The nature of the outflow in gamma-ray bursts

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ABSTRACT

The Swift satellite has enabled us to follow the evolution of gamma-ray burst (GRB) fireballs from the prompt $\gamma$-ray emission to the afterglow phase. The early x-ray and optical data obtained by telescopes aboard the Swift satellite show that the source for prompt $\gamma$-ray emission, the emission that heralds these bursts, is short lived and that its source is distinct from that of the ensuing, long-lived afterglow. Using these data, we determine the distance of the $\gamma$-ray source from the center of the explosion. We find this distance to be $10^{15} - 10^{16}$ cm for most bursts and we show that this is within a factor of ten of the radius of the shock-heated circumstellar medium (CSM) producing the x-ray photons. Furthermore, using the early $\gamma$-ray, x-ray and optical data, we show that the prompt gamma-ray emission cannot be produced in internal shocks, nor can it be produced in the external shock; in a more general sense $\gamma$-ray generation mechanisms based on shock physics have problems explaining the GRB data for the ten Swift bursts analyzed in this work. A magnetic field dominated outflow model for GRBs has some attractive features, although the evidence in its favor is inconclusive. Finally, the x-ray and optical data allow us to provide an upper limit on the density of the CSM of about 10 protons per cubic cm at a distance of $\sim 5 \times 10^{16}$ cm from the center of explosion.

Key words: gamma-rays: bursts, theory

1 INTRODUCTION

The x-ray flux of a large fraction of the bursts detected by Swift exhibits a rapid decline with time, as $\sim t^{-2}$ or faster, for about 10 minutes (Tagliaferri et al. 2003; Nousek et al. 2006; O'Brien et al. 2006) after trigger. This is often followed by a slowly declining light curve (LC), with the flux falling-off as $\sim t^{-1/2}$ for a few hours. The extrapolation of the fast declining x-ray LC backward in time matches the LC during the burst, which suggests that the early x-ray and late $\gamma$-ray emissions are produced by the same source (O'Brien et al. 2006).

The fastest decline of the LC from a relativistic source moving at Lorentz factor $\Gamma_0$ and of angular size $\theta_0 > \Gamma_0^{-1}$ arises when the source switches-off quickly due to, for instance, a rapid adiabatic cooling at the end of the ejecta heating episode. In this case, the observed flux declines as $t^{-2-\beta}$ (Kumar & Panaitescu 2000), where $\beta$ is the spectral index of the burst emission, i.e. $f_\nu \propto \nu^{-\beta}$. The observed decline rate of the early x-ray LC is often at this theoretical limit (O'Brien et al. 2006), therefore the $\gamma$-ray source must have a finite, short life and, consequently, must be distinct from the much longer lived afterglow source.

In this paper we determine some properties of the $\gamma$-ray source and its distance from the center of the explosion using the early time data obtained by instruments aboard the Swift satellite.

2 GAMMA-RAY SOURCE DISTANCE

The early x-ray light curve can be used to determine the distance of the $\gamma$-ray source ($R_\gamma$) from the central explosion, as suggested by Lazzati & Begelman (2006) and Lyu-
tikov (2006). However, instead of using the unknown GRB jet angle to determine $R_\gamma$, as done in previous works, we determine the source radius in terms of the forward shock radius, which has a very weak dependence on the only unknown parameter: the density of the circumstellar medium. In order to exploit this method, we analyze the $\gamma$-ray, x-ray and optical data within the first 10 minutes for ten *Swift* bursts for which we can establish that the steeply falling off portion of the LC is the large-angle emission.

Some conditions need to be satisfied by the rapidly falling-off early x-ray afterglow LC to be identified with the large-angle emission from the $\gamma$-ray source. These conditions are: (i) the temporal decay index ($\alpha$) of the x-ray LC during the steep decline phase should be equal to $2 + \beta$; (ii) the spectral index $\beta$ during early x-ray afterglow should be the same as at the end of the gamma-ray burst; (iii) the x-ray afterglow flux extrapolated to the end of the prompt $\gamma$-ray emission should be the same as the $\gamma$-ray flux at the end of the burst extrapolated to the x-ray band. We apply an additional condition: $t_2/t_1 > 3$, where $t_1$ and $t_2$ are the beginning and end of the steep x-ray decline phase, to ensure that we have a sufficiently long baseline for an accurate determination of $\alpha$ (i.e. this index will not be too sensitive to the uncertainty in the origin of time).

