

Viewing Angle Constraints on GRB 221009A (Postprint)

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Abstract

GRB 221009A, known as the “brightest of all time” (BOAT) gamma-ray burst, was detected by many satellites across all wavelengths. It is the gamma-ray burst with the highest isotropic energy ($E_{\text{iso}} = 1.5 \times 10^{48} \text{J}$) observed to date and is relatively close to Earth (redshift $z = 0.151$). The radiation of gamma-ray bursts originates from relativistic jets, and their isotropic energy may depend on the intrinsic energy of the jet, the jet opening angle, and the viewing angle relative to the jet. Based on the $E_{\text{p,i}}-E_{\text{iso}}$ relation and $\Gamma-E_{\text{iso}}$ relation for long-duration bursts, the angle between the line of sight and the jet edge, θ_{obs} , and the Lorentz factor Γ for GRB 221009A were estimated, yielding $\Gamma = (4.23 \pm 2.81) \times 10^3$ and a viewing angle of $\theta_{\text{obs}} = (0.03 \pm 0.01)^\circ$. This result indicates that for GRB 221009A, the angle between the line of sight and the jet edge is extremely small, i.e., GRB 221009A is observed on-axis, which may be one of the reasons why GRB 221009A has the highest isotropic energy.

Full Text

Preamble

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The Viewing Angle Limitation of GRB 221009A

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Abstract

GRB 221009A, known as the “brightest-of-all-time” (BOAT), was detected by numerous satellites across all wavelengths. It is the gamma-ray burst with the highest isotropic energy ever observed ($E_{\text{iso}} \approx 1.5 \times 10^{48}$ J) and relatively close to Earth (redshift $z = 0.151$). GRB radiation originates from relativistic jets, and their isotropic energy may depend on the jet’s intrinsic energy, jet opening angle, and viewing angle relative to the jet. Based on the long-burst $E_{\text{p,i}}-E_{\text{iso}}$ relation and $\Gamma-E_{\text{iso}}$ relation, we estimate the viewing angle between the line of sight and the jet edge (θ_{obs}) and the Lorentz factor (Γ) for GRB 221009A. The results are $\Gamma = (4.23 \pm 2.81) \times 10^3$ and $\theta_{\text{obs}} = (0.03 \pm 0.01)^\circ$. This indicates that the viewing angle between the line of sight and the jet edge is extremely small, meaning GRB 221009A was observed nearly on-axis, which may be one reason for its record-breaking isotropic energy.

Keywords: gamma-ray burst; jet; relativistic processes

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1. Introduction

Gamma-ray bursts (GRBs) are intense cosmic explosions of gamma rays on stellar scales originating from distant space (redshift distribution range 0.0085–9.4). The classical GRB classification simply divides them into long bursts ($T_{90} > 2$ s) and short bursts ($T_{90} < 2$ s) based on the duration of prompt emission (T_{90} is defined as the time over which photon counts accumulate from 5% to 95%) [1]. Observationally, the isotropic energy of GRBs spans eight orders of magnitude (approximately 10^{39} – 10^{47} J), and E_{iso} typically follows a simple power-law distribution with a cutoff above $(1-3) \times 10^{47}$ J [2]. During 55 years of GRB observations, GRB 170817A had the lowest isotropic energy ($E_{\text{iso}} \approx 10^{39}$ J), while several of the most energetic bursts reached approximately 10^{47} J. However, the existence of GRBs with isotropic energy exceeding $\sim 10^{48}$ J remained unconfirmed until the discovery of GRB 221009A [3].

GRB 221009A is the gamma-ray burst with the highest isotropic energy ever observed ($E_{\text{iso}} \approx 10^{48}$ J) [3], earning it the designation “brightest-of-all-time” (BOAT) and breaking multiple records for gamma-ray bursts observed by humanity. It was detected by numerous satellites across all wavelengths, including Fermi/GBM (GCN 31565) [4], Fermi-LAT (GCN 32637) [5], Swift/BAT/XRT (GCN 32632) [6], Konus-Wind (GCN 31604) [7], and three major scientific facilities of the Institute of High Energy Physics, Chinese Academy of Sciences: the Insight-HXMT satellite (ATel 15660) [8], the High Energy Burst Explorer (HEBS) (GCN 32751) [9], and the Large High Altitude Air Shower Observatory

(LHAASO) (GCN 32677) [10]. Despite its unprecedented isotropic energy, the prompt emission and afterglow characteristics of GRB 221009A are consistent with known long-burst distributions extended to high energies, suggesting it may still result from the death of a massive star that collapsed to form a black hole or magnetar after ejecting its outer layers [11]. This collapse produced a gamma-ray burst containing a narrow, highly collimated jet (opening angle $\sim 1.0^\circ$) surrounded by a broader gas outflow [3, 11]. As the brightest and relatively nearby ($z = 0.151$) GRB ever detected, GRB 221009A may provide an opportunity to reveal interesting features hidden in fainter bursts [11].

