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Constraining Lorentz Invariance Violation Using Short Gamma-Ray Bursts

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Abstract

Lorentz Invariance is a foundational principle in modern physics, but some recent quantum gravity theories have hinted that it may be violated at extremely high energies. Gamma-ray bursts (GRBs) provide a promising tool for checking and constraining any deviations from Lorentz Invariance due to their huge energies and cosmological distances. Gamma-ray bursts, which are the most intense and powerful explosions in the universe, are traditionally divided into long bursts whose observed duration exceeds 2 s, and short bursts whose observed duration is less than 2 s. In this study, we employ a recent sample of 46 short GRBs to check for any deviation from Lorentz Invariance. We analyze the spectral lag of the bursts in our data sample and check for any redshift dependence in the GRB rest frame, which would indicate a violation of Lorentz Invariance. Our results are consistent, to within 1σ, with no deviation from Lorentz Invariance.

Keywords

Lorentz Invariance Violation, Gamma-Ray Bursts, Quantum Gravity

1. Introduction

Lorentz Invariance is a cornerstone of modern physics and an essential symmetry of quantum field theory. It is a requirement of special relativity, which postulates that inertial frames are equivalent. However, recently some quantum field theories have suggested that well-established concepts like Lorentz Invariance may be violated at very high energies that approach the Planck energy scale, about 1.2×10^{19} GeV [1]. Of course, such energies cannot currently be achieved through experiments on Earth, but energetic photons traveling over huge cosmological distances may provide hints or evidence to a possible violation of Lorentz Invariance [2].

Physically, Lorentz Invariance Violation (LIV) can be understood in analogy to how light behaves when it enters a dispersive medium. The speed of light in a dispersive medium is not constant but depends on its wavelength because light waves are sensitive to the specific structure of the dispersive medium. Likewise, according to some quantum gravity theories, exceedingly high-energy photons may be sensitive to the structure of spacetime implying that the speed of light is not constant in vacuum, thus violating Lorentz Invariance [2] [3]. One way to measure this effect is to compare the arrival time of energetic photons, but of different energies, that emanate from the same source, for example a gamma-ray burst (GRB) [4] [5] [6] [7] [8]. A recent study in 2023, by Finke and Razzaque [9], finds possible evidence for LIV in the gamma-ray burst GRB221009A.

In this paper, we use a recent data sample of short GRBs to place constraints on LIV. Short GRBs are bursts with an observed duration less than 2 s, and they are believed to emerge from the coalescence of two compact objects, like two neutron stars or a neutron star and a black hole [10]. In investigating LIV, short GRBs are preferred to long GRBs because the latter have larger and more varied intrinsic spectral lags, which complicates their utilization as probes of LIV [11].

In Section 2, we provide a brief review of the relevant quantum gravity equations that pertain to LIV. In Section 3, we introduce the data sample of short GRBs that we use and then present our analysis and results. Finally, in Section 4 we give our conclusions and future prospects.

2. Quantum Gravity and Lorentz Invariance Violation

According to some quantum gravity models [12], the speed of light in vacuum, typically labeled c, is not constant, and thus the relationship between a photon's energy, E, and its momentum, p, is not given by $E = pc$, but rather by the following dispersion equation, which is obtained through a Taylor expansion:

$$E^2 \approx p^2c^2\left\{1 - s_n\left[\frac{pc}{E_{QG}}\right]^n\right\} \tag{1}$$

where E_{QG} is the quantum gravity energy, s_n is a sign factor which is equal to +1 or −1 depending on whether higher energy photons move slower or faster than lower energy photons, respectively, and n refers to the dependence order of the energy [13].

