Is the Universe Transparent to TeV Photons?

W. Kluźniak
Physics Department, University of Wisconsin, 1150 University Ave., Madison, WI 53706, USA
E-mail: wlodek@cow.physics.wisc.edu

ABSTRACT

Direct observations with ground-based instruments have shown some relatively nearby ($z = 0.03$) extragalactic objects to be powerful sources of electromagnetic radiation in the TeV range. It is thought that such radiation cannot travel much farther through the intergalactic space, but the actual degree to which TeV photons from the (as yet undetected) more distant sources are absorbed by the intervening infra-red background is still an open question, and one which will certainly be resolved by continued monitoring of the sky with present and future detectors. If, as has recently been suggested in the context of attempts to quantize gravity, Lorentz invariance is broken at an energy scale, E_Q (greater than the GUTS scale), the kinematics of photon-photon collisions would be profoundly affected at much lower energies. Specifically, electron-positron pair creation on soft photons may be forbidden at energies as low as $30\,\mathrm{TeV}\sqrt{E_Q/10^{17}\,\mathrm{GeV}}$ and the Universe would then be transparent to high energy photons. The proposition that Lorentz invariance is broken may be verifiable by the techniques of TeV astronomy.

1. Broken Lorentz invariance?

Lorentz invariance has, of course, been found to be satisfied to a high degree in all experiments performed to date. However, it has long been realized that attempts at finding a quantized description of space-time may lead to the appearance of non-Lorentz invariant terms. For example, applying quantum deformations to the 4-dimensional Poincaré group results in a so called $\kappa-$deformed Poincaré algebra[1], which corresponds to discretizing time, while "preserving almost all classical properties of three-dimensional euclidean space." The $\kappa-$deformation leads to a distorted mass shell condition of the form[1,2] $m^2 + \mathbf{p}^2 = [2\kappa \sinh(p_0/2\kappa)]^2$, with similar changes to the law of energy-momentum conservation. Here, κ is presumably the energy scale at which Lorentz invariance no longer holds accurately.

More recently, it has been suggested[3] that in a wider class of approaches to quantizing gravity the photon dispersion relation would be

$$pc = E\sqrt{1 + E/E_{QG}}, \tag{1}$$

where E_{QG} could be as low as $E_{QG} \geq 10^{16}\,\mathrm{GeV} \sim 10^{-3} E_{Planck}$, and would presumably be related, e.g., to some characteristic length scale on which the discrete nature of space-time becomes apparent, $l \sim E_Q^{-1}$. One consequence[3] of photons having a three-momentum of the magnitude given by eq. (1), would be that high-energy electromagnetic radiation would travel with a speed dependent on the photon energy, $v = c(1 - E/E_{QG})$, where c is the ordinary speed of light.

In the discussion below, I assume that the photon dispersion relation of eq. (1) is valid, and show,[4] that it would have drastic effects on the kinematics of photon-photon collisions. When the soft photon has energy E_1 in the optical or infrared range, these new effects would appear when the energy, E_2, of the other photon is in the TeV range, more precisely, when $E_2 \sim \sqrt{E_1 E_{QG}}$. This would make the currently observable Universe transparent to high energy photons. Similar considerations,[5,6] suggest that the Greisen-Kuzmin-Zatsepin cutoff would also not hold, i.e. the universe would be transparent to multi-PeV protons, as well.

2. Extragalactic TeV astronomy and the IR background

TeV photon astronomy is a well established field with the spectrum of at least one steady Galactic source (the Crab pulsar) reliably and reproducibly determined,[7] through observations of the Čerenkov radiation of atmospheric showers. Numerous powerful extragalactic sources, as well, are expected to exist in the violent Universe. However, only the closest are thought to be observable, because of severe attenuation[8,9] of TeV radiation over distances much larger than $\sim 100\,\mathrm{Mpc}$ by pair creation on the infrared background (IR), and (over much shorter distances) of ∼PeV radiation by the 2.7K cosmic microwave background. The limits on the propagation distance of Ultra High Energy (UHE) photons are so well established theoretically, that possible detections[10,11] of two particular gamma-ray bursts (GRBs) at, respectively, more than 50 TeV and more than 13 TeV, were interpreted in the context of supposed Galactic origin of GRBs.

However, the *observational* evidence for (or against) attenuation of the UHE signal over large distances is less secure. It is true, that only a few extragalactic sources have been reported, with the two best established (Markarian 421 and 501) at a relatively close distance (redshift 0.031 and 0.033, respectively), while brighter but more distance blazars in the EGRET catalog (of sources of multi–GeV radiation) have not been observed—this would be consistent with the predicted attenuation. On the other hand, the fairly large distance to these sources and the high energy range of observation (above 20 TeV) were an embarassment to some fairly recent estimates of the attenuation, so now the trend seems to be to constrain[12,13] the IR by fitting the data on Mkn 421 and Mkn 501 to theoretical models of UHE emission, and even to use the suggested attenuation to model Galaxy formation.[14] Further, the observed power-law spectrum of Mkn 421 is clearly different from the "curved" spectrum of Mkn 501, in spite of their nearly identical distance, strongly suggesting[15] different intrinsic spectra in different sources. Moreover, Mkn 421 is known[a] to be extremely variable[16].

[a] With one flare so short (several minutes) that it was possible to limit[17] the "quantum gravity" scale to $E_Q \geq 4 \times 10^{16}\,\mathrm{GeV}$, on the assumption that eq. (1) holds, so that a dispersion would be expected[3] between higher and lower energy photons from Mkn 421, as discussed in Section 1.

