MAKING A SHORT GAMMA-RAY BURST FROM A LONG ONE:
IMPLICATIONS FOR THE NATURE OF GRB 060614

Bing Zhang, Bin-Bin Zhang, En-Wei Liang, Neil Gehrels, David N. Burrows, Peter Mészáros

ABSTRACT

The absence of a supernova accompanying the nearby long GRB 060614 poses a great puzzle about the progenitor of this event and challenges the current GRB classification scheme. This burst displays a short-hard emission episode followed by extended soft emission with strong spectral evolution. Noticing that this burst has an isotropic gamma-ray energy only ~8 times that of GRB 050724, a good candidate of merger-type short GRBs, we generate a “pseudo” burst that is ~8 times less energetic than GRB 060614 based on the spectral properties of GRB 060614 and the $E_p \propto E_{iso}^{1/2}$ (Amati) relation. We find that this pseudo-burst would have been detected by BATSE as a marginal short-duration GRB, and would have properties in the Swift BAT and XRT bands similar to GRB 050724. This suggests that GRB 060614 is likely a more intense event in the traditional short-hard GRB category as would be detected by BATSE. Events like GRB 060614 that seem to defy the traditional short vs. long classification of GRBs may require modification of our classification terminology for GRBs. By analogy with supernova classifications, we suggest that GRBs be classified into Type I (typically short and associated with old populations) and Type II (typically long and associated with young populations). We propose that GRB 060614 belongs to Type I, and predict that similar events will be detected in elliptical galaxies.

Subject headings: gamma-rays: bursts

1. INTRODUCTION

Two classes of gamma-ray bursts (GRBs), namely the long-duration and short-duration categories, were identified in the CGRO/BATSE sample with a rough division at $T_{90} \sim 2$ seconds (Kouveliotou et al. 1993). Afterglow and host galaxy observations of long GRBs strongly suggest that they are associated with deaths of massive stars (Woosley et al. 1993; Paczynski 1998; MacFadyen & Woosley 1999), as is supported by the observed GRB/SN associations (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003b; Malesani et al. 2004; Campana et al. 2006a; Pian et al. 2006). Not long ago, it has been speculated that both data and theory are consistent with the ansatz that every long GRB has a SN associated with it (Woosley & Bloom 2006). The detections of the afterglows of short GRBs (Gehrels et al. 2005; Fox et al. 2005; Villasenor et al. 2005; Hjorth et al. 2005; Barthelmy et al. 2005a; Berger et al. 2005) led to tight constraints on the existence of any underlying supernova (Fox et al. 2005; Hjorth et al. 2005; Berger et al. 2005) and identifications of their host galaxies, some of which are elliptical/early-type with very low star formation rates (e.g. Donaghly et al. 2006). Not long ago, it has been speculated that both data and theory are consistent with the ansatz that every long GRB has a SN associated with it (Woosley & Bloom 2006). The detections of the afterglows of short GRBs (Gehrels et al. 2005; Fox et al. 2005; Villasenor et al. 2005; Hjorth et al. 2005; Barthelmy et al. 2005a; Berger et al. 2005) led to tight constraints on the existence of any underlying supernova (Fox et al. 2005; Hjorth et al. 2005; Berger et al. 2005) and identifications of their host galaxies, some of which are elliptical/early-type with very low star formation rates (Gehrels et al. 2005; Bloom et al. 2006; Barthelmy et al. 2005a; Berger et al. 2005). These are consistent with the the long-held speculation that they are related to the mergers of compact objects (e.g. Paczynski 1986, 1991; Eichler et al. 1989; Narayan et al. 1992). Some short GRBs occur in star forming galaxies (but preferably in regions of low star formation, e.g. Covino et al. 2005; Fox et al. 2005). This is not inconsistent with the merger scenarios (Bloom et al. 1999).