Ten bursts detected by *Swift* between January 2005 and May 2006 meet these four conditions. Four of these bursts have a single-peak LC or are FRED (fast rise, exponential decline) shaped; the remaining six bursts contain multiple peaks. The relevant properties for these 10 GRBs are listed in Table 1.

Consider a $\gamma$-ray source moving at $\Gamma_0$, that turns off at radius $R_\gamma$. After the turn-off, the observed x-ray flux comes from regions of the $\gamma$-ray source that move at an angle $\theta$ larger than $\Gamma_0^{-1}$ with respect to the line of sight (Kumar & Panaitescu 2000) – this will be referred to as the large-angle emission or LAE. The LAE arrives at an observer time $t = (1 + z)R_\gamma \theta^2/2c$ and has a specific intensity smaller than that for $\theta = 0$ by factor $(1 + \theta^2 \Gamma_0^2)^3$. The LAE starts at $t_1$, the end of the prompt phase, and dominates the LC until some time $t_2$ when emission from the forward shock overtakes the rapidly decreasing flux from the $\gamma$-ray source. Thus, the source turn-off radius is $R_\gamma = 2ct_1 \Gamma_0^2/(1 + z)$.

The 0.3–10 keV fluence of the early rapidly declining x-ray LC, starting from the end of the GRB prompt emission to time $t_2$, is greater than ~15% of the GRB fluence for most of the bursts (Table 2). Therefore, the source for the steep x-ray LC is not some minor pulse in the explosion but is responsible for producing a good fraction of the prompt $\gamma$-ray energy, for both FRED and non-FRED bursts. For this reason, $t_1$ appearing in the above equation for $R_\gamma$ should be roughly equal to the burst duration, $t_\gamma$, otherwise the fluence during the LAE would be much less than the observed value.

The radius ($R_{FS}$) and the LF ($\Gamma_{FS}$) of the shock front in the CSM are related by $R_{FS}(t_2) \approx 2ct_2 \Gamma_{FS}^{-1}(t_2)/(1 + z)$. Since the energy of the LAE source is a significant fraction of the total GRB energy, it must have provided a good part of the kinetic energy deposited in the CSM, thus the LF of the LAE source, $\Gamma_0$, should be larger than $\Gamma_{FS}$. Given that $R_{FS}(t_2)/R_\gamma = [\Gamma_{FS}(t_2)/\Gamma_0]^2(t_2/t_\gamma)$, $\Gamma_0 > \Gamma_{FS}(t_2)$ implies that $R_{FS}(t_2)/R_\gamma < t_2/t_\gamma$. For the ten bursts in our sample, $t_2/t_\gamma$ is between 5 and 25; the average value of $t_2/t_\gamma$ is 14.0 for the four FREDs and 13.5 for the six non-FREDs.

If the deceleration time for CSM shock, $t_d$, is less than $t_2$ (as expected because the x-ray flux is decreasing monotonically) then the initial LF of the CSM shock, $\sim \Gamma_0$, is larger than the LF at deceleration by a factor 2, and $R_{FS}(t_d)/R_\gamma$ is smaller than $t_2/t_\gamma$ by a factor $\sim 4$. Therefore, we conclude that $\gamma$-rays are produced within a factor $\sim 4$ of the deceleration radius, on the average, for our sample of bursts.

We now calculate $R_{FS}(t_2)$ and estimate $R_\gamma$. The forward shock radius at time $t_2$ can be calculated from the dynamics of adiabatic blast-waves, which yields $R_{FS}(t_2) = \left[3c^2 t_2 E_{iso}/2 \pi m_p c^2 (1 + z) n_0 \right]^{1/2}$, where $E_{iso}$ is the isotropic equivalent of energy in the FS and $n_0$ is the mean density of the CSM within a sphere of radius $R_{FS}(t_2)$. The former is obtained from the GRB fluence and the CSM density (or an upper limit for $n_0$) is calculated from the x-ray and optical flux at $t_2$. For the bursts in our sample, we find $n_0 \lesssim 10^{-15}$ cm$^{-3}$ provided that x-rays are produced via the synchrotron process (no conditions were imposed on microphysics parameters $\epsilon_e$ and $\epsilon_B$ in this calculation); the constraint on $n_0$ is weaker if $\gamma$-rays are produced via the synchrotron-self-Compton process. From the GRB fluence and assuming $n_0 = 10^{-15}$ cm$^{-3}$, we calculate the forward shock radii $R_{FS}(t_2)$ and LFs, $\Gamma_{FS}(t_2) = [R_{FS}(t_2)/(1 + z)/2ct_2]^{1/2}$, given in Table 2. From $R_{FS}(t_2)$, we calculate the lower bound on the $\gamma$-ray source distance from the center of explosion and find it to be between $10^{15}$ and $10^{16}$ cm. Note that $R_{FS}$ and $\Gamma_{FS}$ have a very weak dependence on $E_{iso}$ and $n_0$ and therefore any error in $E_{iso}$ or $n_0$ has small effect on these quantities.

