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Sensitivity of Astrophysical Observations to Gravity-Induced Wave Dispersion in Vacuo

G. Amelino-Camelia[a], **John Ellis**[b], **N.E. Mavromatos**[c], **D.V. Nanopoulos**[d] and **Subir Sarkar**[c]

[a] Institut de Physique, Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland
[b] Theory Division, CERN, CH-1211, Geneva, Switzerland,
[c] Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, UK
[d] Dept. of Physics, Texas A & M University, College Station, TX 77843-4242, and
HARC, The Mitchell Campus, Woodlands, TX 77381, USA;
Academy of Athens, 28 Panepistimiou Avenue, Athens 10679, Greece.

Abstract

We discuss possible signatures of quantum gravity for the propagation of light, including an energy-dependent velocity (refractive index), dispersion in velocity at a given energy, and birefringence. We also compare the sensitivities of different astrophysical observations, including BATSE data on GRB 920229, BeppoSAX data on GRB 980425, the possible HEGRA observation of GRB 920925c, and Whipple observations of the active galaxy Mrk 421. Finally, we discuss the prospective sensitivities of AMS and GLAST.

We pointed out recently [1] that observations of γ-ray bursters (GRBs) can be used to test models of quantum gravity in which the velocity of light depends on the photon energy E. This is because GRBs combine large distances, $z \sim 1$, with fine time structure, $\Delta t \sim \mathcal{O}(10^{-3})$ s. Assuming a linear dependence of the velocity, $v = c(1 \pm (E/E_{\rm QG})$, we suggested that effective quantum gravity scales $E_{\rm QG}$ up to the Planck scale, $M_{\rm P} \sim 10^{19}$ GeV, can in principle be probed using GRBs, and argued that extant data already has a sensitivity to $E_{\rm QG} \sim 10^{16}$ GeV. Subsequently there have been several interesting developments which we comment on here.

The energy-dependent dispersion effect [1] can be interpreted as a refractive index *in vacuo* induced by quantum gravity. Another possibility is a statistical velocity spread among photons of the same energy E; higher-order quantum-gravity effects may induce $\delta\, v\,(E) \propto E$ which can be probed in a similar manner. Arguments have also been given in the context of a loop representation of canonical quantum gravity [2] for the possibility of energy-dependent birefringence: $v_\pm = c(1 \pm E/E_{\rm QG})$ for $\pm$ photon helicity states, as well as a linear energy dependence of the refractive index *in vacuo*. We note that birefringence effects are, in general, characteristic of theories with (spontaneous) violation of Lorentz invariance [3]; probing such effects might be possible with polarization measurements of GRBs. In each case, the figure of merit for comparing the sensitivities of different sources (at distance D) is the parameter $\eta \equiv (DE/cM_P)/\Delta\, t$, which we now compare for various observations.

We had previously discussed GRB 920229, which exhibited micro-structure in its burst at energies up to ~ 200 keV. We estimated conservatively that a detailed time-series analysis might reveal coincidences in different BATSE energy bands on a time-scale $\sim 10^{-2}$ s, which would yield $\eta \sim 10^{-3}$ i.e. sensitivity to $E_{\rm QG} \sim 10^{16}$ GeV, assuming that GRB 920229 has an (apparently) typical redshift of $\mathcal{O}(1)$, corresponding to a distance of $\sim$ 3000 Mpc. A similar sensitivity might be obtainable with GRB 980425, given its likely identification with the unusual supernova 1998bw [5]. This is known to have taken place at a redshift $z = 0.0083$ corresponding to a distance $D \sim 40$ Mpc (for a Hubble constant of 65 $\rm km\,sec^{-1}Mpc^{-1}$) which is rather smaller than a typical GRB distance. However GRB 980425 was observed by BeppoSAX at energies up to 1.8 MeV, which gains back an order of magnitude in the overall figure of merit. If a time-series analysis were to reveal structure at the $\Delta\,t \sim 10^{-3}$ s level, which is typical of many GRBs [6], it would yield the same sensitivity as GRB 920229, with the advantage that its redshift is known rather than estimated.

A more speculative possibility is offered by GRB 920925c, observed by WATCH [7] and possibly in high-energy γ rays by the HEGRA/AIROBICC array above 20 TeV [8]. Several caveats are in order: taking into account the appropriate trial factor, the confidence level for the signal seen by HEGRA to be related to GRB 920925c is only 99.7% ($\sim 2.7\sigma$), the reported directions differ by 9^0, and the redshift of the source is unknown. Nevertheless, the potential sensitivity is impressive. The events reported by HEGRA range up to $E \sim 200$ TeV, and the correlation with GRB 920925c is within $\Delta\,t \sim 200$ s. Making the reasonably conservative assumption that GRB 920925c occurred no closer than GRB 980425, viz. ~ 40 Mpc, we find a minimum figure of merit $\eta \sim 1$, corresponding to a possible sensitivity to $E_{\rm QG} \sim 10^{19}$ GeV, modulo the caveats listed above. Even more spectacularly, several of the HEGRA GRB 920925c candidate events occurred within $\Delta\,t \sim 1$ s, providing a potential sensitivity even two orders of magnitude higher.

Other astrophysical objects may also provide sensitive experimental probes of the quantum-gravity effects discussed earlier [1]. In particular, a strong limit has been extracted [4] using data from the Whipple telescope on a TeV γ-ray flare associated with the active galaxy Mrk 421. This object has a redshift of 0.03 corresponding to a distance of $\sim$ 100 Mpc. Four events with γ-ray energies above 2 TeV have been observed within a period of 280 s. These provide a figure of merit somewhat larger than we had previously suggested for GRB 920229, and with the capital advantage that the redshift of the source is *known*. Thus a definite limit $E_{\rm QG} > 4 \times 10^{16}$ GeV was derived [4].

What of the future? A new generation of orbiting spectrometers, e.g., AMS [9] and GLAST [10], are being developed, whose potential sensitivities are very impressive. For example, assuming a E^{-2} energy spectrum, GLAST would expect to observe about 25 GRBs per year at photon energies exceeding 100 GeV, with time resolution of microseconds. AMS would observe a similar number at $E > 10$ GeV with time resolution below 100 nanoseconds. For a nominal redshift of $z \sim 0.1$ corresponding to a distance of $D \sim 300$ Mpc, the expected time-delay at 10-100 GeV would be $\Delta\,t \sim 30 - 300$ ms for $E_{\rm QG} \sim 10^{19}$ GeV, which should be simple to detect. We conclude that these missions would be adequate to exclude or establish the existence of quantum-gravity effects such as a refractive index, statistical dispersion or birefringence, if they appear with a linear dependence scaled by $E/M_{\rm P}$. We believe this adds significantly to the scientific case for these experiments since they should be able to constrain significantly interesting theories of fundamental physics.

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