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On the prompt γ-ray emission radii of LGRBs

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Abstract. A simple method has been used to measure the prompt emission radii of 27 Swift and 37 pre-Swift long gamma-ray bursts with known redshift and jet break time. I find that the prompt γ-rays are emitted from a beamed jet with dynamic open angle narrower than its geometric open angle. It is also found that both Swift and pre-Swift long bursts occurred at a similarly upper-limited radius of $\sim 10^{16}$ cm, although Swift/BAT is more sensitive to long bursts than pre-Swift detectors did. These results are consistent with some previous expectations based on Swift early afterglow data, spectral cut-off energy or turbulence model.

Key words. gamma ray: bursts – gamma rays: observations – methods: data analysis

1. Introduction

Gamma-ray bursts (GRBs) are generally thought to be the brightest and fastest but stellarly cosmological event with an initial compact size of $\sim 10^6 - 10^7$ cm. They are usually separated into two groups in terms of γ-ray duration (T_{90}), i.e., long GRBs (LGRBs) with $T_{90} > 2$ s and short GRBs (SGRBs) with $T_{90} < 2$ s (Kouveliotou et al. 1993; Zhang, & Choi 2008). Bursts and their afterglows can be explained with the so-called standard fireball-shock models (Piran 2005a). Alternatively, the external shock model (Mészáros, & Rees 1993; Sari, & Piran 1996; Dermer, Böttcher, & Chiang 1999; Dermer 2004, 2008; Ramirez-Ruiz, & Granot 2007) or the electromagnetic model (Lyutikov, & Blandford 2003; Lyutikov 2006a) had also been invoked in interpreting GRBs. Recently, Narayan, & Kumar (2009) proposed another interesting turbulent model in which they pointed out that all pulses in the γ-ray light-curve are roughly produced from the same site, compatible with the requirement of electromagnetic model in Lyutikov, & Blandford (2003). Furthermore, all above models can reproduce fast variability in their resulting GRB light-curves (Dermer 2008; Lyutikov 2006b; Narayan, & Kumar 2009; Kumar 2007).

However, the primary difference between internal shock and other theoretical models is the prompt γ-ray emitting region. The typical internal shock radius is about $R \sim 10^{12} - 10^{13}$ cm (Rees,& Mészáros 1994; Lazzati, Ghisellini, & Celotti 1999; Piran 2005b), while GRB pulses from an external shock are thought to originate at a representative distance of $10^{15} - 10^{17}$ cm from their central engine (Dermer 2008). Similarly, the emitting regions in the frames of electromagnetic model and turbulence model are at least three orders larger than the internal shock radius. The rela-

Send offprint requests to: Z.-B. Zhang tively precise determination of the distances requires the detection of radiation spectra at any other wavelengths other than the prompt γ-rays during the prompt emission phase (Mészáros 2006). The very early afterglows are usually thought to be associated with the prompt γ-ray emissions (Zhang et al. 2006; O'Brien et al. 2006), which offers us a clue of the same origin site of a burst. Using early X-ray light curves, Lazzati, & Begelman (2006) estimated a lower limit of the prompt emission radii for two bursts (GRB 050219a and GRB 050315) of about 10^{14} cm. Using the forward shock radius, Kumar (2007) derived the distances of 10 LGRBs by analyzing the early X-ray and optical afterglow data and found most LGRBs occurred at $10^{15} - 10^{16}$ cm, similar to the estimate of $\geq 6 \times 10^{15}$ cm by Lyutikov (2006b) within the frame of electromagnetic model.

These diverse radii challenge the basic physics of GRB progenitors. Strictly, it is necessary to measure the γ-ray emitting sites with prompt emission itself other than the late follow-up observations. For this, I utilize the prompt emission observations to study the GRB birth places and compare my measurements with some previous estimates only for several sources. In sections 2, I introduce the analytic method of data analysis and sample selection. The main result and short discussion have been presented in section 3.

