Journal of High Energy Astrophysics 11–12 (2016) 20–28

Contents lists available at ScienceDirect

Journal of High Energy Astrophysics

www.elsevier.com/locate/jheap

Constraining the mass of the photon with gamma-ray bursts

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ARTICLE INFO

Article history:
Received 15 March 2016
Accepted 7 July 2016
Available online xxxx

Keywords:
Radio continuum: general
Gamma-ray burst: general
Photon rest mass

ABSTRACT

One of the cornerstones of modern physics is Einstein's special relativity, with its constant speed of light and zero photon mass assumptions. Constraint on the rest mass m_γ of photons is a fundamental way to test Einstein's theory, as well as other essential electromagnetic and particle theories. Since non-zero photon mass can give rise to frequency- (or energy-) dependent dispersions, measuring the time delay of photons with different frequencies emitted from explosive astrophysical events is an important and model-independent method to put such a constraint. The cosmological gamma-ray bursts (GRBs), with short time scales, high redshifts as well as broadband prompt and afterglow emissions, provide an ideal testbed for m_γ constraints. In this paper we calculate the upper limits of the photon mass with GRB early time radio afterglow observations as well as multi-band radio peaks, thus improve the results of Schaefer (1999) by nearly half an order of magnitude.

1. Introduction

Modern physics theories, especially Maxwellian electromagnetism, Einstein's theory of Special Relativity as well as quantum electrodynamics (QED) are all based on a simple precondition: the speed of light in vacuum is a constant c for all electromagnetic waves, from radio to the γ-ray band. That is, photons are massless particles. Thus, whether the speed of light is a constant across the electromagnetic spectrum plays a fundamental role in physics. If photons have non-zero rest mass, various key theories should be affected. Although enormous successes have been achieved based upon the theories aforementioned, it is still necessary to put the massless photon assumption to test with as many independent methods as possible.

The mass of photon can be measured via two types of approaches, laboratory experiments and astronomical observations (Tu et al., 2005, and references therein). According to Heisenberg's uncertainty principle, currently the best limit of photon rest mass m_γ one can achieve should be $m_\gamma \approx \hbar/c^2\Delta T$, here $\hbar$ is the Planck constant, and ΔT the age of the Universe. With ΔT known to be in the order of 10^{10} years, the value of m_γ inferred from various tests should be no smaller than $\approx 10^{-66}$ g (Tu et al., 2005). The laboratory measurements based upon Coulomb's law, Ampère's law, and other electromagnetic phenomena have achieved very stringent constraints, with a lower limit of $m_\gamma < (0.7 \pm 1.7) \times 10^{-52}$ g from measurements of torque on rotating magnetized toroid (Tu et al., 2006). On the other hand, astronomical tests utilizing various principles, from dispersions of astrophysical radiations caused by non-zero photon mass, to magneto-hydrodynamics (MHD) related phenomena, can provide independent tests on the mass limit of photons other than laboratory measurements.

Currently the mass limit of photon adopted by Particle Data Group is $m_\gamma \leq 1.783 \times 10^{-51}$ g, nearly 24 orders of magnitude smaller than electron's mass m_e (Olive et al., 2014), and this value is measured from observations of MHD phenomena in planetary magnetic fields (Ryutov, 2007). Besides, Chibisov (1976) obtained a more stringent limit of $m_\gamma \leq 3 \times 10^{-60}$ g, by analyzing the stability of magnetized gas in galaxies, although this result depends on the applicability of virial theorem and other assumptions. Goldhaber and Nieto (2003) also put a limit on the mass of photon of 10^{-52} g considering the stability of plasma in Coma Cluster. However, since astronomical MHD phenomena can be quite complicated, such constraints could be more model-dependent in many cases.

Besides, Accioly and Pazszko (2004) obtained a result of $m_\gamma \leq 10^{-40}$ g based on gravitational deflections of radio waves. While Schaefer (1999) got a limit of $m_\gamma \leq 4.2 \times 10^{-44}$ by comparing the time-delay of photons with different frequencies from a wide range of explosive astronomical events, including gamma ray

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http://dx.doi.org/10.1016/j.jheap.2016.07.001
2214-4048/

bursts (GRBs for short), Type Ia supernovae with high redshift, TeV flares from blazar Mrk 421, as well as the Crab Pulsar. And with a lower observational frequency as well as a shorter time scale, the time delay between the radio afterglow and prompt γ-ray emission of GRB 980703 yielded the best result in this analysis. Since the basic idea behind the time-delay method is quite simple and does not related to any specific models, more reliable constraints can be obtained.

In this paper we present our analysis of limit on m_γ with a larger GRB radio afterglow sample provided by Chandra and Frail (2012), thus improving the results of Schaefer (1999). In Section 2 the basic equations and method are presented. Our analysis is based on multi-wavelength radio afterglows as well as prompt emissions for each GRB, and data from more than 60 GRBs are utilized. Our results are presented in Section 3. Also we make an attempt to incorporate synchrotron radiation model for afterglows in our analysis, thus making the time delay shorter, in order to get more stringent constraints. Section 4 summarizes our results and a conclusion is drawn. Throughout our analysis we adopt the standard ΛCDM cosmology with the cosmological parameters based upon 9-year observations of *Wilkinson Microwave Anisotropy Probe* (WMAP), that is, $H_0 = 69\ \mathrm{km\,s^{-1}Mpc^{-1}}$, $\Omega_m = 0.286$, and $\Omega_\Lambda = 0.714$ (Hinshaw et al., 2013).

