CORRELATION BETWEEN PEAK ENERGY AND PEAK LUMINOSITY IN SHORT GAMMA-RAY BURSTS

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ABSTRACT

A correlation between the peak luminosity and the peak energy has been found by Yonetoku et al. as \( L_p \propto E_{\gamma,\text{peak}}^{2.0} \) for 11 pre-Swift long gamma-ray bursts (GRBs). In this study, for a greatly expanded sample of 148 long GRBs in the Swift era, we find that the correlation still exists, but most likely with a slightly different power-law index, i.e., \( L_p \propto E_{\gamma,\text{peak}}^{1.7} \). In addition, we have collected 17 short GRBs with necessary data. We find that the correlation of \( L_p \propto E_{\gamma,\text{peak}}^{1.4} \) also exists for this sample of short events. It is argued that the radiation mechanism of both long and short GRBs should be similar, i.e., of quasi-thermal origin caused by the photosphere, with the dissipation occurring very near the central engine. Some key parameters of the process are constrained. Our results suggest that the radiation processes of both long and short bursts may be dominated by thermal emission, rather than by the single synchrotron radiation. This might put strong physical constraints on the theoretical models.

Key words: gamma-ray burst: general – methods: statistical – radiation mechanisms: general

Online-only material: color figures

1. INTRODUCTION

Cosmic gamma-ray bursts (GRBs) are the most violent and farthest stellar explosions observed so far. One of their advantages is that GRBs can be used to explore the very early cosmos by virtue of their high cosmological redshifts (\( z \)). The highest redshift measured in GRBs is now up to 9.4 (Cucchiara et al. 2011), which makes them a promising tool for cosmological studies. This profits from a number of empirical spectral energy relations discovered during the past decade, i.e., the spectral lag (\( \tau_{\text{rel}} \)), the minimum rise time (\( \tau_{\text{RT}} \)) of GRB pulses, the peak or isotropic luminosity (\( L_p \) or \( L_{\text{iso}} \)), the rest-frame peak energy (\( E_{\gamma,\text{peak}} \)), the isotropic energy (\( E_{\text{iso}} \)), and the jet-corrected energy (\( E_{\gamma,\text{jet}} \)). The familiar relations include

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E_{\gamma,\text{peak}} \propto L_p,\quad E_{\text{iso}} \propto L_p,\quad E_{\text{jet}} \propto L_p.
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Motivated by the above situations, we now focus on studying the $E_{p,i}-L_p$ relation of short bursts in statistics and try to explain its origin physically. Sample selection and data analysis are given in Section 2. The newly discovered $E_{p,i}-L_p$ relation is presented in Section 3. Implications of this relation are described in Section 4. We end our study with conclusions and discussions in Section 5.

2. SAMPLE

To study the $E_{p,i}-L_p$ relation of short bursts, the observed data of duration, redshift, peak flux, and peak energy are basically necessary and should be available in advance. Seventeen short GRBs with measurements of $T_{90}$, $z$, $P$, and $E_{p,i}$ have been gathered and listed in Table 1, of which GRB 050709 and GRB 090510 are, respectively, detected by Fermi/GBM and HETE-2, and others are detected by Swift/BAT. Among the 17 events, four special “short” bursts shown in Table 1 are taken from Ghirlanda et al. (2009).

Norris et al. (2010) investigated the threshold effect on the detection of short GRBs with extended emission (EE) and found that the detection rate corrected for the physical threshold effect would be larger than the current rate of ~25% estimated for the whole short burst sample. Meanwhile, short bursts with and without EE are thought to originate from different progenitors (Norris et al. 2011). The properties of short bursts with EE and their initial peaks are highly similar to those of the classical long and short bursts, respectively (Sakamoto et al. 2011). It happens that about one fourth of short bursts have the EE component in our short GRB sample in Table 1. The ratio is roughly the same as that of the whole sample of short bursts. The matter of how to reclassify the short GRBs with EE in terms of their confusing observational features may be puzzling. Therefore, it is very interesting to compare classical short bursts with the short ones with EE via some empirical luminosity relations.

