IN SEARCH OF PROGENITORS FOR SUPERNOVALESS GAMMA-RAY BURSTS 060505 AND 060614: RE-EXAMINATION OF THEIR AFTERGLOWS*

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ABSTRACT

GRB 060505 and GRB 060614 are nearby long-duration gamma-ray bursts (LGRBs) without accompanying supernovae (SNe) down to very strict limits. They thereby challenge the conventional LGRB-SN connection and naturally give rise to the question: are there other peculiar features in their afterglows which would help shed light on their progenitors? To answer this question, we combine new observational data with published data and investigate the multiband temporal and spectral properties of the two afterglows. We find that both afterglows can be well interpreted within the framework of the jetted standard external shock wave model, and that the afterglow parameters for both bursts fall well within the range observed for other LGRBs. Hence, from the properties of the afterglows there is nothing to suggest that these bursts should have another progenitor than other LGRBs. Recently, Swift-discovered GRB 080503 also has the spike + tail structure during its prompt γ-ray emission seemingly similar to GRB 060614. We analyze the prompt emission of this burst and find that this GRB is actually a hard-spike + hard-tail burst with a spectral lag of 0.8 ± 0.4 s during its tail emission. Thus, the properties of the prompt emission of GRB 060614 and GRB 080503 are clearly different, motivating further thinking of GRB classification (and even identification of faint core-collapse SNe). Finally, we note that, whereas the progenitor of the two SN-less bursts remains uncertain, the core-collapse origin for the SN-less bursts would be quite certain if a windlike environment can be observationally established, e.g., from an optical decay faster than the X-ray decay in the afterglow’s slow cooling phase.

Key words: gamma rays: bursts – gamma rays: observations

Online-only material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe since the big bang. They fall into two (partially overlapping) populations according to their observed duration: γ-ray durations (measured as the time in which 90% of the fluence is emitted) longer than 2 s are defined as long-duration GRBs (LGRBs), while bursts with duration shorter than 2 s are defined as short-duration GRBs (SGRBs; Kouveliotou et al. 1993). It is widely accepted that at least the majority of LGRBs are driven by the collapse of massive stars (e.g., Woosley & Bloom 2006), although some LGRBs may be generated by the merger of compact objects (e.g., Kluźniak & Ruderman 1998; Rosswog et al. 2003). The strongest evidence for the collapsar scenario is the detection of bright Ic supernova (SN) component photometrically and spectroscopically associated with nearby LGRBs such as GRB 980425, GRB 030329, GRB 031203, and XRF 060218 (Galama et al. 1998; Hjorth et al. 2003; Malesani et al. 2004; Sollerman et al. 2006; Pian et al. 2006; Campana et al. 2006). On the other hand, SGRBs may be powered by the merger of binary compact objects (e.g., Eichler et al. 1989; Narayam et al. 1992). This connection is observationally bolstered by the association of some SGRBs with old stellar populations and lack of accompanying bright SN components in cases such as GRB 050509B (Hjorth et al. 2005a), GRB 050709 (Fox et al. 2005; Hjorth et al. 2005b), and GRB 050724 (Berger et al. 2005; Malesani et al. 2007). However, challenging this simple picture, some SGRBs displayed violent X-ray flares occurring at least ~100 s after the triggers, e.g., GRB 050709 (Fox et al. 2005) and GRB 050724 (Barthelmy et al. 2005; Campana et al. 2006; Malesani et al. 2007). This suggests long-lasting activity of the central engine and hence the current understanding of the GRB progenitor mechanism may be too simple (e.g., Fan et al. 2005; Dai et al. 2006; Rosswog 2007). There is also evidence for activity of the inner engine on much longer timescales (several days) for GRB 050709 (Watson et al. 2006) and GRB 070707 (Piranomonte et al. 2008).

The whole picture became more complicated after the discovery of GRB 060505 and GRB 060614, because both bursts are nearby LGRBs according to the conventional taxonomy but they are observationally not associated with SNe down to very strict limits (Fynbo et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006). In this sense, they share the expected observational properties of both conventional LGRBs and SGRBs. GRB 060505 had a fluence of $(6.2 ± 1.1) \times 10^{-7}$ erg cm$^{-2}$ in the 15–150 keV band, and a $T_{90}$ duration of 4 ± 1 s (Hullinger et al. 2006; McBreen et al. 2008). It was found to be associated with a bright, star-forming H II region within its host galaxy at $z = 0.089$ (Ofek et al. 2007; Thöne et al. 2008). In the compact-star merger scenario, the diameter of the H II region...
and the location of the GRB within it suggest that the delay time from birth to explosion of GRB 060505 was \( \lesssim 10 \) Myr. This is marginally matching the lower limit of the delay-time region for SGRBs (Ofek et al. 2007). On the other hand, the age of the H II region of \( \sim 6 \) Myr (Thöne et al. 2008) and is consistent with the expectation for core-collapse in a massive star. The prompt emission of GRB 060614 consisted of a hard-spectrum component lasting \( \sim 5 \) s followed by a soft-spectrum component lasting \( \sim 100 \) s. Mangano et al. (2007) reported a photon index \( \Gamma = 1.63 \pm 0.07 \) for the time interval \([-2.83, -5.62]\) s since the BAT trigger (\( \chi^2 / \text{dof} = 48.2/56 \)) and \( \Gamma = 2.21 \pm 0.04 \) for \( 5.62-97.0 \) s since the BAT trigger (\( \chi^2 / \text{dof} = 40.9/56 \)). The fluences in the two components are \((3.3 \pm 0.1) \times 10^{-6} \) erg cm\(^{-2}\) and \((1.69 \pm 0.02) \times 10^{-5} \) erg cm\(^{-2}\) in the 15–350 keV band, respectively (Gehrels et al. 2006). Its host galaxy has a redshift of \( z = 0.125 \) (Price et al. 2006). The host of GRB 060614 is very faint with an absolute magnitude of about \( M_B = -15.3 \) (Fynbo et al. 2006). Its specific star formation rate is quite low, but within the range covered by LGRB hosts (similar, e.g., to that of the GRB 050824 host galaxy; Sollerman et al. 2007).

