ACT-01/09
CERN-TH-PH/2008-005
MIFP-09/03
January 2009

Probing a Possible Vacuum Refractive Index with γ-Ray Telescopes*

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Abstract

We have used a stringy model of quantum space-time foam to suggest that the vacuum may exhibit a non-trivial refractive index depending linearly on γ-ray energy: $\eta - 1 \sim E_\gamma / M_{QG1}$, where M_{QG} is some mass scale typical of quantum gravity that may be $\sim 10^{18}$ GeV: see [1] and references therein. The MAGIC, HESS and Fermi γ-ray telescopes have recently probed the possible existence of such an energy-dependent vacuum refractive index. All find indications of time-lags for higher-energy photons, but cannot exclude the possibility that they are due to intrinsic delays at the sources. However, the MAGIC and HESS observations of time-lags in emissions from AGNs Mkn 501 and PKS 2155-304 are compatible with each other and a refractive index depending linearly on the γ-ray energy, with $M_{QG1} \sim 10^{18}$ GeV. We combine their results to estimate the time-lag Δt to be expected for the highest-energy photon from GRB 080916c measured by the Fermi telescope, which has an energy ~ 13.2 GeV, assuming the redshift $z = 4.2 \pm 0.3$ measured by GROND. In the case of a refractive index depending linearly on the γ-ray energy we predict $\Delta t = 25 \pm 11$ s. This is compatible with the time-lag $\Delta t \leq 16.5$ s reported by the Fermi Collaboration, whereas the time-lag would be negligible in the case of a refractive index depending quadratically on the γ-ray energy. We suggest a strategy for future observations that could distinguish between a quantum-gravitational effect and other interpretations of the time-lags observed by the MAGIC, HESS and Fermi γ-ray telescopes.

[*] *Addendum* **to 'Derivation of a Vacuum Refractive Index in a Stringy Space-Time Foam Model', Phys. Lett. B 665, 412 (2008).**

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The advent of the new generation of ground-based Čerenkov γ-ray telescopes, represented by MAGIC [2] and HESS [3], together with the launch of the Fermi (née GLAST) γ-ray telescope [4], have inaugurated a new era in γ-ray astronomy. It has been suggested that, in addition to high-energy astrophysics, such instruments may be used to probe fundamental physics. Specifically, data from γ-ray telescopes may be used to probe the existence of a possible energy-dependent vacuum refractive index [5], such as might be induced by quantum-gravitational effects in space-time foam: see [1] and references therein.

Since the publication of [1], each of the MAGIC, HESS and Fermi Collaborations has reported time-lags in the arrival times of high-ernergy photons, as compared with photons of lower energies. Following an earlier publication by the MAGIC Collaboration [2], the present authors, A. S. Sakharov and E. K. G. Sarkisyan joined the MAGIC Collaboration in a quantitative analysis [6] of the arrival times of individual photons from the AGN Mkn 501, which has a redshift $z = 0.034$, finding an indication of an energy-dependent time-lag $\Delta t/E_\gamma = 0.030 \pm 0.012$ s/GeV. More recently, the HESS Collaboration has published a cross-correlation analysis of the AGN PKS 2155-304 [7], which has a redshift $z = 0.116$, finding a time-lag $\Delta t = 28 \pm 25$ s between the light curves for E_γ in the energy ranges $(200, 800)$ and > 800 GeV. Finally, the Fermi Collaboration has made a preliminary report of a 4.5-second time delay between the onsets of high- (> 100 MeV) and low-energy (> 100 KeV) emissions, and a time-lag $\Delta t = 16.5$ s for a photon with energy $13.2^{+0.70}_{-1.54}$ GeV from the GRB 080916c [8].

These observations provide a basis for discussing possible interpretations of time-lags in the arrival times of energetic photons, and provide pointers for possible future analyses that we discuss in this *addendum* to [1].

