Redshift Dependence of the Low-energy Spectral Index of Gamma-Ray Bursts Revisited (Postprint)

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Abstract

A negative correlation was found to exist between the low-energy spectral index and the redshift of gamma-ray bursts (GRBs) by Amati et al. It was later confirmed by Geng & Huang and Gruber et al., but the correlation was also found to be quite dispersive when the sample size was significantly expanded. In this study, we have established two even larger samples of GRBs to further examine the correlation. One of our samples consists of 316 GRBs detected by the Swift satellite, and the other one consists of 80 GRBs detected by the Fermi satellite. It is found that there is no correlation between the two parameters for the Swift sample, but there does exist a weak negative correlation for the Fermi sample. The correlation becomes even more significant when the spectral index at the peak flux is considered. It is argued that the absence of the correlation in the Swift sample may be due to the fact that Swift has a very narrow energy response so that it could not measure the low-energy spectral index accurately enough. Further studies based on even larger GRB samples are solicited.

Full Text

Preamble

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Redshift Dependence of the Low-energy Spectral Index of Gamma-Ray Bursts Revisited

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Abstract

A negative correlation between the low-energy spectral index and the redshift of gamma-ray bursts (GRBs) was initially reported by Amati et al. and subsequently confirmed by Geng & Huang and Gruber et al. However, the correlation was found to be quite dispersive when the sample size was significantly expanded. In this study, we have compiled two even larger GRB samples to re-examine this correlation: one comprising 316 GRBs detected by the Swift satellite and another comprising 80 GRBs detected by the Fermi satellite. We find no correlation between the two parameters for the Swift sample, but a weak negative correlation does exist for the Fermi sample. The correlation becomes more significant when the spectral index at the peak flux is considered. We argue that the absence of correlation in the Swift sample may be due to Swift's narrow energy response, which prevents accurate measurement of the low-energy spectral index. Further studies based on even larger GRB samples are encouraged.

Key words: (stars:) gamma-ray burst: general – methods: statistical – catalogs

1. Introduction

Gamma-ray bursts (GRBs) are the most violent stellar explosions in the universe. Initially discovered in 1967 by the Vela Satellites (Klebesadel et al. 1973), they have been intensively studied for over forty years as more events have been detected (Qin et al. 2021; Yuan et al. 2022a; Liu et al. 2022). GRBs are generally believed to be triggered by the death of massive stars or the merger of binary compact systems. Among the current research interests are empirical correlations between various GRB parameters.

For instance, the correlation between E_p (the peak energy) and $E_{\rm iso}$ (the equivalent isotropic energy), known as the Amati relation, has been investigated by Amati et al. (2002, 2009), Virgili et al. (2012), Azzam & Alothman (2013), Geng & Huang (2013), and Demianski et al. (2017). Similarly, the correlation between E_p (the peak energy) and L_p (the peak luminosity), known as the Yonetoku relation, has been studied by Yonetoku et al. (2004), Ghirlanda et al. (2005), and Zhang et al. (2012). Both relations were discussed in Yonetoku et al. (2010)

and Tsutsui et al. (2013), and Wang et al. (2020) explored additional empirical correlations beyond these established relations.

Redshift (z) is an important parameter for GRBs. Many studies have examined relations between z and other parameters. For example, Zhang et al. (2014a) investigated correlations between z and L_{iso}, E_{iso}, $E_{p,\mathrm{rest}}$, and $E_{p,\mathrm{obs}}$ (see also Sakamoto et al. 2011; $E_{p,\mathrm{obs}} = E_{p,\mathrm{rest}}/(1+z)$; Ukwatta et al. 2012). They found a positive correlation between z and L_{iso} for Swift GRBs. Wei & Gao (2003) and Zitouni et al. (2014) studied the z–E_{iso} and z–L_{iso} relations, while the z–L_p relation has been investigated by numerous researchers (Lloyd-Ronning et al. 2002; Goldstein 2012; Salvaterra et al. 2012; Zhang et al. 2014b; Zitouni et al. 2018).

The low-energy spectral index, α, is also an important parameter characterizing the prompt emission of GRBs. Geng et al. (2018) derived values of α through numerical simulations considering synchrotron emission mechanisms. The correlation between α and E_p has been studied extensively (Gruber et al. 2014; Li et al. 2019; Duan & Wang 2020; Li 2022), and Tang et al. (2019) investigated the correlation between α and E_{iso}.

Interestingly, Amati et al. (2002) found a negative correlation between z and α, which can be expressed as $\alpha = -0.13\log(1+z)+0.04$ (where log denotes base-10 logarithm). Their study was based on a sample of only nine GRBs. Later, Geng & Huang (2013) and Gruber et al. (2014) confirmed this correlation, updating it to $\alpha = -0.07\log(1+z) + 0.02$ using a significantly expanded sample of 65 GRBs. However, Geng & Huang (2013) also noted that the correlation was quite dispersive. Therefore, further investigation of this $z - \alpha$ correlation is warranted.