2. Velocity dispersion from non-zero photon mass

In this section we present our methods of analysis. Supposing the rest mass of photon is m_γ, according to Einstein's theory of special relativity, the energy of the photon can be expressed as

$$E = h\nu = \sqrt{p^2c^2 + m_\gamma^2 c^4}. \tag{1}$$

In the case of $m_\gamma \neq 0$, the group velocity v_p of photon in vacuum is no longer a constant, and changes with photon energy E (or frequency ν) according to the dispersion relation

$$v_p = \frac{\partial E}{\partial p} = c\sqrt{1 - \frac{m_\gamma^2 c^4}{E^2}} = c\sqrt{1 - A\nu^{-2}} \approx c(1 - 0.5A\nu^{-2}), \tag{2}$$

where $A = \frac{m_\gamma^2 c^4}{h^2}$.

It is easily seen from Equation (2) that the lower frequency, the slower the photon propagates in vacuum. For explosive events with short time scales such as GRBs, assuming photons with different frequencies emitted simultaneously, the time delay of low energy photons relative to high energy ones thus can be used to calculate the rest mass of a photon. In reality radiations of different bands arise at different times. For example, during a GRB explosion high energy photons should be radiated earlier than X-ray to radio afterglows, and radio afterglows with higher frequencies emerge earlier than lower frequency ones (e.g., see Chandra and Frail, 2012). Therefore, by ignoring such intrinsic time delays, this method can be used to put an upper limit on the photon rest mass.

In our analysis we consider a photon with a higher frequency (energy) ν_1, and another photon with a lower frequency ν_2. Schaefer (1999) did not explicitly clarify what kind of cosmological distance is used to calculate the δt, while we improve their previous analysis by taking this factor into account. Assuming the high energy photon is emitted at redshift z, the comoving distance from source to Earth-based observers for the high energy photon ν_1 with a non-zero mass should be

$$D(z,\nu_1) = \frac{c}{H_0}\int_0^z [1 - \frac{1}{2}A\nu_1^{-2}\frac{1}{(1+z')^2}]\frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}. \tag{3}$$

Suppose the low energy photon **with** ν_2 arrives at Earth later with a nominal redshift difference $z = -\delta z$, $\delta z \ll 1.0$, the comoving distance traveled by **this photon** is

$$D(z,\nu_2) = \frac{c}{H_0}\int_{-\delta z}^z [1 - \frac{1}{2}A\nu_2^{-2}\frac{1}{(1+z')^2}]\frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}. \tag{4}$$

Since the two photons should travel the same comoving distance before they reach Earth, we have

$$D(z,\nu_1) = D(z,\nu_2). \tag{5}$$

Thus the time delay δt of the low energy photon ν_2 is

$$\delta t = \frac{\delta z}{H_0} = \frac{B}{2H_0}(\nu_2^{-2} - \nu_1^{-2})\int_0^z \frac{dz'}{(1+z')^2\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}, \tag{6}$$

where $B = \frac{2H_0\delta t}{(\nu_2^{-2} - \nu_1^{-2})H(z)}$, and $H(z) = \int_0^z \frac{\mathrm{d}z'}{(1+z')^2\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$. With a little algebra, the mass of photon can be calculated from the time delay between ν_1 and ν_2 as

$$\begin{aligned} m_\gamma &= B^{1/2}hc^{-2} \\ &= \left[\frac{2H_0\delta t}{\left(\nu_2^{-2} - \nu_1^{-2}\right)H(z)}\right]^{1/2} hc^{-2} \\ &\simeq 7.4\times 10^{-48}\left[\frac{2H_0\delta t}{\left(\nu_2^{-2} - \nu_1^{-2}\right)H(z)}\right]^{1/2}\ \mathrm{g} \end{aligned} \tag{7}$$

It can be seen that in order to get a tighter constraint, a lower ν_2, a larger z, as well as a shorter δt are preferred. Thus, explosive events with radio emissions occurring at cosmological distances are the most favorable choices. In our analysis we use cosmological GRBs, with their short durations as well as radio afterglows, to put stringent constraints on the upper limit of the photon mass m_γ. However, it should be noted that since $m_\gamma \propto \delta t^{1/2}/\left(\nu_2^{-2} - \nu_1^{-2}\right)^{1/2}$, the result of m_γ is more dependent on ν_2 rather than δt.

For cosmological GRBs, an intrinsic time delay between prompt gamma-ray emission and radio afterglow does exist, and this should be the most important contributor of the observed δt. Since prompt emissions are originated from internal interactions of the burst ejecta, and radio afterglows are from later interactions between ejecta and circumburst medium, such a δt_{int} is always positive for radio photons. The exact value of δt_{int} is hard to know, since early radio afterglows are subject to synchrotron self absorptions, and their starting phases are hard to detect. However, as long as $\delta t_{int} > 0$ stands, what we get from observational data still can provide upper limits of the mass of photons.

Other processes can also be responsible for dispersions between photons with different energies. One of such process is Lorentz invariance violation (LIV), that is, dispersion caused by Planck scale fluctuations of space–time itself. However recent works show that linear LIV does not exist, while time delay from possible higher order items can be completely omitted (e.g., see Abdo et al., 2009; Vasileiou et al., 2013). Besides, high energy photons rather than radio waves suffered most from LIV. Thus we ignore LIV effects in following calculations. Another possible source of time delay is deviation from Einstein's Equivalence Principle (EEP). If such deviation exists, two photons with different energies travel at dif-