It needs to be noted that GRB 071020 and GRB 080913A in Table 1 are generally believed to be “short” bursts despite their prompt $\gamma$ duration longer than 2 s, since their spectral features in both the prompt and the afterglow phases are very similar to those of short-hard ones (Greiner et al. 2009; Ghirlanda et al. 2009). The $T_{90}$ classification of GRBs is thus not very strict, and some median bursts would not be clearly classified. In order to compare with previous $E_{p,i}-L_p$ relations of BATSE GRBs (Yonetoku et al. 2004) and Swift plus BATSE bursts (e.g., Wang et al. 2011), we have collected 148 long GRBs (110 Swift/BAT bursts, 10 Fermi/GBM bursts, and 28 Konus-wind bursts) with the necessary quantities measured to construct a combined sample for getting the updated $E_{p,i}-L_p$ relation.

The observer-frame peak energy ($E_{p,o}$) and the rest-frame peak energy ($E_{p,i}$) are related by $E_{p,i} = E_{p,o}(1+z)$, where $E_{p,o}$ is derived as $E_{p,o} = (2 + \alpha)E_0$ from the $\nu F_\nu$ spectrum, of which $\alpha$ and $E_0$ are, respectively, the lower energy index and break energy fitted with the Band function (Band et al. 1993) for the photon count spectrum in the observer frame. The observer-frame isotropic peak luminosity is determined by $L_p = 4\pi d_L^2 P_{\text{iso},o}$, where the luminosity distance $d_L$ is

$$d_L = cH_0^{-1}(1+z)\int_0^{z}dz'\Omega_m(1+z')^3 + \Omega_L(1+z')^{-1}\Omega_0^{-1/2}$$

calculated on the assumption of $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_L = 0.73$ (e.g., Dai et al. 2004). $P_{\text{iso},o}$ is the bolometric peak flux that is corrected for $k$-correction, $P_{\text{iso},o} = P \propto K$, based on the observed peak flux $P$ (see Bloom et al. 2001; Amati et al. 2002; Schaefer 2007). We caution that the median $K$ value of 1.7 we used for short bursts is slightly larger than the former value.

### Table 1: A Sample ($N = 17$) of Short GRBs with Measured Redshifts

| GRB | $T_{90}$ | $z$ | $L_p$ | $K$ | $E_{p,i}$ | Refs |
|-----|---------|----|-------|-----|---------|------|
| 050509B | 0.04 | 0.225 | 0.51 ± 0.3 | 15–350 | 0.009 ± 0.004 | 2.8 | 102 ± [10] (6,6,5,5) |
| 050709 | 0.07 | 0.16 | 5.1 ± 0.5 | 2–400 | 0.53 ± 0.05 | 1.5 | 100 ± [19] (7,2,2,7) |
| 050813 | 0.6 | 1.8 | 0.41 ± 0.19 | 15–350 | 16.07 ± 7.5 | 1.7 | 150 ± [15] (6,6,5,5) |
| 051221A | 1.4 | 0.547 | 46 ± 13 | 20–2000 | 69.1 ± 6 | 1.2 | 621 ± 144 (6,6,5,5) |
| 060502B | 0.131 | 0.287 | 1.89 ± 1.49 | 15–350 | 0.04 ± 0.01 | 2.7 | 193 ± [19] (6,6,5,5) |
| 061006A | 1 | 0.4377 | 21 ± 2 | 20–2000 | 17.8 ± 2.3 | 1 | 955 ± 267 (1,2,2,2) |
| 061201 | 0.76 | 0.111 | 2.54 ± 1.95 | 15–350 | 1.27 ± 0.25 | 1.3 | 969 ± 508 (6,6,5,5) |
| 061217 | 0.21 | 0.827 | 0.44 ± 0.2 | 15–350 | 2.49 ± 1.1 | 1.7 | 216 ± [22] (6,6,5,5) |
| 070429B | 0.47 | 0.904 | 0.43 ± 0.14 | 15–350 | 3.37 ± 1.08 | 1.9 | 813 ± [81] (6,6,5,5) |
| 070714B | 2 | 0.92 | 1.2 ± 0.9 | 15–350 | 14 ± 1 | 1 | 2150 ± 1113 (3,2,2,2) |
| 070724A | 0.4 | 0.457 | 0.14 ± 0.06 | 15–350 | 0.23 ± 0.11 | 2.2 | 119 ± 12 (6,6,5,5) |
| 070809 | 1.3 | 0.2187 | 0.17 ± 0.08 | 15–350 | 0.005 ± 0.02 | 1.9 | 91 ± [9] (6,6,5,5) |
| 071020B | 4 | 2.145 | 6 ± 0.6 | 20–2000 | 220 ± 10 | 1 | 1013 ± 205 (4,2,2,2) |
| 071227A | 1.8 | 0.383 | 3.5 ± 1.1 | 20–1300 | 3.11 ± 1.28 | 1.8 | 1383 ± [138] (6,6,5,5) |
| 080913A | 8 | 6.7 | 0.13 ± 0.08 | 15–350 | 114 ± 15 | 1 | 1009 ± 200 (4,2,2,2) |
| 090426 | 1.2 | 2.609 | 0.34 ± 0.23 | 15–350 | 18.22 ± 5.7 | 2.1 | 177 ± 82 (6,6,5,5) |
| 090510B | 0.3 | 0.903 | 40 ± 4 | 8–4000 | 516 ± 112 | 0.6 | 8373 ± 761 (6,6,8,8) |

