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

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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 $E_p \propto E_{\rm iso}^{1/2}$ (Amati) relation. We find that this pseudoburst 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. Events like GRB 060614 that seem to defy the traditional short versus 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

Online material: color figure

1. INTRODUCTION

Gamma-ray bursts (GRBs) have been classified into long- and short-duration categories (Kouveliotou et al. 1993).[8] Long GRBs are believed to be associated with deaths of massive stars (Woosley et al. 1993; Paczyński 1998; MacFadyen & Woosley 1999). The associations between supernovae and some GRBs (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004; Campana et al. 2006a; Pian et al. 2006) led to the speculation that every long GRB has a supernova (SN) associated with it (Woosley & Bloom 2006). On the other hand, short GRBs are discovered in elliptical/early-type galaxies with very low star formation rates (Gehrels et al. 2005; Bloom et al. 2006; Barthelmy et al. 2005a; Berger et al. 2005) or in the regions of low star formation in star-forming galaxies (Covino et al. 2006; Fox et al. 2005). Tight constraints on the existence of any underlying supernova (Fox et al. 2005; Hjorth et al. 2005; Berger et al. 2005) have been placed for short GRBs. All these are consistent with short GRBs being related to the mergers of compact objects (e.g., Paczyński 1986, 1991; Eichler et al. 1989; Narayan et al. 1992; 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. 2007, in preparation) at a low redshift $z = 0.125$ (Price et al. 2006), it is not associated with any underlying SN with limiting magnitude 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 a SN, 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. 2006; Norris & Bonnell 2006). However, based on the duration criterion, this event definitely belongs to the long category ($T_{90} \sim 100$ s in the Burst Alert Telescope [BAT] band). The light curve 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*: extended emission is observed following short GRB 050709 (Villasenor et al. 2005) and GRB 050724 (Barthelmy et al. 2005a). This raises the issue of how to define a short GRB (e.g., Donaghy et al. 2006). The consensus is that multidimensional criteria (other than duration and hardness alone) are needed.

We notice that GRB 060614 is more energetic (with an isotropic gamma-ray energy $E_{\rm iso} \sim 8.4 \times 10^{50}$ ergs) than typical short GRBs, such as 050709 ($E_{\rm iso} \sim 2.8 \times 10^{49}$ ergs) and 050724 ($E_{\rm iso} \sim 10^{50}$ ergs), although still much less energetic than typical long GRBs (with $E_{\rm iso}$ typically $\sim 10^{52}$ 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 $T_{90} \sim 100$ s and the gamma-ray fluence $S_\gamma = (2.17 \pm 0.04) \times 10^{-5}$ 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 $\chi^2/{\rm dof} = 60/56$. A cutoff power law or

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[8] The dividing line between the two types of GRBs is likely arbitrary and detector-dependent (e.g., Donaghy et al. 2006).

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, and 100–350 keV, with a time bin of 64 ms. The results are shown in Figures 1*a*–1*d* (see also Gehrels et al. 2006). Since the first peak of the light curves starts at 2 s before the trigger, we define t_0 as 2 s prior to the trigger time for convenience. All the light curves are highly variable, with three bright, sharp peaks between t_0 and $t_0 + 5$ s, a gap of emission from $t_0 + 5$ s to $t_0 + 10$ s, and long, softer extended emission up to $\sim t_0 + 100$ s. By comparing the four light curves, 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 nine 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 Figure 1*e*. It is seen that Γ steadily increases with time. The Spearman correlation analysis yields a relation between Γ and $\log t$ as