GRB 060614 poses a great puzzle to the above clean bimodal scenario. Being a long GRB (Gehrels et al. 2006; V. Mangano et al. 2006, in preparation) at a low redshift $z = 0.125$ (Price et al. 2006), it is surprising that deep searches of an underlying supernova give null results: the limiting magnitude is hundreds of times fainter than SN 1998bw, and fainter than any Type Ic SN ever observed (Gal-Yam et al. 2006; Fynbo et al. 2006; Della Valle et al. 2006). This raises interesting questions regarding whether this is a collapsar-type event without supernova, or is a more energetic merger event, or belongs to a third class of GRBs (e.g. Gal-Yam et al. 2006). From the prompt emission analysis, GRB 060614 has very small spectral lags (Gehrels et al. 2006), being consistent with the property of typical short GRBs (Yi et al. 2005; Norris & Bonnell 2006). However, based on the duration criterion, this event definitely belongs to the long category ($T_{90} \sim 100s$ in the BAT band). One interesting feature is that the lightcurve is composed of a short-hard episode followed by an extended soft emission component with strong spectral evolution. A growing trend in the “short” GRB observations has been that they are not necessarily short, as observed by Swift and HETE-2. For example, the lightcurve of GRB 050709 (Villasenor et al. 2005) consists of a short-hard pulse with $T_{90} \sim 0.2s$ and a long-soft pulse with $T_{90} \sim 130s$. GRB 050724 (Barthelmy et
al. 2005a) has a prominent emission lasting for $\sim 3s$ followed by a long, soft, less prominent emission peaking at $\sim 100s$ after the trigger, and XRT observations reveal strong flare-like activities within the first hundreds of seconds. All these raise the issue of how to define a short GRB (e.g. Donaghy et al. 2006). The consensus is that multi-dimensional criteria (other than duration and hardness alone) are needed.

We notice that GRB 060614 is more energetic (with an isotropic gamma-ray energy $E_{\text{iso}} \sim 8.4 \times 10^{50} \text{ ergs}$) than typical short GRBs, such as 050709 ($E_{\text{iso}} \sim 2.8 \times 10^{49} \text{ ergs}$) and 050724 ($E_{\text{iso}} \sim 10^{50} \text{ ergs}$), though still much less energetic than typical long GRBs (with $E_{\text{iso}}$ typically $\sim 10^{52} \text{ ergs}$ or higher). This raises the interesting possibility that it might be an energetic version of the short GRBs. The purpose of this Letter is to test this hypothesis.

2. DATA ANALYSIS

We first proceed with an analysis of the data of GRB 060614. This burst was detected by Swift/BAT on 2006 June 14 at 12:43:48 UT. This is a long, bright burst, with $T_{90} \sim 100s$ and the gamma-ray fluence $S_{90} = 2.17 \pm 0.04 \times 10^{-5} \text{ ergs cm}^{-2}$ in the 15-150 keV band (Gehrels et al. 2006). We reduce the BAT data using the standard BAT tools. The time-integrated spectrum is well fitted by a simple power law ($N \propto E^{-\Gamma}$) with $\Gamma = 1.90 \pm 0.04$ and $\chi^2/dof = 60/56$. A cutoff power law or a broken power law does not improve the fitting. The spectrum shows a strong temporal evolution, with $\Gamma \sim 1.5$ at the beginning and $\Gamma \sim 2.2$ near the end. To clearly display this spectral evolution effect, we split the observed light curves into four energy bands, i.e. 15-25, 25-50, 50-100, 100-350 keV, with a time bin of 64 ms. The results are shown in Fig 1(a)-(d) (see also Gehrels et al. 2006). Since the first peak of the light curves starts at 2 seconds before the trigger, we define $t_0$ as 2 seconds prior to the trigger time for convenience. All the light curves are highly variable, with three bright, sharp peaks between $t_0 \sim t_0 + 5s$, a gap of emission from $t_0 + 5s$ to $t_0 + 10s$, and long, soft extended emission up to $t_0 + 100s$. By comparing the 4 lightcurves, one can clearly see that the contribution of the soft photons increases with time, indicating a clear hard-to-soft spectral evolution. We perform a detailed time-dependent spectral analysis by dividing the light curve into 9 segments, which roughly correspond to the significant peaks in the light curve. We fit the spectra for each time segment with a simple power law model. The results are shown in Fig 1(e). It is seen that $\Gamma$ steadily increases with time. The Spearman correlation analysis yields a relation between $\Gamma$ and $\log t$ as

$$\Gamma = (1.50 \pm 0.07) + (0.38 \pm 0.04) \log t$$  \hspace{1cm} (1)

at 1$\sigma$ confidence level, with a correlation coefficient $r = 0.97$, a standard deviation 0.06, and a chance probability $p < 10^{-4}$ for $N = 9$.

