Messages from GRB 060218

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GRB 060218 is a watershed event. Statistically, its detection suggests that there is likely a distinct low-luminosity (LL) population of gamma-ray bursts (GRBs) whose event rate is much higher than that of conventional high-luminosity GRBs. This LL population may give significant contribution to the diffuse neutrino background flux at energies higher than $10^{16}$ eV. The spectral lag of this burst is very long, and roughly follows the luminosity–lag relation of normal GRBs. This, along with the fact that it follows the $E_p$–$E_{iso}$ relation as well, suggests that X-ray flashes (XRFs) are natural extension of GRBs in the softer regime and that GRBs and XRFs share the same radiation physics. We discuss how the broadband data pose strong constraints on possible models of the prompt emission of this GRB.

Keywords: gamma-ray bursts; X-ray emission; neutrino; luminosity function

1. Introduction

GRB 060218 was a unique event detected by Swift (Campana et al. 2006). It has a very smooth lightcurve with extremely long duration ($T_{90} \sim 2000$ s), a very low luminosity ($L_{iso} \sim 10^{47}$ ergs s$^{-1}$) and a very low redshift ($z=0.0331$, Mirabal et al. 2006)—the second lowest after GRB 980425/SN 1998bw at $z=0.0085$ (Galama et al. 1998). Similar to GRB 980425, it is associated with a Type Ic supernova SN2006aj (Pian et al. 2006). A breakthrough made by the Swift panchromatic observation is the identification of a soft thermal component in the X-ray Telescope (XRT) spectrum (Campana et al. 2006). This thermal component has a temperature of $kT \sim 0.17$ keV and an evolving effective emission radius $R_{BB} \sim 10^{12}$ cm, which may be interpreted as the emission from the shock breakout of the supernova. The spectral fit to the BAT–XRT data indicates that the non-thermal component is a cut-off power law, with $E_p$ evolving from approximately 80 keV at the beginning towards approximately 5 keV at later times (Campana et al. 2006), suggesting an X-ray flash (XRT). Radio afterglow observations (Soderberg et al. 2006) reveal that the kinetic energy of this gamma-ray burst (GRB) is only moderate. This fact, together with the theoretical modelling of the SN spectra (Mazzali et al. 2006), suggests that the progenitor star of this event may not be massive enough to form a black hole and that the central engine is likely a neutron star.

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One contribution of 35 to a Discussion Meeting Issue ‘Gamma-ray bursts’.
2. Statistics: a distinct low-luminosity GRB component?

Within less than 10 years, two very low-\(z\) GRBs (980425 and 060218) have been discovered. The volume enclosed by \(z<0.033\) is very small, \(V_{z<0.033}\approx 0.01\) Gpc\(^3\). One can naively estimate the local event rate of these low-luminosity (LL) GRBs (\(\rho_{0}^{\text{LL}}\)) by \(\rho_{0}^{\text{LL}}V_{z<0.033}(T_{\text{Bepp}}^{\text{Bepp}}/4\pi + T_{\text{Swift}}^{\text{Swift}}/4\pi) \approx 2\), where \(T_{\text{Bepp}} \approx 6\) year and \(T_{\text{Swift}} \approx 1.5\) year are the operation times for the BeppoSAX and Swift missions, respectively, and \(\Omega_{\text{Bepp}}^{\text{Bepp}} \approx 0.123\) and \(\Omega_{\text{Swift}}^{\text{Swift}} \approx 1.33\) are the solid angles covered by the two missions, respectively. This rough estimate gives \(\rho_{0}^{\text{LL}} \approx 800\) Gpc\(^{-3}\) yr\(^{-1}\), which is much greater than the local event rate of the conventional high-luminosity (HL) GRBs of 1 Gpc\(^{-3}\) yr\(^{-1}\) (e.g. Schmidt 2001). Assuming this conventional event rate, the Poisson chance probability of detecting these two low-\(z\) events is only \(3.4\times 10^{-6}\). Even if one considers a simple extrapolation of the HL population to the LL regime (e.g. Guetta et al. 2004), the expected local rate is only up to 10 Gpc\(^{-3}\) yr\(^{-1}\). The Poisson probability of detecting GRB 980425 and GRB 060218 is only \(3.3\times 10^{-4}\). We note that the Poisson probability of detecting one low-\(z\) event (e.g. GRB 980425) is low but still not low enough to lead to a confident suggestion of a high event rate of LL-GRBs. It is the detection of GRB 060218 that greatly reduces the Poisson probability and makes the case much stronger.

A high event rate for LL-GRBs has been independently derived by several groups (e.g. Cobb et al. 2006; Liang et al. 2006; Pian et al. 2006; Soderberg et al. 2006). By investigating the one- and two-dimensional distributions of luminosity and red shift for a sample of GRBs with known red shift, we (Liang et al. 2006) have performed a detailed analysis to constrain the luminosity function of both HL and LL populations of GRBs. Our constrained luminosity function (figure 1a) suggests that LL-GRBs form a distinct new component in the GRB luminosity function. In order not to overpredict too many bursts with moderate luminosities (e.g. \(10^{48}\) to \(10^{49}\) erg s\(^{-1}\)) at moderate...
red shifts (e.g. \( z \approx 0.1 \)), the LL-GRB luminosity function must cut off sharply beyond \( L_b \approx 10^{47} \text{erg s}^{-1} \), so that LL-GRBs are not a simple extrapolation of HL-GRBs towards low luminosities. This bimodal distribution is also evident in the two-dimensional luminosity–red shift distribution of GRBs (figure 1b). While HL-GRBs are clustered in a ‘continent’, the two LL-GRBs form a distinct ‘peninsula’ or ‘island’ in the log \( L - \log z \) space. From the view that GRB 060218’s central engine may be a neutron star rather than a black hole (Mazzali et al. 2006; Soderberg et al. 2006), one would speculate that the apparent bimodal distribution in the luminosity function is related to the two distinct types of central engines involved, e.g. HL-GRBs involve black holes, while LL-GRBs involve neutron stars.