$$\Gamma = (1.50 \pm 0.07) + (0.38 \pm 0.04) \log t \qquad (1)$$

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

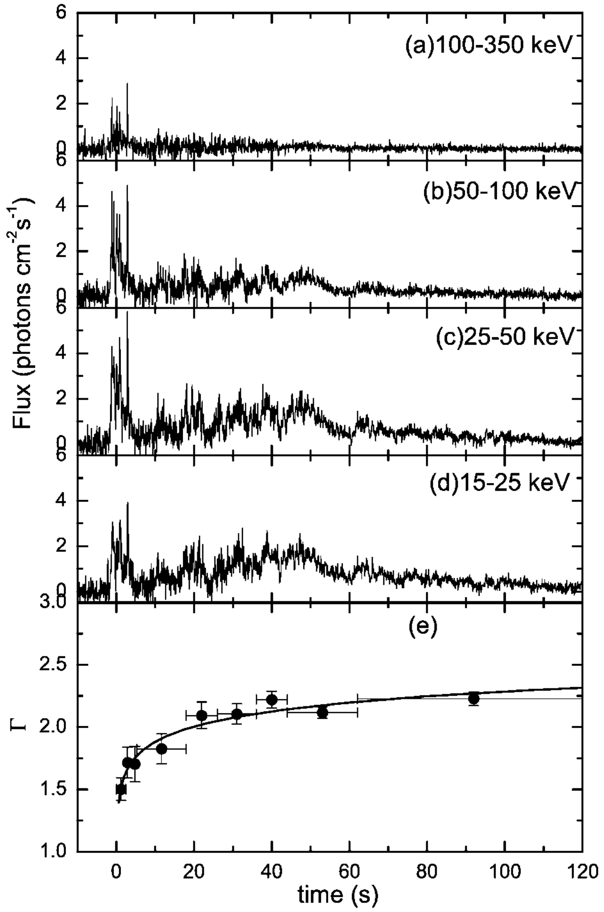

FIG. 1.—(*a*–*d*) Light curves of GRB 060614 in different energy bands. (*e*) Temporal evolution of the photon index.

3. GENERATING A PSEUDOBURST FROM GRB 060614

We want to downgrade GRB 060614 by a factor of ~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 pseudoburst.

One technical difficulty is how to derive the spectral parameters of the pseudoburst when $E_{\rm iso}$ is degraded. The spectra of both long and short GRBs can be fitted by the Band function characterized by three parameters: the break energy E_0 and the photon indices Γ_1 and Γ_2 before and after the break, respectively (Band et al. 1993; Preece et al. 2000; Cui et al. 2005). The peak energy of the νf_ν spectrum is $E_p = (2 + \Gamma_1)E_0$. For long-duration GRBs and their soft extension X-ray flashes, most bursts satisfy a rough relation $E_p \propto E_{\rm iso}^{1/2}$ (Amati et al. 2002; Lamb et al. 2005; Sakamoto et al. 2006a). GRB 060614 is found to also satisfy the relation (Amati et al. 2006). More intriguingly, within a given burst, a similar relation $E_p \propto L_{\rm iso}^{1/2}$ 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 $E_{\rm iso}$ 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 pseudoburst: to generate a pseudoburst with $E_{\rm iso} \sim 8$ times smaller, the time-dependent E_p's of the pseudoburst are systematically degraded by a factor of ~3.

A challenging task is to determine E_p for each time segment. The BAT is a narrowband (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. We have 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 codetected by BAT and Konus-*Wind*. Using the sample of Zhang et al. (2007), we find that the simple power law index Γ is well correlated with E_p (Fig. 2). The Spearman correlation analysis gives

$$\log E_p = (2.76 \pm 0.07) - (3.61 \pm 0.26) \log \Gamma \qquad (2)$$

at the 1 σ confidence level, with a correlation coefficient 0.94, a standard deviation 0.17, and a chance probability $p < 10^{-4}$ for $N = 27$. A similar correlation was independently derived by Sakamoto et al. (2006b) recently. In Figure 2, we have also plotted the bursts with E_p measured with Konus-*Wind* and *HETE-2*. They are generally consistent with correlation (2). This empirical relation is adopted in our generation of the pseudoburst.