3. GENERATING A PSEUDO BURST FROM GRB 060614

We want to downgrade GRB 060614 by a factor of $\sim 8$ to match the isotropic energy of GRB 050724. GRB 050724 has a robust association with an elliptical host galaxy (Barthelmy et al. 2005a; Berger et al. 2005), and hence, is a good candidate for a compact star merger progenitor. It also has well detected early to late X-ray afterglows (Barthelmy et al. 2005a; Campana et al. 2006b; Grupe et al 2006) to be directly compared with our pseudo burst.

One technical difficulty is how to derive the spectral parameters of the pseudo burst when $E_{\text{iso}}$ is degraded. The spectra of both long and short GRBs can be fitted by the Band function, a smoothly-joint broken power law function characterized by three parameters: the break energy $E_0$ and the photon indices $\Gamma_1$ and $\Gamma_2$ before and after the break, respectively (Band et al. 2003; Preece et al. 2000; Cui et al. 2005). The peak energy of the $\nu \nu \nu$ spectrum is $E_p = (2 + \Gamma_1)E_0$. It has been discovered that for long duration GRBs and their soft extension X-ray flashes, most bursts satisfy a rough relation $E_p \propto E_{\text{iso}}^{1/2}$ (Amati et al. 2002; Lamb et al 2005; Sakamoto et al. 2006a). GRB 060614 is found to also satisfy the relation (Amati 2006). More intriguingly, within a given burst, a similar relation $E_p \propto E_{\text{iso}}^{1/2}$ generally applies (Liang et al. 2004). Such an empirical relation is likely related to the fundamental radiation physics, independent of the progenitors. For example, in the internal shock synchrotron model, such a relation could be roughly reproduced if the Lorentz factors of various bursts do not vary significantly (e.g. Zhang & Mészáros 2002). Alternatively, a general positive dependence of $E_p$ on $E_{\text{iso}}$ is expected if $E_p$ reflects the thermal peak of the fireball photosphere (Mészáros et al. 2002; Rees & Mészáros 2005; Ryde et al. 2006; Thompson et al. 2006). We therefore assume the validity of the Amati-relation to generate the pseudo burst: to generate a pseudo burst with $E_{\text{iso}} \sim 8$ times smaller, the time-dependent $E_p$’s of the pseudo burst are systematically degraded by a factor of $\sim 3$.

A challenging task is to determine $E_p$ for each time segment. The BAT is a narrow band (15-150 keV) instrument, and usually it is difficult to constrain $E_p$ directly from the Band-function spectral fit. About 80% of the GRB spectra observed by BAT can be only fitted by a simple power law. In deriving GRB radiative efficiency of a sample of Swift bursts, we developed a method to derive $E_p$ by combining spectral fits and the information of the hardness ratio (Zhang et al. 2007). The derived $E_p$’s are generally consistent with the joint spectral fits for those bursts co-detected by BAT and Konus-Wind, suggesting that the method is valid. Using the sample of Zhang et al. (2007), we find that the simple power law index $\Gamma$ is well correlated with $E_p$ (Fig 2). The Spearman correlation analysis gives

$$\log E_p = (2.76 \pm 0.07) - (3.61 \pm 0.26) \log \Gamma$$  \hspace{1cm} (2)

at 1$\sigma$ confidence level, with a correlation coefficient 0.94, a standard deviation 0.17, and a chance probability $p < 10^{-4}$ for $N = 27$. Recently Sakamoto et al. (2006b) independently derived a similar relationship using the $E_p$ data of those GRBs simultaneously detected by Swift and Konus-Wind. In Figure 2, we have also plotted the bursts with $E_p$ measured with Konus-Wind and HETE-2. They are generally consistent with the correlation (2). This empirical relation is adopted in our generation of the pseudo burst.