3 GAMMA-RAY GENERATION MODELS

3.1 Forward-Shock

Although we find that the burst and early afterglow data are not incompatible with $R_\gamma \sim R_{FS}(t_2)$, the forward shock (FS) model for $\gamma$-ray generation can be ruled out because the $\gamma$-ray production mechanism is short-lived and because the FS produces too much optical flux (see below). Furthermore, Ramirez-Ruiz & Granot (2006) have pointed out that the the relations between the spectral peak, flux and burst duration expected if $\gamma$-rays are produced in the forward shock are not satisfied by the GRB prompt emission.

All ten bursts in our sample have deep optical upper limits or detections a few minutes after the burst – typically at the beginning of the steeply declining x-ray LC – provided by the UV-optical telescope aboard *Swift*. From the x-ray flux and spectrum at the time of the optical observations, we estimate the expected flux in the optical band and find it to exceed the observed value or upper limit by two orders of magnitude or more (Table 2). A large extinction in the optical can be ruled out because late time optical data show it to be less than a factor 2. Moreover, in those

1 If the density of the CSM is set by the mass loss from the GRB progenitor star then this small mean density of $\sim 10^{-15}$ cm$^{-3}$ along the jet axis, within the radius $R_{FS}(t_2) \sim 5 \times 10^{16}$ cm, means that the mass loss rate divided by the wind speed from the progenitor star in the polar region, in the last $\sim 100$ year of its life, was smaller than typical Wolf-Rayet stars by at least a factor of a few 10s.
cases with optical detections, the optical spectrum is consistent with $f_{\nu} \propto \nu^{-1}$, similar to the spectrum in the x-ray band. Thus, the deep optical upper limits set by UVOT require that the spectrum of the x-ray/$\gamma$-ray source turns over at lower energies and becomes steeper than $f_{\nu} \propto \nu^{1/3}$, i.e., that the optical band often lies below the synchrotron self-absorption frequency ($\nu_{\text{sa}}$) of the early x-ray/$\gamma$-ray emission. It also implies that the optical flux detected at early times must come from a different source.

A straightforward calculation of forward shock emission shows that, if the x-ray emission at time $t_1$ is produced via the synchrotron process, then $\nu_{\text{sa}} \ll 2 \, \text{eV}$. This result holds even when we allow for an external medium enriched with up to $10^9$ e$^\pm$ pairs per proton. Therefore, the forward shock model does not satisfy the $\nu_{\text{sa}} > 2 \, \text{eV}$ requirement needed to reconcile the optical and x-ray data at early times. If x-rays arise from synchrotron-self-Compton process then the spectrum below 0.3 keV can be as steep as $f_{\nu} \propto \nu$, however, the optical flux associated with the underlying synchrotron radiation exceeds the observed limit.

### Table 1. GRB sample

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<th>GRB</th>
<th>FRED?</th>
<th>$\alpha$</th>
<th>$\beta_{\gamma}$</th>
<th>$\beta_{x}$</th>
<th>$z$</th>
<th>$E_{\text{iso,52}}$</th>
<th>$T_90$</th>
<th>$t_2$</th>
<th>$V$</th>
<th>$t_{\text{opt}}$</th>
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<td>4.3±0.36</td>
<td>1.2±0.09</td>
<td>1.6±0.25</td>
<td>1.95</td>
<td>8.0</td>
<td>96</td>
<td>400</td>
<td>&gt;18.5</td>
<td>140</td>
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<td>yes</td>
<td>3.1±0.32</td>
<td>0.53±0.15</td>
<td>0.70±0.11</td>
<td>23</td>
<td>120</td>
<td>720</td>
<td>&gt;19.5</td>
<td>190</td>
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<tr>
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<td>4.8±1.2</td>
<td>1.7±0.41</td>
<td>1.7±0.41</td>
<td>3.0</td>
<td>70</td>
<td>550</td>
<td>&gt;18.7</td>
<td>170</td>
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<td>0.98±0.19</td>
<td>1.1±0.08</td>
<td>5.3</td>
<td>67</td>
<td>65</td>
<td>1300</td>
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<td>36</td>
<td>900</td>
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<td>2.03</td>
<td>1.1</td>
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<tr>
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<td>4.41</td>
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<td>11</td>
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<td>17.8</td>
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Table 2. Calculated quantities