Our procedure is the following. (1) Using the E_p-Γ 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 pseudoburst, i.e., $E_p^{\rm pseudo} = E_p^{060614}(E_{\rm iso}^{\rm pseudo}/E_{\rm iso}^{060614})^{1/2} = E_p^{060614}(E_{\rm iso}^{050724}/E_{\rm iso}^{060614})^{1/2}$. (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

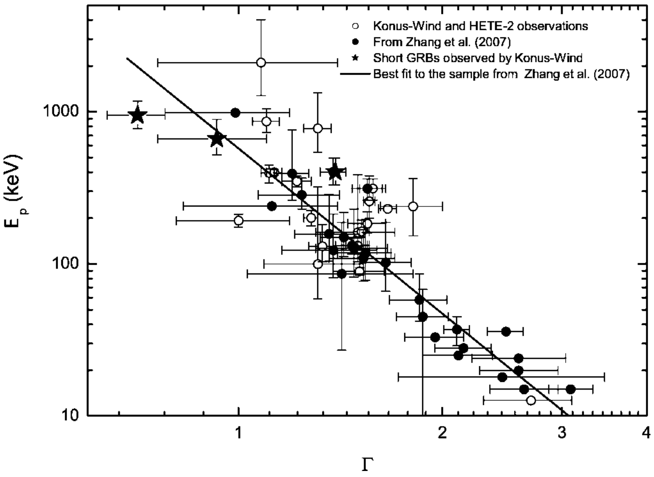

FIG. 2.—E_p as a function of the photon index Γ in a simple power law model for the sample of GRBs presented in Zhang et al. (2007). The measured E_p data from Konus-*Wind* and *HETE-2*, including both long (*open circles*) and short (*star symbols*) bursts, are also plotted.

BAT and X-Ray Telescope (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 light curve 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 light curve 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 light curve to match the tail of the pseudoburst (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 (*black*) are shown in Figure 3 as compared with the observed light curves of GRB 050724. Very encouraging results are obtained. The BAT-band light curve of the pseudoburst is characterized by short, hard spikes (with $E_p \sim 150$ keV at first 2 s) 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 light curve to the Burst and Transient Source Experiment (BATSE) band (inset of Fig. 3*a*) and by using the BATSE threshold (0.424 counts cm^{-2} s^{-1}), one gets $T_{90} \sim 4.4$ s. This number marginally places the pseudoburst 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 pseudoburst is very similar to GRB 050724.

4. CONCLUSIONS AND DISCUSSION

We have "made" a marginally short-hard GRB from the long GRB 060614.[9] The only assumption made is the validity of the $E_p \propto E_{\rm iso}^{1/2}$ relation, which is likely related to the radiation physics only. The results suggest that had GRB 060614 been less energetic (as energetic as GRB 050724), it would also have

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[9] Without introducing the Amati relation, a previous attempt to change long bursts to short ones (Nakar & Piran 2002) led to negative results.