**Notes.** References are given in order of duration, redshift, peak flux, and rest-frame peak energy, respectively. (1) Hurley et al. 2006; GCN 5702; (2) Ghirlanda et al. 2009; (3) Kodaka et al. 2007; GCN 6637; (4) Greiner et al. 2009; (5) Butler et al. 2007 (http://butler.lab.asu.edu/swift/); (6) http://heasarc.nasa.gov/docs/swift/swiftsc.html; (7) Villasenor et al. 2005; (8) Ackermann et al. 2010.

a GRBs 051221A, 061201, and 071227 are, respectively, detected by Swift/BAT.

b Values without measured errors have been given a 10% fluctuation, as shown by square brackets.

c The value of $K = 1$ has been assigned to the four GRBs selected from Ghirlanda et al. (2009).

d “Short” GRBs with extended emission. GRB 090510 is taken from Abdo et al. (2009), others are drawn from Norris et al. (2010).

e “Long” GRBs with short-hard properties (see the text in Section 2).
of $K \sim 1$ for long bursts (Bloom et al. 2001). Furthermore, we have assigned a 10% fluctuation as the uncertainties of $E_p$ and $P$ for several bursts whose measurement errors are unknown.

3. THE UPDATED $E_{p,i}$–$L_p$ RELATION

Using 11 BATSE long bursts with known redshifts, Yonetoku et al. (2004) first fitted the $E_{p,i}$–$L_p$ relation with

$$\frac{L_p}{10^{52} \text{ erg}} = \kappa \times \left( \frac{E_{p,i}}{1 \text{ keV}} \right)^v,$$

where the parameters $\kappa$ and $v$ are constrained as

$$\frac{L_p}{10^{52} \text{ erg}} = (2.34^{+2.29}_{-1.76}) \times 10^{-5} \times \left( \frac{E_{p,i}}{1 \text{ keV}} \right)^{2.0\pm0.2},$$

from which one can draw a concise expression as $L_p \propto E_{p,i}^{2.0}$. Their result is consistent with an earlier plot shown by Wei & Gao (2003). Ghirlanda et al. (2005) restudied this relation with a larger sample of 16 BATSE bursts and confirmed the relation of $L_p \propto E_{p,i}^{2.0}$. The index of $v \simeq 2$ indicates that the synchrotron radiation mechanism in a simple standard internal shock scenario is highly supported (Zhang & Mészáros 2002; Wei & Gao 2003; Rees & Mészáros 2005). Very recently, Wang et al. (2011) analyzed a combined sample of 116 long GRBs including 31 pre-Swift bursts and 85 Swift/BAT bursts and derived the $E_{p,i}$–$L_p$ relation as