<table>
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<tr>
<th>GRB</th>
<th>LAE fluence(a)</th>
<th>optical flux ratio(b)</th>
<th>$\Gamma_{FS}$ ($t_2$)</th>
<th>$R_{FS}$ ($t_2$)(c)</th>
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<tr>
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<td>82</td>
<td>8.2</td>
<td>1.4</td>
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<td>4.6</td>
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<td>9.2×10$^2$</td>
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<td>11</td>
<td>0.53</td>
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<td>0.66</td>
<td>5.0×10$^2$</td>
<td>55</td>
<td>4.8</td>
<td>0.19</td>
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<td>5.9</td>
<td>0.21</td>
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<td>0.13</td>
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<td>2.9×10$^2$</td>
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<td>6.7</td>
<td>0.86</td>
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<td>2.8×10$^4$</td>
<td>67</td>
<td>4.2</td>
<td>0.48</td>
</tr>
<tr>
<td>060223a</td>
<td>0.17</td>
<td>200</td>
<td>3.8</td>
<td>0.49</td>
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</tbody>
</table>

The first optical data for GRB 060223a was obtained at 187s after the BAT trigger whereas the steep decline of the x-ray LC ended at 85s ($t_2 = 85s$). The extrapolation of the x-ray flux at 85s to the optical band gives a V-mag of 16.3 whereas the observed flux at 187s was 17.8 mag. For all other bursts UVOT measurements were between $t_1$ and $t_2$.

(a) Ratio of fluence from the end of GRB to time $t_2$ in 0.3-10 keV band and the fluence in 15-150 keV band during the burst. (b) Ratio of the expected to observed optical flux (or upper limit) at the time of UVOT observation. The expected flux is the extrapolation of the x-ray flux to the optical band using the XRT spectral index. (c) In units of 10$^{46}$ cm.

3.2 Internal Shocks

We now consider the internal shock model for prompt $\gamma$-ray generation. According to this model, fluctuations in the LF of the relativistic outflow lead to collisions between faster and slower ejecta, producing internal shocks and $\gamma$-ray radiation. No relationship is expected, in general, between where these collisions take place and the deceleration radius, whereas we find the average $R_{FS}(t_d)/R_{\gamma} \lesssim 4$. We also found that the average value of $R_{FS}(t_d)/R_{\gamma}$ is the same for bursts with multiple $\gamma$-ray light curve spikes and for FRED bursts. This suggests that gamma-rays are produced at a radius that is not set by the variability time scale of the
central engine, contrary to what is expected in the internal shock model.

The GRB ejecta should consist of baryonic material and/or $e^\pm$ in order to undergo internal shocks. The interaction of such ejecta with the CSM launches a reverse shock moving into the ejecta, heating it and producing synchrotron radiation that peaks in the optical band (Panaitescu & Mészáros 1998) and declines with time as $t^{-2}$ (Sari & Piran 1999). It is widely believed that such an emission from shocked ejecta was seen for GRBs 990123 and 021211.

In Figure 1, we show the early optical light curve for these two bursts resulting after subtracting the extrapolation of the late time optical emission, which arises in the forward shock. This extrapolation is justified because the optical light curves for many Swift bursts display a single power-law decline from $\sim 300$ s to hours (Panaitescu et al. 2004; Fan & Piran 2006). We find that, after subtracting the forward shock contribution, the early light curves of GRBs 990123 and 021211 decline as $f_{\text{opt}} \propto t^{-2.5}$. This decline is steeper than expected for the reverse-shock optical emission and is similar to that of the early x-ray LCs. Therefore, it is likely that the steeply falling early optical emissions of these bursts are produced via the same mechanism as the early x-ray, i.e. the LAE from the $\gamma$-ray source (Panaitescu et al. 2006). This interpretation is also supported by the observations that for both these bursts the prompt emission spectrum below the peak is $f_{\nu} \propto \nu^{1/3}$.

