Spectral Lag Transition of 32 Fermi Gamma-Ray Bursts and Their Application on Constraining Lorentz Invariance Violation

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Abstract

The positive-to-negative transition of spectral lag is an uncommon feature reported in a small number of gamma-ray bursts (GRBs). An application of such a feature has been made to constrain the critical quantum gravity energy \(E_{QG}\) of the light photons under the hypothesis that the Lorentz invariance might be violated. Motivated by previous case studies, this paper systematically examined the up-to-date GRB sample observed by Fermi Gamma-ray Burst Monitor for the lag transition feature to establish a comprehensive physical limit on the Lorentz invariance violation (LIV). This search resulted in 32 GRBs with redshift available, which exhibit the lag transition phenomenon. We first fit each of the lag–\(E\) relations of the 32 GRBs with an empirical smoothly broken power-law function, and found that the lag transition occurs typically at about 400 keV. We then implemented the LIV effect into the fit, which enabled us to constrain the lower limit of the linear and quadratic values of \(E_{QG}\), which are typically distributed at \(1.5 \times 10^{14}\) and \(8 \times 10^9\) GeV, respectively.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Gravitation (661); Quantum gravity (1314)

1. Introduction

The spectral lag of gamma-ray bursts (GRBs) was first introduced by Norris et al. (1996) to describe the phenomenon that GRB light curves in higher energy bands peak earlier than those in lower energy bands. Subsequent studies (e.g., Norris et al. 2000; Yi et al. 2006) showed that long GRBs are always characterized by significant lags, whereas short GRBs always present zero, sometimes negative, lags. On the other hand, the exact physical mechanism that causes spectral lags remains incompletely resolved to date. Considering the relativistic beaming nature of a GRB jet, one may naturally expect that the so-called “high-latitude” effect can cause photons at higher latitudes to arrive at the observer later and with softened observed energy. Such effect was used by Salamonson (2000), Ioka & Nakamura (2001), and Norris & Bonnell (2006) to explain the overall statistical properties of the observed lags as well as the luminosity–lag correlation (Schafer 2004). By assuming an intrinsic spectral shape and a temporal profile, Shen et al. (2005) found that the curvature effect marginally interpreted the observed lags, yet extreme physical parameter values are required. Furthermore, Uhm & Zhang (2016) demonstrated that the high-latitude curvature effect alone was not sufficient to account for the spectral lags. Rather, one must consider the intrinsic curved spectral shape, the evolution of the magnetic field strength, and the rapid bulk acceleration of the emission zone to interpret some observed spectral lag features. The aforementioned theories successfully explain the positive lags; however, the rarely observed negative lags remain a more complex matter that can be used to infer the different radiation origins (Zhang et al. 2011), radiation mechanisms (Li 2010; Zhang et al. 2011), or emission regions (Toma et al. 2009) of low- and high-energy photons.

In the context of fundamental physics, the delay of high-energy photons, formulated as negative lag in this study, can be used to test the violations of Lorentz invariance, a hypothesis that is widely pursued in quantum gravity (QG). Lorentz invariance violation (LIV) occurs at the Planck energy scale \((E_{Pl} = \sqrt{\hbar c^5/\pi} \approx 1.22 \times 10^{19}\) GeV\) in QG theories (Mattice 2005; Amelino-Camelia 2013). The LIV effect can be manifested through vacuum dispersion, which leads photons with higher energy to travel at lower speeds (Amelino-Camelia et al. 1998). GRBs are one of the ideal probes for testing LIV due to their large cosmological distance, small variability timescale, and very-high-energy photons. Abdo et al. (2009a) and Vassileiou et al. (2013, 2015) employed the time lag between high-energy (~31 GeV) and low-energy photons of GRB 090510 to derive lower limits of linear and quadratic QG energy, which are \(E_{QG,1} > (1 - 10) \times E_{Pl}\) and \(E_{QG,2} > 1.3 \times 10^{15}\) GeV. Abdo et al. (2009b) obtained \(E_{QG} > 10^{18}\) GeV based on the observation of GRB 080916C. The Major Atmospheric Gamma Imaging Cherenkov telescope detected TeV-scale photons of GRB 190114C (MAGIC Collaboration et al. 2019) and Acciari et al. (2020) constrained linear and quadratic LIV with the time delays of TeV photons. They obtained \(E_{QG,2} > 6.3 \times 10^{10}\) GeV \((E_{QG,2} > 5.6 \times 10^{10}\) GeV\) and \(E_{QG,1} > 0.58 \times 10^{15}\) GeV \((E_{QG,1} > 0.55 \times 10^{15}\) GeV\) for the subluminal (superluminal) case. However, above lower limits of \(E_{QG}\) depends on the time lags between single high-energy photons and some assumptions of intrinsic lag. In order to further constrain the LIV effect, the most optimal use of lag to date has been to fit the keV–MeV multiwavelength measurements of spectral lags (Agrawal et al. 2021), including their positive-to-negative transitions, with a model incorporating LIV information. A fit of this type yields some deeper limits on the QG energy (see, e.g., Wei et al. 2017; Du et al. 2021). This approach has, however, only been applied in a few GRBs. A systematic study is required to determine whether the positive-to-negative transition is common in a large sample of GRBs.
and, if possible, to identify some additional constraints on the LIV effect according to the large sample lag data.

