Intrinsic Distribution of Gamma-Ray Bursts (I):Insights from Fermi-GBM Observations

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Abstract

Investigating the intrinsic distributions of Gamma-Ray Bursts (GRBs) is crucial for understanding their physical origins, as these phenomena are closely linked to the central engine of extreme explosions, radiation mechanisms, and cosmological evolution. In this study, utilizing observational data from the Fermi Gamma-ray Burst Monitor (GBM) and adopting the Band function as the spectral model, we generated a simulated sample incorporating instrumental response and background noise through Monte Carlo simulations. Spectral fitting not only successfully reproduced the distribution characteristics of the Band function parameters (α, β, E_{p}) observed in actual data, but also revealed that deviations in the β parameter primarily stem from statistical uncertainties under low signal-to-noise conditions, thereby validating the reliability of the simulation and fitting procedures. Building on this, we systematically derived the intrinsic distributions of key parameters for long GRBs, including luminosity, isotropic energy , and redshift. Based on these results, the local rate of GRBs was calculated to be 1.41 $\pm$ 0.22 Gpc^{-3} yr^{-1}. This study comprehensively calibrates the sensitivity and spectral recovery capability of the Fermi/GBM detector, providing essential observational constraints for theoretical modeling and cosmological studies of gamma-ray bursts.

Full Text

Preamble

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ABSTRACT

Investigating the intrinsic distributions of Gamma-Ray Bursts (GRBs) is crucial for understanding their physical origins, as these phenomena are closely linked to the central engine of extreme explosions, radiation mechanisms, and cosmological evolution. In this study, utilizing observational data from the Fermi Gamma-ray Burst Monitor (GBM) and adopting the Band function as the spectral model, we generated a simulated sample incorporating instrumental response and background noise through Monte Carlo simulations. Spectral fitting not only successfully reproduced the distribution characteristics of the Band function parameters (α, β, Ep) observed in actual data, but also revealed that deviations in the β parameter primarily stem from statistical uncertainties under low signal-to-noise conditions, thereby validating the reliability of the simulation and fitting procedures. Building on this, we systematically derived the intrinsic distributions of key parameters for long GRBs, including luminosity, isotropic energy, and redshift. Based on these results, the local rate of GRBs was calculated to be 1.41 $\pm$ 0.22 Gpc−3yr−1. This study comprehensively calibrates the sensitivity and spectral recovery capability of the Fermi/GBM detector, providing essential observational constraints for theoretical modeling and cosmological studies of gamma-ray bursts.

Keywords: Gamma-ray bursts (629) –Gamma-ray detectors (630) –High Energy astrophysics (739)

1. INTRODUCTION

Gamma-ray bursts (GRBs), which release energy in gamma rays on the order of 10^{51} ergs, are the most powerful explosions in the universe. They are usually classified into two populations depending on the main duration (T90) of γ-ray emission. Long GRBs (lGRBs) have a duration longer than 2s, while short GRBs (sGRBs) are the opposite. The prompt emission phase of GRBs can usually be fitted by a smooth broken power law, known as the Band function (D. Band et al. 1993). Thanks to the launch of the Fermi satellite, the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT) cover seven orders of magnitude in energy of the GRB spectral band (W. B. Atwood et al. 2009; C. Meegan et al. 2009), making it possible to obtain a more comprehensive spectrum shape of prompt emission than in the Swift era.

There may be three main components in GRB prompt spectra (B.-B. Zhang et al. 2011): a non-thermal Band component, a quasi-thermal component (such as in GRB 090902B, (A. A. Abdo et al. 2009)), and a non-thermal power law component extending to high energies. The first of these is the most common case. For the power law with a high energy cutoff, constraints are mainly provided by a higher peak energy compared to the observed energy band. The synchrotron model can deal well with the observed spectrum for bright GRBs (D.-Z. Wang et al. 2022). For GRBs with low-energy index α higher than -2/3 (the death-line of synchrotron), additional physical effects such as the Klein-Nishina regime (E. Nakar et al. 2009) or time-dependent electron injection can accommodate the dilemma (K. Liu et al. 2021). The synchrotron model can also reproduce the correlation in GRB physical configuration (F. Xu et al. 2023), such as the Amati relation (Amati, L. et al. 2002) (Ep,z   Eγ,iso^1/2) and Yonetoku relation (D. Yonetoku et al. 2004)(Ep,z   Lγ,p^1/2). However, a small fraction of GRBs with high-energy index in the range $[-10, -4]$ show some high-energy cutoff feature. This could be caused by large errors in spectral fitting (small effective area of GBM) or a much softer electron injection spectrum.

To address this problem, we implement detector simulation for GBM. In this work, we analyze the GBM detected bursts and simulate the trigger of each burst. Then we construct the ^2 statistic and use Minuit to minimize it to obtain the best-fitting parameters, as well as their error estimates. In Section 2, we outline the experiment simulation and GRB samples. Section 3 states the results and conclusions are made in Section 4.

