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Lorentz violation from gamma-ray bursts

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ABSTRACT

The constancy of light speed is a basic assumption in Einstein's special relativity, and consequently the Lorentz invariance is a fundamental symmetry of space–time in modern physics. However, it is speculated that the speed of light becomes energy-dependent due to the Lorentz invariance violation (LV) in various new physics theories. We analyse the data of the energetic photons from the gamma-ray bursts (GRBs) by the Fermi Gamma-Ray Space Telescope, and find more events to support the energy dependence in the light speed with both linear and quadratic form corrections. We provide two scenarios to understand all the new-released Pass 8 data of bright GRBs by the Fermi-LAT Collaboration, with predictions from such scenarios being testable by future detected GRBs.

Since the launch of the Fermi Gamma-Ray Space Telescope (Fermi) in 2008, the Fermi Large Area Telescope (LAT) on board the Fermi has detected a number of gamma-ray bursts (GRBs) with over 10 GeV photons [1]. These GRBs with measured redshifts and detected energetic photons have been deemed as useful for probing the Lorentz violation (LV) physics [2], as Lorentz invariance is predicted to be broken at the Planck scale ($E \sim E_{\rm Pl} = \sqrt{\hbar c^5/G} \simeq 1.22 \times 10^{19}$ GeV) [3,4]. As several brightest GRBs with different redshifts have been detected by LAT for now [1,5], it is necessary to check the possibility of finding evidence for or against Lorentz violation effect in high energy photons from these GRBs.

As a consequence of Lorentz violation, the speed of light could have an energy dependence from the expression $v = \partial E/\partial p$. In a general model-independent form, the modified dispersion relation of photon can be expressed by the leading term of the Taylor series as

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

which corresponds to a modified light speed

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

where n = 1 or n = 2 corresponds to linear or quadratic energy dependence, and $s_n = \pm 1$ is the sign of the LV correction. If $s_n = +1 (s_n = -1)$, the high energy photons travel in vacuum slower (faster) than the low energy photons. The nth-order Lorentz violation scale is characterized by the Lorentz violation parameter $E_{\rm LV,\,n}$. Because of the spectral dispersion, two GRB photons emitted simultaneously by the source would arrive on Earth with a time delay (Δt) if they have different energies. With the magnification of the cosmological distances of the GRBs and the high energies of these photons, the time delay (Δt) caused by the effect of Lorentz violation would be measurable [2]. Taking account of the cosmological expansion, we write the formula of the time delay as [6]:

$$\Delta t = t_{\rm h} - t_{\rm l} = s_{\rm n}\frac{1+n}{2H_0}\frac{E_{\rm h}^n - E_{\rm l}^n}{E_{\rm LV,n}^n}\int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}. \tag{3}$$

Here, $t_{\rm h}$ is the arrival time of the high energy photon, and $t_{\rm l}$ is the arrival time of the low energy photon, with $E_{\rm h}$ and $E_{\rm l}$ being the photon energies measured by the LAT. We adopt the cosmological constants $[\Omega_m, \Omega_\Lambda] = [0.272, 0.728]$ determined by the latest data from WMAP [7] and the Hubble constant $H_0 = 73.8 \pm 2.4\ {\rm km\ s^{-1}Mpc^{-1}}$ measured by the Hubble Space Telescope recently [8].

However, there are big ambiguities in applying Eq. (3) to analyse the data, because there are also time delays due to the intrinsic properties of GRBs. Some works constrained the quantum gravity (QG) scale $E_{\rm QG} > E_{\rm Pl}$ with some statistic methods [9,10] and the sharp shape showed in the light curve of the short GRB 090510 [11,12], but such big constraints have no support from the other

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long GRBs. On the other hand, there are also works [13,14] supporting the Lorentz violation at the energy scale of 10^{17} GeV by including the intrinsic time lags of the high energy photons emitted at the GRB source. In our work, we will analyse all the data of bright GRBs newly released by the Fermi-LAT Collaboration [15], to consider the Lorentz violation effect in the time delays by including also the intrinsic time lag, following the approach in Refs. [13,16].

In Eq. (3), a larger energy difference could cause a larger detectable time delay, so we first analyse the data of the photons with highest energies from 6 bright GRBs, which are GRBs 080916C, 090510 (short GRB), 090902B, 090926A, 100414A, and 130427A. Among these GRBs, only GRB 090510 is a short GRB (with duration time <2 s), while the rest are long GRBs (with duration time >2 s). The photon data of our candidates are collected from the latest Pass 8 Fermi-LAT event reconstruction [15]. As the data of GRB 130427A have not been re-analyzed with Pass 8, we use the Pass 7 data downloaded from the Fermi-LAT Data Server. In addition, the 4 highest energy photons associated with GRB 130427A have comparable energies, but the first 73-GeV photon which arrived 18 s after the onset of this GRB will be analyzed together with the photons of the earlier bright GRBs. As the redshift of GRB 130427A ($z = 0.34$) [17] is smaller than those of other considered GRBs, the large time delays (>200 s) measured in the rest 3 high energy gamma-rays are less likely to be the consequence of the Lorentz violation effect, but more possible to be caused by the large intrinsic time lags between these high energy gamma-rays and the trigger gamma-rays. For GRB 080916C, both the 2 high energy photons in Pass 8 data are included in our analysis due to the large distance ($z = 4.35$) [18], as both of these events could show detectable LV-induced time lags.