In this paper, we utilize the Fermi Gamma-ray Burst Monitor (GBM) GRB catalog to analyze all z-known GRBs with positive-to-negative lag transitions and use these results to place some further constraints on the LIV effect. Data selection and reduction are described in Section 2. Our model of the spectral lag is presented in Section 3. The constraints on LIV and fitting results with our model are presented in Section 4, followed by a brief summary and discussion in Section 5.

2. Data

To date, more than 1000 GRBs have been observed by Fermi/GBM (von Kienlin et al. 2020), of which 135 long-duration bursts with redshift are measured. These bursts constitute our initial sample, which is further screened for the positive-to-negative lag transitions. The final sample for this study, as shown in Table 1, includes 32 GRBs. For each GRB, we extracted its multiwavelength light curves and calculated its lags using the following steps.

1. Light-curve extraction. In accordance with Yang et al. (2020), Zhang et al. (2021), and Wang et al. (2021), we selected the time-tagged event data from the sodium iodide (NaI) scintillation and bismuth germanate scintillation detectors on board Fermi/GBM that had the smallest separation from the location of the burst. Using those data, we then extract the multiwavelength light curves in a number of N energy bands, with a bin size of $\Delta t$, between the energy range of $[E_1, E_2]$. Here N, $\Delta t$, $E_1$, and $E_2$ are initially set as free parameters and determined by a series of trials on a burst-by-burst basis so that each of the light curves must have a signal-to-noise ratio $\sigma \geq 5$. The final choices of those parameters are listed in Table 1.

2. Lag calculation. We calculate spectral lags for any pair of light curves between the lowest energy band and any other band, using the method described in Zhang et al. (2012).
As shown in Figure 1, we plot the lags for each burst as a function of $E$, the median of the energy boundaries of the higher energy bands. One can see that each of our sample exhibits a positive-to-negative lag transition.

3. The Model

To model the observed lag–$E$ behaviors in Figure 1, one has to consider the following two components:

1. The intrinsic lag, $\Delta t_{\text{int}}$, due to the GRB radiation itself. As pointed out in Section 1, the exact physical process causing spectral lags remains an open question. Yet, modeling the intrinsic lag behavior is crucial to distinguish between lags caused by intrinsic mechanisms and negligible LIV-induced lags. Nevertheless, some previous studies (e.g., Wei et al. 2017) assume a simple power-law model for $\Delta t_{\text{int}}$. However, such a power-law model does not account for the negative lags. In this study, we use a smoothly broken power-law (SBPL) fits.
function to model the energy-dependent lags, i.e., \( \Delta t_{\text{int}} \) is in the form of

\[
\Delta t_{\text{int}} = \zeta \left( \frac{E - E_{\text{b}}}{E_{\text{b}}} \right)^{\alpha_1} \left[ \frac{1}{2} \left( 1 + \left( \frac{E - E_{\text{b}}}{E_{\text{b}}} \right)^{1/\mu} \right) \right]^{(\alpha_2 - \alpha_1)/\mu},
\]

(1)

where \( \zeta \) is the normalization amplitude, \( \alpha_1 \) and \( \alpha_2 \) are the two slopes before and after the transition energy, \( E_{\text{b}} \), and \( \mu \) measures the smoothness of the transition. We note that when \( \alpha_1 = \alpha_2 \), Equation (1) becomes a simple power law, as used in Wei et al. (2017).