$$\frac{L_p}{10^{52} \text{ erg}} = (1.28^{+0.17}_{-0.15}) \times \left( \frac{E_{p,i}}{300 \text{ keV}} \right)^{1.40\pm0.12},$$

in which the expression of $L_p \propto E_{p,i}^{1.4}$ is obviously different from the so-called Yonetoku relation as mentioned above. In this work, we combine 148 long bursts with confirmed redshifts from the Swift, Fermi, and Konus data sets to retrieve the luminosity relation as

$$\frac{L_p}{10^{52} \text{ erg}} = (7.24^{+6.56}_{-3.44}) \times 10^{-5} \times \left( \frac{E_{p,i}}{1 \text{ keV}} \right)^{1.72\pm0.11},$$

leading to $L_p \propto E_{p,i}^{1.7}$ with a linear correlation coefficient of $R = 0.79$ and a chance possibility lower than 0.001, as shown in Figure 1. Our derived value of $v \simeq 1.7$ is located just between 1.4 and 2.0, marginally consistent with Yonetoku’s value within the 1σ level. It is very important to identify which one should be more reliable because the underlying physics will emerge once the $v$ value is exactly decided, as suggested by Rees & Mészáros (2005).

On the other hand, the $E_{p,i}$–$L_p$ relation has not yet been obtained for short bursts due to the limited number of short GRBs with redshift measurements in the past decade. Now, however, 17 short bursts with measured redshifts are available to examine the possible luminosity relation. Hence, we can fit them with Equation (1) for the first time in Figure 2 and present the new $E_{p,i}$–$L_p$ relation as follows,

$$\frac{L_p}{10^{52} \text{ erg}} = (1.07^{+1.51}_{-0.91}) \times 10^{-5} \times \left( \frac{E_{p,i}}{1 \text{ keV}} \right)^{1.73\pm0.44},$$

where we obtain $L_p \propto E_{p,i}^{1.7}$ with a linear correlation coefficient of $R = 0.72$ and a chance possibility of $P \sim 0.001$, which is surprisingly in agreement with that of long bursts as shown in Equation (4). In Figure 3, we compare the $E_{p,i}$–$L_p$ relation....
Figure 2. Rest-frame peak energy vs. peak luminosity for 17 short GRBs with measured redshifts. The solid line is the best fit to the observed data in the logarithmic frame of axes. The dashed and dotted lines correspond to its $1\sigma$ and $3\sigma$ scatters ($\sigma = 0.86$), respectively. “Short” GRBs with EE are symbolized with dark filled stars, and “long” bursts with short-hard properties are marked with open circles.

(A color version of this figure is available in the online journal.)

Figure 3. Comparison of rest-frame peak energy vs. peak luminosity for 17 short (filled diamond) and 148 Swift long (empty diamond) GRBs. The best-fit lines (solid) and their $3\sigma$ levels (dotted) are, respectively, taken from Figures 1 and 2. They are symbolized by the thick line and the thin line, individually.

(A color version of this figure is available in the online journal.)
of short bursts with that of long ones and find that they are consistent with each other within 3σ levels. It is very attractive that short GRBs with EE and “long” bursts with short-hard properties, compared with classical short bursts, have larger values of $E_{p,i}$ and $L_p$. Three kinds of short bursts populate in different regions on the $E_{p,i}$–$L_p$ plane. More interestingly, short bursts with EE reside at the high end of their $E_{p,i}$–$L_p$ relation, while “long” bursts with short-hard features seem to favor the $E_{p,i}$–$L_p$ relation of long bursts. In the following, we shall interpret the potential implication of the consistency of both kinds of bursts on the fundamental GRB physics.

