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Light speed variation from gamma-ray bursts

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ABSTRACT

The effect of quantum gravity can bring a tiny light speed variation which is detectable through energetic photons propagating from gamma ray bursts (GRBs) to an observer such as the space observatory. Through an analysis of the energetic photon data of the GRBs observed by the Fermi Gamma-ray Space Telescope (FGST), we reveal a surprising regularity of the observed time lags between photons of different energies with respect to the Lorentz violation factor due to the light speed energy dependence. Such regularity suggests a linear form correction of the light speed $v(E) = c(1 - E/E_{\mathrm{LV}})$, where E is the photon energy and $E_{\mathrm{LV}} = (3.60 \pm 0.26) \times 10^{17}$ GeV is the Lorentz violation scale measured by the energetic photon data of GRBs. The results support an energy dependence of the light speed in cosmological space.

It is a basic assumption in Einstein's relativity that the speed of light is a constant c in free space. However, it is speculated from quantum gravity that the Lorentz invariance will be broken at the Planck scale ($E \sim E_{\mathrm{Pl}} = \sqrt{\hbar c^5/G} \approx 1.22 \times 10^{19}$ GeV), thus the light speed may receive a correction of the order $E_{\mathrm{photon}}/E_{\mathrm{Pl}}$ due to the Lorentz invariance Violation (LV). As the photon energy E_{photon} is very small in comparison with the Planck energy E_{Pl}, the correction to the light speed is too tiny to be detectable in most circumstances. Amelino-Camelia et al. [1,2] first suggested to use distant astrophysical sources of energetic photons to test the light speed energy dependence. For energetic photons from a gammy ray burst (GRB), the large cosmological distance from the source to an observer can amplify the tiny photon speed variation into observable quantities such as the arrival time lags between photons with different energies. The Fermi Gamma-ray Space Telescope (FGST) [3,4] is a space observatory launched in 2008 to perform gamma-ray astronomy observations. The Fermi Large Area Telescope (LAT) on board the FGST has detected a number of GRBs with over 10 GeV photons [5,6]. Provided that the redshifts of some GRBs have been measured by optical and X-ray telescopes, these data would offer us an opportunity to find evidence for or against the light speed variation in cosmological space.

For energy $E \ll E_{\mathrm{Pl}}$, the modified dispersion relation of the photon can be expressed in a general form as the leading term of Taylor series

$$E^2 = p^2c^2\left[1 - s_n\left(\frac{pc}{E_{\mathrm{LV},n}}\right)^n\right], \tag{1}$$

from which we can derive the modified light speed, using the relation $v = \partial E/\partial p$,

$$v(E) = c\left[1 - s_n\frac{n+1}{2}\left(\frac{pc}{E_{\mathrm{LV},n}}\right)^n\right], \tag{2}$$

where $n = 1$ or $n = 2$ corresponds to linear or quadratic energy dependence of the light speed respectively, $s_n = \pm 1$ indicates whether the high energy photon travels slower ($s_n = +1$) or faster ($s_n = -1$) than the low energy photon, and $E_{\mathrm{LV},\,n}$ represents the nth-order Lorentz violation scale to be determined by the data. Taking the cosmological expansion of the universe into consideration, the light speed variation due to Lorentz violation with dispersion relation Eq. (2) can produce a time lag (measured in the observer reference system) between two photons with different energies as [7,8]

$$\Delta t_{\mathrm{LV}} = s_n\frac{1+n}{2H_0}\frac{E_{\mathrm{h}}^n - E_{\mathrm{l}}^n}{E_{\mathrm{LV},n}^n}\int_0^z\frac{(1+z')^n \mathrm{d}z'}{\sqrt{\Omega_{\mathrm{m}}(1+z')^3 + \Omega_\Lambda}}, \tag{3}$$

where E_{h} and E_{l} are the energies of the observed high-energy and low-energy photons, z is the redshift of the GRB source, and $H_0 = 67.3 \pm 1.2$ km s^{-1} Mpc^{-1} is the present day Hubble expansion rate [9] while $\Omega_m = 0.315^{+0.016}_{-0.017}$ and $\Omega_\Lambda = 0.685^{+0.017}_{-0.016}$ are the pressureless matter density of the Universe and the dark energy density of the ΛCDM Universe respectively [9].

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Table 1
The data of high energy photon events from GRBs with known redshifts.