The spectral lag has been invoked as a quantity that can be used to classify bursts such that SGRBs have zero lag and LGRBs fall on a well-defined lag–luminosity relation (Norris et al. 2000; Norris & Bonnell 2006). For GRB 060614, Gehrels et al. (2006) found that the spectral lags for the hard and soft components in the prompt \( \gamma\)-ray emission are both consistent with zero lag, falling entirely within the range for SGRBs. For GRB 060505, on the other hand, McBreen et al. (2008) found using the Suzaku/WAM and Swift/BAT data that the spectral lag for the prompt \( \gamma\)-ray emission is \( 0.36 \pm 0.05 \) s, consistent with an LGRB identity. Furthermore, lags of LGRBs and SGRBs, regardless of their physical origins, appear to overlap quite significantly according to statistics of 265 Swift bursts (see Figure 1 in Bloom et al. 2008). Alternatively, the so-called Amati relation can be used to provide hints on which class GRB 060505 and GRB 060614 belong to. According to this relation derived from the observed GRBs with sufficient data, all SGRBs are outliers because of their relatively higher \( v F_\nu \) peak energy, while all LGRBs, except the peculiar long GRB 980425, are consistent with this relation. Amati et al. (2007) find that GRB 060614 follows the relation whereas GRB 060505 does not. Hence, based on properties of the prompt emission other than the duration, it seems impossible to establish clear evidence about which class of bursts GRB 060505 and GRB 060614 belong to.

To gain further insight on this topic, in this work we add our own observational data to already published data and study the afterglows of GRB 060505 and GRB 060614. We aim to determine from the afterglow properties whether these two bursts differ from other LGRBs, besides being SN-less, to provide further clues to the nature of their progenitors. The observations of the two afterglows and data reduction are presented in Sections 2.1 and 2.2. At the beginning of Section 3, we briefly introduce the leading external shock wave model employed to explain GRB afterglows, and apply it to GRB 060505 in Section 3.1. GRB 060614 has been studied by Mangano et al. (2007); in Sections 3.2 and 3.3, we re-analyze this burst and provide analytical and numerical constraints on the afterglow parameters, respectively. In Section 4, we discuss possible progenitors of these two bursts in comparison with the recently discovered GRB 080503, which we define as the first hard-spike + hard-tail Swift GRB.

Throughout this paper, we use the notation \( F_\nu (\tau) \propto \tau^{-\alpha} \nu^{-\beta} \) for the afterglow monochromatic flux as a function of time, where \( \nu \) represents the observed frequency and \( \beta \) is the energy index which is related to the photon index \( \Gamma \) in the form of \( \beta = \Gamma - 1 \). The convention \( Q_x = \langle Q \rangle / 10^4 \) has been adopted in cgs. In addition, we consider a standard cosmology model with \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.3 \), and \( \Omega_\Lambda = 0.7 \).

### 2. OBSERVATIONS AND DATA REDUCTION

#### 2.1. GRB 060505

The field of GRB 060505 was observed with the European Southern Observatory (ESO) Very Large Telescope (VLT) and the FORS1 instrument on two epochs (see also Fynbo et al. 2006). On May 6.4, slightly more than one day after the burst, the field was observed in the \( B, V, R, I \), and \( z \) bands. In order to be able to subtract the underlying host galaxy, in particular the hosting star-forming region within the host galaxy (Thöne et al. 2008), the field was observed again on September 14.2, again in the \( B, V, R, I, \) and \( z \) bands. The journal of observations is given in Table 1. Due to strong fringing and lack of calibration data, we decided not to include the \( z \)-band data in the analysis.