2. The LIV lag. LIV-induced lag can be written as

\[
\Delta t_{\text{LIV}} = \frac{1 + n}{2H_0} E_{QG,n} \int_0^\infty \left( 1 + z' \right)^{\nu} \frac{dz'}{\sqrt{\Omega_m (1 + z')^3 + \Omega_\Lambda}},
\]

(2)

where the following cosmological parameters are adopted (Planck Collaboration et al. 2020): \( H_0 = 67.36 \) km \( \cdot \) s\(^{-1} \), Mpc\(^{-1} \), \( \Omega_m = 0.315 \), and \( \Omega_\Lambda = 1 - \Omega_m \). A detailed derivation of LIV-induced lag can be found in the Appendix.

In this paper, we consider both the linear \( (n = 1) \) and quadratic \( (n = 2) \) cases of Equation (A4), which, when fitted the observational data, can provide constraints on the corresponding QG energy scales, \( E_{QG,1} \) and \( E_{QG,2} \).

Finally, the observed energy-dependent lags can be modeled by

\[
\tau = \Delta t_{\text{int}} + \Delta t_{\text{LIV}},
\]

(3)

which is directly fitted to the observational data in Section 4.

4. The Fit

For each burst, we first fit its observed lags using the SBPL as shown in Equation (1). We can use this information to determine various features of the lag behavior, such as the break energy \( E_{\text{b}} \), and the slopes prior and post \( E_{\text{b}} \). The fit is performed using the McEasyFit (Zhang et al. 2015) tool, which is a self-developed Bayesian Monte Carlo fitting package.
ensuring reliable and realistic best-fit parameters and their uncertainties based on converged Markov chains. The priors of the free parameters are set to uniform distributions in the range listed in Table 2. Our model successfully fit the data. The best-fit parameters as well as their constraints are listed in Table 3. The model-predicted curves using the best-fit parameters are overplotted as black solid lines in each panel of Figure 1.

Next, we fit the observed data with the LIV-induced model as in Equation (3). This introduces an additional free parameter, \( E_{QG,0} \). The prior of \( E_{QG,0} \) is set as a uniform distribution in logarithmic scale in range of \([0,10^{20}]\)GeV for \( n = 1 \), or \([0,10^{15}]\)GeV for \( n = 2 \) (Table 2). In addition, we require the \( \Delta E_{\text{LIV}} \) term in Equation (3) not to dominate over \( \Delta E_{\text{int}} \) so that \( \Delta E_{\text{int}} \) still shows a negative-to-positive transition in order to be consistent with the observations. Such a requirement can be reflected in the log-likelihood function in McEasyFit as

\[
L(\Theta) = \begin{cases} 
-\infty & \alpha_1 < \alpha_2 \\
\frac{1}{2} \sum \left( \frac{t_{\text{obs}} - t_{\text{model}}(\Theta)}{\sigma(t_{\text{obs}})} \right)^2 & \alpha_1 \geq \alpha_2 
\end{cases},
\]

where \( \Theta \) represents the free fitting parameters. The above approach allowed us to successfully fit the observed data of each GRB and constrain the lower limits of its linear and quadratic QG energies. Figure 2 shows an example of the posterior probability distributions of fitting parameters for GRB 130427A. For all of the GRBs in our sample, the \( E_{QG} \) lower limits are listed in Table 3 and correspond to the dashed lines in Figure 1.

Upon fitting the entire sample of 32 GRBs, we obtained the following key statistical properties of the lag behavior, as well as the constraints on the QG energy:

1. The distribution of the lag transition energy, \( E_b \), is a lognormal shape with a median value of \( E_b = 398 \) keV (Figure 3(a));
2. The slopes for the \( \tau - E \) relation prior and post the break are distributed as a Gaussian function. The median values of the \( \alpha_1 \) and \( \alpha_2 \) are 1.27 and \(-3.52\) respectively (Figures 3(b) and (c));
3. The linear QG energy lower limits are constrained at a large range from \( 8.2 \times 10^{12} \) to \( 5.5 \times 10^{15} \)GeV. The
distribution of the lower limits is a lognormal shape with a median value of $1.5 \times 10^{14}$ GeV (Figure 3(d));

4. The quadratic QG energy lower limits are also constrained at a large range from $6.2 \times 10^4$ to $1.7 \times 10^7$ GeV. The distribution of the lower limits is a lognormal shape with a median value of $8 \times 10^5$ GeV (Figure 3(e)).

