A NEW CLASSIFICATION METHOD FOR GAMMA-RAY BURSTS

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ABSTRACT

Recent Swift observations suggest that the traditional long versus short gamma-ray burst (GRB) classification scheme does not always associate GRBs to the two physically motivated model types, i.e., Type II (massive star origin) versus Type I (compact star origin). We propose a new phenomenological classification method of GRBs by introducing a new parameter $\epsilon = E_{\gamma,\text{iso}}/E_{\gamma,\text{iso},0.3}$, where $E_{\gamma,\text{iso}}$ is the isotropic gamma-ray energy (in units of $10^{52}$ erg) and $E_{\gamma,\text{iso},0.3}$ is the cosmic rest-frame spectral peak energy (in units of 100 keV). For those short GRBs with "extended emission," both quantities are defined for the short/hard spike only. With the current complete sample of GRBs with redshift and $E_{\gamma,p,z}$ measurements, the $\epsilon$ parameter shows a clear bimodal distribution with a separation at $\epsilon \sim 0.03$. The high-$\epsilon$ region encloses the typical long GRBs with high luminosity, some high-$z$ "rest-frame-short" GRBs (such as GRB 090423 and GRB 080913), as well as some high-$z$ short GRBs (such as GRB 090426). All these GRBs have been claimed to be of Type II origin based on other observational properties in the literature. All the GRBs that are argued to be of Type I origin are found to be clustered in the low-$\epsilon$ region. They can be separated from some nearby low-luminosity long GRBs (in 3$\sigma$) by an additional $T_{90}$ criterion, i.e., $T_{90, z} \lesssim 5 \text{s}$ in the Swift/BAT band. We suggest that this new classification scheme can better match the physically motivated Type II/I classification scheme.

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

Online-only material: color figures

1. INTRODUCTION

Phenomenologically, gamma-ray bursts (GRBs) are classified as long versus short with a division line at the observed duration $T_{90} \sim 2 \text{s}$ (Kouveliotou et al. 1993). Robust associations of the underlying supernovae (SNe) with some long GRBs (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004; Modjaz et al. 2006; Pian et al. 2006) and the fact that long GRB host galaxies are typically irregular galaxies with intense star formation (Fruchter et al. 2006) suggest that they are likely related to the deaths of massive stars, and the "collapsar" model has been widely recognized as the standard scenario for long GRBs (Woosley 1993; Paczyński 1998; Woosley & Bloom 2006). Observational breakthroughs led by the Swift mission (Gehrels et al. 2004) suggest that at least some short GRBs are associated with nearby host galaxies with little star formation (Tanvir et al. 2005) and that they are not associated with an underlying SN (Gehrels et al. 2005; Villasenor et al. 2005; Fox et al. 2005; Hjorth et al. 2005; Berger et al. 2005), favoring the idea that they are produced by mergers of two compact stellar objects, such as NS–NS and NS–BH mergers (Eichler et al. 1989; Narayan et al. 1992; Nakar 2007).

