

Limits on the Chirality of Interstellar and Intergalactic Space

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Abstract. We raise the question of whether velocities of left and right circularly-polarized photons might be different (for reasons other than the well-known Faraday effect). Such a difference could manifest itself either in the time profiles of pulsed or bursting astronomical sources or in the rotation of the direction of polarization of linearly polarized radiation from them. The existing observations of pulsars, gamma ray bursters, and quasar jets are used to set limits to the difference in speed, $|c(L) - c(R)|/\bar{c}$ between 10^{-17} and 10^{-32} .

Key words: Chirality—propagation of light vacuum properties.

1. Introduction

Our notions of the properties of the vacuum, as well as of the role of symmetries and their breaking, have gone through fundamental changes during this century. Nor do we still believe that interstellar (or intergalactic) space remotely resembles a vacuum. Space is known to be pervaded by electromagnetic fields and waves, by atoms, molecules, ions, and electrons, and by gravitational fields and waves. It is expected also to harbour seas of three species of neutrinos (with a presumed excess of left-handed ones, at least for the electron neutrino) and a Higgs field. Some of these are known to have left-right asymmetries of various kinds, and others are conjectured to, including the gravitational field (Morrison & Gold 1957; Schiff 1958; Leitner & Okubo 1964). Finally, some metrics that are solutions of Einstein's field equations, including the Gödel (1944) metric for a rotating universe, predict differences in the propagation of photons as a function of polarization (Korotkii & Obukhov 1995). Other forms of rotating universe can already be ruled out because of their enormous effects on the isotropy of the microwave background (Collins & Hawking 1973).

We ask here (not for the first time) whether any of these might show up by giving right and left circularly-polarized photons different speeds in interstellar or intergalactic space. The one combination already known to do this is, of course, charged particles plus magnetic field, as discovered by Faraday while shining visible light through crystals in the presence of a 19th century magnetic field. In the astronomical context, Faraday's effect rotates the plane of polarization of an electromagnetic wave by an amount

$$\Delta\phi = 8.1 \times 10^5 \lambda^2 \int n_e B dz,$$

(Zombeck 1990), where $\Delta\phi$ is rotation in radians, λ is the wavelength of the observed radiation in meters, n_e is the electron density per cubic centimeter (more massive charged particles being much less effective), B is the magnetic field along the line of sight in Gauss, and z is distance to the source in parsecs.

The existence of the Faraday rotation and corrections for it have been part of radio astronomy for as long as it has been recognized that some radio sources are linearly polarized (Murray & Hargreaves 1954 on solar radio bursts; Kuz'min & Udal'tov 1959 on the Crab Nebula). Notice that, because of the λ^2 factor, you could look through an entire universe (3000Mpc) of ionized baryons ($n_e = 10^{-6} \text{ cm}^{-3}$) pervaded by a magnetic field as strong as that found inside clusters of galaxies (10^{-7} G) and find that the Faraday rotation is utterly negligible for any wavelength shorter than about 6 mm, giving us the entire infrared, optical, ultraviolet, X-ray, and gamma ray regions to explore. Again because of the λ^2 dependence, Faraday rotation at centimeter wavelengths is easily and habitually corrected for in reporting direction of linear polarization of radio sources, and is in fact frequently very small into the centimeter regime (Brown *et al.* 1992 and many other studies).

We will, in what follows, stay away from contexts in which needed corrections for Faraday rotation are large enough that there is any risk that the observations, by being too widely spaced in wavelength, might have missed any integral number of 180° rotations. Ordinary special relativistic invariance requires that $\Delta c/c$ in a true vacuum be proportional to wavelength. Thus the longest radio wavelengths may be the most fruitful hunting ground, but they are also the most difficult to explore.

2. Existing and improved limits

The most stringent published limit on $|c(L) - c(R)|/\bar{c}$ of which we are aware comes from the sharpness of the pulses of pulsar 1937 + 21. Losseco *et al.* (1989), using published data, concluded that the difference in arrival time between the two circular polarizations could not be more than the total pulse width of $50 \mu\text{sec}$. Given the pulsar distance of about 2.5 kpc, this sets a limit of $\Delta c/c = 2 \times 10^{-16}$. Their particular interest was in limiting the extent to which gravitational forces might violate conservation of the product of parity, time reversal, and charge conservation. Klein & Thorsett (1990), making use of improved observations of the pulsar at 430 MHz in all Stokes parameters (Thorsett & Stinebring 1990), set a limit of $1 \mu\text{sec}$ to the difference in arrival times, corresponding to $\Delta c/c \leq 10^{-17}$. A deliberate campaign to observe a number of suitable pulsars in both circular and linear polarizations might improve this limit by an order of magnitude (Thorsett 1995). It would be difficult to do better for both observational and theoretical reasons. First, the desire to look at distant pulsars at relatively short wavelengths means working with faint sources, for which precise timing is difficult. Second, because we have no real theoretical understanding of the pulsar emission process, there is no guarantee that the leading edge of a pulse does not systematically have a particular polarization. It is, therefore, unlikely that anything except upper limits can be extracted from pulsars.