2. METHODOLOGY

In our study, we develop a program to generate a sample of gamma-ray bursts (GRBs) and simulate the observational effects of the Fermi-GBM detector on these events. The program constructs the GRB sample based on key parameters including the spatial distribution (redshift z), spectral model (Band function), and luminosity function ((Lp)), and validates these parameters using actual Fermi-GBM observational data.

2.1. Production of the GRB Sample

The number density distribution of GRBs, n(Lp, z), is jointly determined by the peak luminosity (Lp) and redshift (z), and is expressed as (D. Wanderman & T. Piran 2010):

n(Lp, z)dlog(Lp)dz = (Lp)R(z)dlog(Lp)dz

Here, R(z) represents the spatial distribution of GRBs within the redshift interval [z, z + dz], and (Lp) denotes the luminosity function distribution within the logarithmic interval [log Lp, log Lp + d log Lp]. They are described as:

R(z) = RGRB(z) (dV(z)/dz) / [(1 + z) * sqrt(Ωm(1 + z)^3 + ΩΛ)]

In this study, we adopt H0 = 67 km s−1 Mpc−1, Ωm = 0.3 and ΩΛ = 0.7. RGRB(z) describes the comoving spatial density of GRBs at redshift(z), modeled using an empirical broken power law (EBPL) (Y.-H. Yao et al. 2020):

RGRB(z) = 0 * (1 + z)^{n1}, for z ≤ z1 RGRB(z) = 0 * (1 + z1)^(n1-n2) * (1 + z)^{n2}, for z > z1

Here, 0 is the local event rate, and the empirical parameters are fixed at n1 = 1.2, n2 = −0.6, and z1 = 3.3.

The luminosity function (Lp) takes the form of a broken power law:

 (Lp) = A * (Lp/Lp*)^$ $1, for Llower ≤ Lp < Lp* (Lp) = A * (Lp/Lp*)^$ $2, for Lp* ≤ Lp ≤ Lupper*

where A is a normalization constant. The other parameters are set to: Llower = 10^{49} erg s−1, Lupper = 10^{55} erg s−1, Lp* = 10^{52}.4 erg s−1, $ $1 = -0.18, and $ $2 = -1.1. After constructing the GRB density distribution n(Lp, z), we further assign intrinsic properties to each GRB event, including spectral features and temporal characteristics. The spectrum is described by a simplified Band function (D. Band et al. 1993; D. L. Band et al. 2009):

N(E) = J0 * E^α * exp[−E(2+α)/Ep], for E ≤ Ec N(E) = J0 * E^β * Ec^(β−α), for E > Ec

where the critical energy Ec = (α−β)/(2+α) * Ep, J0 is the normalization constant (in units of ph ·cm−2 ·s−1 ·keV−1), α and β are the low and high energy photon indices, respectively, and the peak energy Ep is determined via the empirical Ep-Lp relation (B. Yu et al. 2009; S. Qi & T. Lu 2012). The temporal property is characterized by the T90 duration, defined as the time interval over which 90% of the total fluence is accumulated. T90 is related to the isotropic energy Eiso and the average luminosity Lave through the simplified relation:

T90 = (1 + z) * Eiso / Lave

Here, Eiso is determined from the empirical Eiso-Lp relation (G. Ghirlanda et al. 2012; J. Kakuwa et al. 2012). We verify that the Lp-Ep and Lp-Eiso relations of the triggered GRBs in our generated sample are consistent with the empirical correlations, as shown in Figure 1.

2.2. The ^2 Statistic

Using the above framework, we generate a Monte Carlo sample of GRBs with specific parameters (α, β, Ep, Lp, z, T90). To simulate the detection process by Fermi-GBM, the maximum burst triggering time window is set to td = 8 s (C. Meegan et al. 2009). The burst significance in a single NaI detector is evaluated by comparing the expected signal counts to the background counts. The signal count rate ns is calculated as:

ns = [Emin to Emax] Aeff(E,) * N(E) dE

where Aeff(E,) is the energy-dependent effective area of the detector, based on laboratory calibration data (C. Meegan et al. 2009); this study uses Emin = 8 keV, Emax = 1000 keV. A detection threshold of 4.5σ is applied for Fermi-GBM, and at least two NaI detectors are required to trigger simultaneously.

In our simulation, the 12 NaI detectors and 2 BGO detectors are configured according to their actual flight positions. Since the focus is on the instantaneous detection effect, the influence of orbital surveying is neglected.

Following the configuration of the detectors and the trigger conditions described above, spectral fitting analysis was performed on the sample of bursts that successfully triggered the detection system. For GRBs triggering at least two NaI detectors, we incorporate Poisson noise and define the ^2 statistic. The best-fit parameters are obtained by minimizing the ^2 function. Within each energy bin, the observed counts are modeled as the sum of Poisson-distributed signal and background contributions. The energy range is divided into 60 logarithmic bins from 8 keV to 1000 keV for NaI detectors, and 100 logarithmic bins from 0.1 MeV to 10 MeV for BGO detectors. For detector i (NaI/BGO) in energy bin j, the predicted count is given by Cij = P(Ns,ij) + P(Nb,ij). The ^2 statistic is defined as:

^2 = Σ_i Σ_j [(Ns,ij_{hat} + P(Nb,ij) - Cij)^2 / (Ns,ij_{hat} + P(Nb,ij))]

If a GRB triggers three or more NaI detectors, the three detectors with the smallest angular distance to the source are selected. The BGO detector most directly aligned with the source is chosen to further minimize ^2.