However, several lines of observational evidence in the Swift era suggest that duration is not necessarily a reliable indicator of the physical nature of a GRB. (1) The non-detection of a SN signature associated with the nearby long GRBs 060614 and 060505 (Gehrels et al. 2006; Gal-Yam et al. 2006; Finbog et al. 2006; Della Valle et al. 2006) disfavors the conventional collapsar scenario of long GRBs (Woosley & Bloom 2006). Some observational properties of the ∼100 s long GRB 060614 are very similar to those of some short GRBs (Gehrels et al. 2006; Zhang et al. 2007), making it likely associated with the physical category that most short GRBs belong to. (2) Significant soft "extended" gamma-ray emission and late X-ray flares are observed in a handful of "short" GRBs (Barthelmy et al. 2005; Norris & Bonnell 2006; Perley et al. 2009), suggesting that they are not necessarily short. A new physically motivated classification scheme, i.e., Type II (massive star origin) versus Type I (compact star origin), was proposed (Zhang 2006; Zhang et al. 2007). Kann et al. (2010, 2008) systematically studied the optical afterglow emission properties of Type II and Type I GRBs, and suggested that these properties carry important information about the nature of GRB progenitors. A full definition of Type I/II GRBs as well as the multiple observational criteria are presented in Zhang et al. (2009). (3) Two high-redshift gamma-ray bursts, GRB 080913 at $z = 6.7$ (Greiner et al. 2009; Pérez-Ramírez et al. 2010) and GRB 090423 at $z = 8.2$ (Tanvir et al. 2009; Salvaterra et al. 2009), appear as intrinsically short GRBs. Their observed durations are (8 ± 1) s and ~10.3 s in the Swift/BAT band, respectively. Corrected for redshift, the durations of these two high-$z$ GRBs are shorter than 2 s in the rest frame. The physical origin of these high-$z$ GRBs has been subject to debate (Greiner et al. 2009; Pérez-Ramírez et al. 2010; Tanvir et al. 2009; Salvaterra et al. 2009). Although compact star mergers may occur at such a high redshift (Belczynski et al. 2010), various observational properties of these two GRBs point toward the massive star origin (Zhang et al. 2009; Lin et al. 2010; Belczynski et al. 2010). (4) A more striking case is GRB 090426, whose observed BAT band $T_{90}$ is only 1.2 ± 0.3 s, and the rest-frame duration is only ~0.3 s at $z = 2.699$ (Levesque et al. 2009). It greatly exceeds the previous short GRB redshift record, i.e., $z = 0.923$ for GRB 070714B (Graham et al. 2009). Phenomenologically, this is an unambiguous short-duration GRB, but the available afterglow and host galaxy properties point toward a different picture: it has a blue, very luminous, star-forming putative host galaxy with a small angular offset of the afterglow location from the center and a medium density typical of Type II GRBs. All these suggest that the burst is more closely related to the core collapse of a massive star (Levesque et al. 2009; Antonelli et al. 2009).
Monte Carlo simulations suggest that the compact star merger model cannot interpret both the *Swift* $z$-known short GRB sample and the BATSE short GRB sample. Instead one may need a mix of GRBs from compact star mergers and from massive star core collapses to account for the observed short GRB population (Virgili et al. 2009; Cui et al. 2010).

In summary, the traditional long versus short GRB scheme no longer always corresponds to the two distinct physical origins, i.e., collapse of massive stars (Type II GRBs) versus mergers of compact stars (Type I GRBs; Zhang 2006; Zhang et al. 2007, 2009; Bloom et al. 2008). Zhang et al. (2009) proposed a procedure (a flow chart, see their Figure 8) invoking a full set of observational characteristics, including supernova (SN)–GRB association, specific star-forming rate (SFR) of the host galaxy, burst location offset, burst duration, hardness, spectral lag, statistical correlations, energetics, and afterglow properties, to judge the physical category of a GRB. On the other hand, for most GRBs one may not immediately retrieve all the information needed for such a classification. It would be interesting to search for additional phenomenological classification schemes to see whether there exist other quantities, especially those invoking prompt GRB emission properties only, that can give a good indication of the physical nature of a GRB. This motivates us to explore a new phenomenological classification method. In addition to the burst duration, we think both the burst energy and the spectral properties in the burst rest frame would carry important information about the nature of the burst. In this paper, we propose a new discriminator based on the isotropic burst energy and rest-frame peak energy ($E_{\text{p,iso}}$) of the $v\nu$ spectrum of the prompt gamma rays. We will show that this classification method is more closely connected to the Type II/I physical classification scheme.

2. SAMPLE

In order to develop our classification method, we use a sample of all GRBs with both redshift and spectral parameters known up to 2010 March. Our sample includes 137 GRBs. They are detected by *BeppoSAX*, *HETE-2*, *Swift*, *Suzaku*, and *Fermi*. Most of them are taken from Amati et al. (2008, 2009), Kann et al. (2010), Krimm et al. (2009), Zhang et al. (2009) and references therein. Their isotropic gamma-ray energy ($E_{\gamma,\text{iso}}$) is calculated in the GRB rest-frame $1–10^4$ keV band with the spectral parameters in order to avoid instrument selection effect. The soft XRF 080109 (Soderberg et al. 2008), whose emission is in the XRT band ($0.3–10$ keV) instead of the BAT band, is also included in our sample. The XRT and UVOT observations place a limit of its $E_{\text{p}}$ in the range $0.037$ keV $< E_{\text{peak}} < 0.3$ keV. We adopt $E_{\text{peak}} \approx 0.12^{+0.03}_{-0.08}$ keV (Li 2008). Eight bursts in our sample (GRBs 050709, 050724, 051210, 060614, 061006, 061210, 070714, and 071227) are the so-called short GRBs with “extended emission” discussed in the literature. For these GRBs, both parameters ($E_{\gamma,\text{iso}}$ and $E_{\text{p,iso}}$) are derived for the initial hard spike only (extended emission excluded).

