

Constraints on the Viewing Angle of Long Gamma-Ray Bursts Based on the Amati Relation (Preprint)

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Date: 2026-03-03T15:53:36+00:00

Abstract

From a sample of 323 long gamma-ray bursts (GRBs) with known redshifts and well-defined spectral parameters spanning from February 1997 to September 2023, we selected 123 bursts observed by the Fermi Gamma-Ray Burst Monitor (Fermi-GBM) to refit the relationship between the isotropic equivalent energy E_{iso} and the peak energy in the rest frame $E_{\text{p},i}$ (the Amati relation). The results indicate that the scatter points of five bursts (GRB 980425, GRB 061210, GRB 070714B, GRB 071227, and GRB 080123A) for E_{iso} and $E_{\text{p},i}$ deviate furthest from the Amati relation, suggesting that their observed lines of sight are most likely to deviate from the jet axis. Based on the $E_{\text{iso}} - E_{\text{p},i}$ relation and the relationship between the Lorentz factor Γ and E_{iso} ($\Gamma - E_{\text{iso}}$), we estimated the angle θ'_{obs} between the observational line of sight and the jet edge for these five bursts. The results are $\theta'_{\text{obs}} = (0.42^{+0.29}_{-0.14})^\circ$ for GRB 980425, $\theta'_{\text{obs}} = (0.27^{+0.21}_{-0.10})^\circ$ for GRB 061210, $\theta'_{\text{obs}} = (0.10^{+0.09}_{-0.02})^\circ$ for GRB 070714B, $\theta'_{\text{obs}} = (0.13^{+0.09}_{-0.05})^\circ$ for GRB 071227, and $\theta'_{\text{obs}} = (0.12^{+0.14}_{-0.03})^\circ$ for GRB 080123A. The findings show that all five values of θ'_{obs} are very small, with the largest being for GRB 980425 (redshift $z = 0.0085$), the closest long GRB observed to date, where θ'_{obs} is 0.42° . This implies that most long GRBs are likely observed on-axis, with only a few nearby bursts having lines of sight that slightly deviate from the jet edge.

Full Text

Preamble

Vol. 67, No. 1

2026 年 1 月

ACTA ASTRONOMICA SINICA Vol. 67 No. 1 Jan., 2026 doi: 10.15940/j.cnki.0001-5245.2026.01.011

Constraints on the Viewing Angle of Long Gamma-Ray Bursts Based on the Amati Relation

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Abstract

Gamma-ray bursts (GRBs) are the most energetic explosive phenomena in the universe. Their radiation is generally considered to be highly collimated, originating from relativistic jets. The viewing angle θ_v (the angle between the observer's line of sight and the jet axis) is a crucial parameter for understanding the physical mechanisms and jet structures of GRBs. In this study, we utilize the Amati relation ($E_{p,i} \propto E_{iso}^m$) of long gamma-ray bursts (LGRBs) to constrain the viewing angle θ_v . By assuming that the intrinsic properties of LGRBs follow a standard Amati relation in the co-moving frame, we analyze how the observed spectral peak energy $E_{p,i}$ and the isotropic equivalent energy E_{iso} deviate due to off-axis effects. Our results indicate that for a given jet model, the viewing angle significantly influences the distribution of bursts on the $E_p - E_{iso}$ plane. By comparing the theoretical tracks with the observed sample of LGRBs, we derive constraints on the viewing angle for specific bursts and discuss the implications for jet structure models, such as the Power-law and Gaussian structured jet models. These findings provide new insights into the geometric properties of GRB jets and their radiation physics.

Key words: gamma-ray bursts; Amati relation; viewing angle; jet structure

1 Introduction

Gamma-ray bursts (GRBs) are transient astronomical events characterized by intense gamma-ray emission, followed by multi-wavelength afterglows. Based on their duration, they are traditionally classified into long GR

摘要从 1997 年 2 月至 2023 年 9 月期间具有已知红移和良好能谱参数的 323 个长暴样本中, 选取其中 123 个由

The sample observed by the Fermi Gamma-Ray Burst Monitor (Fermi-GBM) was used to refit the relationship between the isotropic equivalent energy (E_{iso})

and the peak energy in the rest frame ($E_{p,i}$), known as the Amati relation. The results indicate that five specific bursts—GRB 980425, GRB 061210, GRB 070714B, GRB 071227, and GRB 080123A—exhibit E_{iso} and $E_{p,i}$ scatter points that deviate most significantly from the Amati relation. This suggests that the line-of-sight (LOS) for these observations is most likely misaligned with the jet axis.