The speed of propagation of light, v_γ, is simply the group velocity and can be calculated by differentiating E with respect to p:

$$v_\gamma = \frac{\partial E}{\partial p} \approx c\left\{1 - s_n\left[\frac{n+1}{2}\right]\left[\frac{E}{E_{QG}}\right]\right\} \tag{2}$$

According to Equation (2), the speed of propagation of light in vacuum is energy dependent and not constant, which violates Lorentz Invariance and implies that photons of different energies emanating from the same source, for example a GRB, would exhibit a spectral time delay, typically called a spectral lag, Δt_{LIV}, which can be expressed as [11] [14]:

$$\Delta t_{LIV} = -s_n \left[\frac{1+n}{2H_0}\right]\left[\frac{E_h^n - E_l^n}{(1+z)^n E_{QG}^n}\right]\int_0^z \frac{(1+z)^n}{h(z)}\mathrm{d}z \quad (3)$$

where H_0 is the Hubble constant, E_h and E_l are the high and low energies in the GRB's rest frame, respectively, and $h(z)$ is the Hubble expansion rate, which is given by [11]:

$$h(z) = \sqrt{\Omega_m (1+z)^3 + \Omega_\lambda} \quad (4)$$

where z is the GRB's redshift, and Ω_m and Ω_λ are the matter and curvature density parameters, respectively. To simplify the notation, Equation (3) can be rewritten as [11]:

$$\Delta t_{LIV} = a_{LIV} \cdot K(z) \cdot (1+z) \quad (5)$$

where $K(z)$ includes the terms that depend on z and a_{LIV} includes the other parameters. In the rest frame of the burst, the spectral lag due to LIV is simply:

$$\frac{\Delta t_{LIV}}{1+z} = a_{LIV} \cdot K(z) \quad (6)$$

It is important to keep in mind that GRBs may have intrinsic spectral lags, due to their prompt and delayed gamma-ray emissions, that have nothing to do with LIV, and this intrinsic spectral lag must be factored in and included. In this study, we assume the intrinsic spectral lag is constant for the short GRBs that we use and is given, in the rest frame of the burst, by:

$$\frac{\Delta t_{int}}{1+z} = b \quad (7)$$

where b is a constant. Now, we can combine the intrinsic spectral lag with that due to LIV to obtain the total observed spectral lag:

$$\Delta t = \Delta t_{LIV} + \Delta t_{int} = a_{LIV} \cdot K(z) \cdot (1+z) + b \cdot (1+z) \quad (8)$$

Thus, if there is no LIV, then Δt should be directly proportional to $(1 + z)$, and a plot of Δt versus $(1 + z)$ should exhibit linear behavior with a slope b.

3. Data, Analysis, and Results

The data sample that we use consists of 46 short GRBs, which we took from the recent study by Xiao *et al.* [11]. The bursts in the sample consist of GRBs observed by either the *Fermi* satellite or the *Swift* satellite and have a redshift range from 0.0098 to 2.6. To extract the spectral lag, [11] selected the energy bands in the rest frame of the burst to be 15 - 70 keV and 120 - 250 keV. They then applied a new technique, the improved Li-CCF method, to extract the observed spectral lags, Δt.

Our first step involved plotting Δt as a function of $(1 + z)$ and checking whether we obtain a good linear fit, and if so, extracting the slope, b_o. As **Figure 1** shows, we obtained a good linear fit with a best-fit value of $b_o = 1.41 \pm 0.41$ ms and a reduced chi-square of 1.05 with a *p*-value of 0.38 for the chi-square distribution. Note that if the *Swift* and *Fermi* satellites gave different values of Δt for the same burst, then we took the mean value.

Our next step involved binning the data in redshift while keeping, as much as possible, the number of bursts per bin the same. We then applied a linear fit similar to what we did in **Figure 1** and extracted the value of the slope, b, for each bin, and then compared these values of b with that for the entire sample – namely, b_o. The point is that we wanted to check whether the values of b showed any evolution or dependence on redshift, which would hint at a possible LIV contribution, or whether they were consistent with a constant value. We repeated our analysis with a different number of bins to check whether binning introduced any biases. Our results are presented in **Figure 2**, and the different panels show our results for the different bin numbers that we used.

