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An Amati-Like Correlation for Short Gamma-Ray Bursts

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Abstract

Gamma-ray bursts (GRBs) are by far the most powerful explosions in the universe. Over the past two decades, several GRB energy and luminosity correlations were discovered for long gamma-ray bursts, which are bursts whose observed duration exceeds 2 seconds. One important correlation, the Amati relation, involves the observed peak energy, $E_{p,obs}$, in the νF_{ν} spectrum and the equivalent isotropic energy, E_{iso}. For many years, it was believed that the Amati correlation applied only to long GRBs. In this paper, we use a recent data sample that includes both long and short GRBs to re-examine the issue of whether the Amati correlation applies to long GRBs only. Our results indicate that although short bursts do not follow the Amati relation in the strict sense, they do exhibit a correlation between the intrinsic peak energy, $E_{p,i}$, and E_{iso} that is very similar to the Amati relation but with a different normalization and slope. The paper also discusses the physical interpretation of this correlation in the context of the internal shock model.

Keywords

Gamma-Ray Bursts, Peak Energy Correlations, Energy Indicators

1. Introduction

Gamma-ray bursts (GRBs) are immensely powerful stellar explosions with an equivalent isotropic energy, E_{iso} that can exceed 10^{54} erg [1]. Their light curves consist of intense and complex pulses that typically last for a few seconds and their spectra are nonthermal peaking between 10 and 10^4 keV. Although the radiation produced by GRBs is believed to emanate from jets, the exact mechanism behind the formation of these jets is still not well understood [2].

Over the past two decades, several GRB energy and luminosity correlations were discovered. Some of these correlations were obtained from the light curves, like the time-lag and variability relations [3] [4], while others were obtained from the spectra and include the Amati relation [5] [6] [7] [8], the Ghirlanda relation [9], the Yonetoku relation [10] [11], and the Liang-Zhang relation [12]. These correlations are important for two reasons. First, if calibrated properly they can be used as cosmological probes to constrain cosmological parameters [12]-[18]. Second, they are effective tools that might shed light on the physics of GRBs [19] [20].

This paper focuses on one of these correlations, namely the Amati relation, and examines whether it applies to both short (observed duration < 2 s) and long bursts (observed duration > 2 s) or only to long bursts, as currently believed. Section 2 provides essential background regarding peak-energy correlations, in general, and the Amati relation in particular. Our data sample, results, and physical interpretation are provided in Section 3, and our conclusions are provided in Section 4.

2. Peak Energy Correlations and the Amati Relation

Gamma-ray burst correlations involving the peak energy were first discovered in 1995 by [21], who studied 399 bursts observed by the BATSE instrument and discovered a correlation between $E_{p,obs}$ and the peak flux, F_p. They calculated F_p from the photon count data in the 256 ms time bin and the 50 - 300 keV energy band. They then selected those bursts with $F_p > 1$ photon·cm^{-2}·s^{-1} and divided them into five bins of varying width, each with approximately 80 bursts. They discovered a correlation between the mean observed peak energy, $\langle E_{p,obs} \rangle$, and the logarithm of F_p with a statistical significance of $\rho = 0.90$ and $P = 0.04$.

A study by [22] later found a strong correlation between $E_{p,obs}$ and the bolometric fluence, S_{bol}, in the same energy range as [21]. They expressed the correlation as follows:

$$\log\left(E_{p,obs}\right) \approx 0.29\log\left(S_{bol}\right), \tag{1}$$

with a Kendall correlation coefficient $\tau = 0.80$ and a chance probability $P = 10^{-13}$. However, it is important to remember that their selection criteria, $F_p > 3$ photons·cm^{-2}·s^{-1} and $S_{bol} > 5 \times 10^{-6}$ erg·cm^{-2}, included only the most luminous GRBs. The correlation discovered by [22] was the basis for later studies that led to the discovery of important peak-energy correlations like the Amati relation and the Ghirlanda relation.