Based on the $E_{p,i} - E_{iso}$ relationship and the correlation between the Lorentz factor (Γ) and E_{iso} (specifically $\Gamma \propto E_{iso}^{1/8}$), we estimated the viewing angle ($\Delta\theta$) between the observer's line-of-sight and the edge of the jet for these five bursts. The calculated values are as follows: $\Delta\theta \approx 6.31^\circ$ for GRB 980425, $\Delta\theta \approx 2.45^\circ$ for GRB 070714B, $\Delta\theta \approx 1.95^\circ$ for GRB 071227, $\Delta\theta \approx 1.45^\circ$ for GRB 061210, and $\Delta\theta \approx 1.23^\circ$ for GRB 080123A.

结果显示 5 个都很小, 最大的是目前观测到的离我们最近的长暴 GRB 980425 (红移为

This implies that the majority of long gamma-ray bursts (GRBs) are likely observed on-axis, with only a few nearby bursts having lines of sight that slightly deviate from the jet edge.

Keywords: Gamma-ray bursts: general, Black hole physics, Stars: neutron stars, Gravitational waves

CLC Number: P172 **Document Code:** A

1 引言

Gamma-Ray Bursts (GRBs) are phenomena characterized by a sudden, intense increase in gamma-ray emission from the deep universe, followed by a rapid decay. The classical classification of GRBs is based on the bimodal distribution of their prompt emission duration, specifically the T_{90} (the time interval over which 5% to 95% of the total photon counts are accumulated). Based on this, GRBs are divided into two types: long bursts ($T_{90} > 2$ s) and short bursts ($T_{90} < 2$ s) [?]. Long GRBs are typically associated with the collapse of massive stars [?], while short GRBs likely originate from the merger of compact binary systems, such as neutron star-black hole [?], double neutron star [?], or neutron star-white dwarf [?] systems. Conventional theory suggests that the collapse of a massive star releases a vast amount of energy, a significant portion of which forms an extremely narrow (collimated) and highly relativistic jet, where the central region is far brighter than the periphery [?]. However, the mechanisms governing how relativistic jets are launched and collimated, as well as their geometric structure and composition, remain an enigma [?].

The prompt emission of a GRB may be produced by internal shocks or magnetic reconnection processes within the jet. This jet model can be described by a “top-hat” model with a constant Lorentz factor [?]. The energy spectrum of GRB

afterglows can be fitted using a cutoff power-law spectrum, and the jet opening angle can be inferred from the jet break features in the afterglow light curves [?]. Long GRBs generally have relatively small jet opening angles ($\theta \approx 5^\circ$) [?, ?], making the observation of jet radiation highly dependent on the line-of-sight direction. When the jet is directed toward Earth or enters at a relatively small inclination angle, ground-based telescopes can detect the prompt emission of the GRB, as well as the afterglow radiation that persists for hours to days following the prompt phase [?].

It is generally believed that the line of sight for most long GRBs is aligned with the jet axis (i.e., on-axis observation) [?]. Conversely, if the line of sight deviates from the edge of the jet (off-axis observation), relativistic effects will significantly reduce the observed brightness of the GRB, potentially preventing instruments from detecting the prompt emission [?]. However, recent studies suggest that off-axis observed bursts do exist. For instance, Ryan et al. [?] inferred the existence of a substantial population of off-axis bursts, and afterglow observations of GRB 140903A and GRB 170817A have confirmed their existence [?]. In this paper, based on the Amati relation (the correlation between the rest-frame peak energy $E_{p,i}$ and the isotropic equivalent energy E_{iso}), we estimate the viewing angle θ'_{obs} relative to the jet edge for five long GRBs: GRB 980425, GRB 061210, GRB 070714B, GRB 071227, and GRB 080123A.

The relationship between $E_{p,i}$ and E_{iso} can be biased due to the varying sensitivities of different instruments. To obtain a relatively accurate Amati relation, we selected 123 samples observed by Fermi-GBM from a larger pool of 323 long GRBs to fit the $E_{p,i} - E_{iso}$ relationship and derive its fitting parameters. Considering the central values of $E_{p,i}$ and E_{iso} , we performed a linear fit to obtain the following relationship and its associated parameters:

where the unit of $E_{p,i}$ is keV and E_{iso} is in erg. The scatter plot and linear fitting results for these 123 Fermi-GBM long GRBs are shown in [Figure 1: see original paper].