Our procedure is the following. (1) Using the $E_p - \Gamma$ relation (eq.[2]) we estimate $E_p$ as a function of
time for GRB 060614; (2) Using the Amati-relation, we derive $E_p$ as a function of time for the pseudo burst, i.e., $E_{p,\text{pseudo}} = E_{060614}^{\text{iso}}(E_{060614}^{\text{iso}}/E_{060614}^{\text{pseudo}})^{1/2} = E_p^{060614}(E_{050724}^{\text{iso}}/E_{060614}^{\text{iso}})^{1/2}$; (3) Assuming photon indices $\Gamma_1 = 1$ and $\Gamma_2 = 2.3$ for the Band-function and keeping the same normalization of the Band function, we calculate the counts in the BAT and XRT bands as a function of time and make the light curves in the BAT and XRT bands with this spectrum. (4) We generate a white noise similar to that of GRB 050724; (5) We adjust the amplitude of the lightcurve in the BAT band to ensure that the gamma-ray fluence above the noise level of the pseudo GRB in the BAT band is the same as that of GRB 050724. (6) Using the time-dependent spectral parameters, we extrapolate the BAT lightcurve to the XRT band. We also process the XRT data of GRB 060614, which has a steep decay component following the prompt emission. We adjust the XRT lightcurve to match the tail of the pseudo burst (blue lightcurve in Fig.3), as has been the case for the majority of Swift bursts (e.g., Tagliaferri et al. 2005; Barthelmy et al. 2005b; Nousek et al. 2006; Zhang et al. 2006; O'Brien et al. 2006; Liang et al. 2006). The simulated light curves (red) are shown in Fig.3, as compared with the observed lightcurves of GRB 050724. Very encouraging results are obtained. The BAT-band lightcurve of the pseudo burst is characterized by short, hard spikes (with $E_p \sim 150$ keV at first 2 seconds) followed by very weak and faint emission episodes at later times. The softer components merge with the background. We estimate $T_{90} \sim 53$ s in the BAT band. By extrapolating the lightcurve to the BATSE band (inset of Fig.3a) and by using the BATSE threshold (0.424 cts cm$^{-2}$ s$^{-1}$), one gets $T_{90} \sim 4.4$ s. This number marginally places the pseudo burst in the short category (Donaghy et al. 2006). All the previous soft spikes in the BAT band of GRB 060614 are now moved to the XRT band to act as erratic X-ray flares (e.g., Burrows et al. 2005), which are also present in GRB 050724 (Barthelmy et al. 2005a). It is clear that the pseudo burst is very similar to GRB 050724.

4. CONCLUSIONS AND DISCUSSION

We have "made" a marginally short hard GRB from the long GRB 060614. The only assumption made is the validity of the $E_p \propto E_{\text{iso}}^{1/2}$ relation, which is likely related to the radiation physics only. The results suggest that had GRB 060614 been less energetic (say, as energetic as the more typical short GRB 050724), it would also have been detected as a marginal short GRB by BATSE. Along with the facts that GRB 060614 has very small spectral lags (Gehrels et al. 2006) and that there is no supernova association (Gal-Yam et al. 2006; Fynbo et al. 2006; Della Valle et al. 2006), our finding strengthens the hypothesis that GRB 060614 is a more energetic version of the previously-defined short-hard class of bursts. The lower-than-normal star-forming rate of the host galaxy and its large offset from the bright UV regions (Gal-Yam et al. 2006) is also consistent with such a picture.