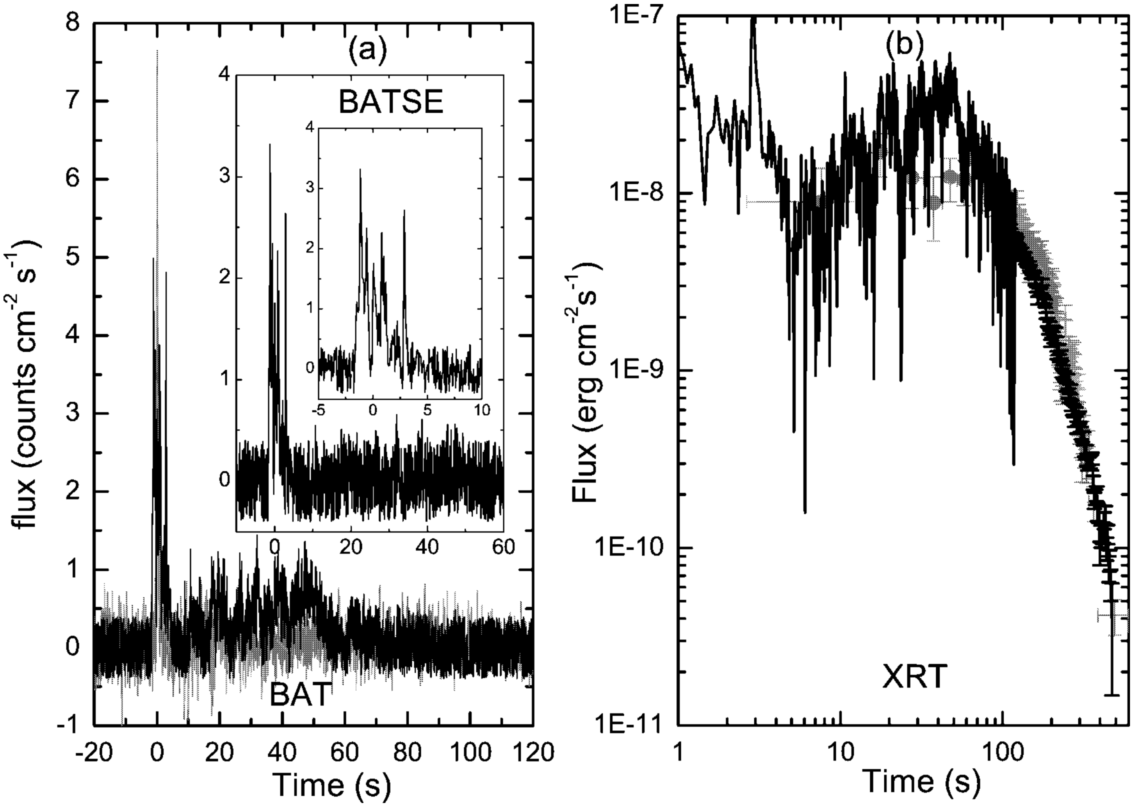

FIG. 3.—Simulated gamma-ray and X-ray light curves of the pseudoburst (*black*) as compared with those of GRB 050724 (*gray*). (*a*) The gamma-ray light curves in the BAT (*main panel*) and BATSE (*inset*) bands. The zero-level horizontal lines denote the detector thresholds. The innermost inset zooms in on the detail of the short-hard spikes as observed by BATSE. (*b*) Light curves of the soft extension extrapolated to the XRT band. Also shown is the XRT light curve of GRB 060614, rescaled to match that of the pseudoburst. [*See the electronic edition of the Journal for a color version of this figure.*]

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), that there is no SN association (Gal-Yam et al. 2006; Fynbo et al. 2006; Della Valle et al. 2006), that the star-forming rate is low, and that it has a large offset from the bright UV regions (Gal-Yam et al. 2006), our finding strengthens the hypothesis that GRB 060614 is a more energetic event in the short-hard class of bursts.

By making such a connection, the traditional long-soft versus short-hard GRB classification dichotomy based primarily on burst duration seems to break down. The duration of GRB 060614 is far longer than the traditional 2 s separation point (Kouveliotou et al. 1993), or even the 5 s point identified by Donaghy et al. (2006). Yet, 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. Barthelmy et al. (2005a) and Faber et al. (2006) suggest neutron star–black hole mergers as the possible progenitor to extend the accretion episodes. Dai et al. (2006) invoked the magnetic activity of a postmerger massive neutron star to interpret flares. Rosswog (2006) suggest that some debris may be launched during the merger process, which would fall back later to power flares. Alternatively, disk fragmentation (Perna et al. 2006) or a magnetic field barrier near the accretor (Proga & Zhang 2006) would induce intermittent accretion that powers the flares. Finally, King et al. (2007) suggest a white dwarf–neutron star merger to interpret Type I GRBs (cf. Narayan et al. 2001). More detailed numerical simulations are needed to verify these suggestions.

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