GRB	z	$t_{\rm high}$ (s)	$t_{\rm low}$ (s)	$E_{\rm obs}$ (GeV)	$E_{\rm source}$ (GeV)	$\frac{\Delta t_{\rm obs}}{1+z}$ (s)	K_1 ($\times\ 10^{18}$ s · GeV)
080916C(1)	4.35 ± 0.15	16.545	5.984	12.4	66.3	1.974	4.46 ± 0.45
080916C(2)	4.35 ± 0.15	40.509	5.984	27.4	146.6	6.453	9.86 ± 0.99
090510	0.903 ± 0.003	0.828	−0.032	29.9	56.9	0.452	7.21 ± 0.73
090902B	1.822	81.746	9.768	39.9	112.6	25.506	12.9 ± 1.3
090902Bs		11.671		11.9	33.6	0.674	3.84 ± 0.39
		14.166		14.2	40.1	1.559	4.58 ± 0.47
	1.822	26.168	9.768	18.1	51.1	5.812	5.84 ± 0.59
		42.374		12.7	35.8	11.554	4.10 ± 0.42
		45.608		15.4	43.5	12.700	4.97 ± 0.51
090926A	2.1071 ± 0.0001	24.835	4.320	19.5	60.6	6.603	6.53 ± 0.66
100414A	1.368	33.365	0.288	29.7	70.3	13.968	8.70 ± 0.88
130427A	0.3399 ± 0.0002	18.644	0.544	72.6	97.3	13.509	9.02 ± 0.91
140619B	2.67 ± 0.37	0.613	0.096	22.7	83.5	0.141	7.96 ± 0.82

Data of GRBs are from Ref. [6] (see Table 2 therein) for GRBs 080910C, 090510, 090902B, 090926A, and 100414A, from Ref. [11] (see Table 1therein) for GRB 100414A, and from the Fermi website [14] for 140619B. The references for the redshifts of these GRBs are [15] (GRB 080916C), [16] (GRB 090510), [17] (GRB 090902B), [18] (GRB 090926A), [19] (GRB 100414A), [20] (GRB 130427A), and [13] (GRB 140619B). $t_{\rm high}$ and $t_{\rm low}$ denote the arrival time of the high energy photons and the peak time of the first pulse of low energy photons respectively, with the trigger time of GBM as the zero point. Therefore $\Delta t_{\rm obs} = t_{\rm high} - t_{\rm low}$ is the observed time lag between the high energy and low energy photons. $E_{\rm obs}$ and $E_{\rm source}$ are the energy measured by Fermi LAT and the corresponding intrinsic energy at the source of the GRBs, with the cosmological expansion factor $(1+z)$ being considered to transform $E_{\rm obs}$ to $E_{\rm source}$, i.e., $E_{\rm source} = (1+z)E_{\rm obs}$. K_1 is the Lorentz violation factor calculated from Eq. (8) with a unit of (s·GeV).

Unfortunately, the intrinsic mechanism of GRBs is not well understood yet, hence there are big uncertainties as to how to apply Eq. (3) to analyze the data of GRB photons. Since the photons in one GRB are not emitted from the source at the same time, the time lags observed between them consist of not only $\Delta t_{\rm LV}$ caused by the Lorentz violation as expressed in Eq. (3), but also the intrinsic time lag at the source $\Delta t_{\rm in}$ (measured in the source reference system) between different photon events. So we should write the observed time lag between two photon events as [10]

$$\Delta t_{\rm obs} = \Delta t_{\rm LV} + (1+z)\Delta t_{\rm in}, \tag{4}$$

with $\Delta t_{\rm LV}$ as in Eq. (3). Then we need careful consideration for a reliable criteria to determine $\Delta t_{\rm obs}$ and $\Delta t_{\rm in}$. It was assumed in Refs. [11,12] that the trigger time $t_{\rm trigger}$ of Fermi Gamma-ray Burst Monitor (GBM) is the onset time of the GRB. This assumption leads to $\Delta t_{\rm obs} = t_{\rm high} - t_{\rm trigger}$, where $t_{\rm high}$ is the observed arrival time of high energy photons. In fact the trigger time of GBM is related not only with some amount of the detected low energy photons, but also with the detection limits of the observation equipment, i.e. GBM itself, so it may not be an objective standard adherent to the intrinsic GRB dynamics. Here we choose the peak time of the first main pulse of low energy photons from a GRB as the signal time of low energy photons, so

$$\Delta t_{\rm obs} = t_{\rm high} - t_{\rm low}, \tag{5}$$

where $t_{\rm low}$ is the peak time of the first pulse of low energy photons. As the first low energy peak is recorded as an intensive pulse of large number of low energy photons ranging between 8 ∼ 260 keV, it can serve as a significant benchmark which is related to the intrinsic mechanism of the GRB objectively and naturally, so that choosing it as a signal for the low energy photons is more reasonable.