4 We note that $T_{90}$ depends on the detector’s sensitivity and energy band. In our analysis, we define $T_{90}$ using the BAT energy band and sensitivity. In the *Swift* era, it is found that some “short” GRBs (as observed in the BATSE band) have extended emission. It is the convention of the *Swift* team and the community to define a “short” GRB based on the duration of the short spike only, with the extended emission excluded. Observationally, the spectrum of the short spike is much harder than that of the extended emission; the latter shares many properties with X-ray flares. For the same burst, the “extended emission” depends on redshift, since it may be buried within the background if the redshift is high enough. We therefore use only information of the short/hard spike to perform our classification.

5 It was proposed that those GRBs having $T_{90,z} = 1–5$ s may be an intermediate population based on the excess of the GRBs over the bimodal distribution of $T_{90,z}$. Although these GRBs are less energetic and have dimmer afterglows than typical long GRBs, they share many similar properties of typical GRBs, such as spectral lag and spectrum–energy correlations. They may be a sub-group of the long GRBs (de Ugarte Postigo et al. 2010).
that, given the same observed GRB (known fluence and $E_p$), the implicit $z$-dependence of $\varepsilon(\kappa) \propto D_L^2(z)/(1+z)^{1+z}$ essentially vanishes at $z > 2$ if $\kappa = 5/3$ (see Figure 2 for a comparison of the $z$-dependence of $\varepsilon$ for different $\kappa$). We therefore define

$$\varepsilon \equiv \frac{E_{\gamma,\text{iso}}}{E_{p,2}},$$

(2)

which removes the redshift dependence for high-$z$ GRBs. This parameter may be more suitable for the classification of high-$z$ GRBs, such as GRBs 090423 and 080913.

We calculate $\varepsilon$ for the bursts in our sample and show the log $\varepsilon$ distribution in Figure 1(b). A clear bimodal feature is found, with a division line at $\sim 0.03$ (high-$\varepsilon$ versus low-$\varepsilon$). The high-$\varepsilon$ portion follows a lognormal distribution with $\varepsilon = 0.80 \pm 0.11$ ($1\sigma$). For low-$\varepsilon$ it is $0.003 \pm 0.002$. We test the bimodality of the log $\varepsilon$ distribution with the KMM algorithm and obtain a chance probability $p < 10^{-4}$. The overall correct allocation rate of GRBs in the two categories (high-$\varepsilon$ versus low-$\varepsilon$) is as high as 99.8%, indicating that $\varepsilon$ is a new parameter for GRB classification.

It is generally believed that GRBs originate either from core collapses of massive stars (Type II) or mergers of compact stars (Type I). One may ask whether this phenomenal classification matches the physical schemes for Types I and II. The origins of most GRBs in our sample have been discussed extensively in the literature (Zhang et al. 2009; Kann et al. 2010, 2008). We therefore examine how the members in our two new categories (high-$\varepsilon$ versus low-$\varepsilon$) are associated with the two physical model types. To define the physical category of the GRBs, we apply the flow chart of Zhang et al. (2009, see their Figure 8). We denote all “Type II” or “Type II candidates” as “Type II,” and “Type I” or “Type I candidates” as “Type I” (which includes the Type I Gold sample and most other short/hard GRBs in Zhang et al. 2009). We note that these definitions are fully consistent with those adopted in Kann et al. (2010, 2008). Figure 1 displays all the GRBs in our sample in the $\varepsilon - T_{90,2}$ plane. Different symbols are used to mark different groups. For examples, triangles denote the GRBs that are believed to be of Type II origin, among which the black triangles denote the traditional long GRBs and the blue triangles denote those GRBs with $T_{90,2}$ shorter than 2 s.
The red circles denote those GRBs that are believed to have Type I origin. Six green stars denote nearby low-luminosity GRBs with supernova associations. It is remarkable to see that the \( \epsilon \) classification clearly separates Type II GRBs from Type I GRBs.