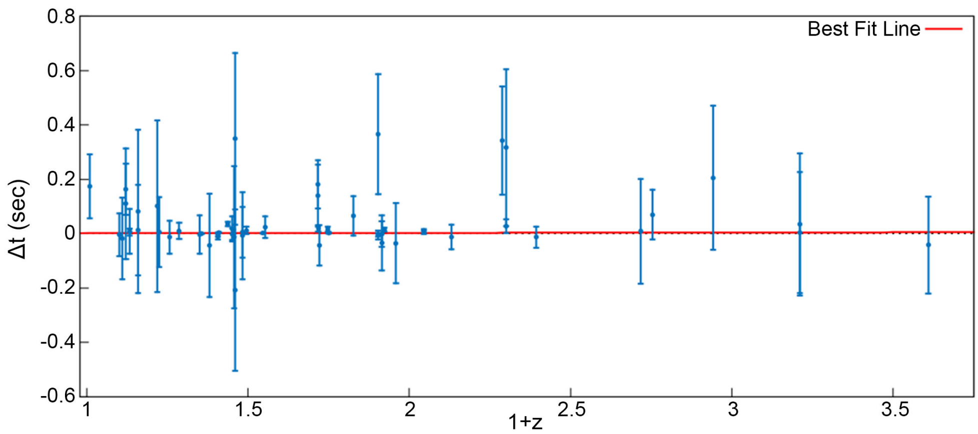

Figure 1. The observed spectral lag as a function of redshift with the best linear fit.

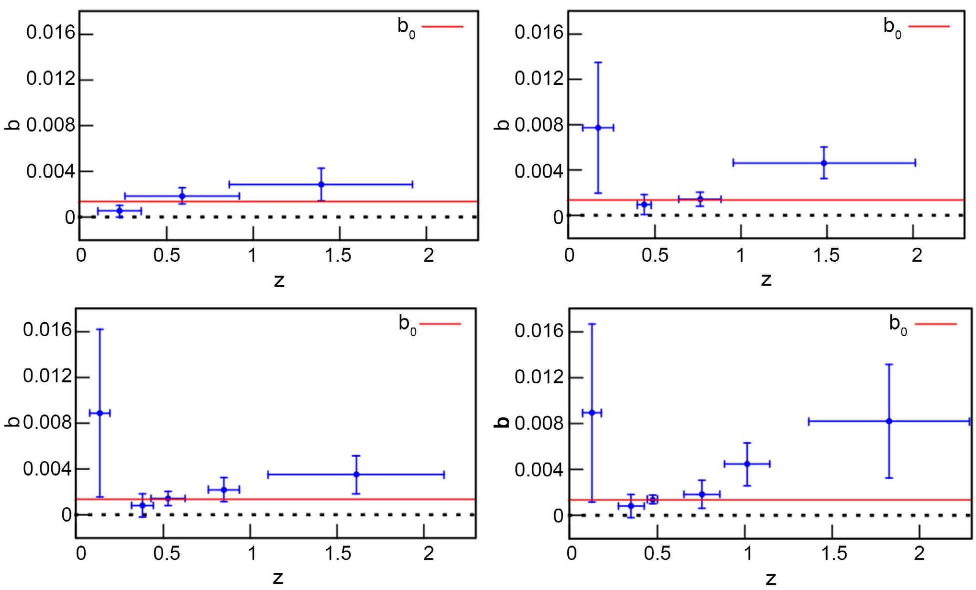

Figure 2. Comparison of the best linear fit slope for each bin, b, with that for the entire sample, b_o. The different panels show the results obtained for different bin numbers: 3, 4, 5, and 6 bins.

Our results, shown in **Figure 2**, indicate that when 3 bins were used, b showed no redshift dependence or evolution, but when a higher number of bins was used, there were hints of small deviations from what is expected for Lorentz Invariance, but we caution that these deviations are not statistically significant, and our results are consistent with no LIV at the 1σ level.