Furthermore, a good fraction of Swift bursts have been followed in the optical starting at a few minutes after the burst and most of these have either weak optical flux or very stringent upper limit on the flux (Roming et al. 2005). Therefore, we lack evidence for the expected reverse-shock emission from a baryonic/leptonic ejecta. There are various possibilities to account for a dim reverse-shock emission including the obvious one that there is no reverse shock because the baryonic/leptonic component in GRB outflows is small and the bulk of the explosion energy is carried outward by magnetic fields.

### 3.3 Modeling GRB prompt emission

We can obtain further insights regarding $\gamma$-ray sources by modeling the average properties of the prompt emission in our set of GRBs. The basic procedure is to calculate the synchrotron and IC radiations for a relativistic, shock heated medium and compare this to the average burst spectrum and variability timescale. This synchrotron and IC radiation is completely described by five parameters: $B$, $\tau_e$, $\Gamma_0$, $N_e$, and $\gamma_i$, which are respectively, magnetic field strength, optical depth of the source to Thompson scattering, the LE of the source, the total number of shocked electrons, and the lowest LF of electrons in the source comoving frame just behind the shock front; the electron distribution just behind the shock front is a power-law function of index $p$ which is constrained by the observed high energy spectra. The distribution in the source as a whole has a more complicated shape due to radiative losses which we calculate using the five parameters. We determine which part of the 5D parameter space produces radiation matching the observed low energy spectral index, peak energy, flux at the peak, and average pulse duration of the GRBs in our sample. The solutions we find apply to any relativistic-shock heated medium – internal or external shocks.

We first attempt to describe the prompt emission of these 10 bursts with synchrotron radiation. The low energy (20-150 keV) spectral index for 6 of the 10 bursts is $0.5 < \beta < 1$, and therefore the synchrotron cooling frequency ($\nu_c$) should be larger than about 150 keV and the injection frequency $\nu_i$ below 20 keV. This constraint along with peak flux of 0.2 mJy and pulse duration of 10s produces a 5D solution space with $\Gamma_0 > 600$ and $R_\gamma = (N_e\sigma_T/4\pi\tau_e)^{1/2} \geq 10^{17}$ cm (fig. 2a). This is in contradiction to what we found using the steep x-ray light curve decay $\sim R_\gamma \geq 10^{18}$ cm and bulk LF of $< 100$ (table 2). This discrepancy suggests that synchrotron radiation from a relativistically shocked heated medium (internal or external shocks) cannot describe the prompt $\gamma$-ray emission properties of the GRBs in our sample. For the remaining four GRBs, $1.2 < \beta < 1.8$ and both $\nu_i$ and $\nu_c$ should be below 20 keV. The synchrotron solutions for this case for the most part are very similar to the previous synchrotron case. There are a few intriguing solutions consistent with the $\Gamma_0$ and $\Gamma_0$ found in the LAE calculation, but the prompt optical flux is very bright, and can also be ruled out. Therefore, we rule out synchrotron emission in shock heated medium as the mechanism for GRB prompt emission.

Is it possible that the $\gamma$-rays were produced via synchrotron-self-Compton (SSC) process in a relativistic shock? We perform the 5D parameter space search for SSC radiation for both of the values cases described above and find that (for either $\beta_\gamma$) the source radius $R_\gamma$ and $\Gamma_0$ for the allowed 5D parameter space are consistent with the values we obtained for our sample in table 2 (see fig. 2b). The problem, however, is that the prompt optical flux with SSC is many orders of magnitude larger than the observational upper limits (fig. 2b). It is very unlikely that this large flux has gone undetected because of dust extinction or bursts going off at very high redshifts (Roming et al. 2005). Therefore, we conclude that GRB prompt emission is not due to the SSC process in relativistic shocks either. This means that synchrotron or SSC from any shock model has problems describing the $\gamma$-ray emission in any of the bursts in our sample – and that internal & external shocks can be ruled out as possible $\gamma$-ray emission mechanisms.