The optical data were corrected for bias and flat-fielded using standard techniques. In order to subtract the underlying emission from the host galaxy, we used the ISIS software (Alard & Lupton 1998). In Figure 1, we show the result of the image subtraction. As can be seen, the afterglow is clearly detected in all four bands. We then performed photometry on the afterglow in the following way. We first duplicated an isolated, nonsaturated star in each of the first epoch images to a new empty position following way. We first duplicated an isolated, nonsaturated star in each of the first epoch images to a new empty position following the afterglow parameters, respectively. In Section 4, we discuss possible progenitors of these two bursts in comparison with the recently discovered GRB 080503, which we define as the first hard-spike + hard-tail Swift GRB.
Table 1
Log of Optical Observations of GRB 060505

| Time (day) | Bandpass | Vega Mag | σ (mag) | Instrument | Reference |
|-----------|----------|----------|---------|------------|-----------|
| 0.702     | UVW1     | >20.71   | ...     | UVOT       | 1         |
| 0.706     | U        | >20.31   | ...     | UVOT       | 1         |
| 0.721     | V        | >20.34   | ...     | UVOT       | 1         |
| 0.724     | UVM2     | >22.05   | ...     | UVOT       | 1         |
| 1.102     | r        | 21.65    | 0.16    | GMOS       | 1         |
| 1.118     | g        | 22.37    | 0.08    | GMOS       | 1         |
| 1.125     | I        | 21.21    | 0.04    | VLT+FORS1  | 2         |
| 1.125     | R        | 21.74    | 0.04    | VLT+FORS2  | 2         |
| 1.125     | V        | 22.14    | 0.04    | VLT+FORS1  | 2         |
| 1.125     | B        | 22.48    | 0.04    | VLT+FORS1  | 2         |
| 7.041     | g        | >24.74   | ...     | GMOS       | 1         |
| 7.055     | r        | >24.02   | ...     | GMOS       | 1         |
| 9.078     | g        | >24.54   | ...     | GMOS       | 1         |
| 9.092     | r        | >24.32   | ...     | GMOS       | 1         |
| 9.105     | i        | >22.96   | ...     | GMOS       | 1         |
| 18.0      | R        | >24.95   | ...     | VLT+FORS2  | 3         |
| 21.1      | R        | >24.05   | ...     | D1.5m+DFOSC| 3         |
| 23.1      | R        | >23.95   | ...     | D1.5m+DFOSC| 3         |
| 25.3      | R        | >25.15   | ...     | Keck+LRIS  | 3         |
| 31.1      | R        | >23.75   | ...     | D1.5m+DFOSC| 3         |
| 48.1      | R        | >23.35   | ...     | D1.5m+DFOSC| 3         |

Notes.

a Time since BAT trigger.

b The Vega magnitude is after correction for the Galactic extinction of $E(B-V) = 0.02$ mag, and image subtraction to remove the host contribution.

References. (1) Ofek et al. 2007; (2) This work; (3) Fynbo et al. 2006.

Swift/UVOT data points/upper limits and the late X-ray data point using the ACIS-S detector on board the Chandra X-Ray Observatory in Ofek et al. (2007).

2.2. GRB 060614

Table 2 shows the comprehensive R-band data of the afterglow of GRB 060614 from the Watcher 0.4 m telescope, DFOSC at the Danish 1.5 m telescope (D1.5m), the 1 m telescope at the Siding Spring Observatory (SSO), VLT/FORS1, and VLT/FORS2. The R-band data by the Watcher telescope were processed and made public for the first time, which not only are consistent with other R-band data but provide the accurate peak time, 0.3 days after the BAT trigger, of the R-band afterglow light curve. We have applied the correction for the Galactic extinction, $E(B-V) = 0.057$ mag (Schlegel et al. 1998), and subtracted the contribution of host galaxy, $R_{\text{host}} = 22.46 \pm 0.04$ (Della Valle et al. 2006).

We collected Swift/UVOT data from Mangano et al. (2007). For the UVOT bands, we also applied the correction for Galactic extinction and subtracted the contribution of host galaxy using the template in Mangano et al. (2007).

The Swift/XRT light curve and spectrum data were collected from the UK Swift Science Data Centre (Evans et al. 2007). The X-ray light curves at 0.3 keV and 1.5 keV are shown in Figure 5 so that the spectral slope, $\beta_X \sim 0.89$, in the 0.3–10 keV band is taken into account when we performed the numerical fitting.

The Swift/BAT light curve in the 15–350 keV band was processed with the batgrbproduct task of the HEAsoft 6.5.1.

3. INTERPRETATION OF THE TWO AFTERGLOWS

Suppose the radial density profile of the circumburst medium takes the form $n(r) \propto r^{-k}$, then $k = 0$ if the medium is interstellar medium-like (ISM-like), while $k = 2$ if the medium stellar wind-like (WIND-like).

We use the standard fireball afterglow theory reviewed by, e.g., Piran (2005), with the simple microphysical assumptions of constant energy fractions imparted to the swept-up electrons, $\epsilon_e$, and to the generated magnetic field, $\epsilon_B$, respectively. For the evolution of the synchrotron spectrum, we adopt the prefactors of Equation (1) in Yost et al. (2003) for the ISM scenario, and
those of Equations (11)–(14) in Chevalier & Li (2000) for the WIND scenario. We note that both cases lead to the afterglow closure relations made of the temporal decay index $\alpha$ and the spectral index $\beta$, depending upon the spectral segment and the electron energy distribution index, $p$ (see Tables II and IV of Piran 2005).