It was the very short duration of gamma ray bursters that first started us thinking about the possibility of seeing differential travel time effects. Several searches have already been made for apparent echoes between and within the brighter bursts

(Nemiroff 1995; Norris 1995). Predictably, only upper limits have been found, some of which are interesting for other reasons (e.g., a limit on gravitational lensing by black holes that could make up a major part of cosmic dark matter, Nemiroff *et al.* 1993).

The problem with gamma ray bursters is, of course, that we do not know their distances, not even, for sure, whether they are inside or outside the Milky Way (Lamb 1995; Paczynski 1995). One burst did, however, contain a single spike lasting about 100 μ sec that was not followed by any similar one from the same part of the sky for many days (Nemiroff 1995). Thus the difference in arrival times of the two circular polarizations cannot be more than 100 μ sec. On the two most likely distance scales for bursters (Paczynski 1995; Lamb 1995), the best guesses for the distance are either 30,000 kpc (galactic halo) or 1000 Mpc (moderate cosmological redshift distance). The corresponding limits on $\Delta c/c$ are either 10^{-16} or 10^{-21} , of which the latter is indeed smaller than the pulsar limit. The fact that it pertains to very high energy photons may, however, make it less interesting.

We believe that the most striking upper limits on velocity differences between left and right-handed circularly-polarized light can be derived from linear polarization measurements of quasar jets. There now exist polarization maps of the jet of 3C 273 ($z = 0.158$) at both optical wavelengths (from HST, using the B band filter of the Faint Object Camera, Thomsen *et al.* 1993) and at 6 cm (Brown *et al.* 1992). In both images, the inner knots of the jet show considerable linear polarization essentially parallel to the jet. Further out, where the jet impacts surrounding material, the polarization is largely perpendicular to the jet direction at both wavelengths. The observers, of course, focused their discussions on the implications of these alignments for the mechanisms by which quasar jets are collimated and accelerated and inspired to radiate.

But the alignments also mean that the plane of polarization has not been rotated by more than about 45° en route, unless a remarkable coincidence has occurred at the two wavelengths. The exact limits you get on $\Delta c/c$ will depend on your choice of Hubble constant (distance scale) and curvature of space. For $H = 75$ km/sec/Mpc and $q = 1/2$, 3C 273 is 560 Mpc away from us, a light travel time of 5.9×10^{16} sec. At 6 cm and 4000 Å respectively, $\pi/2$ radians of phase correspond to time intervals of 5×10^{-11} and 3×10^{-16} sec. The implied limit on $\Delta c/c$ is then of order 10^{-27} from the centimeter data and 10^{-32} from the optical data. If you believe that any real effect ought to be proportional to wavelength, then these are really the same number.

Can these limits be improved? Yes, of course, but, like the pulsar result, probably by only about one order of magnitude. In the gamma ray burst case, a serious, signal-hunting algorithm could rule out certain kinds of microstructure within the bursts. But you run out of photons if you try to bin much more finely than 100 μ sec. Planned missions with larger collecting areas will help to remedy this problem (Norris 1995). In the quasar jet case, one can make polarization maps of sources with redshifts larger than that of 3C 273, and this has recently been done by Cawthorne and Gabuzda (1996) for 3C 279 ($z = 0.538$) and 3C 454.3 ($z = 0.859$), both of which show parallel and perpendicular polarization vectors with much the same pattern as for 3C 273. But for most cosmological models, even very large redshifts correspond to distances of 3000–6000 Mpc, only 10 times that of 3C 273, so that one might, at best, push $\Delta c/c$ down to 10^{-28} in the radio and 10^{-33} in the optical range.

3. Possible future directions

We have already remarked that the existing limits can typically be lowered only about an order of magnitude in $\Delta c/c$, even with observations explicitly designed to look for differences in propagation of photons of the two circular polarizations. Nevertheless, it would seem worthwhile for radio observers of variable sources and backgrounds to preserve their data for the separated Stokes parameters and for optical observers to collect polarization data when possible. Potential benefits include: (a) better time resolution when polarizations do not arrive simultaneously, (b) better spatial resolution in cases where photons have passed through regions where refraction is different for left and right-handed radiation so that their paths can deviate from each other, (c) additional information about emission mechanisms when polarization varies through a pulse or flare, and (d) the ability to set limits on new causes of vacuum or intergalactic chirality that might be invented in the future.

4. Conclusions

The existing data on pulsars, gamma ray bursters, and quasar jets can be used to set limits to the difference in velocity between right and left circularly-polarized light in interstellar and intergalactic space due to effects other than the Faraday rotation. The tightest limit, $\Delta c/c = 10^{-32}$, pertains to visible photons and is, therefore, not necessarily much more stringent than the radio limits of 10^{-17} to 10^{-27} , depending on how hypothetical effects might scale with wavelength. Likely dependences include linear (for chirality of the vacuum itself) and quadratic (for effects of chiral molecules). Improved observations oriented around finding differential velocity effects could tighten each of the limits by about a factor 10. The physics of the sources and of the universe itself may preclude doing much better.

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