The most conservative interpretations of the MAGIC, HESS and Fermi time-lags are that they are due to emission mechanisms at the sources. The mechanisms leading to γ-ray emissions from AGNs and GRBs are surely different. However, it is possible that there may be some common systematic effect leading to higher-energy photons being emitted later. For instance, it has been suggested [8] that it may be easier and quicker for sources to accelerate electrons, which are relatively light and therefore may produce the early, lower-energy part of these bursts, whilst sources may take longer to accelerate the heavier protons, which would then contribute later to the higher-energy component. In addition to any such common systematic time-lag, there may be different intrinsic time-lag effects present in AGNs and GRBs, or even between different classes of GRBs that have different underlying mechanisms (e.g., long bursts vs short bursts). There may also be intrinsic fluctuations in the relative emission times of higher- and lower-energy components between different sources of the same class, or even between different features in the time structure of a single source. These different possibilities limit the sensitivities of probes for quantum-gravity effects, and it is clear that they must all be taken into account and controlled before claiming a robust lower limit on any observable effect of space-time foam, and *a fortiori* before claiming the existence of any such effect.

With these points in mind, an analysis of a significant sample of long-burst GRBs was performed in [9], extending earlier analyses [10]. An attempt was made to distinguish intrinsic time-lags at the sources (which were assumed to be independent of redshift) from any time-lag induced by a possible quantum-gravitational effect during propagation, which would be redshift-dependent. In the case of a linear effect on propagation characterized by an energy scale M_{QG1}, the relative time-lag of a higher-energy photon is

$$\Delta t_{\text{no expansion}} \sim \frac{\Delta E}{M_{\text{QG1}}} \frac{L}{c} \tag{1}$$

at small redshifts, where ΔE is the difference in photon energies, c is the speed of light in vacuo, $L = H_0 z c$ is the distance of the source from Earth, and $H_0 \sim 2.5 \times 10^{-18}$ s^{-1} is the current Hubble expansion rate. For sources at a cosmological distance, one must take into account the expansion history of the Universe. We assume that this is described adequately by the standard ΛCDM model of cosmology, so that [9, 10, 11]

$$(\Delta t)_{\text{obs}} = \frac{\Delta E}{M_{\text{QG1}}} \mathrm{H}_0^{-1} \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}, \tag{2}$$

and we assume for concreteness $\Omega_\Lambda \sim 0.73$ and $\Omega_m \sim 0.27$.

The robust analysis in [9] of a sample of GRBs extending to large redshifts found indications of a red-shift-independent intrinsic time-lag as well as fluctuations in the time-lags between different structures. After controlling for these effects, and performing a linear regression analysis in terms of the appropriate function of the redshift:

$$K(z) \equiv \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}, \tag{3}$$

which reduces to z in the small-redshift limit, no significant evidence was found for a redshift-dependent propagation effect, and a lower bound $M_{QG1} > 1.4 \times 10^{16}$ GeV was found at the 95% confidence level. It should be noted that this analysis used photons with energies < 320 KeV, much below those observed by the γ-ray telescopes discussed here, and that the intrinsic time-lags and their fluctuations were at the level of 0.1 s or less.

It was not possible to control for intrinsic effects in the analysis of MAGIC data in [6], which was therefore not as robust as the previous GRB analysis [9], as was made clear in quoting the lower limit $M_{QG1} > 2.1 \times 10^{17}$ GeV at the 95% confidence level [6]. The same remark applies to the lower limit $M_{QG1} > 7.2 \times 10^{17}$ GeV at the 95% confidence level found subsequently in a cross-correlation analysis of HESS data [7].