4. Conclusion

Lorentz Invariance is one of the fundamental principles in modern physics, and checking its validity is an important task since any violation of Lorentz Invariance would have significant consequences regarding key concepts in physics. In this study, we employed a recent sample of short GRBs and used their observed spectral lags to check for any deviation from Lorentz Invariance. To do that, we binned the data in redshift and then checked whether the extracted intrinsic spectral lag for each bin, b, is redshift dependent or whether it is constant and consistent with its no LIV value, b_o. Our results indicate that although there are slight deviations from what is expected for Lorentz Invariance, these deviations are not statistically significant. In the future, it would be important to reexamine this issue using an expanded data sample that includes not just short GRBs, but also long GRBs, assuming that in the future we will have a better understanding of the mechanisms that contribute to the relatively large values and scatter in the spectral lags of long GRBs.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Abdalla, H. and Böttcher, M. (2018) Lorentz Invariance Violation Effects on Gamma-Gamma Absorption and Compton Scattering. *The Astrophysical Journal*, **865**, Article 159. https://doi.org/10.3847/1538-4357/aadb87

[2] Lorentz, M. and Brun, P. (2017) Limits on Lorentz Invariance Violation at the Planck Energy Scale from H.E.S.S. Spectral Analysis of the Blazar Mrk 501. *EPJ Web of Conferences*, **136**, Article No. 03018. https://doi.org/10.1051/epjconf/201713603018

[3] Tavecchio, F. and Bonnoli, G. (2016) On the Detectability of Lorentz Invariance Violation through Anomalies in the Multi-TeV γ-Ray Spectra of Blazars. *Astronomy and Astrophysics*, **585**, Article No. A25. https://doi.org/10.1051/0004-6361/201526071

[4] Amelino-Camelia, G., *et al.* (1998) Tests of Quantum Gravity from Observations of γ-Ray Bursts. *Nature*, **393**, 763-765. https://doi.org/10.1038/31647

[5] Azzam, W.J., Alothman, M.J. and Guessoum, N. (2009) A Possible Redshift Evolution of the Time-Lag and Variability Luminosity Relations for Long Gamma-Ray Bursts. *Advances in Space Research*, **44**, 1354-1358. https://doi.org/10.1016/j.asr.2009.08.003

[6] Burderi, L., *et al.* (2021) Quantum Gravity with THESEUS. *Experimental Astronomy*, **52**, 439-452. https://doi.org/10.1007/s10686-021-09825-6

[7] Du, S.-S., *et al.* (2021) Lorentz Invariance Violation Limits from the Spectral-lag Transition of GRB 190114C. *The Astrophysical Journal*, **906**, Article 8. https://doi.org/10.3847/1538-4357/abc624

[8] Wei, J.-N., *et al.* (2022) Exploring Anisotropic Lorentz Invariance Violation from the Spectral-Lag Transitions of Gamma-Ray Bursts. *Universe*, **8**, Article 519. https://doi.org/10.3390/universe8100519

[9] Finke, J.D. and Razzaque, S. (2023) Possible Evidence for Lorentz Invariance Violation in Gamma-Ray Burst 221009A. *The Astrophysical Journal*, **942**, Article L21. https://doi.org/10.3847/2041-8213/acade1

[10] Zitouni, H., Guessoum, N. and Azzam, W.J. (2022) Testing the Amati and Yonetoku Correlations for Short Gamma-Ray Bursts. *Astrophysics and Space Science*, **367**, Article No. 74. https://doi.org/10.1007/s10509-022-04100-2

[11] Xiao, S., *et al.* (2022) A Robust Estimation of Lorentz Invariance Violation and Intrinsic Spectral Lag of Short Gamma-Ray Bursts. *The Astrophysical Journal*, **924**, Article L29. https://doi.org/10.3847/2041-8213/ac478a

[12] Zhang, H. and Yang, L. (2022) Testing Lorentz Violation with IceCube Neutrinos. *Universe*, **8**, Article 260. https://doi.org/10.3390/universe8050260

[13] Zhang, X. and Ma, B.-Q. (2019) Testing Lorentz Invariance and *CPT* Symmetry Using Gamma-Ray Burst Neutrinos. *Physical Review D*, **99**, Article 043013. https://doi.org/10.1103/PhysRevD.99.043013

[14] Jacob, U. and Piran, T. (2008) Lorentz-Violation-Induced Arrival Delays of Cosmological Particles. *Journal of Cosmology and Astroparticle Physics*, **2008**, Article 031. https://doi.org/10.1088/1475-7516/2008/01/031