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Constraints on the photon mass and charge and test of equivalence principle from GRB 990123

C. Sivaram

Indian Institute of Astrophysics, Bangalore 560034, India

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Abstract. Constraints on the mass and charge of a photon as well as on the parameters relevant to quantum gravity theories are put based on arrival times of radiation at different wavelengths from GRB 990123.

Th January 23 gamma-ray burst GRB 990123 was detected optically (Akerlof et al. 1999; Kulkarni et al. 1999; Sagar et al. 1999) hardly 22 secs, after the burst of γ - rays and in the radio about a day later. This enables a new precision test of the Einstein equivalence principle for photons over a wide (12 orders) energy range. It also puts some more stringent constraints on the photon's rest mass and charge. These constraints are put based on the assumption that the gamma-ray, optical and radio photons were emitted simultaneously and the observed delay in the detection of optical and radio photons relative to gamma rays is thus the maximum which can be attributed to that caused by the presence of a finite mass and charge for the photons. If m_0 be the photon rest mass then a photon of energy E would over traversing a distance D take a longer time Δt to cover this distance as its velocity is now slightly less than light velocity (corresponding to $m_0 = 0$). A simple special relativistic calculation gives for Δt the well known relation :

$$\Delta t = \frac{D}{2c} (m_0 c^2 / E)^2 \tag{1}$$

For photons of two different energies E_1 and E_2 the quantity in brackets in eq. (1) would contain $1/E_1^2$ and $1/E_2^2$. Choosing for E_1 the typical optical photon energy of ~ 1eV and for E_2 the radio photon energy ~ 10^{-5} eV, the observed $\Delta t \sim 10^5$ sec. and $D \simeq 10^{28}$ cms. (as implied by the inferred source red shift of 1.6), we have : (from eq. (1)). (We can neglect $1/E_1$, as compared to $1/E_2$ as $E_1 >> E_2$).

$$m_0 c^2 < \left(\frac{2c\Delta t}{D}\right)^{1/2} \times E_2 < 10^{-12} \text{ eV} \tag{2}$$

So that $m_0 \simeq 10^{-44}$ gm, while not more stringent as compared to similar limits from various other considerations, it is consistent with them. As for the photon charge we can use a similar method to (Cocconi, 1987). See also (Sivaram, 1995). If the photon with energy E has an electric charge q its radius of curvature of trajectory in the intergalactic magnetic field is $R = E/0.3Bq$ and the difference in arc length and consequent difference in arrival time is (Cocconi, 1987).

$$\Delta t = \frac{D}{c}\left(\frac{0.3BSq}{E}\right)^2 \tag{3}$$

Using for E_1, $E_1 \simeq 1$ev, $\Delta t \simeq 20$sec. $D = 10^{28}$ cm, $B = 10^{-9}$ G (as most of the trajectory is intergalactic), eq. (3) gives in terms of the electron charge e, a constraint on q as :

$$\frac{q}{e} < 10^{-29} \tag{4}$$

comparable with that obtained in Sivaram (1995), from considerations of the cosmic microwave background. In addition to the constraints on the photon's mass and charge as given by eqns (2) and (4), the nearly simultaneous arrival of photons over a wide energy range (ranging over twelve orders in magnitude) after a journey of a few gigaparsecs provides a stringent test of the Einstein equivalence principle (for ultrarelativistic particles over this wide energy range) on gigaparsec cosmic scales. Once again we point out that the origin of radiation at different wavelengths could be different and simultaneity in emission need not be the case. In the present case, generation of optical (perhaps reverse shock) follows the gamma ray (from internal shock). The radio (again an aftermath of the reverse shock) follows the optical. This being the observed order of events, the limits derived in this note apply. The general relativistic time delay due to our galaxy can be calculated in a similar fashion as that for radar waves passing near the sun. The time delay is (Misner et al. 1973) :

$$\delta t_\gamma = (1 + \gamma_\gamma) \frac{GM_G}{c^3} \ln[D_s + (D_s^2 + b^2)^{1/2}] \, [\, D_G + (D_G^2 + b^2)^{1/2}] \, / \, b^2 \tag{5}$$

