The initial Lorentz factors of fireballs inferred from the early X-ray data of SWIFT GRBs

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ABSTRACT

Aims. We intend to determine the type of circumburst medium and measure directly the initial Lorentz factor $\Gamma_0$ of GRB outflows.

Methods. If the early X-ray afterglow lightcurve has a peak and the whole profile across the peak is consistent with the standard external shock model, the early rise profile of light curves can be used to differentiate whether the burst was born in interstellar medium (ISM) or in stellar wind. In the thin shell case, related to a sub-relativistic reverse shock, the peak time occurring after the end of the prompt emission, can be used to derive an accurate $\Gamma_0$, especially for the ISM case. The afterglow lightcurves for a flat electron spectrum $1 < p < 2$ have been derived analytically.

Results. In our GRB sample, we obtain $\Gamma_0 \sim 300$ for the bursts born in ISM. We did not find any good case for bursts born in stellar wind and behaving as a thin shell that can be used to constrain $\Gamma_0$ reliably.

Key words. Gamma Rays: bursts — ISM: jets and outflows — radiation mechanism: non-thermal

1. Introduction

Gamma-ray bursters are among the most mysterious celestial objects and have attracted people since its first detection in 1967 (Klebesadel et al. 1973). The time variability of pulses, as short as millisecond, limits this event to a object of the stellar scale. The random occurrence and also the short time-duration of this kind of event lead to difficulties in detection. The dark era of research on Gamma-ray bursts (GRBs) lasts until the release of X-ray afterglow data of GRB 970228, confirming GRBs at the cosmological distances (Costa et al. 1997).

The power-law decay of multi-waveband afterglows of many GRBs are consistent with the standard external shock model (Waxman 1997; Wijers, Rees & Mészáros 1997). However, the multi-waveband afterglows are usually monitored several hours after the burst trigger. The late afterglow, independent on the initial values of the fireball, can not provide us information about the fireball characteristics. The Swift satellite Gehrels et al. (2004), thanks to its rapid response time and accurate localization, X-ray Telescope (XRT), Ultra-Violet Telescope (UVOT) on board and other ground-based telescopes can slew to GRB within tens seconds and then begin observations. The early afterglow data released in Swift era provide us an opportunity to study properties of fireballs, e.g., the initial Lorentz factor of the fireball.

The fireball is expected to be a highly relativistic ejection from the central engine to avoid the “compact problem” (Shemi & Piran 1990, Lithwick & Sari 2001). After the radiation-dominated acceleration phase, the fireball goes into a matter-dominated phase when the fireball is no long accelerated. The fireball keeps an approximately variable velocity until it sweeps up considerable mass of ambient medium. We call this episode as the coasting phase (Piran, Shemi & Narayan 1993). Though the profile of the early afterglow exhibits quite different from burst to burst and also from X-ray to infrared (IR) band, the peaks in the early afterglow light curves may indicate the arrival of the deceleration radius ($R_d$) in some GRBs. For example, Molinari et al. (2007) attributed the peaks in near-infrared afterglows of GRB 060418 and GRB 060607A to the end of the coasting phase and determined the initial Lorentz factors of the fireballs (see also Jin & Fan 2007). Recently, Oates et al. (2009) analyzed the early afterglows of Swift-UVOT data and measured the initial Lorentz factor of GRBs for those showing an early power-law increase in flux.

Different from these works, now we use the early X-ray data of Swift GRBs to constrain the initial Lorentz factors ($\Gamma_0$). As a probe of $\Gamma_0$, the X-ray data is better than the optical data for the following reasons: (1) In the standard fireball model, the X-ray emission decays with time quickly after the outflow has got decelerated, independent of the profile of the medium surrounding the progenitor (Fan & Wei 2003). This is because usually both the typical frequencies of the forward shock (FS) and the reverse shock (RS) emission are below the X-ray band (see Tab.1 for the light curves). The optical emission, however, will increase until the typical synchrotron frequency of the FS drops below the optical band (Sari et al. 1998). (2) In the thin shell case that is of our interest, usually the RS X-ray emission is not strong enough to outshine the FS emission component. The origin of the X-ray peak can thus be reliably established. (3) X-ray afterglows are hardly influenced by the self-absorption effect and dust extinction, different from the emission at lower frequencies.
One disadvantage of our method is that the early X-ray emission of most GRBs have been polluted by the delayed flares (Falcone et al. 2007), powered by the prolonged activity of the central engine. Fortunately, the X-ray flares usually have a decline as steep as $t^{-3-10}$, which is significantly sharper than what the fireball model predicts. So one can distinguish the peak of FS emission from the peak of flare in X-ray band convincingly.

