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

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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 $\gamma$ - 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 $\Delta t$ 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 $\Delta t$ the well known relation:

$$\Delta t = \frac{D}{2c} \left( \frac{m_0 c^2}{E} \right)^2$$

(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 $\sim 1$ eV and for $E_2$ the radio photon energy $\sim 10^{-5}$ eV, the observed $\Delta t \sim 10^5$ sec. and $D \approx 10^{28}$ 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 $E_1 \gg E_2$).

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

(2)
So that \( m_0 \approx 10^{-44} \text{ gm} \), 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).

\[
\Delta t = \frac{D}{c} \left( \frac{0.3BSq}{E} \right)^2.
\]  

(3)

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

\[
\frac{q}{e} < 10^{-29}
\]  

(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) :

\[
\delta t = (1 + \gamma) \frac{G M_G}{c^3} \ln\left[ D_s + (D_s^2 + b^2)^{1/2} \right] \left[ D_G + (D_G^2 + b^2)^{1/2} \right] / b^2
\]  

(5)

Here \( M_G \) is the galaxy mass taken to be \( 6 \times 10^{11} \text{ M}_\odot \), \( \gamma \) is the standard PPN parameter which is 1, in general relativity. The subscript \( \gamma \) in \( \gamma \) 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, \( \delta t - \delta t_\gamma / \delta t_\gamma = (1/2 \gamma_\gamma + 1) \) can be used as a measure of possible violation of EEP. The impact parameter of the rays \( b = 12\text{ kpc} \). \( D_s \) is the distance to the \( \gamma \)-ray burst \( (\approx 10^{28} \text{ cm}) \), \( D_G \) is the size of the galaxy halo \( \approx 60 \text{ kpc} \), i.e. \( D_s > b \), \( D_G \) is comparable to \( b \).

Thus from eq. (5)

\[
\delta t_\gamma \approx 9 \times 10^7 (1 + \gamma_\gamma) \text{ sec}
\]  

(6)
As
\[ \frac{\delta t_y (\gamma_{\text{ray}}) - \delta t_{\text{opt}}}{\delta t_y} = \frac{1}{2} (\gamma_y - \gamma_{\text{opt}}) < 20/9 \times 10^7 \]
(from the observed delay of 20 seconds)

This gives
\[ \gamma_y - \gamma_{\text{opt}} \leq 4 \times 10^{-7} \] (7)

Thus \( \gamma_{\text{ray}} \) 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 \( \delta t \sim 1 \text{day} \)). 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 :

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

\[ \approx \frac{(D)}{(c - \frac{D}{c + \Delta c})} \]

where
\[ \Delta c = c_2(E_2) - c_1(E_1). \]

Thus
\[ \Delta t \approx \frac{(D\Delta c)}{c^2} \] (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 \( l_{\text{min}} \sim E_{\text{QG}} \) 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-Camelia, et al. 1998)

\[ Pc = E \sqrt{1 + E/E_{\text{QG}}} \] (9)

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

\[ V = c(1 - E/E_{\text{QG}}) \] (10)
Thus we can again write for \( \delta t \), (for two photons of energies \( E_1 \) and \( E_2 \)):

\[
\Delta t \simeq \frac{D}{c} \left( \frac{1}{E_1 / E_{\text{QG}}} - \frac{1}{E_2 / E_{\text{QG}}} \right)
\]

\[
\frac{D}{c} \left( \frac{E_1}{E_{\text{QG}}} \right), \quad E_1 \gg E_2
\]

This then gives the lower limit on the value of \( E_{\text{QG}} \) as:

\[
E_{\text{QG}} > \frac{D E_1}{c \Delta t} = 5 \times 10^{16} \text{ GeV}
\]

which thus constraints the quantum gravitational parameters.

This could also be translated into limits on a maximal field strength \( E_{\text{max}} \) in quantum gravity modified electrodynamics, such as in a Born Infeld type theory, where the field equation is effectively,

\[
\nabla \cdot E = \frac{\sqrt{1 - E^2/E_{\text{max}}^2}}{\sqrt{1 - E^2/E_{\text{max}}^2}}
\]

(Sivaram, 1999).

References

Sagar R. et al., 1999, BASI, 27, 3.