Some Theoretical Implications of Short-Hard Gamma-Ray Burst observations

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Abstract

Short-hard and long-soft gamma-ray bursts (GRBs) are two distinct phenomena, but their prompt and afterglow emission show many similarities. This suggests that two different progenitor systems lead to similar physical processes and that the prompt and afterglow observations of short-hard GRBs (SHBs) can be examined using models of long GRBs. Here, I discuss three conclusions that can be drawn from SHB observations. I show that the lower limit on the Lorentz factor of SHBs is typically "only" $10 \sim 50$, significantly lower than that of long GRBs. SHBs with observed X-ray afterglow after 1 day are found to be roughly as efficient as long GRBs in converting the outflow energy into prompt gamma-rays. Finally, I examine the origin of SHBs with X-ray dark afterglows and find that the most plausible explanation is that these SHBs exploded in extremely low density environment ($n \lesssim 10^{-5}$ cm$^{-3}$).

1 Introduction

The distinct nature of short-hard gamma-ray bursts (SHBs; see Nakar, 2007, for a review) was confirmed last year with the detection of the first SHB afterglows (Gehrels et al., 2005; Castro-Tirado et al., 2005; Prochaska et al., 2005; Fox et al., 2005; Hjorth et al., 2005a,b; Bloom et al., 2006; Covino et al., 2006; Berger et al., 2005). These observations indicate that SHBs are associated with an old stellar population (Gehrels et al., 2005; Prochaska et al., 2005; Berger et al., 2005; Nakar, Gal-Yam & Fox, 2006; Guetta & Piran, 2006; Zheng & Ramirez-Ruiz, 2006; Shin & Berger, 2006). This is in contrast to long gamma-ray bursts (long GRBs), which are associated with young massive...
star progenitors (e.g., Fruchter et al., 2006) and likely produced along with a supernova during stellar core-collapse (e.g., Stanek et al., 2003; Hjorth et al., 2003). Therefore short and long GRBs originate from distinct progenitor systems. On the other hand short and long GRBs share many properties. There are many similarities between the temporal structure (McBreen et al., 2001; Nakar & Piran, 2002) and spectral properties (Ghirlanda, Ghisellini & Celotti, 2004) of the prompt emission of short and long GRBs. Observed SHB afterglows share many common features with those observed in long GRBs (Fox & Meszaros, 2006; Nakar, 2007). Therefore, it seems that two different progenitor systems lead to similar physical processes and that the prompt and afterglow observations of SHBs can be examined using models of long GRBs.

Here I discuss the interpretation of three such observations. First, I use the observations of SHB prompt emission in order to derive the lower limit on the Lorentz factors of the emission sources. Second, I roughly estimate the efficiency in which gamma-rays are produced in SHBs with observed late (∼1 d) X-ray afterglows and finally, I discuss different explanation to SHBs with X-ray dark afterglows. All these results and their implications are discussed in more details in Nakar (2007).

2 The Lorentz factor of the outflow

Perhaps the most prominent feature of GRBs is that they are ultra-relativistic sources. In the case of long GRBs this is a well-established result, relying on several independent evidence. The main indication of high Lorentz factor in long GRBs is the opacity constraint, where a lower limit on the Lorentz factor is set by requiring that the source of the prompt emission is optically thin. Some other indications that long GRB outflows propagate close to the speed of light are resolved radio images of the afterglow of GRB 030329 (Taylor et al., 2004), scintillation quenching in the radio afterglow of GRB 970508 (Waxman, Kulkarni & Frail, 1998) and the onset time of the early afterglow (e.g., Sari & Piran, 1999). Here I use the opacity constraint, which is the most robust and model independent method, in order to derive a lower limit on the Lorentz factor of the source of SHB prompt emission.

The prompt emission of short GRBs is non-thermal (Lazzati, Ghirlanda & Ghisellini, 2005), implying that the source is optically thin to the observed photons. On the other hand, if a non-relativistic source is assumed, a calculation of the optical depth, based on the enormous observed luminosity of MeV γ-rays, results in an optical depth $\tau \sim 10^{13}$ (Schmidt, 1978). This conflict can be alleviated if the source of the emission is moving at relativistic velocities towards the observer (e.g., Guilbert, Fabian & Rees, 1983; Piran & Shemi, 1993). The most comprehensive calculation of the opacity limit on the Lorentz
factors of long bursts appears in Lithwick & Sari (2001). Below, I carry out similar analysis, adapting it to the prompt emission spectra of SHBs.