Although these individual LL-GRBs are less energetic and underluminous, due to their much higher event rate, they could give interesting contribution to various diffuse emission backgrounds. For example, assuming that LL-GRBs produce \( \gamma \)-rays in internal shocks similar to HL-GRBs, the protons in LL-GRBs would reach a similar efficiency as in HL-GRBs to produce high-energy neutrinos through photomeson interaction at the \( \Delta \)-resonance. Since the LL-GRBs tend to be X-ray flashes with a lower peak spectral energy \( E_p \), they tend to have dominant contribution at high energies. Calculations (Gupta & Zhang in press; Murase et al. 2006) suggest that the LL population would have a contribution to the diffuse neutrino background comparable to that of the HL population at low energies, and it would have the dominant contribution at energies above \( 10\text{ PeV} (10^{16}\text{ eV}) \).

3. Data analysis: GRB 060218 as a ‘standard’ burst

Amati et al. (submitted) demonstrated that GRB(XRF) 060218 well satisfies the \( E_p \propto E_{\text{iso}}^{3/2} \) relation (Amati relation) discovered in conventional GRBs (Amati et al. 2002), which also extends to some previously observed X-ray flash (XRFs) (Lamb et al. 2005). Here, \( E_p \) is the cosmological rest frame spectral peak energy and \( E_{\text{iso}} \) is the isotropic \( \gamma \)-ray energy. It is interesting to note that two other
nearby GRBs with SN associations, GRBs 980425 and 031203, do not satisfy the relation (Amati et al. submitted). However, Ghisellini et al. (2006) argue that should the softer emission of GRB 980425 be detected (e.g. by an instrument like Swift), the combined γ-ray X-ray analysis might also lead to an $E_p$, satisfying the Amati relation.

We (Liang et al. 2006) took another approach to access the ‘standardness’ of GRB 060218. After subtracting the thermal component discovered by Campana et al. (2006), we split the X-ray non-thermal emission into several different energy channels, i.e. (0.3–2), (2–5), (5–10) keV. Including also the Burst Alert Telescope (BAT) lightcurve (15–150 keV), we performed a detailed analysis of the temporal profiles and spectral lags of the burst. A clear lag of pulse profiles with energy (figure 2a) is revealed. By extrapolating a relation of the pulse peak time and the energy band to the BATSE energy band (which has been used by Norris et al. 2000 to study spectral lags of the BATSE bursts), we found that GRB 060218 has a very large spectral lag that roughly satisfies the empirical log $L$–$\tau$ correlation discovered by Norris et al. (2000) (figure 2b). By contrast, both GRB 980425 and GRB 031203 are also outliers of this relation.

This intriguing fact, along with its compliance with the Amati relation, strongly suggests that GRB 060218 is a ‘standard’ GRB extrapolated to the very faint, long and soft end of the distribution. One important remark is that this does not contradict the claim that LL-GRBs form a distinct population in the luminosity function distribution. Both the Amati relation and the Norris relation are directly related to the radiation mechanism of GRBs. While HL- and LL-GRBs could have different progenitors and central engines, they might well share the same radiation physics (e.g. synchrotron and inverse Compton scattering in internal shocks).

### 4. Theoretical modelling: constraints from the data

Thanks to multi-wavelength coverage by the three instruments on board the Swift satellite and the extremely long duration of the burst, GRB 060218 provides a unique opportunity for us to study the mechanism(s) of GRB jet emission and its association with the supernova explosion. It was suggested that the thermal component identified in the X-ray data is produced as the supernova shock breaks into the dense stellar wind surrounding the progenitor (Campana et al. 2006). Detailed modelling (Li 2007) however suggests that the shock breakout energy may not be as large as the one observed. The smooth non-thermal emission is likely not produced from synchrotron emission (Dai et al. submitted), since the UVOT flux is too low to be incorporated within the synchrotron model, unless self-absorption is invoked (Ghisellini et al. in press). To interpret the non-thermal emission, Dai et al. (submitted) suggest inverse Compton of electrons in an internal shock off the thermal photons. In order to suppress synchrotron emission, the magnetic field equipartition parameter $\varepsilon_B$ needs to be small. Wang et al. (submitted) interpret the non-thermal emission as due to bulk Compton scattering of a mildly relativistic ejecta off the shock breakout thermal photons. Within this picture, no shock is needed and the radiation mechanism of these LL-GRBs is likely different from that of
conventional HL-GRBs. It is however unclear why GRB 060218 satisfies both the Amati relation and the Norris relation. Finally, Fan et al. (2006) suggest that the ‘afterglow’-like power law decay component in the XRT data (Campana et al. 2006) might be a central engine afterglow. The nature of the prompt emission is however not addressed.

A successful model needs to satisfy the following constraints: (i) the optical flux is suppressed, (ii) a low spectral peak energy $E_p$ satisfying the Amati relation (Amati et al. submitted), (iii) a long duration with a long spectral lag roughly satisfying the Norris relation (Liang et al. in press), and (iv) the existence and evolution of the soft thermal component identified in both XRT data and UVOT data (Campana et al. 2006). A consensus among modellers is that this event likely invokes a moderately relativistic jet. However, it is a challenging task to identify the correct model that satisfies all the above constraints.

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References