We have described a few problems with the external and internal shock models and, more generally, for any model based on shock physics. These together with the lack of evidence for baryonic outflow – no firm detection of reverse-shock emission in GRBs – suggests that GRB prompt emission is produced by some very different process. It either involves a very different kind of shock physics than we see during GRB afterglows, which seems unlikely, or $\gamma$-ray generation does not involve shocks, such as, for instance, would be the case when magnetic field transports the energy in GRB outflows and its dissipation produces the radiation we see (cf. Usov 1992, 1994, Thompson 1994, Katz 1997, Meszaros & Rees 1997, Wheeler et al. 2000 & 2002, Vlahakis & Konigl 2001, Spruit et al. 2001, Lyutikov &

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2 Three assumptions were made in these calculations: electron pitch angle distribution is uniform; electrons are not continuously energized as they move downstream from the shock front; and $B$ does not vary by a large factor across the source.
The nature of the outflow in gamma-ray bursts

**Figure 1. Left panel:** Power-law fits to the early and late optical afterglow of GRB 990123. Dotted line shows a power-law fit to the ROTSE data at $50 - 10^3$ s after trigger, solid line is the power-law fit ($\alpha = 1.15 \pm 0.07$) to the forward-shock emission at $10^4 - 10^5$ s, which is back-extrapolated (dashed line) to the epoch of the ROTSE measurements. Dot-dashed line shows the fit to the ROTSE emission with the forward-shock subtracted – the residual flux declines as $t^{-2.64 \pm 0.19}$. **Right panel:** Power-law fits to the early and late optical afterglow of GRB 021211. Dotted line shows the fit to the KAIT data at $100-500$ s, solid line is the fit ($\alpha = 1.07 \pm 0.04$) to the forward-shock emission at $10^3 - 4 \times 10^4$ s, which is back-extrapolated (dashed line) to the epoch of the early KAIT measurements. Dot-dashed line shows the fit to the KAIT emission with the forward-shock subtracted – the residual flux decays as $t^{-2.41 \pm 0.14}$.

**Figure 2. Left panel:** the allowed range of value for $R_\gamma$, $\Gamma_0$ (the LF of the $\gamma$-ray source – blue band) and $\gamma_i$, the minimum LF of shocked electrons close to the shock front, for the case when the prompt GRB emission is produced via the synchrotron process. These results were obtained for a GRB pulse duration of $10$ s, the flux at 100 keV of 0.2 mJy, cooling frequency ($\nu_c$) greater than 150 keV and the synchrotron frequency $\nu_m$ corresponding to $\gamma_i$ less than 20 keV, so that the spectrum in the BAT band corresponds to $f_\nu \propto \nu^{-(p-1)/2}$. For a GRB pulse duration of $1$ s the minimum $R_\gamma$ decreases by a factor of $\sim 4$ and the minimum $\Gamma_0$ increases by a factor of $\sim 2$. The allowed parameter space for synchrotron solution is found to be not very sensitive to the peak flux, $\nu_c$ and $\nu_m$. The allowed range for $R_\gamma$ & $\Gamma_0$ is very similar for the $\gamma$-ray fluxes measured for the 10 bursts in our sample, including the $\nu_m < \nu_c < 20$ keV (i.e. $f_\nu \propto \nu^{-p/2}$) case. For $\nu_c < \nu_m < 20$ keV, there are solutions consistent with the parameters shown in Table 2, but they lead to a too bright optical flux. The large range allowed for $\gamma_i$ encompasses internal and external shock ‘solutions’. **Right panel:** The allowed range of values for $R_\gamma$ and $\Gamma_0$ in the case when the burst emission is synchrotron self-Compton case and for the same burst parameters as for the left panel. Also shown is the optical flux (in mJy) for the SSC solutions. 1 mJy corresponds to an R-magnitude of 16.2; the upper limits on the optical flux for most GRBs in our sample is $< 0.1$ mJy.

Blandford (2003). The Poynting model has some attractive features such as high radiative efficiency, no reverse shock, large radius for $\gamma$-ray source (Lyutikov & Blandford, 2003), and low baryon loading comes for free. The Poynting outflow, however, might have difficulty explaining the observed variability of GRB prompt light curve (personal communication, Piran).
4 SUMMARY

The early x-ray data show that the gamma-ray source is short lived and turns off at a distance of $\sim 5 \times 10^{15}$ cm from the central explosion – which is found to be within a factor of $\sim 10$ of the forward shock radius at early times for all ten bursts in our sample. We have presented arguments that the prompt $\gamma$-ray emission is unlikely to be produced in the external or internal shocks or any mechanism based on shock heating of electrons. In their electromagnetic model, Lyutikov & Blandford (2003) find that $\gamma$-rays are generated at a distance of $\sim 3 \times 10^{16}$ cm from the central explosion, which is comparable to the value that we find. This could just be a coincidence but, considering the problems with shock based models, the lack of reverse-shock optical detection, and very high efficiency for $\gamma$-ray generation, we find the Poynting outflow model for GRBs to be an attractive possibility.

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