A NEW DISCRIMINATOR FOR GAMMA-RAY BURST CLASSIFICATION: THE $E_{\text{peak}}$–FLUENCE ENERGY RATIO

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Received 2010 April 14; accepted 2010 July 30; published 2010 September 9

ABSTRACT

Using the derived gamma-ray burst (GRB) $E_{\text{peak}}$ and fluences from the complete BATSE 5B Spectral Catalog, we study the ensemble characteristics of the $E_{\text{peak}}$–fluence relation for GRBs. This relation appears to be a physically meaningful and insightful fundamental discriminator between long and short bursts. We discuss the results of the lower limit test of the $E_{\text{peak}}$–$E_{\text{iso}}$ relations in the $E_{\text{peak}}$–fluence plane for Burst And Transient Source Experiment bursts with no observed redshift. Our results confirm the presence of two GRB classes as well as heavily suggesting two different GRB progenitor types.

Key words: gamma-ray burst: general – methods: data analysis

1. INTRODUCTION

Classification of gamma-ray bursts (GRBs) is certainly a difficult task. Bursts are divided into long and short classes, based upon the bimodal duration histogram of bursts (Kouveliotou et al. 1993) observed by the Burst And Transient Source Experiment (BATSE), which was on board the Compton Gamma Ray Observatory. One parameter, the split time of 2 s on the $t_{90}$ durations plot (Koshut et al. 1996), was sufficient to classify bursts. Bursts from the two classes have another discriminator, spectral hardness as determined by the ratio of two broad energy channels. This hardness ratio, when used in conjunction with the duration, provides a means for classification, as shown by Kouveliotou et al. (1993). In addition, another classification scheme uses the scatter plot of the fluence and duration fitted with two two-dimensional Gaussians (Balázs et al. 2003). Some have indicated that there are more than two clusters (Mukherjee et al. 1998; Horváth 1998), while Hakki et al. (2000) maintain that the reported third cluster is simply the result of a selection bias. Furthermore, significant overlap is present in the duration comparison of short and long bursts, complicating a clear distinction between the two classes as has been discussed by the authors cited above. In any case, there are difficulties with all aforementioned classification measures in that the $t_{90}$ duration is somewhat subjective in the necessary selections of background regions, while a hardness ratio based upon counts is strongly detector dependent.

The observation that some classically short bursts are extended in duration, when observed in an energy band (BATSE 20–50 keV) different from that of the natural BATSE 50–300 keV band, was reported by Lazzati et al. (2001). The dedicated GRB mission, Swift (Barthelmy et al. 2005), has introduced additional issues, while reinforcing the extended emission of short GRBs at lower energies. Norris et al. (2000) have introduced the time lag between broad energy channels (“spectral lag”) as a classifier: “short” GRBs have approximately zero lag, while the “long” events have a lag that is significantly different from zero. Indeed, having a near-zero lag is the basis for claiming that some bursts observed by the Swift Burst Alert Telescope that are significantly longer than 2 s belong in the “short” class (Norris & Bonnell 2006; Zhang et al. 2006).

Following on the analysis of Nakar & Piran (2005) on the Amati relation (Amati et al. 2002), Band & Preece (2005) investigated the implications of combinations of several observable GRB parameters, derived from an extensive data set of GRBs observed by BATSE. The BATSE data set used was a partial spectral catalog of the peak flux and fluence spectral parameters (Mallozzi et al. 1995), complete up to the end of the BATSE 4B Catalog (Paciesas et al. 1999). The BATSE 5B Spectral Catalog has now been completed (Goldstein et al. 2010), which includes all BATSE bursts with sufficient counts in the spectral data so that they could be analyzed. Based on this comprehensive data set, we present a new GRB classification measure that is as diagnostic as the $t_{90}$ duration for classification, but does not rely on the subjective choices required for the durations calculation (Koshut et al. 1996).

2. MOTIVATION

BATSE data have been used to study the $E_{\text{peak}}$ distributions of GRBs (Kaneko et al. 2006), and the time-integrated $E_{\text{peak}}$ distribution for all bursts shows no evidence of discrimination between short and long bursts. Fluence hardness distributions (Kouveliotou et al. 1993) show some evidence of bimodality (Balázs et al. 2003), but there is only a moderate significance with much overlap (Nakar 2007). Using the BATSE 5B Spectral Catalog, we support previous observations on the distributions of $E_{\text{peak}}$ and fluence. In addition, we split the distributions into long and short duration GRB distributions, following the $t_{90}$ classification of 2 s. The $E_{\text{peak}}$ distribution for short bursts is completely overlapped by that of the long bursts. Although the $E_{\text{peak}}$ values for long bursts are centered around 150 keV, short burst $E_{\text{peak}}$ values are shifted to higher energies around 300 keV. This is consistent with previous findings of Paciesas et al. (2003) and Ghirlanda et al. (2009). Approximately 65% of the fluence distribution for short bursts overlaps that of the fluence distribution for long bursts, with the position of the peak of the short GRB fluence distribution being an order of magnitude less than that for long GRBs.