According to the traditional view, GRB radiation originates from relativistic jets that are collimated for both long and short bursts. Long bursts have typical opening angles of about 5° , but how relativistic jets are emitted and collimated, and the geometric structure and composition of jets, remain long-standing mysteries [3]. It is widely believed that long bursts have relatively high isotropic energy and small jet opening angles, with the core region being much brighter than the outer region. The observed brightness of a GRB depends on the jet's intrinsic energy, jet opening angle, and viewing angle relative to the jet. Laskar et al. [12] revealed that the exceptional brightness of GRB 221009A may result from unusually high jet collimation rather than intrinsically high energy—that is, a narrow jet half-opening angle (θ_j) and small viewing angle relative to the jet (θ_{obs}), rather than high intrinsic jet energy, may be responsible. Multiple studies have proposed small jet opening angles and viewing angles for GRB 221009A [12–17]. For example, Zhang et al. [17] (2024) proposed a pencil-beam jet with half-opening angle $\theta_j = 0.6^\circ$, An et al. [3] (2023) suggested a jet half-opening angle of $\sim 0.7^\circ$, and Cao et al. [15] (2023) explained the emission with a relativistic jet model of half-opening angle $\theta_j = 0.8^\circ$. In summary, the radiation from GRB 221009A may originate from the smallest jet opening angle observed to date. While these studies considered non-aligned jets and proposed small viewing angles, they did not provide specific values. Zou et al. [18] (2018) estimated the viewing angle of GRB 170817A using the rest-frame peak energy $E_{p,i}$ – E_{iso} relation and the Lorentz factor Γ – E_{iso} relation. Here we apply the same method to estimate the viewing angle between the line of sight and jet edge (θ_{obs}) and the Lorentz factor (Γ) for GRB 221009A.

2.1 Theoretical Method

The peak energy E_p of the GRB spectrum f_ν is one of the important physical quantities of GRBs, exhibiting correlations with observables such as flux, luminosity, or isotropic energy. For example, Amati et al. [19] (2002) discovered a tight correlation between isotropic energy E_{iso} and rest-frame peak energy $E_{p,i}$ ($E_{p,i} = E_p(1+z)$), expressed as $E_{p,i} = C(E_{\text{iso}}, 45)^{\alpha}$, where C and α are proportionality coefficients and $E_{\text{iso},45} = E_{\text{iso}}/10^{45}$ J. Since GRBs of different physical origins follow different tracks, this relation is often used as a unique classification scheme when studying burst energy characteristics [20]. Recently, Sun et al. [21] collected data from 45 short bursts and

275 long bursts with known redshifts between February 1997 and January 2019, refitting the Amati relation to obtain parameters with 1σ uncertainties:

$$\lg E_{p,i} = C_1 + C_2 \lg E_{\text{iso}}$$

where for short bursts $C_1 = -15.61^{+2.51}_{-2.14}$ and $C_2 = 0.36^{+0.04}_{-0.05}$, and for long bursts $C_1 = -17.83^{+0.93}_{-0.98}$ and $C_2 = 0.39 \pm 0.02$, with $E_{p,i}$ in units of keV.

As another important parameter for understanding GRB physics, the Lorentz factor Γ also correlates with observables such as peak energy E_p , isotropic energy E_{iso} , and isotropic luminosity L_{iso} . Liang et al. [22] (2010) derived the relation between Lorentz factor Γ and isotropic energy E_{iso} :

$$\lg \Gamma = C_3 + C_4 \lg E_{\text{iso}}, \quad (45)$$

where $C_3 = 2.26 \pm 0.03$, $C_4 = 0.25 \pm 0.03$, and the correlation coefficient $r = 0.91$.

For an off-axis jet with a uniform and sharp-edged structure, the relationships between on-axis and off-axis isotropic energies and peak energies are [23]:

$$E_{p,\text{off}} = a^{-1} E_{p,\text{on}}; \quad E_{\text{iso},\text{off}} = a^{-3} E_{\text{iso},\text{on}}$$

Let θ_j be the half-opening angle of the central jet, θ_{obs} the angle between the line of sight and the jet axis, and θ the angle between the off-axis line of sight and the jet edge. When the Lorentz factor $\Gamma \gg 1$ and $\theta_{\text{obs}} - \theta_j \ll 1$,

$$a = (1 - \beta \cos \theta_{\text{obs}}) / (1 - \beta \cos \theta) \approx 1 + (\Gamma)^2$$

where $\beta = 1 - 1/\Gamma^2$.

We express the off-axis isotropic energy $E_{\text{iso},\text{off}}$ and peak energy $E_{p,\text{off}}$ using the observed E_{iso} and E_p to obtain:

$$\lg \Gamma = [C_3 + (3C_1 + 156C_2 - 3 \lg E_p + \lg E_{\text{iso}}) / (1 - 3C_2)]$$

$$\lg a = (C_1 + 52C_2 - \lg E_p + C_2 \lg E_{\text{iso}}) / (1 - 3C_2)$$

Thus, we can calculate the Lorentz factor Γ and parameter a using equations (5) and (6) for known GRB isotropic energy and peak energy, then substitute into equation (4) to compute the off-axis viewing angle θ between the line of sight and jet edge.