As seen in Figure 4, the updated median values of redshift are 0.7 and 2.1 for short and long GRBs, respectively. The redshift distributions of both kinds of bursts show that they reside at different distances from us statistically. Although the spectral peak energies of short bursts are relatively harder than those of long bursts in the observer frame, both of the rest-frame peak energies are very comparable (e.g., Zhang & Choi 2008; Ghirlanda et al. 2012). In order to explore what causes the slight difference of parameter $\kappa$ in Equations (4) and (5), the luminosity distributions of 17 short and 148 long bursts are illustrated in Figure 5, from which we perform a Gaussian fit to the log $L_p$ distributions and obtain the mean value of $\mu = 52.24 \pm 0.03$ with a standard deviation of $\sigma = 0.5$ ($\chi^2 = 2.4$) for long bursts and $\mu = 52.07\pm0.18$ with a standard deviation of $\sigma = 1.3$ ($\chi^2 = 0.5$) for short bursts. It is interesting to note that their median luminosities are nearly the same. However, a K-S test returns $D = 0.29$ with a probability of 0.11, which is not significant enough for us to judge whether the two kinds of bursts are drawn from different parent populations.

The similarity may be caused by the selection effect. For example, compared with short bursts, long bursts usually have a lower peak flux (Gehrels et al. 2008) but are more distant on average. Therefore, their mean luminosities are more or less similar.

4. IMPLICATIONS

Rees & Mészáros (2005) suggested that a laminar and relativistic jet as seen head on will produce a (probably Comptonized) thermal spectrum peaking at the hard X-ray or $\gamma$-ray energy bands. They also pointed out that the dependence of spectral peak energy on GRB parameters relies on the specific radiation mechanisms forming the spectrum in those energy bands. According to diverse assumptions of the emission mechanism, they proposed three spectral cases that gave rise to the corresponding $E_{p,i}$–$L_p$ relation as

$$
E_{p,i} \propto \begin{cases} 
\Gamma^{-2}e^{-1}L^{1/2} & \text{(Case 1: synchrotron radiation)} \\
\Gamma_0^{-1/2}L^{1/4} \sim L^{(2\beta'+1)/4} & \text{(Case 2: thermal radiation)} \\
\Gamma_2^{-1/4}L^{1/4} \sim L^{(8\beta-1)/4} & \text{(Case 3: Comptonization)},
\end{cases}
$$

where $L = L_p$, $\tau_{\text{var}}$ is the typical variability timescale of the outflow, and $\Gamma$ and $\Gamma_0$ are the Lorentz factor of ejecta and the typical radius of the photosphere from the central engine, respectively. Note that the scaling laws of Cases 1 and 2 were derived as early as 2002 by Zhang & Mészáros (2002). The parameters $\beta$ and $\beta'$ are two power-law indices in their assumed relations of $\Gamma \propto L^\beta$ and $\Gamma_0 \propto L^{-\beta}$. For $\beta' = (0.5, 1)$, one can easily obtain $E_{p,i} \propto (L^{1/2}, L^{3/4})$. Because the observable half-opening angle satisfies $\theta \sim 1/\Gamma$ and $L \propto \theta^{-2}$ (Frail et al. 2001), we can obtain $\Gamma \propto L^{1/2} (\beta = 1/2)$ and then $E_{p,i} \propto L^{3/4}$ for Case 3 in Equation (6).

Comparing the results listed in Equations (2)–(5) with Equation (6), we find that Yonetoku’s result is consistent with Case 1, while Wang et al.’s supports Case 3. However, our results in Equations (4) and (5) indicating the form of $E_{p,i} \propto L^{0.6}$ are coincident with Case 2, from which one can notice that the index 0.6 is just in the range from 1/2 to 3/4. Meanwhile, the parameter $\beta'$ in Equation (6) is then determined to be $\beta' = 0.68$, also within (0.5, 1). The consistent power-law index strongly hints that the spectrum of long and short bursts could result from the same mechanism (see also Ghirlanda et al. 2011b) whose dominant emission is thermal (also Fan et al. 2012), rather than synchrotron or Comptonization. This implies that the single synchrotron mechanism combined with the standard internal shock model is not sufficient to account for all GRB phenomena, especially the $E_{p,i}$–$L_p$ relation.