Lloyd et al. (2000) have shown there is a significant correlation between $E_{\text{peak}}$ and the total fluence in gamma rays, and it is desirable to investigate this correlation for both long and short GRBs. For this reason, we investigate the $E_{\text{peak}}$–fluence distribution for all BATSE bursts with good spectral fits and devise a discriminator between long and short bursts based on the difference in correlation between $E_{\text{peak}}$ and fluence for long and short
bursts. A choice formulation for a discriminator is based on the hardness of a burst. Kouveliotou et al. (1993) used a hardness ratio based on the ratio of calculated fluence in different energy bands to compare to duration estimates. Instead, we propose to use a hardness measure represented by $E_{\text{peak}}/\text{fluence}$. This so-called energy ratio is in units of area and should prove to be a good discriminator between long and short bursts if there is a strong correlation between $E_{\text{peak}}$ and fluence.

3. OBSERVATIONS

From the 5B spectral catalog (A. Goldstein et al. 2010, in preparation), we extract bursts with a good model fit as determined by a 3σ confidence limit, with the time-integrated $E_{\text{peak}}$ and fluence errors for each burst required to be no more than 40% of their respective fitted values. A total of 1121 long bursts and 168 short bursts, classified according to the classical $\xi_0$ cut of 2 s (Kouveliotou et al. 1993), satisfied these criteria. We then calculated the $E_{\text{peak}}/\text{fluence}$ energy ratio for each of these bursts and plot a histogram of these values, as in Figure 1. By using a standard nonlinear least-squares fitting algorithm, we fit a single lognormal function to the distribution with the resulting $\chi^2$ goodness-of-fit statistic 111 for 32 degrees of freedom. We then fit two lognormal functions to the distribution with the resulting $\chi^2$ statistic of 32 for 29 degrees of freedom. Since the two models are nested, we use Pearson’s $\chi^2$ test to show that the large change in $\chi^2$ per degree of freedom results in a chance probability of $5 \times 10^{-17}$ and that the two lognormals are statistically preferred with a high degree of significance.

From this bimodal distribution an obvious distinction between long and short bursts emerges. In Figure 2, we plot two histograms corresponding to long and short bursts as identified by their respective $\xi_0$ estimations to show that the bimodal distribution of the energy ratio is correlated to that of the duration distribution. A Kolmogorov–Smirnov test (K-S) test comparing the long and short burst distributions in Figure 2 to the best-fit lognormal functions in Figure 1, however, finds the correlations to be statistically marginal with 2% and 0.6% respective probabilities that each distribution in Figure 2 is drawn from their respective best-fit lognormal functions in

Figure 1. Histogram of the energy ratio distribution in the 20–2000 keV range for 1289 GRBs. The dotted line shows the best-fit lognormal to the distribution, and the dashed lines show the fit of two lognormal functions. The $\chi^2$ goodness-of-fit statistic for one lognormal is 111 for 32 degrees of freedom, while for two lognormals is 32 for 29 degrees of freedom. Therefore, two lognormal distributions are statistically preferred, resulting in a bimodal distribution for the energy ratio.

Figure 2. Histograms of the energy ratio distributions in the 20–2000 keV range for 1121 long bursts (white) and 168 short bursts (gray). There are clearly two distinct distributions, with long bursts centered around 0.6 and short bursts centered around 1.5. The solid curves are the best-fit lognormal functions, and the dashed lines are the 1σ standard deviation of the distributions.

Figure 1. The energy ratio distribution for short bursts is narrower compared to that of long bursts and is shifted to higher energies, resulting from the fact that short bursts are generally harder than long bursts. It appears that the energy ratio values are a good discriminator between the classical definition of long and short bursts by merging two known discriminators into one quantity, and their relative overlap can be well estimated. Only 4% of long GRBs overlap the 1σ core of the short burst distribution, and 2% of short bursts overlap the 1σ core of the long burst distribution. Similarly, the overlap for the 2σ cores is 11% and 23%, respectively. Comparatively, for our sample, the classical $\xi_0$ overlap of long bursts onto the 1σ (2σ) core of short bursts is 4% (23%), and there is no overlap of short bursts onto either the 1σ or 2σ core of long bursts. The central value for the long burst energy ratio distribution is $\sim 0.06$ while the central value for the short burst distribution is $\sim 1.5$.