2.2 Observational Results

Table 1 lists the observed isotropic energy E_{iso} and peak energy E_p for GRB 221009A. For the coefficients C_1 , C_2 , C_3 , and C_4 , we randomly selected a series of values from Gaussian distributions according to their central values and uncertainties (e.g., 1,000 values each). Similarly, E_{iso} and E_p were sampled from Gaussian distributions based on their observed central values and errors. These values were substituted into equations (5) and (6) to calculate a series of Lorentz factors Γ and parameters a , which were then used in equation

(4) to obtain a series of off-axis viewing angles θ_{obs} . The distributions of Γ and θ_{obs} are shown in Figure 1 [Figure 1: see original paper] and Figure 2 [Figure 2: see original paper], respectively. The average Lorentz factor is $\Gamma = 4.23 \times 10^3$ with an error of 2.81×10^3 , and the average viewing angle between the line of sight and jet edge is $\theta_{\text{obs}} = 0.03^\circ \pm 0.01^\circ$. Our calculations indicate $\Gamma = (4.23 \pm 2.81) \times 10^3$ and $\theta_{\text{obs}} = (0.03 \pm 0.01)^\circ$.

Table 1 Observational data for GRB 221009A

Redshift	E_{iso} (10^{45} J)	E_{p} (keV)	References
0.151	1500 ± 200	1247.4 ± 91.2	[3, 17]

Figure 1 [Figure 1: see original paper] Distribution of the Lorentz factor Γ for GRB 221009A

Figure 2 [Figure 2: see original paper] Distribution of the off-axis viewing angle θ_{obs} between the line of sight and jet edge for GRB 221009A

3. Discussion

The exceptional intensity of GRB 221009A's high-energy emission during the prompt phase could result from several factors: a relatively small jet opening angle capable of producing an energetic burst with $E_{\text{iso}} \sim 10^{48}$ J (i.e., high intrinsic jet energy), a relatively small viewing angle θ_{obs} (the angle between the GRB jet axis and observer's line of sight), and its relatively close proximity to Earth ($z = 0.151$). Laskar et al. ruled out high intrinsic jet energy as the cause of GRB 221009A's exceptional brightness, suggesting that jet opening angle θ_{j} and viewing angle θ_{obs} may be the two key factors explaining its extraordinary luminosity.

The rest-frame peak energy $E_{\text{p,i}}$ of GRBs correlates with various observables such as flux F , isotropic luminosity L_{iso} , and isotropic energy E_{iso} . The Lorentz factor Γ is also crucial for understanding GRB physics. Theoretically, the predicted $E_{\text{p,i}}$ depends not only on isotropic luminosity but also on the initial Lorentz factor of the outflow [22]. In this work, we estimated the viewing angle between the line of sight and jet edge (θ_{obs}) and the Lorentz factor (Γ) for GRB 221009A using the long-burst $E_{\text{p,i}}-E_{\text{iso}}$ and $\Gamma-E_{\text{iso}}$ relations, obtaining $\Gamma = (4.23 \pm 2.81) \times 10^3$ and $\theta_{\text{obs}} = 0.03^\circ \pm 0.01^\circ$. While we used the long-burst $E_{\text{p,i}}-E_{\text{iso}}$ and $\Gamma-E_{\text{iso}}$ relations as the basis for our estimation, other observable relations and their connections to Γ could also be employed to calculate the off-axis viewing angle. We additionally estimated θ_{obs} and Γ using the $\Gamma-L_{\text{iso}}$ [25] relation, yielding $\theta_{\text{obs}} = 0.02^\circ \pm 0.01^\circ$ and $\Gamma = (2.31 \pm 0.65) \times 10^3$. The two results are essentially consistent. This small viewing angle between the line of sight and jet edge indicates that GRB 221009A was observed nearly on-axis, which may be one reason for its record-breaking isotropic energy. Of course, the $L_{\text{iso}}-E_{\text{p,i}}-\Gamma$ [22] relation

could also be used instead of the Γ - E_{iso} or Γ - L_{iso} relations to estimate the viewing angle and Lorentz factor.

For simplicity, we adopted $\theta_{\text{obs}} = \theta_j$ as the off-axis transformation framework [18]. More detailed calculations should include effects at different angles within θ_j and the corresponding arrival times. Additionally, we did not consider structured jets in our study. If a structured jet were considered, different models would need to be adopted to determine the optimal model for this burst, which might not be conclusive. Therefore, even when accounting for jet opening angle θ_j and jet structure, θ_{obs} remains a valid off-axis angle.

Several researchers have proposed small jet opening angle models for GRB 221009A. Zhang et al. [17] suggested that such narrow pencil-beam jets may exist in many GRB samples but escape detection, possibly remaining undetected even in late afterglow phases. Under the assumption of a structured GRB jet model, the small opening angle of GRB 221009A means that observers on Earth can see the brightest core of the structured jet, which combined with the burst's low redshift explains its high flux and isotropic energy [15]. We can predict that more GRBs with $E_{\text{iso}} > 10^{48}$ J exist at higher redshifts ($z > 0.15$), but either their redshifts have not been measured (making E_{iso} unknown) or not all GRBs possess such a narrow, bright core [3].

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