Thus, it is as yet uncertain whether the more distant AGNs are truly invisible in UHE (e.g. 30 TeV) photons. The same is even more true of gamma-ray bursts, where models[18] of UHE emission and TeV observations[10,11,19,20] are even less clear. However, as all GRBs are thought to be cosmological in origin, with redshifts $z = 0.835$, $z = 3.4$, and $z = 0.97$ reported for three particular sources[21,22,23], the importance of potential secure detections of UHE photons in spatial and temporal coincidence with a GRB cannot be overstated, as they could clearly indicate that the universe is transparent to high energy photons.

3. Kinematics of pair creation

It remains to show that with dispersion relation of eq. (1), pair creation is forbidden for very asymmetric photons. This is related to the excess momentum of the higher energy photon. Regardless, of whether an additional term appears, or not, in the dispersion relation for the electron, as in

$$m^2c^4 + p^2c^2 = E^2 + E^3/E_{QG}. \tag{2}$$

and whether or not a term of the same order as the last term in eq. (2) appears in the law of conservation of energy-momentum the result is the same qualitatively: in addition to the usual threshold for pair creation, $E_1E_2 \geq m^2$, there is a maximum energy of the hard photon $E_2 \sim \sqrt{E_1/E_Q}$. This result is really a consequence of the non-existence of the center of momentum when E_2 exceeds $\sim 2\sqrt{E_1/E_Q}$.

As a specific example, suppose that the ususal conservation law is true

$$E_T = E_1 + E_2 = E_1' + E_2' \,, \text{ and } \mathbf{p_1} + \mathbf{p_2} = \mathbf{p_1'} + \mathbf{p_2'} \,. \tag{3}$$

Of course, all calculations must be done in a single frame of reference, because we do not know how to transform frames.

Now, if eq. (2) holds (with eq. [1] a special case for m=0), and if two particles of equal energy are created in a head-on collision of two photons, then[4] eq. (3) holds, i.e., high energy photons are absorbed, only if

$$E_2 \leq 2\sqrt{2E_1/E_{QG}}. \tag{4}$$

To illustrate the independence of the result on the dispersion relation, and indeed the mass, of the electron, consider now that eqs. (1) and (3) hold together with $m^2c^4 + p^2c^2 = E^2$. Then pair creation by two photons of energies E_1, E_2, is possible iff

$$E_1E_2 \geq m^2c^4 + (E_1 - E_2)^2(E_1 + E_2)/(4E_{QG}),$$

yielding the usual threshold for symmetric energies, but also an upper limit to the photon energy, similar to that of eq. (4)

$$\frac{m^2c^4}{E_1} \leq E_2 \leq 2\sqrt{E_1E_{QG}}.$$

4. Conclusions

If Lorentz invariance is modified, the kinematics of photon-photon collisions (as well as of other transformations of particle identity) will certainly be drastically modified. Although, there is no known self-consistent theory of quantum gravity, if it is true that the dispersion relation of eq. (1) will hold for photons in a future theory, it seems very likely, as for the specific examples above, e.g. eq. (4), that the universe will be transparent to photons of energies higher than $(30\,\mathrm{TeV}) \times \sqrt{E_Q/10^{17}\,\mathrm{GeV}}$.

5. References

1) Lukierski, J., Nowicki, A.& Ruegg, H., *Phys. Lett.* **B 293** (1992), 344.
2) Lukierski, J. Ruegg, H. & Zakrzewski W.J., *Ann. Phys.* **243** (1995), 90.
3) Amelino-Camelia, G., *et al.*, *Nature* **393** (1998), 763.
4) Kluźniak, W., *Astroparticle Phys.* (1999), in press.
5) Gonzalez-Mestres L., *Proceedings 25th International Cosmic Ray Conference*, (1997), physics/9705031.
6) Coleman, S. & Glashow, S.L., (1998), hep-ph/9808446.
7) Hillas, A. M., *et al.*, *Astroph. J.* **503** (1998), 744.
8) Wdowczyk, J., Tkaczyk, W. & Wolfendale, A.W., *J. Phys.* **A 5**, (1972), 1419.
9) Stecker, F.W. & de Jager, O.C. *Astroph. J.* **476**, (1997), 712.
10) Plunkett, S.P., *et al.*, *29 ESLAB Symposium*, (1995), astro-ph/9508083
11) Krawczynski, H. *Gamma-Ray Bursts 3rd Huntsville Symposium*, C. Kouveliotou, M.F. Briggs, G.J. Fishman eds., (1996), p. 656.
12) Malkan, M.A. & Stecker, F.W., 1998, *Astroph. J.* **496** (1998), 13.
13) Coppi, P.S. & Aharonian, F.A., *19th Texas Symposium on Relativistic Astrophysics and Cosmology* J. Paul, T. Montmerle, and E. Aubourg, eds., (1999), in press.
14) Primack, J.R., Bullock, J.S., Somerville, R.S. & MacMinn, D., *Astroparticle Phys.* (1999), in press.
15) Krennrich, F. *et al.*, *Astroph. J.* **511**, (1998), 149.
16) Gaidos, J. A., *et al.*, *Nature* **383**, (1996), 319.
17) Biller, S.D., *et al.*, (1998), gr-qc/9810044.
18) Totani, T., *Astroph. J.* **502**, (1998), L13.
19) Amenori, M., *et al.*, *Astron. Astroph.* **311**, (1996), 919.
20) Padilla, L.,*et al.*, *Astron. Astroph.* **337**, 43.
21) Metzger, M.R. *et al.*, *Nature* **387**, (1997), 878.
22) Kulkarni, S. R. *et al.*, *Nature* **393**, (1998), 35.
23) Djorgovski, S.G., *et al.*, *Astroph. J.* **508**, (1998), L17.