It is important to keep in mind that the peak energy correlations found by [21] and [22] were in the observer frame due to the paucity of data points with known redshift. The first rest-frame correlation involving the intrinsic peak energy, $E_{p,i}$, was found by [5] in 2002 and is referred to as the Amati relation. The study by [5] was based on 12 bursts with known redshifts, z, detected by *BeppoSAX*. The intrinsic peak energy is calculated from the observed peak energy by utilizing and applying the z-correction as follows:

$$E_{p,i} = \left(1+z\right) \times E_{p,obs}. \tag{2}$$

On the other hand, E_{iso} can be calculated from the bolometric flux using:

$$E_{iso} = 4\pi d^2 S_{bol} / (1+z), \tag{3}$$

where d is the luminosity distance, which can be calculated from z after assuming a certain cosmological model. In Amati's original paper [5], a flat universe was assumed with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 65\ \text{km}\cdot\text{s}^{-1}\cdot\text{Mpc}^{-1}$. The Amati relation can also be expressed logarithmically as:

$$\log(E_{iso}) = A + B \times \log\left(E_{p,i} / \langle E_{p,i} \rangle\right), \tag{4}$$

where the normalization, A, and the slope, B, are constants, and where $<E_{p,i}>$ is the mean value of the intrinsic peak energy for the entire data sample. Early studies found that the approximate mean values for the fitting parameters are $<A> \approx 53$ and $<B> \approx 1$. Alternatively, the Amati relation can be expressed as:

$$E_{p,i} = K \times \left(E_{iso} / 10^{52}\ \text{erg}\right)^m, \tag{5}$$

where $E_{p,i}$ is in keV, and K and m are constants. In Amati's original study [5], the following values were obtained: $m \approx 0.5$ and $K \approx 95$. However, more recent studies [23] [24] [25] [26] [27] found mean values of $<m> = 0.45$ and $<K> = 141$.

Another important peak-energy correlation is the Ghirlanda relation, which is a correlation between the peak energy and the total energy corrected for beaming, E_γ, which is given by:

$$E_\gamma = \left[1 - \cos(\theta_j)\right] \cdot E_{iso}, \tag{6}$$

where θ_j is the jet's half-opening angle. This correlation was discovered in 2004 by [9] who used 40 GRBs with known E_{iso} and z. According to [9], θ_j can be calculated (in degrees) as follows:

$$\theta_j = 0.161\left[T_b / (1+z)\right]^{3/8} \left[n \cdot n_\gamma \cdot E_{iso}\right]^{1/8}, \tag{7}$$

where T_b (measured in days) is the time for the power-law break in the afterglow light curve, n_γ is the radiative efficiency, n is the density of the circumburst medium (in particles/cm^3), and E_{iso} is measured in units of 10^{52} erg. To compute T_b properly, several issues should be kept in mind [9]:

- The jet break should be detected in the optical window
- The optical light curve should not end at T_b, but should continue beyond it
- The flux from the host galaxy and from any probable supernova should be subtracted out

After considering the above points, the Ghirlanda relation can be expressed as [9]:

$$\log\left(E_{peak} / 100\ \text{keV}\right) = (0.48 \pm 0.02) + (0.70 \pm 0.04) \times \log\left[E_\gamma / 4.4 \times 10^{50}\ \text{erg}\right]. \tag{8}$$

In what follows, we will focus on the Amati relation since in most data samples the jet's half-opening angle in not always available.

3. Data Sample, Results, and Physical Interpretation

The data sample that we used in this study was taken from Table 1 and Table 2 of [28] which consists of 49 long bursts and 18 short bursts. First, we calculated the intrinsic peak energies for all the bursts using Equation (2), then a maximum-likelihood fit of the form expressed in Equation (4) was applied. For the long bursts, the best-fit parameters that we obtained were $A = 53.41$ and $B = 0.85$, with a mean intrinsic peak energy of 2151.8 keV and a linear regression coefficient $r = 0.67$, as shown in **Figure 1**.

For the short bursts, the best-fit parameters that we obtained were $A = 51.69$ and $B = 2.03$, with a mean intrinsic peak energy of 1929.3 keV and a linear regression coefficient $r = 0.86$, as shown in **Figure 2**.

The values obtained for the linear regression coefficient indicate that the fits obtained are statistically significant and that the correlations are strong. Although this is not surprising for long GRBs, which are known to follow the Amati relation, they are surprising for short GRBs, which were thought not to follow the Amati relation. However, it is important to keep in mind that since the fitting parameters, A and B, are appreciably different for the short bursts compared to the long bursts, it is more accurate to state that the short bursts seem to follow an Amati-like correlation rather than the Amati correlation in the strict sense because the Amati correlation is traditionally obtained from the fitting of long rather than short bursts.

