Peak Energy Correlations for Gamma-Ray Bursts

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Abstract

Gamma-ray bursts (GRBs) are the most powerful explosions in the universe. Over the past two decades, several GRB energy and luminosity correlations were discovered. These correlations typically involve an observable parameter, like the observed peak energy, $E_{p,obs}$, and a non-observable quantity, like the equivalent isotropic energy, E_{iso}. This paper provides a brief review of GRB peak energy correlations. Specifically, it focuses on the Amati relation, which correlates $E_{p,obs}$ and E_{iso}, and the Ghirlanda relation, which correlates $E_{p,obs}$ and E_γ, the total energy corrected for beaming. The paper also discusses the physical interpretation of these relations in the context of the internal shock model.

Keywords

Gamma-Ray Bursts, Peak Energy Correlations, Energy Indicators

1. Introduction

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

Over the past two decades, several GRB energy and luminosity correlations were discovered. Some 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 because they can potentially be used as cosmological probes to constrain

cosmological parameters [12]-[18], and also as tools that might shed light on the physics of GRBs [19] [20].

This paper provides a review of the GRB energy correlations that involve the peak energy, $E_{p,obs}$, which is the peak energy observed in the νF_ν spectrum. Section 2 provides a brief background on how the correlations involving $E_{p,obs}$ were first noticed, and Sections 3 and 4 focus, respectively, on two important correlations: the Amati relation and the Ghirlanda relation. This is followed by a discussion of the importance and physical interpretation of these correlations in Section 5, and our conclusions are provided in Section 6.

2. Peak Energy Correlations

GRB correlations involving the peak energy were first noticed in 1995 by [21], who studied 399 GRBs 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 50 - 300 keV energy band and the 256 ms time bin. They then selected those bursts with $F_p > 1$ photon·cm^{-2}·s^{-1} and divided them into 5 bins of varying width, each with about 80 bursts. They found 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 $P = 0.04$.

In 2000, a study by [22] found a strong correlation between $E_{p,obs}$ and the bolometric fluence, S_{tot}, in the same energy range as [21]. They expressed the correlation as:

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

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

3. The Amati Relation

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, detected by *BeppoSAX*, with known redshifts, z. The intrinsic peak energy is calculated from the observed one using:

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

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

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

where d is the luminosity distance, which can be calculated from z after assum-

ing 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 $H_0 = 65$ km·s^{-1}·Mpc^{-1}. The Amati relation can be expressed logarithmically as:

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

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

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

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

4. The Ghirlanda Relation

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

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

where θ_{jet} 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 [28], θ_{jet} can be calculated (in degrees) as follows:

$$\theta_{jet} = 0.161\left[T_{\text{break}}\big/\left(1+z\right)\right]^{3/8}\left[n \cdot n_\gamma \cdot E_{iso}\right]^{1/8}, \tag{7}$$

where T_{break} (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_{break} properly, several issues should be kept in mind [29]:

- The jet break should be detected in the optical window
- The optical light curve should not end at T_{break}, 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 [29]:

$$\log\left(E_{peak}\big/100\ \text{keV}\right) = \left(0.48 \pm 0.02\right) + \left(0.70 \pm 0.04\right) \times \log\left[E_\gamma\big/4.4\times10^{50}\ \text{erg}\right]. \tag{8}$$

5. Physical Interpretation

The first attempt to provide a physical interpretation of correlations involving E_{peak} was carried out by [22] who investigated the $E_{peak} - S_{tot}$ correlation. According to their study, 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, Γ_M. Moreover, they

found that the internal shock model gave a tighter $E_{peak} - S_{tot}$ 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 $\Gamma > \Gamma_M$, where β is the power law index. However, [5] assumed that N_0 and the burst duration are constants, which is not completely justified because GRBs clearly have varying durations.

A recent study [30] investigated whether the $E_{peak} - E_{iso}$ correlation can be obtained in the context of the internal shock model but through the impact of only two shells. The study involved both simulated $E_{peak} - E_{iso}$ distributions and observed data (for 58 bursts), 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 indicated that the $E_{peak} - E_{iso}$ correlation can be obtained theoretically but under certain restrictions. First, most of the dispersed energy should be radiated via 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. Concerning the Ghirlanda relation, the theoretical study by [31] showed that this relation can be obtained theoretically if one assumes that Γ and θ_{jet} are inversely proportional. More specifically, they found that:

$$\left[\theta_{jet,\max}\right]^{2.5} \cdot \Gamma_{\max} = \text{constant}. \tag{9}$$

6. Conclusion

The peak energy correlations of GRBs are important relations that can be utilized to probe the physics of GRBs. The most important peak energy correlations are the Amati relation, which correlates the peak energy and E_{iso}, and the Ghirlanda relation, which correlates the peak energy and E_γ. Both relations can be understood theoretically in the context of the internal shock model, but there are important assumptions that should be kept in mind. When calibrated properly, these relations can be employed as tools to probe different cosmological models and also to probe the underlying physics behind GRBs.

Acknowledgements

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