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Potential Sensitivity of Gamma-Ray Burster Observations to Wave Dispersion in Vacuo

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The recent confirmation that at least some gamma-ray bursters (GRBs) are indeed at cosmological distances [1, 2, 3, 4] raises the possibility that observations of these could provide interesting constraints on the fundamental laws of physics. Here we demonstrate that the fine-scale time structure and hard spectra of GRB emissions are very sensitive to the possible dispersion of electromagnetic waves *in vacuo* **with velocity differences** $\delta v \sim E/E_{\rm QG}$**, as suggested in some approaches to quantum gravity. A simple estimate shows that GRB measurements might be sensitive to a dispersion scale** $E_{\rm QG}$ **comparable to the Planck energy scale** $E_{\rm P} \sim 10^{19}$ **GeV, sufficient to test some of these theories, and we outline aspects of an observational programme that could address this goal.**

It has been suspected that at least some gamma-ray bursters (GRBs) are at cosmological distances, on the basis of their isotropy and the deviation of their brightness distribution from the Euclidean form at the faint end [5]. The first direct evidence for this was provided by the discovery [1] of an extended faint optical source, probably a galaxy, coincident with GRB 970228. Subsequently, the detection of both Mg II absorption lines and O II emission lines in the optical afterglow of GRB 970508 has allowed a measurement of its distance, thanks to a precise determination of its redshift: $z = 0.835 \pm 0.001$ [3, 4]. Such a cosmological distance, combined with the short time structure seen in emissions from some GRBs [5], bestows on GRBs unique features as 'laboratories' for fundamental physics as well as for astrophysics.

Our interest is in the search for possible *in vacuo* dispersion, $\delta v \sim E/E_{\rm QG}$, of electromagnetic radiation from GRBs, which could be sensitive to a type of candidate quantum-gravity effect that has been recently considered in the particle-physics literature. This candidate quantum-gravity effect would be induced by a deformed dispersion relation for photons of the form $c^2\mathbf{p}^2 = E^2\,[1 + f(E/E_{\rm QG})]$, where $E_{\rm QG}$ is an effective quantum-gravity energy scale and f is a model-dependent function of the dimensionless ratio $E/E_{\rm QG}$. In quantum-gravity scenarios in which the Hamiltonian equation of motion $\dot{x}_i = \partial H/\partial p_i$ is still valid at least approximately, as in the frameworks discussed later, such a deformed dispersion relation would lead to energy-dependent velocities $c + \delta v$ for massless particles, with implications for all the electromagnetic signals that we receive from astrophysical objects at large distances. At small energies $E \ll E_{\rm QG}$, we expect that a series expansion of the dispersion relation should be applicable: $c^2\mathbf{p}^2 = E^2\left[1 + \xi E/E_{\rm QG} + \mathcal{O}(E^2/E_{\rm QG}^2)\right]$, where $\xi = \pm 1$ is a sign ambiguity that would be fixed in a given dynamical framework. Such a series expansion would correspond to energy-dependent velocities

$$v = \frac{\partial E}{\partial p} \sim c\left(1 - \xi\frac{E}{E_{\rm QG}}\right) \ . \qquad (1)$$

This type of velocity dispersion results from a picture of the vacuum as a quantum-gravitational 'medium', which responds differently to the propagation of particles of different energies and hence velocities. This is analogous to propagation through a conventional medium, such as an electromagnetic plasma [6]. The gravitational 'medium' is generally believed to contain microscopic quantum fluctuations, which may occur on scale sizes of order the Planck length $L_{\rm P} \sim 10^{-33}$ cm on time scales of order $t_{\rm P} \sim 1/E_{\rm P}$, where $E_{\rm P} \sim 10^{19}$ GeV. These may [7, 8] be analogous to the thermal fluctuations in a plasma, that occur on time scales of order $t \sim 1/T$, where T is the temperature. Since it is a much 'harder' phenomenon associated with new physics at an energy scale far beyond typical photon energies, any analogous quantum-gravity effect could be distinguished from by its different energy dependence: the quantum-gravity effect would increase with energy, whereas conventional medium effects decrease with energy in the range of interest [6].

Equation (1) encodes a minute modification for most practical purposes, since $E_{\rm QG}$ is believed to be a very high scale, presumably of order the Planck scale $E_{\rm P} \sim 10^{19}$ GeV. Even so, such a deformation could be rather significant for even moderate-energy signals, if they travel over very long distances. According to (1), a signal of energy E that travels a distance L acquires a 'time delay', measured with respect to the ordinary case of an energy-independent speed c for massless particles:

$$\Delta t \sim \xi \frac{E}{E_{\rm QG}} \frac{L}{c} \ . \qquad (2)$$

This is most likely to be observable when E and L are large whilst the interval $\delta\, t$ over which the signal exhibits time structure is small. These are the respects in which GRBs offer particularly good prospects for such measurements, as we discuss later.