Band & Preece (2005) showed that the Amati relation (Amati et al. 2002),

$$E_{\text{peak}} = C_A \left( \frac{E_{\text{iso}}}{10^{52} \text{ erg}} \right)^{\eta_A},$$

and the Ghirlanda relation (Ghirlanda et al. 2004),

$$E_{\text{peak}} = C_G \left( \frac{E_{\text{iso}} f_B}{10^{51} \text{ erg}} \right)^{\eta_G},$$

could be converted into a similar energy ratio

$$\frac{E_{\text{peak, obs}}^{1/\eta_i}}{S'_\gamma} \propto F(z),$$

where the $C_i$ in the previous equations are the respective normalization coefficients and $f_B$ is the beaming fraction relevant for the Ghirlanda relation. Here, $S'_\gamma$ is the fluence in gamma rays, and $\eta_i$ are the best-fit power-law indices for the respective models. These energy ratios can be represented as functions of redshift, $F(z)$, and the upper limit of the ratios could be determined for any redshift. The energy ratio upper limit of the Amati relation, as well as the energy ratio upper limit of the Ghirlanda relation, can be projected into the $E_{\text{peak}}$–fluence plane.
where they become lower limits. Using the bursts described above, the $E_{\text{peak}}$ values and fluences can be plotted in this plane. Figure 3 shows the distribution of long bursts in the upper plot and the distribution of short bursts in the bottom plot. The lines denote the lower limits of the Amati and Ghirlanda relations in this plane. Note that the beaming fraction for the Ghirlanda relation, $f_B = 1.0$, which is related to the jet opening angle, $\theta$, by $f_B = 1 - \cos \theta$. This represents the energy radiated by the burst equaling $E_{\text{iso}}$. It can easily be seen that there are two separate distributions in the $E_{\text{peak}}$–$E_{\text{iso}}$ plane. Long bursts appear to be clumped between the Amati and Ghirlanda limits, while the short bursts appear to distribute along the Ghirlanda lower limit.

4. CONCLUSIONS

The energy ratio shows a clear distinction between two different types of GRBs. The fluence encodes the duration of the burst without deriving a subjective $f_B$ estimate, and $E_{\text{peak}}$/fluence physically represents a ratio of the energy at which most of the gamma rays are emitted to the total energy emitted in gamma rays. This quantity effectively serves as a spectral hardness ratio and shows an increased hardness for short bursts compared to long bursts, consistent with Kouveliotou et al. (1993). The distribution of short bursts is narrower, its 1σ width covering less than one order of magnitude in energy, while the long bursts 1σ width covers slightly more than an order of magnitude. This bimodal distribution heavily supports the original distinction between long and short bursts (Kouveliotou et al. 1993) and suggests further investigation is desirable. The correlation between $E_{\text{peak}}$ and the total fluence in gamma rays is of particular interest, as the energy ratio removes the cosmological dependence for the energies involved since its value is merely proportional to the square of the luminosity distance. Because of this reason, the energy ratio could be considered physically superior to the duration classifier for GRBs. The low degree of correlation between the $f_B$ distribution and the energy ratio distribution may be attributed to the fact that the former is an observed quantity in the observer’s frame, while the latter is a quantity that contains spectral information from the rest frame of the GRB. In addition, when comparing the difference in overlap between the energy ratio distributions and the $f_B$ distributions, the overlap for the $f_B$ distributions is marginally less pronounced, but gives little insight to the physical processes in the rest frame of the GRB. Note that there may be a truncation effect with the energy ratio associated with short bursts, due to the inability of BATSE to trigger on very low fluence events and bursts with $E_{\text{peak}}$ outside the BATSE energy range. It is expected that Fermi/GBM will assist in discovering GRBs with $E_{\text{peak}}$ values greater than 1 MeV, alleviating possible truncation effects due to the energy cutoff at the high end of the detector energy band.

While a majority of BATSE bursts (~87%) fail the lower limit test for the Amati relation in the $E_{\text{peak}}$–fluence plane, very few BATSE bursts violate the lower limit for the Ghirlanda relation with $f_B = 1.0$. Especially intriguing is the fact that short GRBs fall close to the lower limit where the energy radiated is isotropic. Decreasing the beaming fraction shifts the lower limit to higher fluences, causing an increasing number of bursts to violate the Ghirlanda relation. In addition, only a few jet breaks have been discovered for short GRBs (Soderberg et al. 2006), and Watson et al. (2006) caution that those discoveries may be misleading due to the flaring activities of short GRB decay. Thus, the Ghirlanda relation, as well as the lack of reliable observed jet breaks for short bursts, suggests that short bursts release energy isotropically (or near isotropically), while longer bursts tend to have a much smaller beaming fraction and consequently have small opening angles. Clearly, the Ghirlanda relation, if accurate, requires short bursts to release energy isotropically, as opposed to beamed radiation release in long bursts (Frail et al. 2001; Nakar 2007). In addition, if short GRBs are isotropic emitters, then virtually all short GRBs should be detectable within a given volume of space. Long GRBs, in general, have a small measured opening angle, and therefore only a small fraction are detectable (van Paradis et al. 2000). Since short GRBs are detected far less frequently than long GRBs (Paciesas et al. 1999), this is indicative of a relatively rare and independent cause for short GRBs.

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