2. The early X-ray afterglow emission

A very bright optical flash has been detected in GRB 990123 (Akerlof et al. 1999). The most widely discussed interpretation is the external RS model (Sari & Piran 1999; Mészáros & Rees 1999 however, it can also be produced by the internal shock model, e.g. Wei 2007). Since then, the RS emission in optical band has been extensively investigated (see Zhang 2007 for a review). However, the RS X-ray emission has just been calculated by a few authors (Fan & Wei 2005; Zou et al. 2005). In this work we focus on the profile of early X-ray afterglow light curves in different cases.

In the Fermi acceleration process, the power-law index of shocked electrons $p > 2$ is resulted (Gallant 2002). It has been taken as the standard scenario and has been widely used in the afterglow calculation (Sari et al. 1998; Chevalier & Li 2000). Some afterglow modeling (Bhattacharya 2001; Dai & Cheng 2001), however, favor a flat electron spectrum $1 < p < 2$, for which a reliable estimate of the afterglow emission is still unavailable. We’ll discuss such a scenario in section 2.2 in some detail.

2.1. The case of $p > 2$

Firstly, we discuss the “thin shell case” (for which $t_X > T_{90}$, where $t_X$ is the crossing time of RS and $T_{90}$ is the duration of the burst), referring to a sub-relativistic RS. Assuming typical parameters (e.g., the fraction of the shock energy given to the electrons $\epsilon_e = 0.1$, the fraction given to the magnetic field $\epsilon_B = 0.01$, the total energy of the fireball $E = 10^{52}\text{erg}$ and $p = 2.3$), we have the typical synchrotron radiation frequency and the cooling frequency of the FS emission $v_{m} = 2 \times 10^{16}\text{Hz (t/1000s)^{-3/2}}, v_{c} = 8 \times 10^{16}\text{Hz} n_{0}^{1/2}(t/1000s)^{-1/2}$ for bursts born in ISM (Sari et al. 1998) and $v'_{m} = 5 \times 10^{16}\text{Hz (t/1000s)^{-3/2}}, v'_{c} = 4.8 \times 10^{15}\text{Hz (t/1000s)^{1/2}}A_{\text{d}}^{-2}$ born in wind medium (Chevalier & Li 2000), where $n$ and $A$ are two medium parameters – $n$ indicates the density of ISM, in unit of cm$^{-3}$, while $A$ is the dimensionless parameter of stellar wind environment. $t$ indicates the observed time postburst. The convention $Q_{10} = Q_{10}^{0}$ has been adopted in this paper, in units of cgs.

Combined with $v'_{m}(t_{X}) > v_{m}(t_{X}), v'_{c}(t_{X}) \approx v_{c}(t_{X})$, we find that both $v_{m}$ and $v_{c}$ of FS and RS emission (marked by the subscripts $f$ and $r$ respectively) are below the X-ray band $v_{X} \sim 10^{17}\text{Hz}$, assuming typical parameters. If the shock parameters are similar for the FS and the RS, the flux contrast between the RS and X-ray emission is that $F_{r}^{X}(t_{X}) = \Gamma_{X} \approx \Gamma_{0}^{4}$. Given the initial Lorentz factors from early Swift-XRT data (Fan & Wei 2005),

$$\frac{F_{r}^{X}(t_{X})}{F_{X}(t_{X})} \approx \Gamma_{0}^{4},$$

where the subscript $X$ represents the parameters measured at $t_{X}$, $\Gamma_{0}$ and $\Gamma_{X}$ represent the initial Lorentz factor and the

1 This expression is valid in the “thin shell” case. In the “thick shell” case, such an expression is an upper limit since the total number of the RS electrons is less than $\Gamma_{0}$ times that of the FS electrons (see eq. (3)).

2 In the so-called “thin shell case”, $\gamma_{34, X} \approx (\Gamma_{0}/\Gamma_{X} + \Gamma_{X}/\Gamma_{0})/2$.

For a typical $p \approx 2.3$, Eq. (1) gives

$$\frac{F_{r}^{X}(t_{X})}{F_{X}(t_{X})} \approx 2^{1-p}\Gamma_{0}^{4-p} \sim \mathcal{O}(0.1),$$

for $\Gamma_{0} \sim \text{a few } \times 100$, which suggests that the RS X-ray emission can be ignored. This conclusion is unchanged if $\nu_{m}$ is actually above $\nu_{X}$ because in such a case the FS X-ray emission would be stronger.