In this study, we expand the GRB sample further to include 316 GRBs detected by Swift and 80 GRBs detected by Fermi. We use this substantially enlarged sample to re-examine the correlation between z and α. The structure of this paper is as follows: Section 2 provides a detailed description of our data sample selection. Section 3 explores the correlation between the low-energy spectral index and redshift, along with other parameter relationships. Finally, Section 4 presents our conclusions and discussion.

2. Sample

We utilize GRBs detected by both Swift and Fermi in this study. Two criteria are applied for selecting appropriate GRBs: (1) the redshift of the burst must be available, and (2) the spectrum must be well-defined. Time-averaged GRB spectra are typically fitted with three types of functions: a single power-law function, a cutoff power-law function, and the Band function (Band et al. 1993). Most GRB spectra can be well-fitted by the Band function, which is expressed as:

$$N(E) = A \begin{cases} \left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right) & \text{for } E \leq (\alpha-\beta)E_0 \\ \left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta} \exp(\beta-\alpha) \left(\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right)^{\alpha-\beta} & \text{for } E > (\alpha-\beta)E_0 \end{cases}$$

where E is the photon energy and A is a scaling factor. This equation contains four parameters: the low-energy spectral index (α), the high-energy spectral index (β), and the peak photon energy (E_p). In our notation, α and β are positive values representing their absolute magnitudes. We have collected all spectral parameters for Swift and Fermi GRBs with measured redshifts.

Fermi has a very wide energy band (8–35,000 keV), so Fermi GRBs are typically best fitted by the Band function, yielding both the low-energy spectral index (α) and the high-energy spectral index (β). In contrast, the Swift/BAT detector has a narrow energy response of 15–150 keV, so Swift GRBs are generally best fitted by either a single power-law function or a cutoff power-law function. In these cases, the derived power-law index can serve as a useful representation of the low-energy spectral index (α), since it is measured in the soft gamma-ray range. Note that for Swift GRBs, the β parameter is completely unavailable.

For Swift GRBs, relevant data were obtained from the NASA Swift website. As a result, our Swift sample includes a total of 316 GRBs, all of which have the necessary redshift and spectral data. The time span of these GRBs ranges from 2005 January 26 to 2023 January 16.

For Fermi GRBs, data were collected primarily from NASA's HEASARC (High Energy Astrophysics Science Archive Research Center) database, supplemented by 24 bursts from Jochen Greiner's online GRB catalog. Our final Fermi sample consists of 80 GRBs with a time span from 2008 September 5 to 2018 July 20.

3. Correlations

In this section, we employ the Swift and Fermi GRB samples to explore empirical correlations involving α and z.

Figure 1 [Figure 1: see original paper] shows the Swift sample on the α–z plane. Overall, the data points are quite scattered, with no obvious correlation between the two parameters. The solid line represents the best-fit result: $\log\alpha = (0.029 \pm 0.030)\log(1+z) + (0.15 \pm 0.014)$. However, the correlation coefficient is very small ($r = 0.055$), indicating that essentially no correlation exists. Error ranges for best-fit parameters are given at the 1σ level throughout this paper.

Figure 2 [Figure 2: see original paper] presents the Fermi GRB sample on the α–z plane (left panel) and β–z plane (right panel). The data points are fitted with linear functions. Notably, GRB 120712A appears as an obvious outlier on the α–z plane, with an anomalously high low-energy spectral index of $\alpha = 6.1 \pm 0.67$; we exclude this event from the fitting procedure. Interestingly, we find a negative correlation between α and z, with the best-fit result $\log\alpha = (-0.18 \pm 0.11)\log(1+z) + (0.049 \pm 0.015)$ and a correlation coefficient of $r = -0.19$. Note that this expression, particularly the slope of -0.18, differs significantly from previous studies, and the correlation remains very weak. In contrast, the right panel shows no correlation between β and z, consistent with the results of Geng & Huang (2013). The best-fit line is $\log\beta = (0.015 \pm 0.055)\log(1+z) + (0.36 \pm 0.025)$, with a correlation coefficient of $r = 0.031$. Comparing the two panels, it is evident that the low-energy spectral index (α) behaves differently from the high-energy index (β) when plotted against redshift.

The Fermi GRBs have well-measured E_p data, allowing us to explore additional correlations. Figure 3 [Figure 3: see original paper] shows the α–E_p plane (left panel) and E_p–z plane (right panel). No obvious correlation is found between α and E_p, nor between E_p and z. These results differ somewhat from previous studies; for example, Geng & Huang (2013) argued that E_p and z are positively correlated. Note that GRB 120712A is again an obvious outlier and is excluded from the fitting procedure.

Since the peak flux time represents an important stage of a GRB, we also investigate the spectral parameters at peak flux. This analysis is limited to the Fermi sample, as peak flux parameters are not available for most Swift GRBs. We denote the low-energy spectral index at peak flux as α_{peak}, with corresponding high-energy index β_{peak} and peak photon energy $E_{p,\text{peak}}$.