For the high energy photon events from GRBs, we adopt photons that have energy higher than 10 GeV and are collected within the 90 s time window in the recent Fermi-LAT event construction [6]. Ref. [6] provided a list of high energy photons from 5 bright GRBs, i.e., GRBs 080916C, 090510, 090902B, 090926A, and 100414A. There are also later observed GRBs 130427A [11] and 140619B [13] with over 10 GeV photons and estimated redshifts. Among these GRBs, GRBs 090510 and 140619B are short bursts (with duration time less than 2 s) while others are long bursts (with duration time longer than 2 s). We list the observed energy $E_{\rm obs}$ and observed arrival time $t_{\rm high}$ of these photons in Table 1, where $t_{\rm high}$ is the recorded arrival time of the photon after the trigger time of GBM.

We download the GBM TTE (Time-Tagged-Events) NaI files of all GRBs listed in Table 1 from the Fermi website [14] and analyze them with the RMFIT package. GBM TTE NaI files record the observed time lags (with the trigger time of GBM as the starting time point) and observed energies of a large number of photons ranging between 8 ∼ 260 keV. The energy scale of these photons is so low in comparison with that of the high energy 10 GeV photons so that the Lorentz violation effect can be neglected for these photons. We bin all these low energy events in 64 ms intervals in order to find the peak position $t_{\rm low}$, which corresponds to the first low energy peak for each GRB. The uncertainty of the determined peak position is of the order of 64 ms and is negligible in our analysis. We list the obtained results of $t_{\rm low}$ for each GRB in Table 1.

According to our above arguments, we take the energies of the photons observed at $t_{\rm low}$ as $E_{\rm l}$ in Eq. (3). Therefore $E_{\rm l}$ is between 8 ∼ 260 keV. Since it is extremely low compared with the energies of the high energy photon events listed in Table 1 ($E_{\rm l} < 10^{-4}E_{\rm h}$), we can set $E_{\rm l} = 0$ and simplify Eq. (3) as

$$\Delta t_{\rm LV} = s_n \frac{1+n}{2H_0} \frac{E_{\rm h}^n}{E_{{\rm LV},n}^n} \int_0^z \frac{(1+z')^n {\rm d}z'}{\sqrt{\Omega_{\rm m}(1+z')^3 + \Omega_\Lambda}}. \tag{6}$$

Because we do not know $\Delta t_{\rm in}$ now, Eq. (4) cannot be used directly. We re-express it as

$$\frac{\Delta t_{\rm obs}}{1+z} = s_n \frac{K_n}{E_{{\rm LV},n}^n} + \Delta t_{\rm in}, \tag{7}$$

where K_n is the Lorentz violation factor

$$K_n = \frac{1+n}{2H_0} \frac{E_{\rm h}^n}{1+z} \int_0^z \frac{(1+z')^n {\rm d}z'}{\sqrt{\Omega_{\rm m}(1+z')^3 + \Omega_\Lambda}}. \tag{8}$$

We can find that if the energy dependence of light speed does exist, there would be a linear relation between $\Delta t_{\rm obs}/(1+z)$ and K_n. These photons with same intrinsic time lags would fall on an inclined line in the $\Delta t_{\rm obs}/(1+z)$ - K_n plot, and we can determine $\Delta t_{\rm in}$ of them as the intercept of the line with the Y axis.

We first consider the situation of the linear form correction of the light speed, i.e., the $n = 1$ case. In Fig. 1, we draw $\Delta t_{\rm obs}/(1+z)$ versus K_1 of all the high energy photon events in Table 1. The X axis is K_1 and the Y axis is $\Delta t_{\rm obs}/(1+z)$. Strictly speaking, no assumption is made when drawing the points in Fig. 1. When trying