In the “thick shell case” (for which $t_{X} < T_{90}$), particularly for a relativistic RS satisfying $\gamma_{34, X} \sim 1 \approx \Gamma_{0}/2\Gamma_{X}$, we have

$$\frac{F_{r}^{X}(t_{X})}{F_{X}(t_{X})} \leq 2(\gamma_{34, X} - 1)^{p}\Gamma_{X}^{2-p}.$$  

As a result, the RS X-ray emission may be able to outshine the FS component.

Thick shell case: The RS X-ray emission is unimportant, so the afterglow is dominated by the FS component. The bulk Lorentz factor $\Gamma$ is nearly a constant in this coasting phase ($t < t_{X}$). We then have $\nu_{m} \propto t^{-k/2}, \nu_{c} \propto t^{k/2-2}$, and the maximal specific flux $F_{\nu_{m}, \text{max}} \propto \gamma_{34, X}^{2(1-k/2)}(k = 0$ for ISM and $k = 2$ for the stellar wind). So the FS X-ray emission evolves as $F_{\nu_{X}}^{r} \propto t^{2-p}\nu^{2-p}/t^{4}$ with time. In the case of ISM, $F_{\nu_{X}}^{r} \propto t^{-2}p(t)$, increasing with time quickly, while in the wind case, $F_{\nu_{X}}^{r} \propto t^{2-p}\nu^{2-p}$, decreasing with time slowly.

Thin shell case: In the case of ISM, we have $\Gamma \propto t^{-1/4}, \nu_{m} \propto t^{3}, \nu_{c} \propto t^{3}$, and then derive $F_{\nu_{X}}^{r} \propto t^{2-p/4}$ (see also Kobayashi 2000) when $t < t_{X}$. The simultaneous FS X-ray emission is $F_{\nu_{X}}^{f} \propto (t^{2-p/4})^{2}$. In the wind case, both the FS and the RS emission decrease with time slowly as $t^{2-p/4}$ when $t < t_{X}$ (see also Fan & Wei 2005).

For $t > t_{X}$, it is well known that $F_{\nu_{X}}^{f} \propto t^{2-p/4}$, independent of the type of circumburst medium.

Please note that in our above analysis, we assume that both $v_{m}$ and $v_{c}$ of FS and RS are well below the XRT band. More general results have been summarized in Tab.1. One can see that $F_{\nu_{X}}^{r} \propto t^{-1/4}$ is also possible but only for a fast cooling forward shock. Its spectrum should be $F_{\nu_{X}} \propto t^{-1/2}$, which can be distinguished from the shallow decline predicted for the FS and RS emission in the wind case at a time $t < t_{p}$.

2.2. The case of $1 < p < 2$

With the shock jump conditions (Bhattacharya 2001) derived a minimum Lorentz factor ($\gamma_{m}$) of the electrons that depends on the maximal one ($\gamma_{M}$), i.e., $\gamma_{m} \approx (2 - p)m_{p}\epsilon_{\text{sh}}\gamma_{M}^{52}/[(p-1)m_{e}]^{1/(p-1)}$, where $\epsilon_{\text{sh}}$ is the Lorentz factor of the shock, $m_{p}$ and $m_{e}$ are the rest mass of protons and electrons, respectively. However, in reality, particle acceleration proceeds from low to high energy. $\gamma_{m}$ and $\gamma_{M}$ should be determined by the first shock crossing and by radiative losses or escape from the acceleration region, respectively. Hence $\gamma_{m}$ should have no “knowledge” of $\gamma_{M}$ (Panaitescu 2006, private communication). Motivated by the above arguments, in this work we assume that $\gamma_{m} \approx \epsilon_{\text{sh}}/(p)(\Gamma_{0} - 1)m_{p}/m_{e}$, where $f(p)$ being a function of $p$. Such treatment requires that only a small fraction $R$ of the upstream material has been accelerated otherwise the energy momentum conservation law will be violated.
Table 1. The temporal behavior of the X-ray afterglow lightcurves in the case of $p > 2$.

