of the sources emit pulses at a constant rate in its own rest frame. Take the semimajor axis to be r_0 and the (constant) orbital speed of the x-ray star to be v_0, so that the projected semimajor-axis and line-of-sight (radial) velocity of the pulsating source are, respectively, $r = r_0 \sin i$ and $v = v_0 \sin i$ (where i is the inclination angle of the orbital plane). The projected radial velocity (toward the observer) will then vary with time as $v(t') = v \cos\omega t'$, where t' is measured in the source frame. Now consider a pulse emitted at the time t' in the source frame. If $v \ll c$, it will arrive at Earth at time

$$t \simeq t' + (D - r\sin\omega t')/(c + kv\cos\omega t'). \qquad (2)$$

For $D \gg r$ and $v \ll c$, Eq. (2) becomes

$$t \simeq t' + \frac{D}{c} - \frac{r}{c}\sin\omega t' - \frac{kDv}{c^2}\cos\omega t'. \qquad (3)$$

Differentiating with respect to t', one has

$$\frac{dt}{dt'} \simeq 1 - \frac{v}{c}\cos\omega t' + \frac{kDv\omega}{c^2}\sin\omega t'. \qquad (4)$$

Clearly, unless $\omega kDv/c^2 \ll 1$, the time between pulses will not fit a simple sinusoidal Doppler curve. In fact, if $\omega kDv/c^2 > 1$, it will appear that pulses arrive from more than one position in the orbit at the same received time. The absence of such "ghosts" (or anomalous pulses) in the observed x-ray pulses from the binary x-ray sources already limits k to $k < k_g$ where

$$k < k_g \equiv Tc^2/2\pi Dv. \qquad (5)$$

If we rewrite Eq. (4) as

$$dt/dt' = 1 - (V/c)\cos(\omega t' + \varphi), \qquad (6)$$

where $V = r\omega\sec\varphi$ and $\tan\varphi = kD\omega/c$, another effect becomes apparent. Consider a small star orbiting about a much larger companion just above its surface. The small star will be eclipsed by its companion, disappearing at time, say, $t_1' = \pi/2\omega$ and reemerging at time $t_2' = 3\pi/2\omega$. From Eq. (3) we see that these two events appear to occur in Earth's frame at times $t_1 = \pi/2\omega + D/c - r/c$ and $t_2 = 3\pi/2\omega + D/c + r/c$. The midpoint of the eclipses, as determined at Earth, will occur at time $(t_1 + t_2)/2 \equiv t_E = D/c + \pi/\omega$. However, as determined by the Doppler curve (when $dt/dt' = 1$), this event will occur at time $t_D \simeq D/c + \pi/\omega - \varphi/\omega(1 + r\omega/c - kDv\omega/c^2)$. Thus for $kDv\omega/c^2 \ll 1$ and $r\omega/c \ll 1$, the time of mideclipse determined by the Doppler curve will be offset from the occultation-determined mideclipse time by an amount $t_E - t_D \simeq \varphi/\omega$. Therefore, the orbital phase as determined by these two independent methods will differ by an amount $\varphi_E - \varphi_D = \tan^{-1}(kD\omega/c)$. For $kD\omega/c \ll 1$, an upper limit on the difference between the orbital phases as determined by these two methods, $\Delta\varphi$, places the further constraint on k:

$$k < k_p \equiv \Delta\varphi c T/2\pi D = (v\Delta\varphi/c)k_g. \qquad (7)$$

Finally, for completeness, I examine the effect pointed out by de Sitter[6] which is usually cited as a major argument against the emission theory. By using the locally measured Doppler velocity $V(t)$, in the emission theory, here derived from the pulse arrival times, an *apparent* orbital eccentricity could appear. To derive this effect, one must assume that $1 \gg kDv\omega/c^2 \gg r\omega/c$ (thus $k\omega D/c \gg 1$). Then the $\sin\omega t'$ term may be neglected, and t' found in terms of t as

$$t' \cong \left(t - \frac{D}{c}\right) + \frac{kDv}{c^2}\cos\left[\omega\left(t - \frac{D}{c}\right)\right]. \qquad (8)$$

Substituting (8) into (6) one has (with $t_0 = D/c$)

$$v(t) \simeq v\cos[\omega(t - t_0) + (kDv\omega/c^2)\cos\omega(t - t_0)]. \qquad (9)$$

If one assumes special relativity to be valid, an elliptical orbit (with eccentricity $e \ll 1$) will show a Doppler velocity[10]

$$v(t) \simeq v\cos[\omega(t - t_0) + 2e\cos\omega(t - t_0)]. \qquad (10)$$

Therefore, the emission theory could lead to an apparent eccentricity in the orbit of binary stars (in addition to any true eccentricity) of $e \simeq k\pi Dv/Tc^2$. An upper limit on any allowed orbital eccentricity would then imply

$$k < k_d = Tc^2 e/\pi v D = 2ek_g. \qquad (11)$$

However, in deriving this effect, one must assume that $kDv\omega/c^2 \gg r\omega/c$, which implies that $kD\omega/c \gg 1$. But none of the sources discussed below (nor, in fact, any of those discussed by de Sitter) satisfies the relation unless $k \gg 1$, contrary to our starting assumption that $k \leq 1$. For $k \leq 1$, some such effect may still arise, but the appar-

TABLE I. Observed properties of binary x-ray sources and derived upper limits on k.