For numerical calculation, we follow the general treatment of Huang et al. (2000) and Fan & Piran (2006), that is, one first calculates the overall dynamical evolution of the GRB outflow, and then calculates the synchrotron radiation at different times, including different corrections such as, e.g., the equal-arrival-time-surface effect and the synchrotron-self-absorption effect.

3.1. Constraints on GRB 060505

To establish a broadband spectral energy distribution (SED), we extrapolate the X-ray flux to the epoch of the optical data (i.e., 1.125 days after the burst). The optical data were corrected for foreground Galactic extinction of $A_B = 0.089$, $A_V = 0.068$, $A_G = 0.055$, and $A_I = 0.040$ (Schlegel et al. 1998). We fit the SED in count space (see Starling et al. 2007) with an absorbed power-law model, where Galactic absorption in the X-rays is fixed at $N_H = 1.8 \times 10^{20} \text{ cm}^{-2}$ (Kalberla et al. 2005) and intrinsic X-ray absorption and optical/UV extinction in the host galaxy are free parameters. Solar metallicity is assumed in the X-ray absorption model, and extinction in the host is assumed to be SMC-like (Pei 1992). The resulting SED is shown in Figure 2. The derived spectral slope is $\beta_{\text{OX}} = 0.97 \pm 0.03$. The host galaxy extinction is consistent with zero, but with a best-fitting value of $E(B-V) = 0.015 \text{ mag}$ and a 90% upper limit of $E(B-V) = 0.05 \text{ mag}$, while the X-ray absorption is found to be $N_H = (0.2^{+0.2}_{-0.1}) \times 10^{22} \text{ cm}^{-2}$ (where errors are quoted at the 90% confidence level). The fit has a $\chi^2$/dof of 5.3/4.

The index $\beta_{\text{OX}} = 0.97 \pm 0.03$ indicates that the cooling frequency $v_c$ is already below the optical at this time and the energy spectral index $p$ is slightly larger than 2. Indeed, the numerical fit, shown in Figure 3, yields $p \sim 2.1$, and other afterglow parameters are $n \sim 1 \text{ cm}^{-3}$, $\epsilon_e \sim 0.1$, $\epsilon_B \sim 0.006$, and $E_k \sim 2.8 \times 10^{50} \text{ erg}$, and the half-opening jet angle $\theta_j \sim 0.4 \text{ rad}$. These parameters are within the range of LGRB afterglows, but the limited data prevent us from getting more insight on the properties of this afterglow. Both the SED measurement and the numerical fit tend to render it unnecessary to employ ad hoc models (e.g., macronova in Ofek et al. 2007) to interpret this afterglow.

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3.2. Preliminary Constraints on GRB 060614

We constructed afterglow SEDs in GRB 060614 at three epochs, i.e., 0.187 days, 0.798 days, and 1.905 days from top to bottom. A broken power law is only required during the first epoch. Refer to Table 3 for detailed measurements.

(A color version of this figure is available in the online journal.)
change the SED during this period. If the injection frequency is between the optical and the X-ray, then it may lead to that the light curves have a very shallow rising in the optical band and a very shallow decay in the X-ray band. Indeed, the observational data fit this interpretation very well (Mangano et al. 2007). We found that this optical-to-X-ray light curve behavior still holds after performing different corrections. The result of our analysis shows that a flat or gradually increasing light curve is generally a description as good as a slow decaying except in the X-ray band. A temporal peak, clearly shown in optical bands, exists to constrain the afterglow properties we use data after ~0.26 days.

The index $\beta_{OX} \sim 0.8$ after ~0.26 days indicates that the afterglow is in the slow cooling case of

$$v_a < v_m < v_O < v_X < v_c$$

until at least a few days. Using the afterglow closure relations, we find $\beta = (p - 1)/2 \sim 0.8$, which gives the energy spectral index $p \sim 2.6$, which then gives the decay index $\alpha = 3(\rho - 1)/4 \sim 1.2$, in good agreement with the observed decay law ($\alpha \sim 1.1$). Furthermore, this $p$ value of ~2.6 is very close to the observed decay index of 2.5 after $t_\delta \sim 1.4$ days, in good agreement with the theoretically predicted decay law after a jet break, i.e., $\alpha \sim p$ at any wavelength from X-ray to optical. Therefore, as discussed by Mangano et al. (2007), the break at $t \sim 1.4$ days is likely the so-called jet break (Rhoads 1999; Sari et al. 1999; Zhang et al. 2006; Nousek et al. 2006).