By making such a connection, the traditional long-soft vs. short-hard GRB classification dichotomy based primarily on burst duration seems to break down. The total duration of GRB 060614 is far longer than the traditional 2 s separation point based on the bimodal distribution of the BATSE bursts (Kouveliotou et al. 1993), or even the 5 s point identified by Donaghy et al. (2006). Yet, given the evidence cited above, it seems entirely likely that there is no fundamental distinction between GRB 060614 and the other short-hard bursts except for the duration. We therefore suggest that the time has come to abandon the terms “short” and “long” in describing GRB classes. Instead, by analogy to supernova classification, we suggest the alternative classes of Type I and Type II GRBs. Type I GRBs are associated with old stellar populations (similar to Type Ia SNe) and the likeliest candidates are compact star mergers. Observationally, Type I GRBs are usually short and relatively hard, but are likely to have softer extended emission tails. They have small spectral lags and low luminosities, falling in a distinct portion of a lag-luminosity plot (Gehrels et al. 2006). They have no associated SNe and can be associated with either early or late type galaxies, but typically are found in regions of low star formation. Type II GRBs are associated with young stellar populations and are likely produced by core collapses of massive stars (similar to Type II and Ib/c SNe). Observationally, they are usually long and relatively soft. They are associated with star forming regions in (usually) irregular galaxies and with SN explosions. According to this classification, we suggest that GRB 060614 is a Type I GRB. It has been noted that a sample of BATSE and Konus-Wind bursts have properties similar to GRB 060614, and we suggest that they belong to Type I as well. A direct prediction of such a scenario is that some 060614-like GRBs will be detected in elliptical galaxies in the future.

The association of GRB 060614 with Type I GRBs exacerbates the problem of how to make extended emission from a merger-type GRB, which arose when extended X-ray flares were detected following GRB 050724. Barthelmy et al. (2005a) and Faber et al. (2006) suggest NS-BH mergers as the possible progenitor to extend the accretion episodes. Dai et al. (2006) argued that the final product of a NS-NS merger may be a heavy, differentially-rotating NS, whose post-merger magnetic activity would give rise to flares following the merger events. Rosswog (2006) suggest that some debris may be launched during the merger process, which would fall back later to power flares at late times. Alternatively, disk fragmentation (Perna et al. 2006) or magnetic field barrier near the accretor (Proga & Zhang 2006) would induce intermittent accretion that power the flares. Finally, King et al. (2006) suggest a WD-NS merger to interpret Type I GRBs (cf. Naylan et al. 2001). More detailed numerical simulations are needed to verify these suggestions.
This work was supported by NASA under grants NNG06GH62G, NNG05GB67G (BZ), NAS5-00136 (DNB) and NAG513286 (PM), and the National Natural Science Foundation of China under grant 10463001 (EWL).