In order to quantitatively assess the clustering feature among different types of GRBs, we derive the GRB distribution probability \( p(\log \epsilon, \log T_{\text{90, z}}) \) from the ratio between the number of GRBs in the grid \( \log \epsilon + d \log \epsilon, \log T_{\text{90, z}} + d \log T_{\text{90, z}} \) and the total number of GRBs in our sample. Since the distribution of \( \epsilon \) is involved in our analysis, we take the error of \( \log \epsilon \) into account in our calculation of \( p \). For a given GRB with \( \log \epsilon + \delta \log \epsilon \), we assume that the probability distribution of this GRB is a normalized lognormal distribution centered at \( \log \epsilon \) with a width of \( \delta \log \epsilon \). The probability \( p(\log \epsilon, \log T_{\text{90, z}}) \) is then obtained by summing up \( p \) over the GRBs in our sample. We take \( d \log T_{\text{90, z}} = 0.35 \) and \( d \log \epsilon = 0.60 \) in our calculation. The contours of the probability distribution are shown in Figure 1(c). One can clearly identify two clustering regions (with \( p(\log \epsilon, \log T_{\text{90, z}}) > 0.01 \)) centered in the high-\( \epsilon \), low-\( T_{\text{90, z}} \) regime.

At the 3\( \sigma \) level, the high-\( \epsilon \) group includes typical long GRBs with high luminosity, some intrinsic short-duration GRBs (including the high-\( \epsilon \) GRB 090423 and GRB 080913), as well as some high-\( z \) short GRBs (e.g., GRB 090426). In contrast, the low-\( \epsilon \) group contains the extensively discussed Type I GRBs, including those with and without extended emission. Based on the probability contours, a low-\( \epsilon \) GRB with \( T_{\text{90, z}} \lesssim 5 \) s in the Swift/BAT band would be identified as a Type I GRB at the 3\( \sigma \) confidence level. GRBs 060614 and 060505 are marginally included in the \( p(\log \epsilon, \log T_{\text{90, z}}) > 0.003 \) region (the light gray region in Figure 1(c)) of Type I GRBs. Nearby low-luminosity long GRBs (LL-GRBs), e.g., GRBs 980425, 031203, 050826, and 060218 (green stars in Figure 1(c)) are out of the 3\( \sigma \) contours of the Type I and Type II GRBs. This may hint at a distinct GRB population as suggested by Liang et al. (2007; see also Soderberg et al. 2004; Cobb et al. 2006).

4. CONCLUSIONS AND DISCUSSION

By introducing a new parameter \( \epsilon \), we have proposed a new phenomenological classification method for GRBs. We demonstrated that GRBs with known redshifts are cozily classified into two classes with a separation \( \epsilon = 0.03 \). Due to the clear bimodal distribution of \( \epsilon \) with little overlap, the overall correct allocation rate of a GRB to a particular category (high-\( \epsilon \) versus low-\( \epsilon \)) is as high as >99.8%, which is much better than the traditional duration classification method. More importantly, this classification scheme is more closely related to the two physically motivated model classes—Type II versus Type I. In particular, the high-\( \epsilon \) category is a good representation of the Type II GRBs, while the low-\( \epsilon \) category, with an additional duration criterion \( T_{\text{90, z}} \lesssim 5 \) s, is a good representation of the Type I GRBs. We suggest that the parameter \( \epsilon \) can be evaluated for future GRBs with \( z \) measurements, and the \( \epsilon \)-based classification may be performed regularly to infer the physical origin of a GRB.

The well separated bimodal distribution of \( \log \epsilon \) depends on our selection of \( \kappa \) in Equation (1). As shown in Figure 2, \( \epsilon \) is insensitive to \( z \) at \( z > 2 \) for a given burst by taking \( \kappa = 5/3 \), but this is not true at low redshift. One may infer that the bimodal distribution is due to the redshift effect. To examine this issue, we re-plot Figure 1 by separating the GRBs into the \( z > 2 \) and the \( z < 2 \) samples (Figure 3, left and middle panels, respectively). We also show the GRB distributions in the \( \log(1+z) - \log(\epsilon) \) plane for all the bursts in our sample in Figure 3. It is found that the clustering feature of \( \log \epsilon \) is not caused by the redshift selection effect. Therefore, \( \epsilon \) is a GRB discriminator for GRBs with both at \( z < 2 \) and \( z > 2 \).

Another concern about our classification method may be sample uniformity. The GRBs in our sample were detected with different instruments with different instrumental threshold. However, our classification method is based on the global energy and spectral information. Different from the burst duration, a well measured \( E_p \) essentially does not depend on the detector, and neither does \( E_{\text{iso}} \). The \( E_p \) values of the GRBs in our sample, which expand almost four orders of magnitude, are well within the energy band of previous and current GRB missions, so they are well measured. The \( E_{\text{iso}} \) values expand almost eight orders of magnitude. Therefore, our sample could be regarded as a complete sample with known \( E_p \) and \( E_{\text{iso}} \) for current missions.