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**Figure 4.** Cumulative redshift distributions of 148 long and 17 short GRBs are displayed with dotted and solid lines, respectively.

(A color version of this figure is available in the online journal.)

**Figure 5.** Histogram distributions of logarithmic luminosity are presented for 148 long (dotted line) and 17 short (solid line) GRBs. They are fitted by Gaussian functions, respectively.

(A color version of this figure is available in the online journal.)
We investigated the relations of the peak luminosity with the peak energy for long and short GRBs in the new-satellite era. We found that a consistent correlation of $L_p \propto E_{p,i}^{1.7}$ coexisted in both long and short GRBs, which provided promising evidence that two kinds of bursts should be produced from the same radiation process. Some key parameters of the process are constrained and suggest that the radiation process of both long and short bursts may be dominated by thermal emission, rather than by the single synchrotron radiation. Our results challenge the theoretical models.

It needs to be emphasized that the index $\nu$ of the $E_{p,i}^{-\nu} - L_p$ relation in the Swift/Fermi era is systematically smaller than that in the BATSE era. Most probably, this phenomenon is due to the different flux threshold as described in Wei & Gao (2003). Moreover, the fact that Swift/BAT is more sensitive to softer and longer GRBs than BATSE (Band 2006; Gehrels et al. 2008) can inevitably lead to a distinguishing measurement of peak luminosity. By virtue of the lower flux threshold, Swift/BAT can detect very faint bursts, which may contribute differently to the updated $E_{p,i}^{-\nu} - L_p$ relation. Meanwhile, Swift and HETE-2 are lower and narrower than BATSE in energy ranges of detectors, which causes the spectral peak energies observed with Swift and HETE-2 to be systematically lower. In addition to the higher sensitivity of Swift/BAT, spectral redshifting and cosmological time dilation move high-redshift bursts into the parameter region where BAT is more sensitive than BATSE. In a sense, the systematically larger redshifts measured by Swift might also affect the power-law index of the $E_{p,i}^{-\nu} - L_p$ relation.

In general, short and long bursts are believed to have different distributions of observed or intrinsic durations, redshifts, spectral hardess, energy injections, circum-burst environments, prompt $\gamma$-ray emitting regions (Zhang et al. 2008, 2011), etc., indicating their diverse origins (e.g., Piran 2004; Zhang 2007; Gehrels et al. 2009 for reviews). However, recent contrastive investigations demonstrate that two classes of bursts are most probably produced by the same radiation mechanism regardless of their different progenitors (e.g., Lee & Ramirez-Ruiz 2007). For instance, Hakki & Preece (2011) studied the distinguishable pulses of short and long GRBs and found some common properties for correlations between duration, peak luminosity, spectral hardness, energy-dependent lag, and asymmetry (see also Zhang et al. 2007). Furthermore, Boci et al. (2010) argued that the correlative pulse relations cannot be obtained as the direct consequence of the synchrotron emission in the framework of the standard relativistic shock model. All of this observational evidence seems to validate that short and long bursts might originate from the same radiation mechanism independent of their different progenitors.

Based on the analysis and discussions mentioned above, we draw our conclusions as follows: (1) long bursts in the Swift era follow the $L_p \propto E_{p,i}^{1.7}$ relation different from that of $L_p \propto E_p^{2.0}$ for the BATSE GRB sample. The difference may be caused by the threshold effect of different detectors. (2) The relation between $L_p$ and $E_{p,i}$ for 17 short bursts is found to be $L_p \propto E_{p,i}^{1.7}$; this agrees well with that of long bursts in the Swift era, except for the minor difference in intercept of logarithmic luminosity. (3) The spectrum of short and long GRBs could be produced by the same radiation mechanism possibly dominated by the thermal component, other than the solely synchrotron or Comptonized process. This would greatly challenge the current theories of both kinds of GRBs.
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