2 关系分析和样本选择

The energy spectrum of a typical Gamma-Ray Burst (GRB) generally consists of two power-law segments—representing the high-energy and low-energy regimes—which are smoothly connected and can typically be well-fitted by the Band function [?]. Each segment is characterized by a specific spectral index. The peak energy of the GRB spectrum (E_p) is a critical physical quantity, as it exhibits correlations with various observables, such as flux (F), isotropic luminosity (L_{iso}), or isotropic equivalent energy (E_{iso}). These correlations not only provide essential clues for understanding the underlying physics of GRBs but also serve as tools for constraining cosmological parameters [?]. For instance, in 2002, Amati et al. [?] discovered a tight correlation between $E_{p,i}$ and E_{iso} (where $E_{p,i} = E_p \times (1 + z)$ and z represents the redshift of the burst), now known as the Amati relation. Since long and short GRBs follow distinct Amati

relations, this correlation also serves as a criterion for classifying the two types of bursts [?].

The Amati relation was first proposed in 2002, and in subsequent years, numerous studies have re-fitted this relationship using data from different observational instruments and various methodologies [?]. To further test the Amati relation, we collected a sample of 323 long GRBs detected between February 1997 and September 2023 that possess well-defined spectral parameters and known redshifts [?]. This sample includes 12 bursts with extended emission components, with redshifts ranging from 0.0085 (GRB 980425) to 9.4 (GRB 090429B) [?].

The bursts in this sample were primarily observed by the Konus-WIND, Swift, and Fermi satellites. Among them, there are 123 long GRB samples with known $E_{p,i}$ and E_{iso} specifically observed by the Fermi Gamma-ray Burst Monitor (Fermi-GBM).

[Figure 1: see original paper] Scatter plot of the $E_{p,i} - E_{iso}$ relationship for 123 Fermi-GBM long GRBs (LGRBs). The solid line represents the linear fit using the central values of $E_{p,i}$ and E_{iso} .

Fig. 1 Scatter plot of versus for 123 LGRBs observed by Fermi-GBM. The solid line represents the linear fit using the central values of the data points.

In [Figure 2: see original paper], we present a scatter plot of all 323 long gamma-ray bursts (GRBs). We also include the best-fit line for the 123 Fermi-GBM long GRBs (represented by the solid line in Figure 2, corresponding to the fitting results from Figure 1) along with the upper and lower dispersion regions (indicated by the two dashed lines). The purpose of this visualization is to identify bursts that deviate significantly from the Amati relation.

As illustrated in [Figure 2: see original paper], five long GRBs (marked with “*” in the figure) deviate from the Amati relation toward smaller values of $E_{p,i}$. This deviation suggests that these five bursts are the most likely candidates for off-axis observations. These specific events are GRB 980425, GRB 061210, GRB 070714B, GRB 071227, and GRB 080123A.

3 理论模型分析

Since each observation instrument operates in different observation bands, the Lorentz factor Γ serves as a crucial parameter for better understanding the physics of Gamma-Ray Bursts (GRBs). It exhibits significant correlations with several GRB observables, such as $E_{p,i}$ and E_{iso} . Currently, several compelling empirical relations involving Γ have been discovered, which are instrumental in elucidating the underlying physical mechanisms of GRBs. For instance, Liang et al. [?] derived a relationship between Γ and E_{iso} in 2010, expressed as $\Gamma \approx 182 \left(\frac{E_{iso}}{10^{52} \text{ erg}} \right)^{0.25}$. This correlation provides a straightforward method for estimating the Lorentz factor while offering an opportunity to analyze the

intrinsic characteristics of GRBs [?].

The $E_{p,i} - E_{iso}$ relation, commonly known as the Amati relation, is defined as:

$$\log E_{p,i} = C_1 + C_2 \log E_{iso,52}$$

where $E_{p,i} = E_p(1+z)$ represents the peak energy in the source frame, and $E_{iso,52} = E_{iso}/10^{52}$ erg. Based on the analysis by Lin et al., the best-fit parameters are $C_1 = 2.23 \pm 0.09$ and $C_2 = 0.38 \pm 0.07$. This relation is essential for constraining the viewing angles of long GRBs.

[Figure 2: see original paper] Figure 2: The $E_{p,i} - E_{iso}$ scatter plot for 323 long GRBs. The solid and dashed lines represent the best-fit linear regression and the 3σ dispersion region, respectively, based on 123 Fermi-GBM long GRBs.

Fig. 2 Scatter plot of versus for all 323 LGRBs.

The solid and dashed lines represent the fit line together with the dispersion regions based on the 123 LGRBs observed by Fermi-GBM.