The values of $E_{LV,1}$ listed in Table 1 are calculated directly by using Eq. (3), where t_l is the trigger time of the GRB detected by the Gamma-Ray Burst Monitor (GBM) [23], and t_h is the arrival time of the high energy photon. Because the photons arrived at the trigger time have low energies at the order of 100 keV [1], we consider E_l in Eq. (3) as 0 approximately in our calculation. From Table 1 we see that the values of $E_{LV,1}$ are all around the order of 10^{17} GeV except for the short GRB 090510, which leads to a large $E_{LV,1} \sim 10^{19}$ GeV [24]. We notice the slight difference in $E_{LV,1}$'s for long GRBs and the large gap between these $E_{LV,1}$'s and that for short GRB 090510. In fact, $E_{LV,1}$'s in Table 1 are calculated under the assumption that both the high energy photons and the onset low energy photons are emitted at the source simultaneously. We may attribute the difference to an intrinsic time lag of the high energy photon emitted at the source as compared with the emission time of the low energy photons. Therefore the slight difference for long GRBs might imply that these high energy photons have comparable intrinsic emission time, while the high energy photon of short GRB 090510 has a quite different intrinsic emission time. Taking into account the intrinsic emission time t_{in} of high energy photons, we write the observed time delay between the onset of GRB (trigger time) photons and the high energy photons as

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

where t_{LV} is now the time lag caused by the Lorentz violation, i.e., Δt in Eq. (3).

Then we re-express Eq. (4) as a linear function in a form:

$$\frac{t_{obs}}{1+z} = \frac{K_n}{E^n_{LV,n}} + t_{in}, \tag{5}$$

where the Lorentz violation factor reads

$$K_n = \frac{1+n}{2H_0}\frac{E^n}{1+z}\int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}, \tag{6}$$

which has a unit as $[\mathrm{s}\cdot\mathrm{GeV}]$. To check the possible linear-dependence of the Lorentz violation effect in the data, we draw the $\frac{\Delta t_{obs}}{1+z}$ versus K_1 plot for all the high energy photons in Table 1 in Fig. 1, where the X axis is K_1 and the Y axis is $\frac{\Delta t_{obs}}{1+z}$. As we can see from Fig. 1, 5 points of photons from 5 long GRBs can be fitted on a straight line, which can be considered as the main line. The intercept of this line with the Y axis corresponds to the intrinsic time lag t_{in}. This means that the intrinsic time lags t_{in} between the highest energy gamma rays and the GRB onset are approximately the same for these 5 gamma-rays of long GRBs. We consider this line as a support for a linear Lorentz violation effect at a scale $E_{LV,1} = (3.05 \pm 0.19) \times 10^{17}$ GeV with the same intrinsic time lag $t_{in} = -12.1 \pm 1.7$ s. Including the energy resolution of LAT for over 10 GeV photons as 10% [25] and the uncertainties of the cosmological parameters and the redshifts to the fitted slope, we get the standard error of $E_{LV,1}$ as 0.7×10^{17} GeV. After we consider these errors, the mixing of Pass 7 data and Pass 8 data do not influence the conclusion of the result. We see that a higher precision is achieved for this result of $E_{LV,1}$ compared to the averaged value $E_{LV,1} = (7.5 \pm 3.4) \times 10^{17}$ GeV corresponding to the 5 gamma-rays without considering the intrinsic emission time effect in Table 1.

In the Pass 8 data of GRB 080916C, a 27.4 GeV photon with a 40.5 s time lag has been reconstructed [15]. The data and the point are shown in Table 1 (080916C(2)) and Fig. 1 (pink square).

Table 1
The data of the GRBs with high energy photons and known redshifts.

GRB	z	t_{obs} (s)	E_{obs} (GeV)	E_{in} (GeV)	$E_{LV,1}$ ($\times 10^{17}$ GeV)	$\frac{t_{obs}}{1+z}$ (s)	K_1 ($\times 10^{18}$ s · GeV)
080916C(1)	4.35 ± 0.15	16.545	12.4	66.3	13.9 ± 1.7	3.092	4.30
090926A	2.1071 ± 0.0001	24.835	19.5	60.6	7.8 ± 0.8	7.993	6.23
100414A	1.368	33.365	29.7	70.3	5.8 ± 0.6	14.090	8.22
130427A[a]	0.3399 ± 0.0002	18.644	72.6	97.3	6.0 ± 0.7	13.915	8.32
090902B	1.822	81.746	39.9	112.6	4.2 ± 0.5	28.967	12.24
090510	0.903 ± 0.003	0.828	29.9	56.9	155 ± 17	0.435	6.75
080916C(2)	4.35 ± 0.15	40.509	27.4	146.6	12.6 ± 1.4	7.572	9.51
		11.671	11.9	33.6	8.8 ± 1.0	4.136	3.65
		14.166	14.2	40.1	8.7 ± 1.0	5.020	4.36
090902Bs	1.822	26.168	18.1	51.1	6.0 ± 0.7	9.273	5.55
		42.374	12.7	35.8	2.6 ± 0.3	15.016	3.90
		45.608	15.4	43.5	2.9 ± 0.3	16.162	4.72

[a] The data of this GRB are from the Pass 7 LAT reconstruction. The references for the redshifts of the GRBs are [18] (GRB 080916C), [22] (GRB 090510), [21] (GRB 090902B), [19] (GRB 090926A), [20] (GRB 100414A), and [17] (GRB 130427A). t_{obs} is the arrival time after the onset of the GRBs, E_{obs} is the measured energy of the photon, E_{in} is the intrinsic energy at the source of the GRBs, and $E_{LV,1}$ is the Lorentz violation parameter of the linear LV model without considering the intrinsic time lag. The standard errors of $E_{LV,1}$'s are calculated with the consideration of the energy resolution of LAT [25] and the uncertainties of the cosmological parameters and the redshifts. K_1 is the Lorentz violation factor with a unit as (s · GeV)