2. Methods and samples

Considering the beaming effect of ultra-relativistic outflows, only the fraction of emissions within a small solid angle of $2\pi(1-cos\theta)$ can be detected by space detectors. Here, $\theta \sim \Gamma^{-1}$ denotes the half-opening angle of a dynamic (or real) jet when its edge can be seen. As the shock passes outwards though the gas envelope, the γ-ray emissions last a duration time of $\Delta t = t_2 - t_1$ in the source frame, where t_1 and t_2 are respectively the first and last emitting time of photons in the rest frame of sources. Accounting for the curvature of photosphere, the comoving time Δt and the observed duration $T_{90} \simeq T_2 - T_1$ are related by a cosmological time dilation factor of $(1+z)^{-1}$, namely

$$T_{90} \simeq [t_2 - t_1 + \frac{R(1-\mu) - \beta c(t_2 - t_1)\mu}{c}](1+z) \quad (1)$$

where $\mu = cos\theta$ and z is the cosmological redshift of a burst. The first term represents the pure correction to the cosmological time dilation. The second term is associated with the curvature and expansion effects of a source on the observations, in which β is the relative velocity connected with lorentz factor Γ as $\beta = \sqrt{1-\Gamma^{-2}}$ and R is the prompt emission radius from the central engine. In an extreme case of $\beta \approx 0$, implying the source is static, the second term degenerates into $(1+z)R(1-\mu)/c$, that is, the pure curvature contributor. The Eq. (1) can be rewritten as

$$T_{90} \simeq [\frac{R}{c}(1-\mu) + \Delta t(1-\beta\mu)](1+z) \quad (2)$$

Assuming the second term in Eq.(2) is negligible in comparison to the first term, say $R(1-\mu)/c \gg \Delta t(1-\beta\mu)$, we have $c\Delta t \ll R$ for an ultra-relativistic outflow ($\Gamma \gg 1, \beta \approx 1$), which indicates that the geometric thickness of emitting shells is far smaller than the typical γ-ray emission radius. In this case, Eq. (2) becomes

$$R \simeq cT_{90,i}/(1-cos\theta) \quad (3)$$

where $\theta = \theta(t)$ is the half-opening angle of dynamic jets and $T_{90,i} = T_{90}/(1+z)$ is the intrinsic duration. Provided outflows are already collimated and its axis points along the line of sight, the half-opening angle of the dynamic jet at the break time of declining afterglows is equal to

$$\theta_j \simeq 0.057 \times (\frac{t_j}{1\mathrm{day}})^{3/8}(\frac{1+z}{2})^{-3/8}(\frac{E_{iso}}{10^{53}\mathrm{erg}})^{-1/8} \times(\frac{\eta_\gamma}{0.2})^{1/8}(\frac{n}{0.1\mathrm{cm}^{-3}})^{1/8} \ \mathrm{radian}$$

where θ_j is called as the generic geometric jet angle and t_j is the jet break time, n is the circum-burst particle density and η_γ is the efficiency of γ-ray radiation compared with total energy in the relativistic ejecta. The circumburst medium is assumed to be homogeneous for LGRBs with a density of $n = 10$

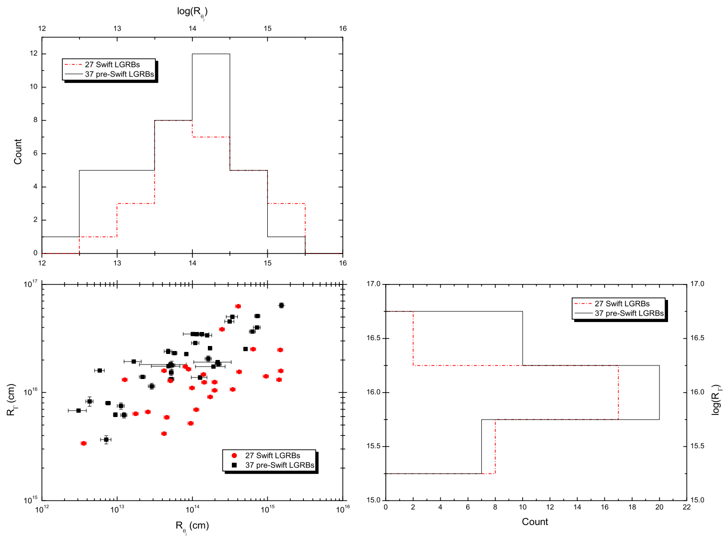

Fig. 1. Correlations between R_{θ_j} and R_Γ as shown in the bottom-left panel. The distributed histograms of R_{θ_j} and R_Γ are displayed in the upper and right panels, respectively.

cm^{-3} (Ghirlanda, Ghisellini, & Lazzati 2004; Kumar 2007). For a burst with measured z and t_j, one can usually calculate θ_j [$=\theta(t_j)$] and get $R_{\theta_j} = cT_{90,i}/(1-cos\theta_j)$ in Eq.(3) once $\eta_\gamma = 0.2$ has been appointed and the isotropic energy E_{iso} is determined by

$$E_{iso} = 4\pi D_l^2 \frac{S_{bolo}}{1+z} \tag{4}$$

where D_l is the luminosity distance and S_{bolo} is the bolometric fluence in γ-rays.