The first attempt to provide a physical interpretation of correlations involving

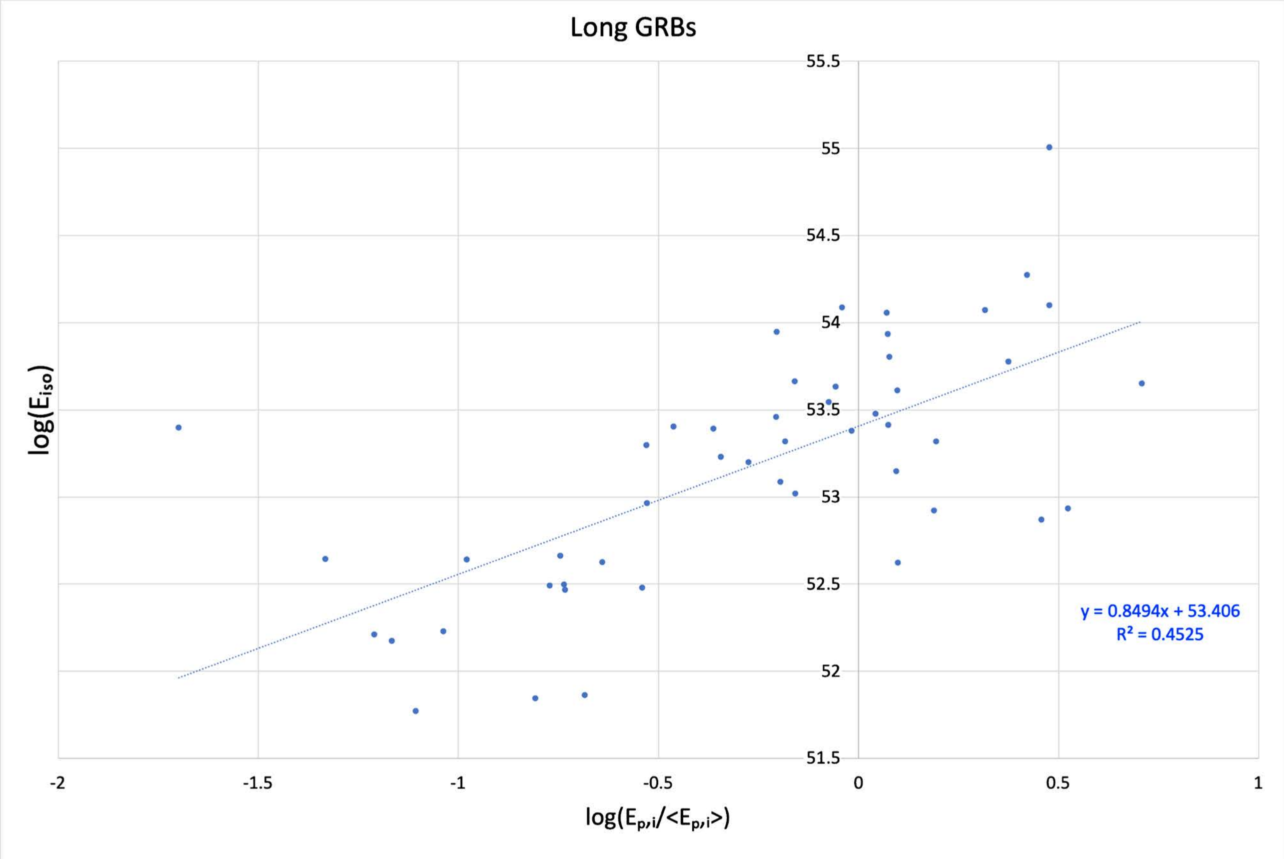

Figure 1. The best-fit Amati relation applied to the sample of 49 long bursts.