The available sample of AGNs is still not large enough for a robust regression analysis. However, one can at least check for consistency between the available MAGIC and HESS results, and gauge the magnitude of possible intrinsic fluctuations in the AGN time-lags. Comparing the time-lag measured by MAGIC for Mkn 501at $z = 0.034$: $\Delta t/E_\gamma = 0.030 \pm 0.012$ s/GeV, with that measured for PKS 2155-304 at $z = 0.116$: $\Delta t/E_\gamma = 0.030 \pm 0.027$ s/GeV, we see that they are compatible with a common, energy-dependent *intrinsic* time-lag at the source. On the other hand, neglecting possible source effects, the one-σ range for the MAGIC time-lag corresponds to $M_{QG1} = (0.48^{+0.32}_{-0.14}) \times 10^{18}$ GeV, which is compatible with the HESS 95% C.L. lower limit of 0.72×10^{18} GeV [12]. The MAGIC and HESS data are compatible with a universal redshift- and energy-dependent *propagation* effect:

$$\Delta t/E_\gamma = (0.43 \pm 0.19) \times K(z) \text{s/GeV}, \tag{4}$$

corresponding to $M_{QG1} = (0.98^{+0.77}_{-0.30}) \times 10^{18}$ GeV [13]. Discriminating between these respective *conservative* and *audacious* interpretations will require considerably more data from sources at different redshifts emitting in different energy ranges. It seems unlikely that the relatively rare and unpredictable sharp energetic flares produced only occasionally by AGNs, which have a relatively restricted redshift range and hence a small lever arm, will soon be able to provide the desired discrimination.

On the other hand, GRBs are observed at a relatively high rate, about one a day, and generally have considerably larger redshifts. The AGN data cannot be used to estimate the possible magnitudes of intrinsic time-lags in GRB emissions, since the sources are very different. Nor can the previous GRB data mentioned earlier be used to estimate the likely GRB time-lags above the KeV range. However, the above-mentioned best fit to the possible redshift- and energy-dependent propagation effect, (4), does provide an estimate of the sensitivity required to probe such an effect in GRB data in the GeV range.

The advent of the Fermi (née GLAST) telescope with its large acceptance offers the possibility of achieving the required sensitivity. Indeed, the Fermi Collaboration has already made a preliminary report of GeV-range γ rays from the GRB 080916c. As already mentioned, there is a 4.5-second time-lag between the onsets of high- (> 100 MeV) and low-energy (< 100 KeV) emissions. Moreover, the highest-energy photon GRB 080916c measured by the Fermi γ-ray telescope had an energy $E = 13.2^{+0.70}_{-1.54}$ GeV, and was detected $\Delta t = 16.5$ s after the start of the burst. Spectroscopic information has been used by the GROND Collaboration [14] to estimate the redshift of GRB 080916c as $z = 4.2 \pm 0.3$ [8]. Assuming this value of the redshift, the best fit (4) would correspond to a time-lag

$$\Delta t = 25 \pm 11 \text{ s} \tag{5}$$

for a 13 GeV photon from GRB 080916c. The consistency between this Fermi measurement and the best-fit estimate (4) is *striking*, but one should keep in mind that all or part of the 16.5 s time-lag of this highest-energy photon could be due to intrinsic effects. Indeed, the 4.5-second time-lag observed for ~ 100 MeV photons could not be explained by a propagation effect that depends linearly on the energy. Because of ignorance of the source mechanism, the preliminary analysis of these data by the Fermi Collaboration [8] quoted a lower bound $M_{QG1} > (1.50 \pm 0.20) \times 10^{18}$ GeV, which is consistent with the MAGIC and HESS results stated previously. It is clear that the Fermi telescope has already demonstrated the sensitivity to probe a possible linearly energy-dependent propagation effect at the level reached by the available AGN data, and it is appropriate and possibly helpful to consider how such an effect could be probed in the future.

If the apparent consistency between the available AGN and GRB data would persist, it would provide much more convincing evidence for a possible linearly energy-dependent propagation effect than could either AGN or the GRB data alone, since the sources are so different in nature. However, 'extraordinary claims require extraordinary evidence', so for the moment we can applaud the efforts of the MAGIC, HESS and Fermi Collaborations to date, wish them good fortune in the future, and stress the advantages of a combined analysis of AGNs and GRBs.