On the other hand, as long as the outflow of one burst slows down consecutively, its initial lorentz factor Γ can be estimated by

$$\Gamma \approx 240 \times E_{iso,52}^{1/8} n_1^{-1/8} (T_{90}/10s)^{-3/8} \tag{5}$$

With this expression, the prompt γ-ray emitting radius in Eq.(3) can then be estimated by

$$R = R_\Gamma \simeq 2cT_{90,i}\Gamma^2 \tag{6}$$

The minimal variability, $(\delta t)_{min}$, and the whole duration can provide the lower and upper limits on the estimation of R, respectively. Unfortunately, the minimal variability within a given GRB is considerably difficult to measure, unlike the duration time. However, Narayan, & Kumar (2009) pointed in their turbulent model that all pulses in GRB light-curve are roughly produced from the same site. This suggests that any pulses of GRB would last long time, comparable with the duration time, with a much lower fluence level.

To calculate the θ_j and then R_{θ_j}, I select sources with measured T_{90}, t_j and z. From Panaitescu (2007) and Kocevski, & Butler (2008), I have chosen 27 Swift LGRBs with measured t_j, of which 13 bursts are well-fitted with standard jet model and the rest are potential jet break candidates. To compare the prompt γ-ray radii for different energy bands and/or instruments, I have also studied the radii of 37 pre-Swift LGRBs in Friedman,& Bloom (2005) of which T_{90}, z and t_j are already known. The t_j of pre-Swift LGRBs are similarly fitted and gotten from the standard jet model (More details about the samples can be found from our another paper in preparation).

3. Results and conclusion

The R distributions have been achieved and displayed in Fig. 1, in which the distances R_{θ_j} derived from the geometric jet and R_Γ from the dynamic jet are also compared. For the 37 pre-Swift bursts, a gaussian fit returns the logarithmically weighted mean radii to be $\langle R_{\theta_j} \rangle = 0.97^{+0.29}_{-0.21} \times 10^{14}$ cm with an error of 0.69 dex ($\chi^2/dof = 1.9$) and $\langle R_\Gamma \rangle = 2.14^{+0.21}_{-0.19} \times 10^{16}$ cm with an error of 0.25 dex ($\chi^2/dof = 1.1$). To check the sensitivity of the distance to detectors, I measured the radii of 27 Swift LGRBs, of which the logarithmically weighted mean radii are $\langle R_{\theta_j} \rangle = 1.32^{+0.51}_{-0.39} \times 10^{14}$ cm with an error of 0.71 dex ($\chi^2/dof = 0.42$) and $\langle R_\Gamma \rangle = 1.29^{+0.09}_{-0.09} \times 10^{16}$ cm with an error of 0.15 dex ($\chi^2/dof = 1.16$).

I find that the radial estimation of LGRBs is highly consistent with some previous results, such as $10^{15} - 10^{16}$ cm (Kumar 2007; Lyutikov 2006b; Narayan, & Kumar 2009) based on early afterglow dataset, $\sim 10^{16}$ cm estimated by spectral cut-off energy (Gupta, & Zhang 2008) and $10^{15} - 10^{17}$ cm in the framework of external shock (Dermer 2007), but significantly larger than the typical value of $10^{12} - 10^{13}$ cm for internal shock interaction (e.g. Piran 2005b). Lazzati, & Begelman (2006) also suggested that the lower limit of the radius would be $R \geq 4 \times 10^{14}$ cm. In some special cases, I report the γ-ray emission distances of GRB 050315 and GRB 050814 to be 1.65×10^{16} cm and 0.69×10^{16} cm, in excellently agreement with 1.4×10^{16} cm and 0.53×10^{16} cm estimated by Kumar (2007), respectively. Consequently, the fundamental physical parameter R is confirmed to be at a distance scale of 10^{16} cm from the above combined considerations. However, this would largely challenge the current theoretical models within the frame of internal shock-fireballs.

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