The non-thermal spectrum of GRBs implies that the source is optically thin to Thompson scattering on $e^-e^+$ pairs\(^1\). An inevitable source for such pairs is the annihilation of photons with rest frame energy $\epsilon_{ph} > m_e c^2$, where $m_e$ is the electron mass. Therefore, the Thompson optical depth for a given pulse during the prompt emission phase is\(^2\):

$$\tau_T \sim \frac{\sigma_T N_{ph} f(\epsilon_{ph} > m_e c^2)}{4\pi R^2}, \quad (1)$$

where $\sigma_T$ is the Thompson cross-section, $N_{\gamma}$ is the total number of emitted photons within the pulse, $f(\epsilon_{ph} > m_e c^2)$ is the fraction of photons that create pairs and $R$ is the radius of the source. Relativistic motion of the source has two effects. First, it reduces the rest frame energy of the observed photons, thereby reducing $f$. Second, for a given observed pulse time, $\delta t$, it increases the emission radius as $R \sim c \delta t \Gamma^2$. The time scales and luminosities of individual pulses in long and short GRBs are similar, but the spectra may be different. While the spectrum of most long GRBs is best described by a Band function (smoothly broken power-law; Preece et al., 2000; Ghirlanda, Celotti & Ghisellini, 2002), the best fits spectrum of most SHBs is a low energy power-law and an exponential cut-off (PLE; Ghirlanda, Ghisellini & Celotti, 2004; Mazets et al., 2004). While this spectral difference may be a result of observational selection effects\(^3\), PLE spectrum should be used when conservatively deriving the lowest Lorentz factor that is consistent with all current observations.

Moreover, Gev photons were observed in several long GRBs (e.g., Schnid et al., 1992; Sommer et al., 1994; Hurley et al., 1994) while there is no report in the literature of a photon harder than 10 MeV that was observed from a SHB. Using a power-law spectrum with a photon index $\alpha$ and an exponential cut-off at $E_0$ ($dN/dE \propto E^\alpha \exp \left[-E/E_0\right]$), Eq. 1 becomes:

$$\tau_T \sim 10^{14} S_{\gamma,-7} d_L^{28} \delta t_{-2} \frac{m_e c^2}{E_0} \Gamma^{-(4-\alpha)} \exp \left[-\frac{\Gamma m_e c^2}{E_0 (1 + z)}\right], \quad (2)$$

where $S_{\gamma}$ is the observed gamma-ray fluence of the pulse, $d_L$ is the luminosity distance to the burst (at redshift $z$) and throughout the paper $N_x$ denotes $N/10^x$ in c.g.s units. Requiring $\tau_T < 1$ results in the following constraint on

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1. Opacity to $\gamma\gamma$ pair production provides less stringent constraints on SHB Lorentz factors.
2. Along the calculation I assume that the source is moving directly toward the observer. If the source is moving at some angle with respect to the line-of-sight then the optical depth increases and so does the lower limit on $\Gamma$.
3. Preference of a PLE fit may for example be a result of low signal-to-noise ratio and low sensitivity of the detector at high energies.
The lower limit on the Lorentz factor of the prompt emission source as a function of the rest frame spectral typical energy $E_0(1+z)$ in units of $m_e c^2$. The limit is derived by the opacity constraint (Eq. 3) using three different low energy power-law slopes $\alpha$. The dots mark three bursts, SHB 050709, SHB 051221A (prompt emission properties are taken from Villasenor et al., 2005; Golenetskii et al., 2005), and a typical SHB (according to Ghirlanda, Ghisellini & Celotti, 2004) at $z=0.5$.