Object	$v_0 \sin i$ (km/sec)	D (kpc)	T (days)	$\Delta\varphi$ (rad)	k_g	k_p
Her X-1[a]	169	~ 6	1.70	<0.06	$<7\times10^{-5}$	$<2\times10^{-9}$
Cen X-3[b]	415	~ 8	2.09	$\cdots$	$<2\times10^{-5}$	$\cdots$
SMC X-1[c]	299	$\gtrsim 60$	3.89	<0.05	$<8\times10^{-6}$	$<4\times10^{-10}$

[a]H. Tananbaum *et al.*, Astrophys. J. Lett. 174, L143 (1972); W. Forman *et al.*, Astrophys. J. Lett. 177, L103 (1972); E. Schreier, private communication.

[b]E. Schreier *et al.*, Astrophys. J. Lett. 172, L79 (1972); G. Fabbiano and E. Schreier, Astrophys. J. 214, 235 (1977); W. Krzeminski, Astrophys. J. Lett. 192, L135 (1974).

[c]E. Schreier *et al.*, Astrophys. J. Lett. 178, L71 (1972); R. Lucke *et al.*, Astrophys. J. Lett. 206, L25 (1976); F. Primini *et al.*, to be published; E. Schreier, private communication.

ent eccentricity will no longer be given by Eq. (11). Since, in any case, the phase argument provides a stronger constraint by a factor $v\Delta\varphi/2ec$ for the binary star systems which we discuss below, we will not use this effect as a test of the emission theory.

There are about 200 known discrete x-ray sources lying in the Galaxy and the nearby Magellanic Clouds. Of these, about ten are now known to pulse regularly at energies up to 70 keV and move in binary systems, providing good clocks with which to test the emission theory. The sources Her S-1, Cen X-3, and SMC X-1 are the best studied examples providing eclipses, accurate Doppler velocities, orbital periods, orbital phase, and good estimates of their distances. (In deriving $v_0 \sin i$, one assumes $k=0$. For $k=1$, as long as $v/c \ll 1$, only a small change in the deduced values of $v_0 \sin i$ arises.) Since the Doppler orbital phase for each of the sources is determined with high accuracy (the uncertainty in φ_D is much less than 1°) the maximum allowed value of $\Delta\varphi$ is taken to be the uncertainty in the eclipse-determined phase. The upper limits on k set from the lack of multiple images or confused pulses (k_g) and from anomalous phase shift (k_p) are also given. Note that the phase shift, which depends *only* on the orbital period and source distance, provides the most stringent upper limit. (For Cen X-3, a reliable eclipse phase has not been determined and is not included.) Of the three objects, the source in the Small Magellenic Clouds (SMC X-1) could provide the strongest limit. In that direction, since the path to the source is primarily through intergalactic space with $N \ll 0.04$ cm^{-3} (see reference cited in footnote c in Table I) it appears that $\chi \gg D$, ensuring the lack of significant interstellar "extinction."

However, to be conservative, we shall take the result from Her X-1 to be the most reliable since the present results assume that any stellar of circumstellar "extinction" must occur predominantly in gas corotating with the pulsating source. This is almost certainly true for Her X-1 which appears to be powered by Roche overflow mass transfer onto the neutron star. For Her X-1, the soft-x-ray cutoff energy derived from model spectral fits implies a gas column density arising in the source emitting region (and corotating with it). However, for sources such as Cen X-3 or SMC X-1 which may be powered by mass accretion from the stellar wind of a companion star, any significant extinction occurring in the stellar wind would still give rise to a time-dependent value of c' (depending on the value of the stellar-wind velocity—typically 10^3 km/sec and greater than the orbital velocity), certainly producing (unobserved) ghost pulses and probably a phase shift (with v_{wind} in place of V_{source}). With these remarks in mind, I conclude that

$$k < 2\times10^{-9}. \qquad (12)$$

This result can be compared with the best terrestrial limit on k. From a time-of-flight measurement of the decay γ rays from 6-GeV π^0 mesons, Alvager *et al.*[4] found $k<10^{-4}$. (While special-relativistic kinematics is used in deriving the pion velocity, the result would change only marginally if the pion velocity were derived using Galilean kinematics.) Thus, the present extraterrestrial limit is about 10^5 times more stringent than the limit set by laboratory experiments.

In conclusion, the observed properties of the binary x-ray sources require that the velocity of electromagnetic radiation (x rays) be independent of the motion of the source to a high degree of accuracy.

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$U(1) \otimes SU(4)_L \otimes SU(4)_R$-Based Weak-Electromagnetic Synthesis with Manifest Left-Right Symmetry

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We present a gauge theory of weak and electromagnetic interactions which is based on the group $U(1)\otimes SU(4)_L \otimes SU(4)_R$ and which implements manifest left-right symmetry in a natural way. The theory is characterized by a rich lepton spectrum and is consistent with recent experimental results in atomic physics and weak trimuon production. Some novel predictions of the theory are discussed.

Recent experimental discoveries,[1-3] especially of phenomena that appear to carry the signature of new heavy leptons,[1,3] suggest that the structure of weak interactions may be somewhat more complex than heretofore suspected. In particular, these findings lend support to the view that gauge models based on the group[4] $U(1)\otimes SU(2)$ may not prove adequate for describing the full gamut of weak interactions.

Our purpose in this note is to present a synthesis of weak and electromagnetic interactions which is based on the group[5] $U(1)\otimes SU(4)_L \otimes SU(4)_R$ (hereinafter called $\mathcal{G}$) and which implements *manifest* left-right symmetry[6] in a natural way. The requirement of freedom from anomalies, in the context of this type of symmetry, leads to a rich lepton spectrum with Han-Nambu-like structure The detailed phenomenological consequences of the model depend on the nature of the symmetry-breaking pattern—a feature shared by *all* theories