Since the optical decay is never faster than the X-ray decay, there is no indication of a WIND-like circumburst medium for this afterglow. Also since radio data are not available, analytical constraint on $v_a$ is impossible for this afterglow. Using the earliest useful data, we put a lower limit on $F_v^{\text{max}}$ and an upper limit on $v_m$ as

$$F_v^{\text{max}} = 1.6(z + 1)D_L^{-2}E_{52}^{0.5}E_{52}n^{-0.5} > 105.5 \times 10^{-3}\text{mJy}$$

and

$$v_m = 3.3 \times 10^{14} (z + 1)^{0.5} \epsilon_{B-2}^{-0.5}E_{52}^{0.5}t_d^{-1.5} < 4.69 \times 10^{14}\text{Hz},$$

(2)

where $t_d = 0.3$ and $z = 0.125$. Using the latest useful data, we put the lower limit on $v_c$ as

$$v_c = 6.3 \times 10^{15} (z + 1)^{-0.5} \epsilon_{B-2}^{-1.5}E_{52}^{-0.5}n^{-1}t_d^{-0.5} > 10^{18}\text{Hz},$$

(3)

where $t_d = 10$. In detail, the above three equations give rise to the constraints

$$\epsilon_{B-2}^{-0.5}E_{52}n > 0.0019$$

$$\epsilon_{B-2}^{-0.5}E_{52}^{0.5} < 1.564$$

$$\epsilon_{B-2}^{-0.5}E_{52}^{-0.5}n^{-1} > 532.4.$$  

3.3. Numerical Constraints on GRB 060614

We find that the afterglow data can be reasonably reproduced by the following parameters (see Figure 5 for a plot of our fit): $p \sim 2.5$, $\epsilon_r \sim 0.12$, $\epsilon_B \sim 0.0002$, $E_k \sim 6 \times 10^{50}$ erg, $n \sim 0.04$ cm$^{-3}$, and $\theta_j \sim 0.08$ rad. The energy injection takes place at $t_\delta \sim 8 \times 10^2$ s and ends at $t_r \sim 2 \times 10^4$ s after the burst, and the energy injection is nearly a constant with a rate $L_{\text{ej}} \sim 1.2 \times 10^{48}\text{ergs}^{-1}$. Substituting these parameters into Equation (8), the numerical constraint is in agreement with the analytical constraint.

If the energy injection is from the wind of a millisecond magnetar, to fit the observational data at the late stage of the whole energy injection period, the magnetar is required to have dipole radiation $L_{\text{dip}}(t) \sim 2.6 \times 10^{38}/(1 + z)$ erg s$^{-1}B_{14}^2R_6^2\Omega_{45}^{1.5}(1 + t/(1 + z)T_c)^{-2}$, where $B_1$ is the dipole magnetic field strength of the magnetar, $R_6$ is the radius of the magnetar, $\Omega$ is the initial angular frequency of radiation, $T_c = 1.6 \times 10^4 B_{14}^{-2}\Omega_{45}^{-2}I_{45}R_s^{-6}$ s is the initial spin-down timescale of the magnetar, and $I \sim 10^{45}$ g cm$^2$ is the typical moment of inertia of the magnetar (Pacini 1967). However, because the optical flux is roughly proportional to $E_k$, where $E_k$ is the sum of the isotropic-equivalent kinetic energy $E_k$ and the injected energy, then the predicted

| Model     | $E(B-V)$ (mag) | $N_{HI}$ (10$^{22}$ cm$^{-2}$) | $\Gamma_1$ | $E_{52}$ (keV) | $\Gamma_2$ | $\chi^2$/dof |
|-----------|---------------|-------------------------------|-----------|---------------|-----------|--------------|
| Epoch 1   |               |                               |           |               |           |              |
| PL+SNC    | <0.02         | <0.02                         | 1.75 ± 0.02 | ...           | ...       | 60/68        |
| BKNPL+SNC | <0.2          | 0.03±0.02                     | 0.9 ± 0.4  | 0.005±0.010   | 1.9 ± 0.1  | 49/66        |
| BKNPL+SNC | <0.04         | 0.03±0.02                     | 1.01 ± 0.01| 0.012±0.01    | 1.86±0.02  | 50/67        |
| Epoch 2   |               |                               |           |               |           |              |
| PL+SNC    | <0.04         | <0.03                         | 1.78±0.02  | ...           | ...       | 42/36        |
| BKNPL+SNC | 0.3±0.2       | 0.10±0.04                     | <1.3       | 0.005±0.025   | 2.2 ± 0.2  | 27/34        |
| BKNPL+SNC | <0.08         | 0.09±0.03                     | 1.3±0.1    | 2.1±0.2       | 31/35      |
| Epoch 3   |               |                               |           |               |           |              |
| PL+SNC    | 0.09±0.06     | 0.06±0.03                     | 1.81 ± 0.04| ...           | ...       | 26/35        |
| BKNPL+SNC | 0.2±0.1       | 0.08±0.03                     | >0.1       | unbounded     | 1.9 ± 0.1  | 24/33        |
| BKNPL+SNC | 0.13±0.07     | 0.07±0.03                     | <0.008     | 1.86±0.07     | 24/34      |
Figure 5. Temporal light curves for the prompt phase (upper panel) and for the afterglow (lower panel) of GRB 060614. Upper panel: the prompt light curve in the 15–350 keV band, consisting of a hard spike of duration \( \sim 5 \) s and a soft tail of \( \sim 100 \) s. Lower panel: numerical fit to the afterglow light curves which consists of an episode of energy injection enclosed by two vertical dashed lines. For clarity, the shown flux densities in the \( R, V, B, U, \text{UVW1}, \text{UVW2}, \text{UVM2}, \text{UVW2} \) 0.3 keV, and 1.5 keV bands are \( 10^3, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 2 \times 10^{-7}, \) and \( 10^{-7} \) times that of their real flux densities, respectively. In our model, the energy injection corresponds to the soft tail in the prompt phase while the main afterglow corresponds to the hard spike—this correlation is illustrated by two arrows from the upper prompt panel to the lower afterglow panel.