We should note that our classification scheme is particularly helpful to diagnose the physical origin of GRBs with a rest-frame short duration (e.g., \( T_{\text{90, z}} < 2 \) s, Table 1). For example, it convincingly classifies GRBs 090423, 080913, and 090426 into the high-\( \epsilon \), and therefore, Type II category, which is otherwise difficult with the duration criterion. The distinction of the \( T_{\text{90, z}} < 2 \) s bursts with different \( \epsilon \) values is also evident from their X-ray afterglow properties. Kann et al. (2008) compared the optical afterglows of Type I GRBs with Type II GRBs and found that those of Type I GRBs have a lower average luminosity and show a larger intrinsic spread of luminosities. In Figure 4, we compare the XRT light curves and the 12 hr X-ray luminosities between the two types of \( T_{\text{90, z}} < 5 \) s GRBs. The low-\( \epsilon \) \( T_{\text{90, z}} < 2 \) s GRBs (Type I, red) are systematically fainter than the high-\( \epsilon \) ones (Type II, blue), whose properties are rather similar to other high-\( \epsilon \) long GRBs (black).

Physically, it is not obvious why the parameter \( \epsilon \) (corresponding to \( \kappa = 5/3 \)) gives a cozier classification scheme. We have tried other \( \kappa \) values in Equation (1), but the classifications defined by other \( \epsilon(\kappa) \) are not as clean as the one defined by Equation (2). As shown in Figure 2, an apparent advantage of \( \kappa = 5/3 \) is to diminish the \( z \)-dependence at high-\( z \) for a given observed GRB.

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6 As shown in Figure 2, a GRB with the same observed fluence and \( E_p \) at higher redshift may have a higher \( \epsilon \). However, the bimodal distribution may not be due to the redshift effect (see Figure 3).

7 We cannot exclude the possibility that this is a selection effect, since high-\( \epsilon \) Type I GRBs may have fainter X-ray afterglows and therefore may not be detected.
One can also discuss the connection between the lognormal distribution of $\varepsilon$ in the high-$\varepsilon$ regime and some empirical relations of Type II GRBs. With the Amati relation $E_{\gamma,z} \propto E_{\gamma,iso}^{0.54}$ (Amati et al. 2009), we find $\varepsilon \propto E_{\gamma,iso}^{0.185}$, insensitive to $E_{\gamma,z}$. Liang & Zhang (2005) discovered an empirical relation among $E_{\gamma,iso}$, $E_{p,z}$, and $t_{b,z}$, namely, $E_{\gamma,iso} \propto E_{p,z}^{1.94 \pm 0.17} t_{\gamma,z}^{-1.24 \pm 0.23}$, where $t_{b,z}$ is the rest-frame break time of the optical afterglow light curve. This gives $\varepsilon \propto E_{\gamma,iso}^{0.27 \pm 0.17} t_{\gamma,z}^{-1.24 \pm 0.23}$, which is sensitive to $t_{b,z}$. A clustering in $\varepsilon$ therefore corresponds to a clustering in $t_{b,z}$. Interpreting the $t_{b,z}$ as the jet break time, the Liang–Zhang relation may be translated into the Ghirlanda relation, $E_{\gamma,iso,52}(1 - \cos \theta_j) \simeq AE_{p,z,52}^{-1.7}$, where $A \sim 0.01 - 0.03$ (Ghirlanda et al. 2004; Dai et al. 2004). Given $\varepsilon \equiv E_{\gamma,iso,52}/E_{p,z,52}^{1.7}$, we obtain $\varepsilon \approx A(1 - \cos \theta_j)^{-1}$, where $\theta_j$ is the jet opening angle. The lognormal $\varepsilon$ distribution ($\varepsilon = 0.80 \pm 0.11$, at $1\sigma$) therefore corresponds to a lognormal jet opening angle distribution for Type II GRBs, i.e., $\theta_j \sim 0.16 \pm 0.03$ rad (assuming $A \sim 0.01$). We note that the jet opening angle derived by Ghirlanda et al. (2004) indeed clusters in a small range. Since the Ghirlanda relation is very difficult to understand physically, we suspect that it may be related to the fact that $\varepsilon$ is quasi-universal for Type II GRBs. Future data with very early or very late optical break times may test which
of the Ghirlanda/Liang–Zhang relations and the fact of a quasi-universal $\epsilon$ is more fundamental.

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