5. Summary and Discussions

In this study, a total of 32 GRBs with positive-to-negative transitions in their spectral lags have been found among the 135 Fermi/GBM long GRBs with redshift measurements, suggesting lag transitions are not uncommon. We systematically processed and analyzed the lags of these 32 GRBs. The observed lag–$E$ relationship of each burst can successfully be fitted by an empirical SBPL function. Such fits yield a typical value of 400 keV for the transition energy. Our results are further applied to constrain the LIV. Incorporating the LIV effect into the fit, the lower limits of linear and quadratic QG energy are derived for each burst. The typical lower limits of $E_{\text{QG},1} \geq 1.5 \times 10^{14}$ GeV and $E_{\text{QG},2} \geq 8 \times 10^5$ GeV of our study are consistent with, and sometimes deeper than, those of previous case studies, such as for GRB 160625B (Wei et al. 2017) and GRB 190114C (Du et al. 2021).

Our findings offer some insight into understanding the lag origins. For instance, some significant negative lags (e.g., $\tau \approx 1$ s is observed in several GRBs) cannot be explained solely by the LIV effect. Thus the SBPL function we proposed in this work appears to be more accurate than the simple power-law function (Wei et al. 2017) to describe the intrinsic lag behaviors in our sample. In addition, our study provides a rich sample for investigating the underlying physical processes that result in the lag transition. These theories include, but are not limited to, the hard-to-soft evolution of a curved spectrum (Liang & Kargatis 1996; Lu et al. 2012) and modified photosphere models (Meng et al. 2018, 2019, 2022).

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Figure 3. The distributions of the best-fit parameters ($E_b$, $\alpha_1$, $\alpha_2$) of the SBPL model and the constrained lower limits of the quantum gravity energy ($E_{\text{QG,1}}$, $E_{\text{QG,2}}$). Each distribution is fitted by a Gaussian or lognormal function.
Appendix

Derivation of LIV-induced Lag

In the QG theory, a small-scale structure in spacetime can cause a deformed photon dispersion relation, which can be formulated as (Amelino-Camelia et al. 1998; Jacob & Piran 2008)

\[ c^2 p^2 = E^2 [1 + f(E/E_{QG})], \]  

(A1)

where \( c \) is the speed of light, \( p \) is the photon momentum, \( E_{QG} \) is the QG energy scale, and \( f(E/E_{QG}) \) is the model-dependent function of the dimensionless ratio of \( E/E_{QG} \). Noticing \( f = 0 \) at \( E = 0 \), \( f \) can be expanded as Taylor series in a small energy condition \( (E \ll E_{QG}) \) at \( a = 0 \) as

\[ f = \sum_{n=0}^{\infty} \frac{f^{(n)}(a)}{n!} \left( \frac{E}{E_{QG}} - a \right)^n = \sum_{n=1}^{\infty} \frac{f^{(n)}(0)}{n!} \left( \frac{E}{E_{QG}} \right)^n. \]  

(A2)

Defining \( E_{QG,n} \) as the \( n \)th-order QG energy by

\[ E_{QG,n}^n = s_n E_{QG}^{n+1} f^{(n)}(0), \]  

(A3)

we can further substitute Equations (A3) and (A2) into Equation (A1), so

\[ c^2 p^2 \simeq E^2 \left[ 1 + \sum_{n=1}^{\infty} \left( \frac{E}{E_{QG,n}} \right)^n \right]. \]  

(A4)

where \( s_n \) represents the sign of the LIV effect. \( s_{\pm} = +1 \) (-1) corresponds to the subluminal (superluminal) scenario so the high-energy photons travel slower (faster) than low-energy photons. We only consider the case where \( s_{\pm} = +1 \) in this work to account for the negative lags.

In practice, it is convenient to replace the right side of Equation (A4) with its leading term in order \( n \), so

\[ c^2 p^2 \simeq E^2 \left[ 1 + s_{\pm} \left( \frac{E}{E_{QG,n}} \right)^n \right]. \]  

(A5)

One can further derive the photon propagating speed as

\[ v(E) = \frac{\partial E}{\partial p} \simeq c \left[ 1 - s_{\pm} \frac{n + 1}{2} \left( \frac{E}{E_{QG,n}} \right)^n \right]. \]  

(A6)

Equation (A6) suggests that two photons with different energy arrive at observers with a time delay, even both are emitted from one GRB concurrently. Considering cosmological expansion, the LIV-induced lag can be written as

\[ \Delta t_{LIV} = - \frac{1 + n E^2 - E_0^n}{2H_0} \int_{c}^{R} \frac{(1 + z')^3 dz'}{\sqrt{\Omega_m (1 + z')^3 + \Omega_{\Lambda}}}. \]  

(A7)

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