The left panel of Figure 4 [Figure 4: see original paper] plots the Fermi sample on the α_{peak}–z plane, revealing a clear negative correlation, albeit with significant scatter. The best-fit result is $\log\alpha_{\text{peak}} = (-0.29 \pm 0.15)\log(1+z) + (0.11 \pm 0.021)$, with a correlation coefficient of $r = -0.29$. Compared with the slope of -0.42 previously derived by Geng & Huang (2013), our slope of -0.29 is significantly flatter. The right panel shows the β_{peak}–z plane, where a weak correlation exists: $\log\beta_{\text{peak}} = (-0.088 \pm 0.070)\log(1+z) + (0.39 \pm 0.027)$, with $r = -0.20$. The data points in this panel are more dispersed than those in the left panel.

Figures 2 and 4 demonstrate that a weak correlation exists between the low-energy spectral index and redshift, with the α–z relation being much less significant than the α_{peak}–z relation. One might expect α and α_{peak} to be positively connected, making these two relations similar. To investigate this discrepancy, Figure 5 [Figure 5: see original paper] plots α against α_{peak} for the Fermi sample. The solid line indicates where $\alpha = \alpha_{\text{peak}}$. We find that α and α_{peak} are not strictly correlated, which explains their different dependence on redshift and reflects the highly variable nature of gamma-ray spectra during a GRB.

Figure 6 [Figure 6: see original paper] illustrates the relationships between α_{peak}, $E_{p,\text{peak}}$, and z. A weak correlation exists between $E_{p,\text{peak}}$ and z: $\log E_{p,\text{peak}} = (0.33 \pm 0.071)\log(1+z) + (2.28 \pm 0.027)$, with correlation coefficient $r = 0.13$. Similarly, a weak correlation exists between α_{peak} and $E_{p,\text{peak}}$: $\log\alpha_{\text{peak}} = (-0.16 \pm 0.15)\log E_{p,\text{peak}} + (0.71 \pm 0.45)$, with $r = -0.16$.

Swift/BAT has a relatively narrow passband (15–150 keV), so the measured spectral index should correspond to the low-energy spectral index of the Band function. Some GRBs are simultaneously detected by both Swift and Fermi, allowing us to compare their spectral indices. Figure 7 [Figure 7: see original paper] shows all overlapping GRBs between the Swift and Fermi samples, comparing their spectral indices. Here, α_S denotes the index measured by Swift, while α_F denotes the low-energy spectral index measured by Fermi. We find that α_S and α_F are not equal for individual events; the former is systematically larger than the latter, and the data points are quite scattered. Figure 8 [Figure 8: see original paper] compares α_S with the low-energy spectral index at peak flux measured by Fermi ($\alpha_{F,\mathrm{peak}}$) for these overlapping bursts. Again, α_S is generally larger than $\alpha_{F,\mathrm{peak}}$. Figures 7 and 8 clearly demonstrate that different detectors can produce very different spectral results for the same GRB, indicating that acquiring accurate GRB spectra remains a challenging task. The differing α–z correlations between samples may thus be caused by systematic distortions in spectral index measurements.

4. Discussion and Conclusions

In this study, we use Swift and Fermi GRB samples to explore the possible correlation between low-energy spectral index and redshift. For the Swift sample, we find no correlation between α and z (Figure 1). In contrast, a weak correlation exists between α and z for the Fermi sample (Figure 2). The correlation becomes more pronounced when the peak flux spectrum is considered, i.e., when α_{peak} is plotted against z (Figure 4).

The different characteristics of the two samples may arise from their different energy responses. Fermi has a very wide energy band (8–35,000 keV), enabling it to provide a much better description of GRB spectra. However, Swift/BAT has a narrow energy response (15–150 keV), so Swift GRB spectra are typically best fitted by a single power-law or cutoff power-law function. In these cases, the power-law spectral index may deviate significantly from the true low-energy spectral index. This conjecture is confirmed when examining overlapping GRBs detected by both satellites: the spectral index reported by Swift is usually quite different from the low-energy spectral index reported by Fermi (Figures 7 and 8), reflecting the difficulty of spectral observations of GRBs.

Amati et al. (2002) proposed a correlation between α and z of the form $\alpha = -0.13\log(1+z) + 0.04$, based on a very small sample. Geng & Huang (2013) updated this correlation to $\alpha = -0.07\log(1+z) + 0.02$ using a significantly expanded sample, finding a much flatter slope and a very dispersive correlation. Our current study yields $\log\alpha = (-0.18\pm0.11)\log(1+z)+(0.049\pm0.015)$ for the Fermi sample, and $\log\alpha_{\mathrm{peak}} = (-0.29\pm0.15)\log(1+z)+(0.11\pm0.021)$ for the peak flux spectrum. The correlation becomes even flatter and more dispersive. Nevertheless, we conclude that a weak correlation does exist between α and z. Further study on this issue is warranted, requiring detectors with relatively wide energy responses to accurately measure GRB spectra. We note that the Einstein Probe, a wide-field (3600 square degrees) X-ray satellite scheduled for launch in late 2023 (Yuan et al. 2018, 2022b), may be very helpful in this regard. With its high X-ray sensitivity, Einstein Probe could significantly increase the sample size of well-localized GRBs.

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