Before doing so, we first review briefly how modified laws for the propagation of particles have emerged independently in different quantum-gravity approaches. The suggestion that quantum-gravitational fluctuations might modify particle propagation in an observable way can already be found in [10, 7]. A phenomenological parametrization of the way this could affect the neutral kaon system [10, 11, 12] has been already tested in laboratory experiments, which have set lower limits on parameters analogous to the $E_{\rm QG}$ introduced above at levels comparable to $E_{\rm P}$ [13]. In the case of massless particles such as the photon, which interests us here, the first example of a quantum-gravitational medium effect with which we are familiar occurred in a string formulation of an expanding Robertson-Walker-Friedman cosmology [14], in which photon propagation appears tachyonic. Deformed dispersion relations that are consistent with the specific formula (1) arose in approaches based on dimensionful "κ" quantum deformations of Poincaré symmetries [9]. Within this general class of deformations, one finds [9, 15] an effect consistent with (1) if the deformation is rotationally invariant: the dispersion relation for massless particles $c^2\mathbf{p}^2 = E_{\mathrm{QG}}^2 \left[1 - e^{E/E_{\mathrm{QG}}}\right]^2$, and therefore $\xi = 1$. It should be noted that a deformed dispersion relation has also been found in studies of the quantization of point particles in a discrete space time [16].

A specific and general dynamical framework for the emergence of the velocity law (1) has emerged [17] within the Liouville string approach [7] to quantum gravity, according to which the vacuum is viewed as a non-trivial medium containing 'foamy' quantum-gravity fluctuations. The reader can visualize the nature of this foamy vacuum by imagining processes that include the pair creation of virtual black holes. Within this approach, it is possible to verify that massless particles of different energies excite vacuum fluctuations differently as they propagate through the quantum-gravity medium, giving rise to a non-trivial dispersion relation of Lorentz 'non-covariant' form, just as in a thermal medium. The form of the dispersion relation is not known exactly, but its structure has been studied [17] via a perturbative expansion, and it was shown in [17] that the leading $1/E_{\mathrm{QG}}$ correction is in agreement with (1).

It has been recently suggested [8] the vacuum might have analogous 'thermal' properties in a large class of quantum-gravity approaches, namely all approaches in which a minimum length L_{min}, such as the Planck length $L_{\mathrm{P}} \sim 10^{-33}$ cm, characterizes short-distance physics. These should in general lead to deformed photon dipersion relations with $E_{\mathrm{QG}} \sim 1/L_{\mathrm{min}}$, though the specific form (1) may not hold in all models, and hence may be used to discriminate between them. In support of (1), though, we recall [17, 15] that this type of non-trivial dispersion in the quantum-gravity vacuum has implications for the measurability of distances in quantum gravity that fit well with the intuition emerging from recent heuristic analyses [18] based on a combination of arguments from ordinary quantum mechanics and general relativity.

We now explain how GRBs provide an excellent laboratory for testing such ideas, now that the cosmological origin of at least some of them has been established. We recall that typical photon energies in GRB emissions are in the range $0.1 - 100$ MeV [5], and it is possible that the spectrum might in fact extend up to TeV energies [19]. Moreover, time structure down to the millisecond scale has been observed in the light curves [5], as is predicted in the most popular theoretical models [20] involving merging neutron stars or black holes, where the last stages occur on the time scales associated with grazing orbits. Similar time scales could also occur in models that identify GRBs with other cataclysmic stellar events such as failed supernovae Ib, young ultra-magnetized pulsars or the sudden deaths of massive stars [21]. We see from equations (1) and (2) that a signal with millisecond time structure in photons of energy around 20 MeV coming from a distance of order 10^{10} light years, which is well within the range of GRB observations and models, would be sensitive to $E_{\rm QG}$ of order 10^{19} GeV $\sim 1/L_{\rm P}$.

Significant sensitivities may already be attainable with the present GRB data. Sub-millisecond time-structure has been seen in GRB 910711 [22], and a recent time-series analysis [23] of the light curve of GRB 920229 using the Bayesian block technique has identified a narrow microburst with a rise and decay timescale of order $100\,\mu$sec. This is seen *simultaneously* in three of the four energy channels of the BATSE detector on the Compton Gamma Ray Observatory, covering the energy regions 20-50 keV, 50-100 keV and 100-300 keV respectively. From the time structure of this microburst we think it should be possible to extract an upper limit of $\Delta\, t \lesssim 10^{-2}$ sec on the difference in the arrival times of the burst at energies separated by $\Delta\, E \sim$ 200 keV. If a burst such as this were to be demonstrated in future to lie at a redshift $z \sim$ 1, as seems quite plausible, the implied sensitivity would be to $E_{\rm QG} \sim 10^{16}$ GeV, and it would be possible to improve this to $\sim 10^{18}$ GeV if the time difference could be brought down to the rise time reported in [23]. We note in passing that the simultaneous arrival of photons of different energies from such a large distance also imposes an upper limit of order 10^{-6} eV on a possible photon mass, but this is much less stringent than other astrophysical and laboratory limits [24].