It is interesting to repeat the above analysis for the case of a possible quadratically energy-dependent effect. We recall that the MAGIC analysis found $\Delta t/E_\gamma^2 = (3.7 \pm 2.6)^{-6}$ s/GeV^2, whereas the HESS result corresponds to $\Delta t/E_\gamma^2 = (3.3 \pm 2.9)^{-5}$ s/GeV^2. (These numbers were estimated using the HESS statement that the average energy difference between photons in the high- and low-energy bins used in their analysis was 0.92 TeV. A more precise number could be obtained by analyzing the arrival times and energies of individual photons.) These results are compatible, but neither has any indication of a non-zero result. The MAGIC result, which is considerably more sensitive, would correspond to $\Delta t/E_\gamma^2 = (1.4 \pm 1.0) \times 10^{-3}$ s/GeV^2 for energetic γ-rays from GRB 080916c at $z = 4.2$. This would imply a time delay of 0.24 ± 0.16 s for the most energetic photon measured by the Fermi telescope, two orders of magnitude less than the time-lag measured. Of course, the observed time-lag could be due solely to intrinsic effects at the source. Nevertheless, it is intriguing that a possible linear energy-dependent effect *could* explain simultaneously all three sets of data, whereas a quadratic effect *could not.*

This point emphasizes the value of a combined analysis of data from sources at different redshifts and in different energy bands: in principle, they could not only distinguish between source and propagation effects, but also between different energy dependences.

We conclude with some theoretical observations.

Many theories of quantum gravity predict non-trivial vacuum refractive indices, varying linearly with the energy scale of photons and with the distance of the source: see [1, 10, 15, 16, 17, 18, 19, 20, 21, 22, 23]. However, there are several stringent restrictions coming from other independent tests of Lorentz symmetry that should be taken into account before any model could be accepted as a possible explanation for any observed photon delays.

Linear energy-dependent effects (with a quantum-gravity energy scale of the order of the Planck mass scale or even larger) on the propagation of charged probes, such as electrons, are already excluded by synchrotron radiation measurements [21, 24, 25], and similar effects for photons in models that entail birefringence are excluded by GRB afterglow measurements [26, 27]. This is a significant restriction, since most models of quantum gravity that are based on a local effective Lagrangian do exhibit birefringence (see e.g. [16, 17, 22]). Moreover, most of these models are characterised by the absence of GZK thresholds for the extinction by microwave background photons of ultra-high-energy photons with energies higher than 10^{19} eV, due to electron-positron pair production. The non-observation of such ultra-high-energy photons imposes severe restrictions on the quantum-gravity linear suppression scale to values more than seven orders of magnitude higher than the Planck scale [28], which may be evaded only if there are energy fluctuations during particle interactions [29]. Another feature of many models is photon decay, which can become possible if modified dispersion relations for photons are present [28].

It is clear from this summary that any model of refraction in space-time foam that exhibits effects at the level of the MAGIC [6], HESS [7] and Fermi sensitivity [8] would be characterised by the following *specific* properties:

(i) photons are *stable* (i.e. do *not* decay) but should exhibit a modified *subluminal* dispersion relation with Lorentz-violating corrections that grow linearly with E/M_{QG1}, where M_{QG1} is close to the Planck scale,

(ii) the medium should not refract electrons, so as to avoid the synchrotron-radiation constraints [21, 24],

(iii) the coupling of the photons to the medium must be independent of photon polarization, so as to avoid birefringence, thus avoiding the stringent pertinent constraints [25, 26, 27], and, moreover,

(iv) the formalism of a local effective field theory lagrangian in an effectively flat space-time breaks down, including higher-derivative local interaction terms to produce a refractive index [22], which would be signalled by quantum fluctuations in the total energy in particle interactions, due to the presence of a quantum-gravitational 'environment' [29].