For $E_0=250$ keV; $z=0.5$; $\alpha=-0.6$ ($\Gamma > 15$)

\[
\frac{\Gamma m_e c^2}{E_0(1+z)} + (4-\alpha) \ln(\Gamma) + \ln \left[ \frac{E_0}{m_e c^2} \right] \gtrsim 30. \tag{3}
\]

The logarithmic dependence on $S_\gamma$, $\delta t$ and $d_L$ is neglected in Eq. 3 (the range of the observed values of SHB pulses may affect the value of Eq. 3 by less than 50%). Figure 1 presents the lower limit on $\Gamma$ as a function of $E_0$ for three values of $\alpha$. This lower limit is $\Gamma \gtrsim 15$ for the majority of the bursts analyzed by Ghirlanda, Ghisellini & Celotti (2004), assuming that they are cosmological, while for SHBs 051221 and 050709 the opacity lower limits are $\Gamma > 25$ and $\Gamma > 4$ respectively. These lower limits are significantly smaller than those obtained for long GRBs ($\Gamma \gtrsim 100$; Lithwick & Sari, 2001). Note however that for both populations only lower limits on the Lorentz factor are available and, while the typical Lorentz factor of SHBs could be significantly lower than that of long GRBs, a precise comparison between the real values of $\Gamma$ is impossible. Additionally, the smaller lower limits on SHB Lorentz factors depend on the best-fit function of their spectra which might be affected by observational selection effects. Hopefully the high energy spectra of SHBs will be securely determined by the upcoming GLAST mission.
3 Gamma-ray efficiency

Figure 2 presents the distribution of the dimensionless ratio $f_{x\gamma} \equiv F_x t/ S_{\gamma}$ of Swift long and short GRBs at $t = 1 \text{ d}$, where $F_x$ is the X-ray ($0.2 - 10 \text{ keV}$) energy flux at time $t$ and $S_{\gamma}$ is the prompt emission gamma-ray fluence ($15 - 150 \text{ keV}$). Within the framework of the standard afterglow model (e.g., Sari, Piran & Narayan, 1998; Granot & Sari, 2002) and as long as the blast wave is quasi-spherical:

$$f_{x\gamma} \equiv \frac{F_x t}{S_{\gamma}} \approx \begin{cases} 10^{-2} \kappa^{-1} \varepsilon_{e,-1}^{-3/2} \varepsilon_{B,{-2}} E_{k,50}^{1/3} n_{1/2} & \nu_x < \nu_c \\ 2 \cdot 10^{-3} \kappa^{-1} \varepsilon_{e,-1}^{-3/2} t_{d}^{-1/3} & \nu_x > \nu_c \end{cases} \quad (4)$$

where,

$$\kappa \equiv \frac{E_{\gamma}}{E_k} \quad (5)$$

represents the $\gamma$-ray efficiency of the prompt emission. $\nu_x$ is the X-ray frequency and $\nu_c$ is the synchrotron cooling frequency. $E_k$ is the kinetic energy of the blast wave and $E_{\gamma}$ is the energy emitted in $\gamma$-rays (both energies are isotropic equivalent). Radiative loses of the blast wave energy, which are expected to affect $E_k$ by a factor of order unity, are neglected. The exact power of the parameters in Eq. 4 (e.g., $\varepsilon_e$) depends weakly on $p$ (assuming here $2.1 < p < 2.8$). For simplicity I use approximate power values. I also neglect weak dependence (power-law indices below $1/4$) on parameters, since these cannot affect the result significantly (the lack of dependence on $n$ is exact). Following Nakar (2007) the synchrotron self-Compton cooling is neglected as well.

Assuming that microphysics of collisionless shocks does not vary significantly between bursts (either long or short) $\varepsilon_e \approx 0.1$ and $\varepsilon_B \approx 0.01$ are adopted. Under this assumption, for long GRBs at late time ($\sim 1 \text{ d}$; but before the jet-break), one expects $\nu_c < \nu_x$ in which case $f_{x\gamma}$ is almost a direct measure of the $\gamma$-ray efficiency, $\kappa$. As evident from Fig. 2, for long GRBs $f_{x\gamma}(1d) = 0.1 - 10^{-3}$ implying $\kappa_{LGRB} \approx 0.01 - 1$. The high efficiency of long GRBs is a well known result (Freedman & Waxman, 2001; Lloyd-Ronning & Zhang, 2004; Granot, Königl & Piran, 2006; Fan & Piran, 2006). Figure 2 also shows that the values of $f_{x\gamma}$ for SHBs with observed X-ray afterglows are comparable to those of long GRBs, $\sim 0.01$.