The expected signal counts Ns,ij_{hat} are computed from the spectral parameters to be fitted. The optimization algorithm employs two safeguards to ensure computational robustness: 1) A maximum iteration limit of 500 cycles is imposed, and 2) A convergence tolerance threshold of 0.01 is established. The optimization procedure terminates automatically when either condition is satisfied.

3. RESULTS

3.1. Simulating Detection versus GBM Observation

To ensure the representativeness of the experimental sample, we collected 689 long gamma-ray bursts (lGRBs) up to 2018. Those GRBs satisfy the GOOD level of S. Poolakkil et al. (2021), which have less parameter fitting error to ensure sufficient statistics. In Figure 2, we present the spectral parameters (α, β, Ep) along with their fitting errors.

For easier comparison and clearer visualization, the intrinsic distributions of these parameters are shown in black lines, normalized in the same manner as the observed data. The simulated detection and fitting results are in excellent agreement with the observed parameter distributions. For the low-energy index α, the distributions of the triggered bursts and the subpopulation of the overall sample are similar. In contrast, differences are observed for the high-energy index β and the peak energy Ep. When β is relatively small (-3.0), the lack of statistics in the high-energy range reduces the effectiveness of the fitting. This bias can be attributed to Poisson fluctuations in the high-energy photon counts. Taking the low-statistics energy range of the BGO detectors as an example, Poisson noise fluctuations approximately follow a Gaussian distribution. Increases and decreases in counts within this energy range are equally probable, but for a power-law-like spectrum, a decrease in counts tends to result in a softer fitted spectrum with higher weight. The peak energies of the simulated bursts successfully reproduce the distribution of the observed sample, which is predominantly concentrated above several hundred keV. Higher Ep values produce stronger signal counts (assuming a constant background count rate), making them more likely to be triggered.

The distributions of T90, fluence, isotropic energy, and peak luminosity are shown in Figure 3. The ̂2 value indicates that the simulation results are in excellent agreement with the observational data. It is worth noting that, in terms of T90, the triggered gamma-ray bursts constitute a subpopulation similar to the overall sample—since T90 is a derived quantity in the simulations. Furthermore, in the top-right panel of Figure 3, the primary reason why gamma-ray bursts in the high-fluence range are not fully observed is due to the limited field of view of the detector.

3.2. The Burst Rate

For lGRBs, they should track the history of star formation. And at high redshift, the GRB rate may exceed the model predictions (e.g., F. J. Virgili et al. (2011); B. E. Robertson & R. S. Ellis (2011)). As shown in Figure 4, our simulation also implies a relatively higher burst rate beyond z = 3. The empirical parameters z1, n1, n2 are fixed at 3.3, 1.2 and -0.6, respectively. Considering the detector threshold and the correlation between physical parameters, the local burst rate is 0 = 1.41 ± 0.22 Gpc−3 yr−1 for lGRBs, a little higher than 1 Gpc−3 yr−1 (D. Wanderman & T. Piran 2010; H. Sun et al. 2015; G.-X. Lan et al. 2019), which barely considered the threshold effects. The GRB formation rate approaches the density evolution case of G.-X. Lan et al. (2019), which proves the rationality of our parameter combination. For a more imminent situation, z1 $<$ 3, the theoretical model' s predicted number of outbreaks exhibits a systematic deviation from the actual observed results, specifically manifesting as significantly higher theoretical expectations than the statistically observed quantities at the low-redshift end. So a higher break redshift z1 is favored by our simulation.

3.3. Physical Implication of the Simulation Result

Our simulation implies that the Band component is a more common situation than shown by experimental fitting. At least, we do not need a new spectral model such as cutoff power-law with more uncertain physical mechanism. Those cutoff-like Band functions are formed by low statistics in spectral fitting. Since the high-energy component is harder than the traditional perspective, a more intense spectral break below the gamma-ray band is needed to explain the Fermi-LAT detection rate, with more constraint of burst Lorentz factor (Y. Chen et al. 2018). Time-resolved spectral analysis proposed the same offset of high-energy index β for lower significance pulses (H.-F. Yu et al. 2019). Considering the time evolution of GRB pulses is not referred to in this work, we still cannot exclude the possibility that the observed spectrum is a result of overlapping by softer single pulses.

4. CONCLUSION

In this work, we first simulate the detection of GRBs by GBM and fit each trigger to search for the spectral shape distribution at the emission site. All the simulated results match well with observation. The soft tail of the high-energy index β is attributed to the lack of signal counts in high-energy bins. The burst rate with redshift is in accordance with other works within a reasonable error range. Our work implies a wide range of GRBs can be described by the Band function, on the premise of conforming to Amati and Yonetoku relations. Moreover, the local burst rate is $0 = 1.41 \pm 0.22$ Gpc−3 yr−1 for lGRBs. Further, we also need the correspondence between simulation and observation for other experiments, such as Swift and Fermi-LAT, which we leave for future work.

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