A model with all these properties has been suggested by us [20, 21, 23] within the framework of string/brane theory, based on a stringy analogue of the interaction of a photon with internal degrees of freedom in a conventional medium. We modelled the space-time foam as a gas of point-like D-brane defects (D-particles) in the bulk space-time of a higher-dimensional cosmology where the observable Universe is a D3-brane. Within this class of D-foam models, we have recently re-derived [1] a refractive index for photon propagation in vacuo using a detailed modelling of the interaction of an open string, representing a photon, with a D-particle. During this interaction, an intermediate open string state is created, which stretches between the D-particle and the D3-brane. The D-particle is excited in the process, and subsequently decays re-emitting the photon, with a causal time delay that increases linearly with the photon energy. The whole process is consistent with the stringy uncertainty principles, as shown in detail in [1]. An important feature of the model is that only electrically-neutral excitations can be captured by the D-particles, whereas the D-particle foam looks transparent to charged particles such as electrons. This is because the capture process entails [1] a splitting of the open-string state representing matter excitations. Charged excitations are characterized by an electric flux flowing across the string, and when the latter is cut in two pieces as a result of its capture by the D-particle defect, the flux should go somewhere because charge is conserved. For this reason, our stringy model avoids the stringent constraints coming from synchrotron radiation [21, 24, 25]. Moreover, the independence of the time delay from the photon polarization implies the absence of birefringence effects, thus avoiding the very strong constraints on such Lorentz-violating effects inferred from GRB afterglows [26, 27]. The model also predicts energy fluctuations during particle interactions [29], thereby evading the GZK constraint [28].

The interactions of photons with the D-particle foam generate [1] an effective subluminal refractive index $\eta(E)$ for light propagating in this space-time, since light being slowed down by the medium effects. In fact, our model of D-particle foam has many analogies with the simple harmonic oscillator model discussed in [30] as a description of the refraction of light in conventional media. The rôle of atomic electrons in the conventional model, represented by harmonic oscillators, is played by the D-particle defects. However, being stringy in nature, they are characterised by an infinity of oscillation modes. The role of the restoring force that keeps atomic electrons in position during the scattering of light is played [1] by the intermediate-state flux-carrying strings, that are stretched between the D-particle and the D3-brane during the capture of the photon (represented as an open string with each end attached to the D3-brane) by the D-particle.

It is not clear to us whether other candidates of space-time foam, in particular [18, 19] could satisfy simultaneously all the requirements (i)-(iii) mentioned above. For instance, although there are claims [18, 19] that there is no birefringence, it is not clear whether these candidates are derived from local effective lagrangians and how they could avoid the stringent constraints [28] imposed by the absence of ultrahigh-energy photons and photon decays [28]. On the other hand, as a result of the presence of D-particles in our model of space-time foam, and their recoils, the local effective lagrangian description breaks down, and thus the stringent constraints of [28] are evaded [29].

We close by repeating that, with measurements of only a few AGN flares from MAGIC and HESS, it is not possible to disentangle with any certainty intrinsic source effects from propagation effects. For this one would need statistically significant populations of AGN data. Unfortunately the occurrence of fast flares in AGNs is currently unpredictable, and since no correlation has yet been established with observations in other energy bands that could be used as a trigger signal, only serendipitous detections are currently possible. However, the encouraging news from the GRB front, in particular from the Fermi γ-ray telescope, leads to the hope that there will soon be many more observations of energetic photons from GRBs like 080916c, which could play an increasingly important role in future quantum gravity tests. In particular, the different redshifts of GRB data could help disentangle source and propagation effects, and the different energy ranges of the GRB and AGN data could help distinguish between different possible energy dependences.

Acknowledgements

The work of J.E. and N.E.M. is partially supported by the European Union through the Marie Curie Research and Training Network *UniverseNet* (MRTN-2006-035863), and that of D.V.N. by DOE grant DE-FG02-95ER40917.

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