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

optical flux at the early stage of the energy injection period (e.g., \( t \sim 0.02 \) days in Figure 5) would be much higher than the observed flux. In detail, at \( t \sim 0.02 \) days, there would be \( \bar{E}_k \sim E_k + L_{\text{inst}} t \sim 3E_k \), indicating that the predicted optical flux should be \( \sim 3 \) times the observed flux. Therefore, the magnetar model is not convincing.

Note that the prompt \( \gamma \)-ray light curve may have two components: the earlier hard spike with an isotropic energy \( E_{\gamma,h} \sim 3.7 \times 10^{50} \) erg and the latter soft tail (sometimes called extended emission) with an isotropic energy \( E_{\gamma,s} \sim 1.7 \times 10^{51} \) erg. The early part is spectrally hard thus the outflow might be ultrarelativistic, while the latter part is spectrally soft suggesting the bulk Lorentz factor of the outflow became lower. This is because the optically thin condition yields a lower limit on \( \Gamma \geq 20(L_{\text{outflow}}/10^{50} \text{ erg s}^{-1})^{1/2} \delta t^{-1/5} \), where \( L_{\text{outflow}} \) is the total luminosity of the outflow, and \( \delta t \) is the typical variability timescale of the late soft \( \gamma \)-ray emission (Rees & Meszéras 1994). In our numerical calculation, we find the bulk Lorentz factor of the forward shock \( \Gamma \sim 26 \) at \( t \sim 10^3 \) s, while \( \Gamma \sim 16 \) at \( t \sim 2 \times 10^4 \) s. If the energy carried by the material of the late-time GRB ejecta satisfies the relation \( E(\geq \Gamma) \propto \Gamma^{-5} \) (Rees & Meszéras 1998) for \( 16 < \Gamma < 26 \), the constant energy injection form taken in the afterglow modeling can be reproduced (Zhang et al. 2006). In this model, for the outflow accounting for the hard spike emission, the energy efficiency is \( \sim E_{\gamma,h}/(E_{\gamma,h} + E_k) \sim 40\% \), while for the outflow accounting for the soft tail emission, the energy efficiency is \( \sim E_{\gamma,s}/[L_{\text{inst}}(t_e - t_i) + E_{\gamma,s}] \sim 8\% \). The decreasing efficiencies from early spike to late tail may be due to the smaller contrast between the Lorentz factors of the fast material and that of the slow material.

4. DISCUSSION AND CONCLUSION

As shown in several early papers, for GRB 060505 (Fynbo et al. 2006) and GRB 060614 (Fynbo et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006) there is no accompanying SN emission, down to limits hundreds of times fainter than the archetypical SN 1998bw that accompanied GRB 980425, and fainter than any Type Ic SN ever observed. Multimwavelength observations of the early afterglow exclude the possibility of significant dust obscuration. For GRB 060505 the properties of the host galaxy (Ofek et al. 2007; Thöne et al. 2008) as well as the spectral lag of the prompt emission (McBreen et al. 2008) is most consistent with the properties expected for the long-duration class of GRBs. For GRB 060614 the duration of the prompt emission places the burst firmly within the long-duration class of GRBs, but the negligible spectral lag (Gehrels et al. 2006) and the relatively modest star formation activity of the host galaxy is more similar to the expected properties for the short-duration class of GRBs. In this paper, we have investigated whether or not the properties of the two afterglows could provide some hints to the most likely progenitor types for these bursts.

For GRB 060505, the numerical fit of its afterglow shows that the standard jetted external shock wave model is consistent with the data, yielding a typical ISM density of \( n \sim 1 \text{ cm}^{-3} \), a wide jet angle of \( \theta_j \sim 25^\circ \), and a possible jet break at \( t_b \sim 3 \) days. For GRB 060614, the standard external shock wave model is again consistent with the data, but apparently needing to invoke energy injection. The afterglow shows the clearest achromatic jet break among all Swift bursts studied so far, decaying in a broken power law from \( \alpha_1 \sim -1.1 \) to \( \alpha_2 \sim -2.5 \) at \( t_b \sim 1.4 \) days. An
spikes are consistent with zero; the lag for the tail of GRB 060614 is consistent with zero, while the lags for the tail of GRB 080503 are 0.

energy bins, shown in Figure 6, for comparison study. For GRB 080503, we extracted the BAT light curves in different