| Emission regime | ISM | Wind |
|-----------------|------|------|
| Thin shell case (FS) | $t < t_p$ | $v_j > \max[v'_j, v'_m]$ | $t^2$ |
| | $t = t_p$ | $v_j < v_c < v_m$ | $t^{1/2}$ |
| Thick shell case (FS) | $t > t_p$ | $v_j < v_c < v_m$ | $t^{-3}$ |
| Thin shell case (RS) | $t < t_p$ | $v'_m < v'_j < v_m$ | $t^{1/2}$ |
| | $t < t_p$ | $v'_m < v'_j < v'_m$ | $t^{1/2}$ |

Note — Observationally the crossing time $t_c$ marks the beginning of the late sharp decline, in this work we denote such a timescale by $t_p$. $t_j$ is the jet break time.

Assuming that the shock-accelerated electrons have a power-law energy distribution $dn/d\gamma \propto (\gamma - 1)^{-p}$ for $\gamma_m \leq \gamma \leq \gamma_M$, with the shock jump conditions that $\gamma'_m = \gamma_m$, $\gamma'_p = \gamma_p$, and $\gamma'_f = \gamma$, the Lorentz factor is limited by the synchrotron losses and is given by [Cheng & Wei 1996]

$$\gamma_M \approx 4 \times 10^7 B^{-1/2},$$

$$B = \sqrt{32\pi c \Gamma_h (\Gamma_h - 1)n_0 \epsilon c e^2},$$

the afterglow lightcurves in the case of $1 < p < 2$ are different from those presented in Tab 1 by a factor of $\mathcal{R}$ given below.

Assuming the X-band is above max[$v'_j$, $v'_m$, $v_j$, $v_m$], the flux contrast between the RS and the FS emission can be estimated by (for a thin shell)

$$\mathcal{F}_j(t_s) \approx \mathcal{F}_m(t_s) \approx \frac{\Gamma_j(\gamma_M - 1)^{-p-1}(\gamma_M - 1)^{2-p}}{(\Gamma - 1)^{-p-1}(\Gamma - 1)^{2-p}} \approx \frac{1}{2} \Gamma_j^p \left( \frac{\Gamma_M}{\Gamma - 1} \right)^{2-p} \left( \frac{\gamma_M - 1}{\Gamma - 1} \right)^{2-p}.$$  

As a result, in the thin shell case, the RS X-ray emission is usually outshone by the FS X-ray radiation for both a flat electron spectrum ($1 < p < 2$) and a standard electron spectrum ($p > 2$).

Table 2. The temporal behavior of the X-ray afterglow lightcurves in the case of $1 < p < 2$.

| Emission regime | ISM | Wind |
|-----------------|------|------|
| Thin shell case (FS) | $t < t_p$ | $v_j > \max[v'_j, v'_m]$ | $t^2$ |
| | $t = t_p$ | $v_j < v_c < v_m$ | $t^{1/2}$ |
| Thin shell case (RS) | $t < t_p$ | $v'_m < v'_j < v_m$ | $t^{1/2}$ |
| | $t < t_p$ | $v'_m < v'_j < v'_m$ | $t^{1/2}$ |

3. Case studies

In this work, we focus on the thin shell case, i.e., $t_p = t_j > T_{90}$. As summarized in Tab 1 and Tab 2, the outflow expanding into the ISM will give rise to an increase not shallower than $t^2$, while expanding into the wind can not account for an increase steeper than $t^{1/2}$. Therefore we can judge whether the GRB was born in ISM or wind medium according to the sharpness of flux increase. One can also speculate that the X-ray data for the GRBs born in ISM is not a very good probe of the initial Lorentz factor of the ejecta due to the lack of a distinguished peak for typical parameters that give rise to $\gamma_S > \max[v_m, v_j]$.

The number of GRBs recorded by XRT exceeds 160 till August 1st, 2008. Most of them, however, play no role in constraining $\Gamma_0$. For our purpose, the light curves have to be characterized by: (i) There is a distinguished/single peak. (ii) Across the peak, a smooth transition to a single power-law decay is fol-
shift $z=1.95$ was found from absorption lines of the afterglow spectrum \citep{Wiersema08}. As shown in Fig.1, a quick increase in flux $\propto r^{-4}$ is obvious up to $\sim 360$ s after the GRB trigger. After the peak time, the late afterglow exhibited a broken power-law – a relatively shallow decline $\propto r^{-0.86}$ followed by a $\sim r^{-1.87}$ profile. We attribute the late steep decline to the jet effect of this GRB. With a flat electron spectrum $p \sim 1.5$, both the temporal behavior of lightcurves in the two late episodes and the X-ray spectrum $F_{\nu} \propto \nu^{-0.74 \pm 0.06}$ can be well reproduced providing that $v_{c} > \max[v_{\nu f}, v_{\nu m}]$ (see Tab.I).