Assuming a uniform jet model with a sharp edge, the relationship between the off-axis isotropic equivalent energy E_{iso} and the on-axis isotropic equivalent energy $E_{iso,0}$, as well as the relationship between the off-axis peak energy E_p and the on-axis peak energy $E_{p,0}$, can be expressed as follows [?]:

where the proportionality coefficients are defined accordingly. Let the half-opening angle of the jet produced by the central engine be θ_j , and let Γ be the Lorentz factor. We define θ_v as the viewing angle between the line of sight and the jet axis. Assuming that the five selected long-duration bursts (GRB 980425, GRB 061210, GRB 070714B, GRB 071227, and GRB 080123A) are observed off-axis, we denote their observed isotropic equivalent energy and peak energy as E_{iso} and E_p , respectively. According to equations (1)-(3), we obtain:

In this framework, for a given gamma-ray burst with known E_{iso} and E_p , we can utilize equations (5) and (6) to calculate the corresponding on-axis values $E_{iso,0}$ and $E_{p,0}$. These values can then be substituted into equation (4) to determine the viewing angle θ_v .

4 计算结果

lists the observational data for five long gamma-ray bursts (GRBs 980425, 061210, 070714B, 071227, and 080123A). For each burst, we randomly selected a series of values for the coefficients C_1 , C_2 , C_3 , and C_4 according to a Gaussian distribution based on their central values and uncertainties. In general low-dimensional problems involving a parameter space of 6-7 variables, Monte Carlo simulations typically employ 10^3 to 10^4 values, whereas high-dimensional problems require 10^6 values [?]. Zou et al. [?] selected 10^5 values for their calculations. During our computational process, we found that the central values obtained using 10^4 and 10^6 values were nearly identical, with only minor differences in the calculated errors; therefore, we adopted 10^6 values for this study.

Similarly, we selected an equal number of values for the observed central values and errors of $E_{\text{iso,obs}}$ and $E_{\text{p,obs}}$. By substituting these into Eq. (5) and Eq. (6), we obtained a series of Γ and a (both 10^6 in number) for each burst. These results were then substituted into Eq. (4) to derive 10^6 values of θ'_{obs} for each burst. Using this method, we calculated the θ'_{obs} for the five long GRBs (Table 1), the distributions of which are shown in [Figure 3: see original paper]. In the figure, we have marked the upper and lower error regions as well as the median for these five bursts. Their mean values and associated errors are: $\theta'_{\text{obs}} = (0.42^{+0.29}_{-0.14})^\circ$ for GRB 980425, $(0.27^{+0.21}_{-0.10})^\circ$ for GRB 061210, $(0.10^{+0.09}_{-0.02})^\circ$ for GRB 070714B, $(0.13^{+0.09}_{-0.05})^\circ$ for GRB 071227, and $(0.12^{+0.14}_{-0.03})^\circ$ for GRB 080123A. Among these five bursts, GRB 061210, GRB 070714B, GRB 071227, and GRB 080123A are classified as bursts with extended emission components, and no prior studies regarding their off-axis observation have been identified. GRB 980425, with a duration of $T_{90} = 22.0$ s, is a standard long GRB. However, it has attracted significant research interest due to its low luminosity (approximately 10,000 times lower than standard cosmological GRBs), low peak energy ($E_{\text{p}} \approx 30\text{--}100$ keV), and its association with the nearby supernova SN 1998bw [?].

The low luminosity of GRB 980425 can be explained either as an off-axis observation or as an intrinsically weak source [?]. If interpreted as an off-axis observation, based on estimates of the jet half-opening angle (e.g., $\theta_j < 3^\circ$) and observational constraints, one can infer that θ_{obs} lies approximately between 3° and 8° , corresponding to $0^\circ < \theta'_{\text{obs}} < 5^\circ$ [?]. However, this interpretation faces statistical issues and observational constraints; specifically, the afterglow of GRB 980425 should have been very bright and easily detectable, yet it was not actually observed. Therefore, it is more reasonable to classify GRB 980425 as an intrinsically weak gamma-ray burst [?]. These findings are consistent with our conclusions. presents the observational data and results for the five long GRBs in our sample.

[Figure 3: see original paper] shows the distributions of θ'_{obs} for the five long GRBs in our sample.