T tail structure in the prompt emission phase. The

the new classification. This burst also has a temporal spike +

and is applicable to GRB 060505 and GRB 060614, which then

classification expands the range of the conventional short class,

GRBs, or Type II, would comprise the conventional long class

(possible) long-soft tail would be ascribed to the conventional

proposed, in which GRBs featuring a short-hard spike and a

of short (<2 s) and long (≥2 s) GRBs, a new classification was

After discovery of these two GRBs, to reconcile all SN-

of other LGRBs. If it had not been for the observed absence of associated SNe we would have no reason,

from the afterglow properties, to question their classification as

achromatic peak, especially in the UBV bands, occurs at ~0.3
days, which we interpret as resulting from an episode of strong

energy injection as Mangano et al. (2007) suggested. Numerical

fit yields a circumburst density of n ~ 0.04 cm⁻³ and a jet angle

of θj ~ 5°. The inferred afterglow parameters for the two bursts

fall within the range for other LGRBs. If it had not been for the

observed absence of associated SNe we would have no reason,

from the afterglow properties, to question their classification as

LGRBs.

After discovery of these two GRBs, to reconcile all SN-

observed and SN-less GRBs within the conventional framework

of short (<2 s) and long (≥2 s) GRBs, a new classification was

proposed, in which GRBs featuring a short-hard spike and a

(possible) long-soft tail would be ascribed to the conventional

short class, or Type I in the new taxonomy, while all other

GRBs, or Type II, would comprise the conventional long class

(Zheng et al. 2007; see also Kann et al. 2007). The new

classification expands the range of the conventional short class,

and is applicable to GRB 060505 and GRB 060614, which then

would be SN-less due to a merger-related progenitor rather than

SN-less massive stellar death.

However, a recent burst, GRB 080503, seems to challenge

the new classification. This burst also has a temporal spike +
tail structure in the prompt emission phase. The T90 values of

the initial spike and the total emission in the 15–150 keV

band are 0.32 ± 0.07 s and 232 s, respectively (Perley et al.

2009). The fluence of the nonspike emission measured from

5 s to 140 s after the BAT trigger in the 15–150 keV band is

0.04 erg cm⁻², being around 30 times that of the spike emission in the same band. This fluence ratio is much

higher than the ratio of around 6 for GRB 060614, and higher

than any previous similar Swift GRB. For GRB 060614 and

GRB 080503, we extracted the BAT light curves in different

energy bins, shown in Figure 6, for comparison study. For

GRB 080503 we have analyzed the spectral evolution during the

prompt emission period by BAT and XRT and list our analysis

and that of other groups in Table 4. From these we conclude

that (1) the results of different groups are fully consistent

with each other. (2) The photon indices for the spike and

nonspike emissions are consistent within their error regions

(90% confidence level). A strong spectral softening from the

spike phase to the nonspike phase can be excluded. A cutoff

power-law fit does not improve the fitting, yielding the error of

Epeak larger than 100%. (3) During the BAT–XRT overlap period,

the XRT spectra are always harder than the BAT spectra, which

implies that the BAT + XRT spectra (0.3–150 keV) would be

harder than the BAT spectra (15–150 keV) alone. This adds

Table 4

Comparison of Power-law Spectral Evolution for GRB 060614 and
GRB 080503

| GRB       | Time Interval (s) | Photon Index | Error² | χ²/dof | Bandpass (keV) | Reference |
|-----------|------------------|--------------|--------|--------|----------------|-----------|
| GRB 060614 | 2.83–5.62        | 1.63         | 0.07   | 48.2/56 | 15–150         | 1         |
| ···        | 5.62–97.0        | 2.21         | 0.04   | 40.9/56 | 15–150         | 1         |
| ···        | 97.0–176.5       | 2.37         | 0.13   | 42.6/56 | 15–150         | 1         |
| GRB 080503 | 0.2–0.6          | 1.74         | 0.28   | 78.1/58 | 15–150         | 2         |
| ···        | 10–200           | 1.93         | 0.14   | 38.3/58 | 15–150         | 2         |
| ···        | 0.0–0.7          | 1.59         | 0.28   | 69/59   | 15–150         | 3         |
| ···        | 10–170           | 1.91         | 0.12   | 52/59   | 15–150         | 3         |
| ···        | 81–282           | 1.27         | 0.03   | 59/32   | 15–150         | 3         |
| ···        | 81–280           | 1.33         | 0.05   | 696/714 | 0.3–10         | 4         |
| ···        | 83–107           | 1.00         | 0.13   | 3/0.3   | 0.3–10         | 5         |
| ···        | 107–128          | 1.11         | 0.13   | 3/0.3   | 0.3–10         | 5         |
| ···        | 128–150          | 1.42         | 0.14   | 3/0.3   | 0.3–10         | 5         |
| ···        | 150–185          | 1.66         | 0.16   | 3/0.3   | 0.3–10         | 5         |
| ···        | 185–256          | 1.77         | 0.16   | 3/0.3   | 0.3–10         | 5         |

Note. a Errors are quoted at the 90% confidence level.