**GBR 080413B:** The BAT light curve showed a single peaked structure with a duration of about 3 seconds \citep{Stamatikos08}. The early XRT data recorded a steep increase in flux, peaking around 167 s from the trigger. The X-ray light curve is well fitted by a simple power-law, with a decay slope of $0.88 \pm 0.06$ from 167 s to $10^{4}$ s after the burst trigger \citep{Troja08}. Based on the detection of numerous absorption features, including Fe II, Mg II and Mg I lines, \cite{Vreeswijk08} inferred a redshift $z = 1.10$. The XRT spectrum is $F_{\nu} \propto \nu^{-1.05 \pm 0.1}$. The decline and the spectrum are roughly consistent with the fireball afterglow model supposing that $p \sim 2$ and $v_{c} > \max[v_{\nu f}, v_{\nu m}]$ (see Tab.I).

### 3.2. wind case?

**GBR 080307:** In the first orbit of the XRT data, the emission rose slowly, $\propto t^{0.6}$, peaking at $\sim 240$ s after the BAT trigger, after which the decay can be modeled with a single power-law with the temporal index $\alpha = 1.83 \pm 0.08$ up to several ks after the burst trigger, though there was an abnormal flat in flux later \citep{Page08}. The X-ray spectrum is $F_{\nu} \propto \nu^{-0.74 \pm 0.22}$. As shown in Tab.I in the thin shell case, for $v_{\nu f} < v_{c} < v_{\nu m}$, the FS emission of an ejecta expanding into the stellar wind can give rise to an initial rise $t^{0.5}$, roughly consistent with the data. However, this model gives a decline $t^{-1.4}$ after the X-ray peak, deviating from the data significantly. *So this event won’t be included in our $\Gamma_{0}$ constraint.*

**GBR 080409:** The XRT began observing this burst 84 seconds after the BAT trigger. The light curve showed an initial increase with a power-law slope of $\sim 0.6$ and entered a peak at $\sim 509$s after the burst onset. The light curve then turned over to decay with a power-law slope of $0.89 \pm 0.09$ \citep{Holland08}. The XRT spectrum is $F_{\nu} \propto \nu^{-1.2 \pm 0.6}$. Similar to GBR 080307, an initial rise $t^{0.6}$ may be the FS emission of an ejecta born in wind. However, this model gives a decline $t^{-1/4}$ after the X-ray peak unless we have seen the edge of the ejecta for which the decline can be as steep as $t^{-1}$ (see Tab.I). *Again, we won’t include it in the following $\Gamma_{0}$ constraint.*

### 3.3. determining the initial Lorentz factor

In our sample, the peaks appearing in the early X-ray afterglow light curves are related to the position of the outflow $R_{d}$ from the central engine. At this time, the swept medium has an energy comparable to that of the GRB outflow and the instant Lorentz factor at $R_{d}$ is about half of the initial one. Based on the assumption above, we can measure the initial Lorentz factor of GRBs in ISM case \citep{Blandford76}:

$$\Gamma_{0} = \left( \frac{24 E_{p} (1+z)^{3}}{\pi n_{m} c^{5} \eta_{d}^{\frac{1}{2}}} \right)^{1/8},$$

\[7\]
where $E_v$ is the isotropic energy of prompt gamma-ray emission. Here, we take the radiation efficiency $\eta = 0.2$ in the calculation according to Guetta, Spada & Waxman (2001) and Molinari et al. (2007). The densities $n \sim 1$ cm$^{-3}$ in ISM case is assumed. Since $\Gamma_0$ is weakly dependent on the unknown density of the circumburst medium in the ISM case, it can be measured relatively accurately. The results have been presented in Tab.2. Usually we have $\Gamma_0 \sim \sqrt{2}$, consistent with some other independent probes (Sari & Piran 1999; Lithwick & Sari 2001; Zhang et al. 2006; Molinari et al. 2007; Jin & Fan 2007; Pe'er et al. 2007; Zou & Piran 2009; Zou et al. 2009), some of which are independent of the profile of the circumburst medium.