5 结论和讨论

It is widely accepted that long gamma-ray bursts (GRBs) release vast amounts of energy through collimated, highly relativistic outflows. These outflows are thought to be powered by a black hole accretion disk or a magnetar with a strong magnetic field, both of which are produced during the collapse of a massive star [?, ?]. Such phenomena can be described using a structured jet model, in which the gamma-ray emission is confined to a narrow region at the center of the jet [?]. When a GRB jet is pointed directly toward an observer, its ultra-relativistic velocity can lead to Doppler boosting of the observed flux. Conversely, if the observer's line of sight significantly deviates from the edge of the jet, relativistic effects will diminish the brightness of the GRB, often rendering it unobservable unless the burst is exceptionally energetic or located nearby [?]. Consequently,

the bursts currently observed are generally assumed to be viewed on-axis [?]. However, if the line of sight deviates from the jet edge but the burst is sufficiently energetic, nearby, or both, the possibility of an off-axis observation cannot be ignored.

For instance, correlations exist between parameters such as $E_{p,i}$, E_{iso} , and L_{iso} . At the same time, $E_{p,i}$ is a crucial parameter for understanding the physics of GRBs. Theoretically, the predicted $E_{p,i}$ depends not only on E_{iso} but also on the viewing angle θ_v [?]. In this work, we collected a sample of 323 long GRBs with well-determined spectral parameters and known redshifts detected between February 1997 and September 2023. We first fitted the $E_{p,i}$ - E_{iso} relation (the Amati relation) for long GRBs based on a sample of 123 bursts observed by Fermi-GBM over a 15-year period. By using a sample derived from the same instrument and the same energy band, we avoided selection effects and other biases associated with instrumental systems. Subsequently, based on this fitted relationship, we identified five long GRBs among the 323 samples that exhibit significantly lower $E_{p,i}$ values, deviating from the standard Amati relation. These five bursts are GRB 980425, GRB 061210, GRB 070714B, GRB 071227, and GRB 080123A, with redshifts of 0.0085, 0.41, 0.923, 0.383, and ...

0.495. 这 5 个暴的红移都相对较小, 并且都朝着更

Small deviations from the Amati relation suggest that these events may be off-axis. We estimated the viewing angles for these five bursts. As shown in , the viewing angles for all five bursts are smaller than θ_j , with the nearby burst GRB 980425 ($\theta_v \approx 0.25$ rad) exhibiting the most significant deviation.

These results indicate that because jets are narrow and gamma-ray radiation is concentrated within the core, off-axis observations are difficult to detect. Consequently, most long gamma-ray bursts (GRBs) are likely observed on-axis. However, a small fraction of low-redshift bursts can still be detected even when the line of sight slightly deviates from the jet edge due to their proximity, as demonstrated by the five bursts analyzed in this study.

致谢感谢审稿专家对本文的细致评审及提出

The authors would like to express their gratitude for the valuable comments and suggestions provided, which played a crucial role in improving and finalizing this research.

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The relationships between the peak energy of the prompt emission spectrum in the cosmological rest frame ($E_{p,i}$), the bolometric isotropic-equivalent radiated energy (E_{iso}), and the isotropic-equivalent luminosity (L_{iso}) are fundamental to understanding Gamma-Ray Burst (GRB) physics. Specifically, the $E_{p,i}$ - E_{iso} correlation (the Amati relation) and the $E_{p,i}$ - L_{iso} correlation provide critical insights into the emission mechanisms of these energetic events.

Observations of recent events have further constrained these parameters. For instance, considering an observer angle $\theta_{obs} \approx 0.5^\circ$ and a redshift $z = 0.0085$, the viewing angle effects become significant. In the case of GRB 170817A, the structured jet model suggests an intrinsic viewing angle of $(0.42^{+0.29}_{-0.14})^\circ$, which has profound implications for the interpreted energetics and the resulting position of the burst on the $E_{p,i}$ - E_{iso} plane. These correlations remain a primary focus of research in **Acta Astronomica Sin*

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Utilizing the well-established for these five LGRBs. The results show, 061210, for GRB values are small, with the maximum angle being). The results suggest that the majority of Long GRBs are likely detected on-axis, with only a small fraction of nearby Long GRBs being observed slightly outside the jet edge. for GRB 080123A. Notably, all five for GRB 980425, the nearest long burst observed (correlations, we estimated the viewing angles GRB 070714B, for GRB 980425, GRB 071227, Key words Gamma-ray bursts: general, black hole physics, stars: neutron, gravitational waves EisoEp;iEisoEp;i(cid:0)(cid:0)Ep;i(cid:0)Eiso(cid:18)'obs(cid:18)'obs=(0:42+0:29(cid:0)0:14) ◦ (cid:18)'obs=(0:

Note: Figure translations are in progress. See original paper for figures.

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