Here M_G is the galaxy mass taken to be $6 \times 10^{11}\, M_\odot$, γ is the standard PPN parameter which is 1, in general relativity. The subscript γ in γ emphasizes that it need not be the same for photons of all energies, these time delays will differ if the Einstein equivalence principle (EEP) is violated. Thus the ratio, $\delta t_\gamma - \delta t_{\gamma'}/\delta t_\gamma \simeq ½\,(\gamma_\gamma - \gamma_{\gamma 1})$ can be used as a measure of possible violation of EEP. The impact parameter of the rays $b = 12$kpc. D_s is the distance to the γ-ray burst ($\simeq 10^{28}$ cm), D_G is the size of the galaxy halo $\simeq 60$ kpc, i.e. $D_s >> b$, D_G is comparable to b.

Thus from eq. (5)

$$\delta t_\gamma \simeq 9 \times 10^7\, (1 + \gamma_\gamma) \text{ sec} \tag{6}$$

As

$$\frac{\delta t_\gamma(\gamma_{ray}) - \delta t_{opt}}{\delta t_\gamma} = ½ (\gamma_\gamma - \gamma_{opt}) < 20/9 \times 10^7$$

(from the observed delay of 20 seconds)

This gives

$$\gamma_\gamma - \gamma_{opt} \leq 4 \times 10^{-7} \tag{7}$$

Thus γ_{ray} and optical photons 'see' the same gravitationally induced time delay to about 4 parts in 10^7 and the difference between gamma and radio photons is about one part in 10^3 (as here $\delta t \sim$ 1day). If future detectors are able to register simultaneously neutrino and gravitational waves during gamma rays bursts, all the above formulae would give similar constraints on their properties and limits on violation of EEP for them also.

Another interesting constraint has to do with the precision to which the velocity of light is constant for different photon energies. Writing for the time delay in this case as :

$$\delta t = \frac{D}{c_1(E_1)} - \frac{D}{c_2(E_2)}$$

$$\simeq \frac{(D}{(c} - \frac{D)}{c + \Delta c)}$$

where

$$\Delta c = c_2(E_2) - c_1(E_1).$$

Thus

$$\Delta t \simeq \frac{(D\Delta c)}{(c^2)} \tag{8}$$

We have $\Delta c/c < 10^{-18}$, which is also a test of the precision to which Lorentz invariance is unbroken. Again it is of interest to note that recently it has been suggested that in a large class of quantum gravity approaches (in which the existense of a minimum length $l_{min} \sim E_{QG}$ is assumed) a deformed photon dispersion arises which can possibly yield constraints based on the above GRB. Specifically this is assumed to be of the form : (Amelino-Camellia, et al. 1998)

$$Pc = E\sqrt{1+E/E_{QG}} \tag{9}$$

where E_{QG} is the quantum gravity scale, which could be as low as 10^{-3} E_{planck}, i.e $E_{QG} > 10^{16}$ GeV. One of the consequences could be that high energy photons would not travel at the speed of light, but at a speed of

$$V = c(1 - E/E_{QG}) \tag{10}$$

Thus we can again write for δt, (for two photons of energies E_1 and E_2) :

$$\Delta t \simeq \frac{(D}{c\,(1-E_1 / E_{QG})} - \frac{D)}{c\,(1-E_2 / E_{QG})}$$

$$\simeq \frac{D}{c}\left(\frac{E_1}{E_{QG}}\right),\ E_1 >> E_2 \qquad (11)$$

This then gives the lower limit on the value of E_{QG} as :

$$E_{QG} > \frac{DE_1}{c\Delta t} = 5 \times 10^{16}\ \text{GeV}$$

which thus constraints the quantum gravitational parameters.

This could also be translated into limits on a maximal field strength E_{max} in quantum gravity modified electrodynamics, such as in a Born Infeld type theory, where the field equation is effectively, $\frac{\nabla . E}{\sqrt{1 - E^2/E^2_{max}}}$ with an effective dielectric constant $\varepsilon \doteq (1 - E^2 / E^2_{max})^{1/2}$ (Sivaram, 1999).

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