4. Conclusion

We use the current Swift-XRT data to constrain the profile of the circumburst medium and then measure the initial Lorentz factor of the fireballs. As a reliable probe, the X-ray light curves should have the following characters for our purpose: (i) There is a distinguished peak. (ii) Across the peak, a smooth transition to a single power-law flux is followed, and the whole profile must be consistent with the standard afterglow model. The early peaks accompanying with steep decay, usually steeper than $t^{-3}$, are abandoned. Among the ~ 160 Swift bursts we have checked, only 4 events meet such requests because in most events the early X-ray emission is polluted by the emission powered by the prolonged activity of the central engine. In all these 4 bursts, the initial increase of the X-ray flux is quicker than $t^{-2}$, strongly suggests a constant low-density medium. In general, we find $\Gamma_0 \sim \sqrt{2}$, consistent with the constraints obtained in other analysis. Please note that in this work all the events in the sample are bright GRBs. For the nearby subluminous events, like GRB 980425, GRB 031203, GRB 060218 and GRB 060614, a reliable estimate of their initial Lorentz factors are still unfeasible at present.

In our analysis we did not find a good case for the burst born in stellar wind and behaving as a thin shell (see section 3.2). One possible reason is that usually the wind medium is so dense that the outflow has got decelerated significantly in a timescale $t < T_{90}$. So the X-ray data is likely to be not suitable as a probe of the initial Lorentz factor of GRB outflows for most of events occurring in the wind medium.

Note added in manuscript.—After the acceptance of the paper, the details of the X-ray afterglow data of GRB 090113 became available (Krimm et al. 2009): The $0.3 - 10$ keV light curve shows an initial period of roughly constant emission. For $t > 530$ sec, the light curve can be modelled with a power-law decay as $t^{-1.3}$. The X-ray spectrum is $F_\gamma \propto \nu^{-1.20 \pm 0.20}$. One can see that with $p \sim 2.4$, both the temporal and the spectral behaviors of this X-ray afterglow are well consistent with the forward shock emission model in the case of a wind medium and $\dot{m}_x > \text{max}(\dot{m}_v, \dot{m}_f, T_{90})$. The initial Lorentz factor can be estimated as $\Gamma_0 = \sqrt{\frac{4E_f}{c^3 n m_c^2 \gamma}}$, where $A$ is related to the regular wind parameter $A_3$ by $A = 3 \times 10^{35} A_3$. Assuming $\gamma \sim 1.0$, we have $E_{\gamma} \sim 7.9 \times 10^{51} \text{erg}$ and $\Gamma_0 \approx 121 A_{34}^{1/4}$.

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| GRB     | $z$  | $E_{\gamma}(10^{52}\text{erg})$ | $T_{90}(\text{s})$ | $t_p(\text{s})$ | medium type | $\Gamma_0$ | references |
|---------|------|---------------------------------|-------------------|----------------|--------------|------------|------------|
| 060801  | 1.131| 0.35                            | 0.5               | 110            | ISM         | 280        | 1,2,3      |
| 060926  | 3.208| 1.0                             | 8.0               | 430            | ISM         | 234        | 4,2,5      |
| 080319C | 1.95 | 6.13                           | 34                | 360            | ISM         | 274        | 6,7        |
| 080413B | 1.1  | 1.53                           | 8.0               | 167            | ISM         | 271        | 8,9        |
| 090113  | 0.79 | 9.1                            | 9.1               | 523            | wind        | 121$A_{-1/4}$ | 10        |

References: 1 Cucchiara et al. (2006); 2 Butler et al. (2007); 3 Sato et al. (2006); 4 D’Elia et al. (2006); 5 Cummings et al. (2006); 6 Wiersema et al. (2008); 7 Stamatikos et al. (2008a); 8 Vreeswijk et al. (2008); 9 Barthelmy et al. (2008); 10 Tueller et al. (2009)

$a$ redshift of GRB

$b$ isotropic equivalent energy of prompt $\gamma$-ray emission (1-10$^{4}$keV in the burst frame for bursts with defined redshift or 1-10$^{4}$ keV in the observer frame for bursts with undefined redshift to consistent with the catalog in Butler et al. (2007))

$c$ time duration of GRB

$d$ the calculated initial Lorentz factor of fireballs (assuming $n = 1\text{cm}^{-3}$ for ISM case)

$e$ assuming $z=1$ to derive $E_{\gamma}$ for GRB 090113 with undefined redshift