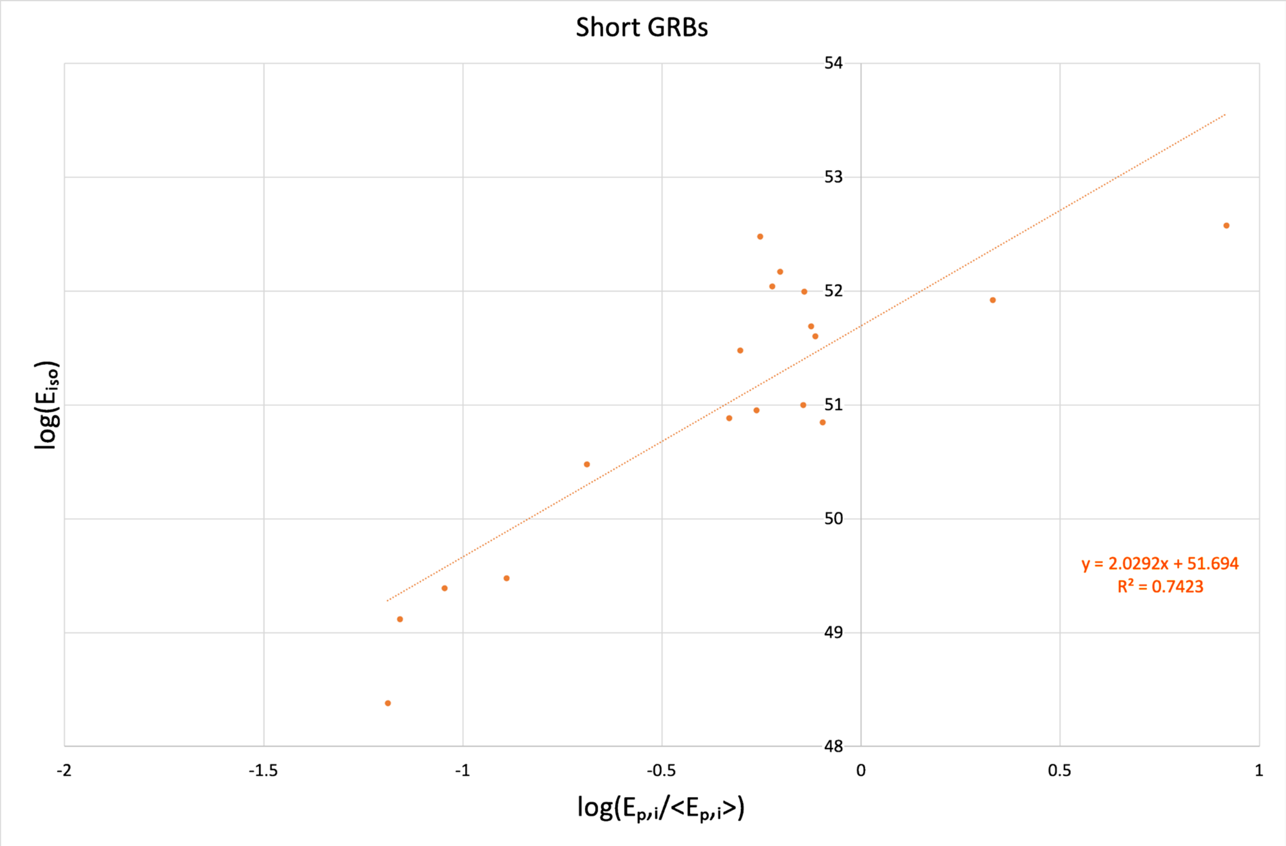

Figure 2. The best-fit Amati relation applied to the sample of 18 short bursts.

the peak energy was carried out by [22] who investigated the E_{peak} - S_{bol} correlation. What they found is that this correlation can be obtained rather easily by assuming a thin synchrotron radiation process by a power law distribution of electrons with a Lorentz factor, Γ, that exceeds some minimum value, $\Gamma_{\min}$. Moreover, they found that the internal shock model gave a stronger E_{peak} - S_{bol} correlation than the external shock model.

The above results were confirmed by [5] who showed that the E_{peak} - E_{iso} correlation (the Amati relation) can be obtained by assuming an optically thin synchrotron shock model with an electron distribution given by: $N(\Gamma) = N_0(\Gamma)^{-\beta}$, for $\Gamma > \Gamma_{\min}$, where β is the power law index. However, it is important to keep in mind that [5] assumed that N_0 and the burst duration are constants, which is not completely justified because GRBs clearly have varying durations [29] [30].

A recent study [31] investigated whether the E_{peak} - E_{iso} correlation can be obtained in the context of the internal shock model but through the impact of just two shells rather than many shells. The study involved both simulated E_{peak} - E_{iso} distributions and observed data (for 58 GRBs), and it included only bright *Swift* GRBs with $F_p > 2.6$ photons·cm^{-2}·s^{-1} in the 15 - 150 keV energy band. The results showed that the E_{peak} - E_{iso} correlation can be obtained theoretically but under certain restrictions. First, most of the dispersed energy should be radiated by a few electrons. Second, the range in the Lorentz factors used should be tight. Finally, the variability timescale for Γ should scale with the mean value of Γ.

4. Conclusion

The peak energy correlations of GRBs are important relations that can be utilized to probe the physics of GRBs. One of the most important peak energy correlations is the Amati relation, which correlates the peak energy and E_{iso}. Previous studies had found evidence that the Amati relation applied to long GRBs only. Our current study indicates that although the short bursts do not follow the Amati relation in the strict sense, they do follow an Amati-like relation albeit with a different slope and normalization. As more data on short bursts become available, it is important to confirm these results because they have important implications regarding the understanding of the physics behind short GRBs and their potential use, along with long GRBs, as tools to probe different cosmological models.

Conflicts of Interest

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

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