REFERENCES

Amati, L. 2006, MNRAS, 372, 233
Amati, L., et al., 2002, A&A, 390, 81
Band, D. et al. 1993, ApJ, 413, 281
Barthelmy, S. D. et al. 2005a, Nature, 438, 994
Barthelmy, S. D. et al. 2005b, ApJ, 635, L133
Berger, E. et al. 2005, Nature, 438, 988
Bloom, J. S., Sigurdsson, S. & Pols, O. R. 1999, MNRAS, 305, 763
Bloom, J. S. et al. 2006, ApJ, 638, 354
Burrows, D. N. et al. 2005, Science, 309, 1833
Campana, S. et al. 2006a, Nature, 442, 1008
Campana, S. et al. 2006b, A&A, 454, 113
Covino, S. et al. 2006, A&A, 447, L5
Cui, X. H., Liang, E. W, & Lu R. J., 2005, ChJAA, 5, 151
Dai, Z. G., Wang, X. Y., Wu, X. F. & Zhang, B. 2006, Science, 311, 1127
Della Valle, M. et al. 2006, Nature, in press (astro-ph/0608322)
Donaghy, T. Q. et al. 2006, ApJ, submitted (astro-ph/0605070)
Eichler, D., Livio, M., Piran, T. & Schramm, D. N. 1989, Nature, 340, 126
Faber, J. A. et al. 2006, ApJ, 641, L93
Fox, D. B. et al. 2005, Nature, 437, 845
Fynbo, J. P. U. et al. 2006, Nature, in press (astro-ph/0608313)
Galama, T. J. et al. 1998, Nature, 395, 670
Gal-Yam, A. et al. 2006, Nature, in press (astro-ph/0608257)
Gehrels, N. et al. 2005, Nature, 437, 851
Gehrels, N. et al. 2006, Nature, in press (astro-ph/0610635)
Grupe, D. et al. 2006, ApJ, 653, 462
Hjorth, J. et al. 2003, Nature, 423, 847
Hjorth, J. et al. 2005, Nature, 437, 859
King, A., Olsson, E. & Davies, M. B. 2006, MNRAS, in press (astro-ph/0610452)
Kouveliotou, C. et al. 1993, ApJ, 413, L101
Liang, E. W., Dai, Z. G. & Wu, X. F. 2004, ApJ, 606, L29
Liang, E. W. et al. 2006, ApJ, 646, 351
Lamb, D. Q., Donaghy, T. Q., Graziani, C. 2005, ApJ, 620, 355
MacFadyen, A. I. & Woosley, S. E. 1999, ApJ, 524, 262
Malesani, D. et al. 2004, ApJ, 609, L5
Mészáros, P., Ramirez-Ruiz, E., Rees, M. J. & Zhang, B. 2002, ApJ, 578, 812
Nakar, E. & Piran, T. 2002, MNRAS, 330, 920
Narayan, R., Paczynski, B. & Piran, T. 1992, ApJ, 395, L8
Narayan, R., Piran, T. & Kumar, P. 2001, ApJ, 557, 949
Norris, J. P. & Bonnell, J. T. 2006, ApJ, 643, 266
Nousek, J. A. et al. 2006, ApJ, 642, 389
O’Brien, P. T. et al. 2006, ApJ, 647, 1213
Paczynski, B. 1986, ApJ, 308, L43
Paczynski, B. 1998, ApJ, 494, L45
Perna, R., Armitage, P. J. & Zhang, B. 2006, ApJ, 636, L29
Pian, E., et al. 2006, Nature, 442, 1011
Preece, R. et al. 2000, ApJS, 126, 19
Price, P. et al. 2006, GCN report #5275
Proga, D. & Zhang, B. 2006, MNRAS, 370, L61
Rees, M. J. & Mészáros, P. 2005, ApJ, 628, 847
Rosswog, S. 2006, MNRAS, submitted (astro-ph/0611140)
Ryde, F. et al. 2006, ApJ, 652, 1400
Sakamoto, T. et al., 2006a, ApJ, 636, L73
Sakamoto, T. et al., 2006b, ApJL, submitted
Stanek, K. Z., et al. 2003, ApJ, 591, L17
Tagliaferri, G. et al. 2005, Nature, 436, 985
Thompson, C., Mészáros, P. & Rees, M. J. 2006, ApJ, submitted (astro-ph/0608282)
Villasenor, J. S. et al. 2005, Nature, 437, 855
Woosley, S. E., et al. 1993, ApJ, 405, L273
Woosley, S. E. & Bloom, J. S. 2006, ARA&A, 44, 507
Yi, T. F., Liang, E. W., Qin, Y. P., Lu, R. J. 2006, MNRAS, 367, 1751
Zhang, B. & Mészáros, P. 2002, ApJ, 581, 1236
Zhang, B. et al. 2006, ApJ, 642, 354
Zhang, B. et al. 2007, ApJ, in press (astro-ph/0610177)
Fig. 1.— Panel (a)-(d): Light curves of GRB 060614 in different energy bands. Panel (e): Temporal evolution of the photon index.
Fig. 2.— $E_p$ as a function of the photon index $\Gamma$ in a simple power law model for the sample of GRB presented in Zhang et al. (2007). The measured $E_p$ data from Konus-Wind and HETE-2, including both long (open circles) and short (stars) bursts, are also plotted.
Fig. 3.—The simulated gamma-ray and X-ray lightcurves of the pseudo burst (red) as compared with those of GRB 050724 (grey). Panel (a): The gamma-ray lightcurves in the BAT (main panel) and BATSE (inset) bands. The zero-level horizontal lines denote the detector thresholds. The innermost inset zooms in on the detail of the short-hard spikes as observed by BATSE. Panel (b): Light curves of the soft extension extrapolated to the XRT band. The blue curve is the XRT lightcurve of GRB 060614, re-scaled to match that of the pseudo burst.