These levels of sensitivity are even more interesting in light of the fact that recent theoretical work on quantum gravity, particularly within string theory, appears to favor values of the effective scale characterizing the onset of significant quantum-gravity effects that are somewhat below the Planck scale, typically in the range 10^{16} to 10^{18} GeV [25]. If our scale $E_{\rm QG}$ were indeed to be given by such a novel effective quantum-gravity scale, parts of the GRB spectrum with energies around 0.1 MeV and millisecond time structure (or energies of order 100 MeV and 1-second time structure, or energies around 1 TeV and 1-hour time structure) might be sensitive to the type of candidate quantum-gravity phenomenon discussed in this paper.

In order to provide some quantitative comparison of the GRB sensitivity to this phenomenon with that of other astrophysical phenomena, we can compare values of the "sensitivity factor" $\eta \equiv |\Delta t^*|/\delta\, t$, where $\delta\, t$ represents the time structure of the signal, whilst $\Delta\, t^*$ is the time delay acquired by the signal if $E_{\rm QG} \sim E_{\rm P}$, namely $\Delta t^* \sim \pm E\, L/(c\, E_{\rm P})$. As already discussed, GRB emission with millisecond time structure and energy around 20 MeV that travels a distance of order 10^{10} light years has $\eta \sim 1$. Another interesting possibility is that we may observe lensing of a GRB by a foreground galaxy [26, 27]. The burst would then reach us by two or more different paths whose light travel times would differ typically by weeks up to years. Since conventional gravitational lensing is achromatic, any *energy-dependence* in the time delay would be a direct probe of the new physics of interest, and would be independent of the actual emission mechanism of gamma-ray bursts. We note that the HEGRA [28] and Whipple [29] air Čerenkov telescopes have already searched for TeV emission from the direction of GRBs, motivated by the EGRET detection [30] of emission up to 18 GeV from GRB 940217. If such searches were to prove successful and moreover identified a lensed GRB, one would be able to infer via (2) a sensitivity to $\eta \sim 10^{-6}$.

As observed in [17], which did not consider GRBs whose cosmological distances were not then established, pulsars and supernovae are among the other astrophysical phenomena that might at first sight appear well suited for probing the physics we are interested in here, in light of the short time structures they display. However, although pulsar signals have very well defined time structure, they are at relatively low energies and are observable over distances of at most 10^4 light years. If one takes an energy of order 1 eV and postulates generously a sensitivity to time delays as small as 1 μsec, one estimates a sensitivity to $\eta \sim 10^{-10}$. With new experiments such as AXAF it may be possible to detect X-ray pulsars out to 10^6 light years, allowing us to probe up to $\eta \sim 10^{-8}$.

Concerning supernovae, we observe that neutrinos from Type II events similar to SN1987a, which should have energies up to about 100 MeV with a time structure that could extend down to milliseconds, are likely to be detectable at distances of up to about 10^5 light years, providing sensitivity to $\eta \sim 10^{-4}$. We have also considered the cosmic microwave background. Although the distance travelled by these photons is the largest available, the only possible signature is a small distortion of the Planck spectrum due to the frequency-dependence of c, which we estimate to be of order $\Delta I(\nu)/I(\nu) \sim \nu/E_{\mathrm{P}} \sim 10^{-32}$, which is quite negligible.

We conclude that, in principle, GRBs allow us to gain many orders of magnitude in the sensitivity factor η. Moreover, and most importantly, this high sensitivity should be sufficient to probe values of the effective scale characterizing the onset of quantum-gravity effects extending all the way up to the Planck scale, as illustrated by the estimates we have provided. Ideally, one would like to understand well the short-time structure of GRB signals in terms of conventional physics, so that the novel phenomena discussed here may be disentangled unambiguously. However, even in the absence of a complete theoretical understanding, sensitive tests can be performed as indicated above, through the serendipitous detection of short-scale time structure [23] at different energies in GRBs which are established to be at cosmological distances. Detailed features of burst time series should enable the emission times in different energy ranges to be put into correspondence. Since any time shift due to quantum-gravity effects of the type discussed here would *increase* with the photon energy, this characteristic dependence should be separable from more conventional in-medium physics effects, which *decrease* with energy. To distinguish any quantum-gravity shift from effects due to the source, we recall that the medium effect would be *linear* in the photon energy, which would not in general be the case for time shifts at the source. To disentangle any such effects, it is clear that the most desirable features in an observational programme would be fine time resolution at high photon energies.

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