Cosmology

Synchrotron radiation and quantum gravity

Arising from: Jacobson, T., Liberati, S. & Mattingly, D. *Nature* **424**, 1019–1021 (2003)

Quantum gravity may cause the vacuum to act as a non-trivial medium (space–time foam), which alters the standard Lorentz relation between the energy and momentum of matter particles, thereby modifying their dispersion relations. Jacobson, Liberati and Mattingly[1] argue that synchrotron radiation from the Crab nebula imposes a stringent constraint on any modification of the dispersion relation of the electron that might be induced by quantum gravity, but their analysis does not constrain any modification of the dispersion relation of the photon[2,3]. Such quantum-gravity effects need not obey the equivalence principle[4] in the sense of being universal for all matter particles, as exemplified by quantum-gravity models in which photons are the only standard-model particles able to 'see' special quantum-gravity configurations that modify their dispersion relations. This implies that photons may be the only sensitive probe of quantum-gravity effects on particle dispersion relations, and the results of Jacobson *et al.* do not exclude all possible modifications of dispersion relations, even if they are suppressed by only a single power of the Planck mass (the characteristic quantum-gravity scale) — contrary to some subsequent interpretations of their results.

As pointed out previously[4], there are theoretical models in which quantum gravity produces Lorentz invariance-violating effects for neutral particles, such as the photon, but not charged particles, such as the electron. One model of space–time foam[3] suggests a linear modification of the dispersion relation for the photon: $p_\gamma = E_\gamma - (E_\gamma^2/M_{QG})$, where p_γ (E_γ) is the photon's momentum (energy) and M_{QG} is some characteristic scale associated with quantum gravity, which may be of the same order as the Planck mass $M_P \approx 10^{19}$ GeV. However, this model[3] predicts that there is no such modification of the dispersion relation for the electron[4], and hence is compatible with the constraint[1] from the Crab nebula. In such models, constraints on the electron and nucleon dispersion relations[1,5,6] are irrelevant, leaving measurements on time profiles of very remote γ-ray bursts[2,7] as the best approach for probing quantum-gravity effects.

The basic reason for this violation of the equivalence principle in the quantum-gravity model[3] is its description of space–time foam by using quantum defects in space–time with vacuum quantum numbers, as in one interpretation of Liouville string theory[8]. These can be excited only by particles that are neutral under the gauge group of the standard model, such as photons, and such interactions give the vacuum a non-trivial refractive index for light of different frequencies (energies)[2]. Charged particles, such as electrons, cannot form such excitations, so do not 'see' the space–time foam at all, and hence obey the usual Lorentz kinematics. As a result of the excitation of the vacuum by an energetic photon, space–time is distorted and the photon travels with a velocity smaller than the (supposedly universal) speed of light *in vacuo*, *c*, as postulated in the special and general theories of relativity.

As the electron has no interaction with the quantum-gravitational vacuum medium in this approach, it emits no Čerenkov radiation, despite travelling faster than photons, thus avoiding the vacuum Čerenkov radiation constraint[9], as well as the Crab nebula constraint derived by Jacobson *et al.*[1] The model in ref. 3 also avoids the strong constraints described in ref. 10, as well as many other constraints on quantum-gravity effects[11]. Claims that modified dispersion relations for photons would result in phase incoherence of light, and thereby destroy diffraction patterns in images of extragalactic sources[12], have been criticized by Ng[13], who pointed out that the induced incoherent effects had been overestimated[12] by a large factor. In the specific model of ref. 3, the re-emission of the photon by a space–time defect is accompanied by a random phase in its wave function, destroying any cumulative phase incoherence. Finally, we note that, as the nucleon is a bound state, it is more complex to analyse, but we also do not expect it to exhibit a linear modification of the normal Lorentz-invariant dispersion relation, avoiding other constraints[5,6].

The strong bound of Jacobson *et al.*[1] on the electron underlines the interest in probing directly the dispersion relation of the photon. The study of the arrival times of photons from γ-ray bursts[2] still appears to be the best experimental probe of any possible refractive index for photons, and should be pursued further. It has already established a lower limit on M_{QG} close to 10^{16} GeV (ref. 7), and current (HETE, INTEGRAL) and future (GLAST, AMS) high-energy space missions have the potential to reach the Planck scale for any linear quantum-gravity modification of the photon's dispersion relation.

John Ellis*, N. E. Mavromatos†‡, D. V. Nanopoulos§||¶, A. S. Sakharov*#

**Department of Physics, CERN Theory Division, 1211 Geneva 23, Switzerland*
e-mail: Alexandre.Sakharov@cern.ch
†Department of Physics, King's College London, University of London, London WC2R 2LS, UK
‡Departamento de Fisica Teorica, Universidad de Valencia, 46100, Burjassot, Valencia, Spain
§George P. and Cynthia W. Mitchell Institute for Fundamental Physics, Texas A&M University, College Station, Texas 77843, USA
||Astroparticle Physics Group, Houston Advanced Research Center, Mitchell Campus, Woodlands, Texas 77381, USA
¶Academy of Athens, Division of Natural Sciences, Athens 10679, Greece
#Swiss Institute of Technology, ETH–Zürich, 8093 Zürich, Switzerland

doi:10.1038/nature02481

1. Jacobson, T., Liberati, S. & Mattingly, D. *Nature* **424**, 1019–1021 (2003).
2. Amelino-Camelia, G., Ellis, J., Mavromatos, N. E., Nanopoulos, D. V. & Sarkar, S. *Nature* **393**, 763–765 (1998).
3. Ellis, J., Mavromatos, N. E. & Nanopoulos, D. V. *Phys. Rev. D* **62**, 084019(1–10) (2000).
4. Ellis, J., Mavromatos, N. E. & Sakharov, A. S. *Astropart. Phys.* **20**, 669–682 arXiv:astro-ph/0308403 (2004).
5. Carroll, S. *Nature* **424**, 1007–1008 (2003).
6. Myers, R. C. & Pospelov, M. *Phys. Rev. Lett.* **90**, 211601(1–4) (2003).
7. Ellis, J., Mavromatos, N. E., Nanopoulos, D. V. & Sakharov, A. S. *Astron. Astrophys.* **402**, 409–424 (2003).
8. Ellis, J., Mavromatos, N. E. & Nanopoulos, D. V. *J. Chaos Solit. Fract.* **10**, 345–362 (1999).
9. Liberati, S., Jacobson, T. & Mattingly, D. *Phys. Rev. D* **67**, 124011(1–26) (2003).
10. Alfaro, J. & Palma, G. *Phys. Rev. D* **67**, 083003(1–18) (2003).
11. Ellis, J., Mavromatos, N. E. & Nanopoulos, D. V. *Phys. Rev. D* **65**, 064007(1–7) (2002).
12. Lieu, R. & Hillman, L.W. *Astrophys. J.* **585**, L77–L80 (2003).
13. Ng, Y. J. *Mod. Phys. Lett. A* **18**, 1073–1097 (2003).