For some SHBs the circum-burst density can be low, in which case it is not

4 Note that I assume here that all the energy in the external shock at 1 d was available during the gamma-ray emission. If this is not the case and there is a significant energy injection into the external shock at late time, then the efficiency is even higher (e.g., Granot, Königl & Piran, 2006).
Fig. 2. A histogram of the ratio between the X-ray energy flux at time $t$ multiplied by $t$ and the prompt gamma-ray fluence. This is an estimate of the ratio between the energy emitted in the late X-ray afterglow and in the prompt emission. The ratio is given for Swift long bursts (thin line) and for SHBs with X-ray afterglow observed after $\sim 1$ day (thick line). The upper limits at $t \sim 100$ s for two Swift SHBs without detected X-ray afterglow are marked with arrow (thick line + arrow). Reference: Swift archive, http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table.
clear wether $\nu_c$ is above or below the X-ray band at 1 day. If $n \gtrsim 0.01 \text{ cm}^{-3}$ then $\nu_x \lesssim \nu_c$ and $\kappa_{\text{SHB}} \sim 0.1$. If the density is significantly smaller then $\nu_x > \nu_c$ and $\kappa$ decreases as $n^{1/2}$. Since SHBs with observed afterglows are typically located within their host galaxy light (e.g., Fox et al., 2005), most likely $n \gg 10^{-4} \text{ cm}^{-3}$, so $\kappa \sim 0.01 - 0.1$. We can conclude that at least in some SHBs (those with observed X-ray afterglow) the gamma-ray efficiency is most likely similar to that of long GRBs (see Bloom et al., 2006; Lee, Ramirez-Ruiz & Granot, 2005, for a specific exploration of the efficiency of SHB 050509B).

4 X-ray dark afterglows

Early X-ray afterglow from long GRBS is always detected. In contrast, there are several SHBs with tight upper limits on any early ($< 100 \text{ s}$) X-ray emission. The values of $f_{\gamma \gamma} \lesssim 5 \cdot 10^{-5}$ for these bursts are exceptionally low (Fig. 2). Making the plausible assumptions that the gamma-ray efficiency of these bursts is typical ($\kappa \sim 0.1$) as are the initial Lorentz factor and the micro-physical parameters, these values of $f_{\gamma \gamma}$ indicate that these events occurred in extremely low density environments, $n \lesssim 10^{-5} \text{ cm}^{-3}$, typical for the intergalactic medium. This result suggests that these SHBs occurred outside of their host galaxies.

While low density is needed to explain X-ray dark afterglows when the most plausible assumptions are considered, alternative solutions are viable when some of these assumptions are relaxed. For example, assuming an inter-stellar density ($n \gtrsim 0.01 \text{ cm}^{-3}$), the low $f_{\gamma \gamma}$ value can be explained by ultra-efficient gamma-rays production ($\kappa \gtrsim 100$), by unusually low electron and magnetic field energies ($\epsilon_e^{3/2} \epsilon_B \lesssim 10^{-6}$) or by low initial Lorentz factor $\Gamma_0 \lesssim 20$. The latter case can explain the faint early afterglow because low $\Gamma_0$ results in a late deceleration time (and therefore the afterglow onset), $t_{\text{dec}} \gg 100 \text{ s}$.

5 Discussion

I considered several theoretical constraints that can be drawn from the observations of the prompt and afterglow emission of SHBs. I derived a constraint on the Lorentz factor of the prompt emission source, based on the time scales, luminosity and spectrum of the prompt emission. These model independent lower limits imply that SHBs are ultra-relativistic, but as $\Gamma > 10 - 50$ is typically consistent with the observations they may be significantly less relativistic than long GRBs.

Analysis of the X-ray flux of SHB afterglows after 1 day in the context of
the standard external shock model implies that SHBs are as efficient as long GRBs in converting the energy of the relativistic outflow to prompt gamma-rays. This result, together with the high prompt emission variability (Nakar & Piran, 2002), indicates that the prompt emission is most likely a result of internal dissipation within the outflow (Sari & Piran, 1997; see Nakar 2007 for other indications that support this conclusion).

SHBs with X-ray dark afterglows are most likely occur in a low density environment, $n \lesssim 10^{-5}$ cm$^{-3}$, which is expected in the inter-galactic medium. This result support a model of long-lived progenitor systems ($\gtrsim 1$ Gyr) that experience a strong natal “kick” ($\gtrsim 100$ km/s), as predicted in the case of a merger of neutron star with another neutron star or a black hole (e.g., Bloom, Sigurdsson & Pols, 1999; Belczynski et al., 2006).

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