References. (1) Mangano et al. 2007; (2) This work; (3) Mao et al. 2008; (4) The UK Swift Science Data Centre; (5) Perley et al. 2009.
more evidence that from spike to nonspike the spectra did not soften considerably. In addition, note that for all conventional LGRBs (e.g., from BATSE), there is a general trend that the spectra during the prompt emission would soften mildly from the beginning time to the ending time (Norris et al. 2000). Therefore, the prompt spectral evolution of GRB 080503 is different from that of GRB 060614.

In addition, we computed the spectral lags in different energy bands using the 64 ms binning light curves, following the method in Norris et al. (2000) and Chen et al. (2005). The lag during the initial spike phase is consistent with zero. From 5 to 50 s since BAT trigger, the lags are $8.0^{+0.3}_{-0.4}$ s for the 25–50 keV versus 15–25 keV band and $8.0^{+0.4}_{-0.5}$ s for the 50–100 keV versus 15–25 keV band, respectively, both well above the lag range for SGRBs. Again the lag of GRB 080503 is in contrast with that of GRB 060614. The redshift of GRB 080503 was not measured mainly because its optical afterglow became very faint shortly after its BAT trigger, but the g-band photometric detection imposes a limit of approximately $z < 4$ (Perley et al. 2009). In Figure 7, we show the possible location of GRB 080503 in the spectral lag–peak luminosity plane relative to the locations of previous LGRBs and SGRBs. As can be seen, for the extended emission of GRB 080503, its position is outside the SGRB population at a very high confidence level regardless of its redshift. For the spike emission of GRB 080503, its position is within the SGRB population because of a peak luminosity comparable to that of the extended emission while a negligible spectral lag.

As Perley et al. (2009) point out, the very faint optical and X-ray afterglows of GRB 080503 (never exceeding 25 mag in deep observations starting at $\sim 1$ hr after the BAT trigger) may indicate the circumburst density is very low. This is consistent with the fact that the afterglow is located away from any host galaxy down to 28.5 mag in deep Hubble Space Telescope imaging. The redshift of GRB 080503 is unknown, with an upper limit of about 4. These observational signatures contribute to put GRB 080503 into the merger class. If we ignore the lag function in classifying GRBs and relax the restriction of “soft-tail” for a Type I GRB to “either soft- or hard-tail,” then it would be (even more) ambiguous, also operationally difficult to define the type of spike + tail GRBs among all long GRBs, especially among those at $z > 0.7$ for which an SN search in their afterglows is difficult or impossible. Bearing in mind that GRBs can be either luminous or underluminous, and the redshift could be either high or low, then the problems would be: up to what duration should be classified as a spike, and how much should the flux ratio be for the spike component over the nonspike component? If GRB 080503 is interpreted as a merger burst, then it enhances the possibility that a merger could produce a long GRB, at least in the prompt emission phase, mimicking the one produced by a collapsar. GRB 080503 is a dark burst with the optical–to-X-ray spectral slope $\beta_{XX}$ well below 0.5, the critical value for defining a dark burst (Jakobsson et al. 2004), at 0.05 days after the burst. We speculate that some other dark bursts may have their progenitor same as GRB 080503.

The progenitors of GRB 060505 and GRB 060614 remain uncertain based on their observations and the current GRB and SN theory. Other than the lack of an SN component, their afterglows are actually not peculiar when compared with the afterglows of other LGRBs. According to the current theoretical study, in the core-collapse scenario the “fallback”–formed black holes or progenitors with relatively low angular momentum could produce such SN-less GRBs (e.g., Nagataki et al. 2003; Fryer et al. 2006; Sumiyoshi et al. 2006; Tominaga et al. 2007; Nakazato et al. 2008; Kochanek et al. 2008; Valenti et al. 2009 for observational existence of an extremely faint Type Ibc SN), or in the merger scenario the two compact objects also could produce such SN-less GRBs if the formed remnant, a differentially rotating neutron star or an uniformly rotating magnetar, has not collapsed into a black hole immediately (Kluźniak & Ruderman 1998; Rosswog et al. 2003). A difference existing in the afterglows between these two scenarios is that the collapsar model predicts a WIND-like circumburst medium created by the Wolf–Rayet progenitor star, while the merger model does not. As a matter of fact, the WIND signature is not clearly evident in most LGRBs, but this should not necessarily lead to the merger origin for these bursts because the definite WIND signature is an ideal case for a constant wind off a massive star. If lucky enough, the core-collapse origin for an SN-less GRB (no matter whether it has the hard-spike + soft-tail structure) will be quite certain if in the afterglow, either the X-ray flux $F_X(t)$ decays as $\propto t^{-\alpha}$ with its spectrum as $\propto \nu^{-\alpha(2\alpha-1)/3}$ for the $v_m < v_X < v_c$ stage (normally in early afterglow), or the optical decay index is larger than the X-ray decay index by a factor of $\sim 1/4$ for the slow cooling phase of the WIND scenario.

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