

Letter to the Editor

Rapid fading of optical afterglows as evidence for beaming in gamma-ray bursts

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Abstract. Based on the refined dynamical model proposed by us earlier for beamed γ -ray burst ejecta, we carry out detailed numerical procedure to study those γ -ray bursts with rapidly fading afterglows (i.e., $\sim t^{-2}$). It is found that optical afterglows from GRB 970228, 980326, 980519, 990123, 990510 and 991208 can be satisfactorily fitted if the γ -ray burst ejecta are highly collimated, with a universal initial half opening angle $\theta_0 \sim 0.1$. The obvious light curve break observed in GRB 990123 is due to the relativistic-Newtonian transition of the beamed ejecta, and the rapidly fading optical afterglows come from synchrotron emissions during the mildly relativistic and non-relativistic phases. We strongly suggest that the rapid fading of afterglows currently observed in some γ -ray bursts is evidence for beaming in these cases.

Key words: Gamma rays: bursts – ISM: jets and outflows – stars: neutron – relativity

1. Introduction

The cosmological origin of γ -ray bursts (GRBs) has been well established due to recent discovery of multi-wavelength afterglows (Costa et al. 1997; Metzger et al. 1997; Galama et al. 1997; Wijers, Rees & Mészáros 1997; Piran 1999). However, we are still far from resolving the puzzle of GRBs, because their “inner engines” are well hidden from direct afterglow observations. Some GRBs localized by BeppoSAX satellite have implied isotropic energy release of more than 10^{54} ergs (Kulkarni et al. 1998, 1999; Andersen et al. 1999; Harrison et al. 1999), which forces many theorists to deduce that GRB radiation must be highly collimated. Obviously, whether GRBs are beamed or not has become one of the most important problems that need to be solved urgently.

In the literature, it is generally believed that afterglows from jetted GRB remnant are characterized by an obvious break in the light curve during the *relativistic phase*, due to both the

jet edge effect (Panaitescu & Mészáros 1999; Kulkarni et al. 1999; Mészáros & Rees 1999) and the lateral expansion effect (Rhoads 1997, 1999). The breaking point is determined by $\gamma \sim 1/\theta$, where γ is the Lorentz factor of the jet and θ is the half opening angle. Recently we have developed a refined dynamical model that can correctly describe the overall evolution of an ultra-relativistic jet to non-relativistic phase with the expanding velocity as small as $10^{-3}c$ (Huang et al. 2000a). Surprisingly enough, our detailed numerical results (Huang, Dai & Lu 2000b) show that the break theoretically predicted in light curve does not appear during *the relativistic phase*, i.e., the time determined by $\gamma \sim 1/\theta$ is not a breaking point. However, an obvious break does appear within the relativistic-Newtonian transition region, the degree of which is found to be parameter dependent (Huang, Dai & Lu 2000b). Generally speaking, the Newtonian phase of jet evolution is characterized by a rapid decay of optical afterglows, with the power-law timing index $\alpha \sim 1.8 - 2.1$.

In practical observations, the power-law decay indices of afterglows from GRB 980326, 980519 and 991208 are anomalously large, $\alpha \sim 2.0$ (Groot et al. 1998; Owens et al. 1998; Castro-Tirado et al. 1999b), and optical light curves of GRB 990123 and 990510 even show obvious steepening at observing time $t \geq 1 - 2$ d (Kulkarni et al. 1999; Harrison et al. 1999; Castro-Tirado et al. 1999a). Recently GRB 970228 was also reported to have a large index of $\alpha \sim 1.73$ (Galama et al. 1999b). These phenomena have been widely regarded as evidence for beaming (Sari, Piran & Halpern 1999; Castro-Tirado et al. 1999a). The purpose of this *Letter* is to study these cases numerically, based on our refined beaming model (Huang et al. 2000a). It is found that optical afterglows from these GRBs can be easily reproduced, thus a jet model is strongly favored.

2. Model

The importance of non-relativistic expansion phase to our understanding of GRB afterglows has been stressed very early by Huang et al. (1998a, b). A refined generic model that is appropriate for both ultra-relativistic and non-relativistic isotropic blastwaves has been proposed (Huang, Dai & Lu 1999a, b). Very

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recently, a similarly refined dynamical model for beamed GRB ejecta was also developed (Huang et al. 2000a). Our calculation here will be based on this model. For completeness, we describe the model briefly here. For details please see Huang et al. (2000a).

Let R be the distance from the burster in the burster frame, M_{ej} be the initial ejecta mass, n be the particle number density of the surrounding interstellar medium (ISM), and m be the swept-up ISM mass. The evolution of the beamed ejecta is described by (Huang et al. 2000a), where $\beta = \sqrt{\gamma^2 - 1}/\gamma$, m_p is the proton mass, c_s is the co-moving sound speed, ϵ is the radiative efficiency (here we consider only adiabatic jets, for which $\epsilon \equiv 0$), $\hat{\gamma} \approx (4\gamma + 1)/(3\gamma)$ is the adiabatic index (Dai, Huang & Lu 1999).

A strong blastwave will be generated due to the interaction of the jet and the ISM. Synchrotron radiation from the shock accelerated ISM electrons gives birth to afterglows (Sari, Piran & Narayan 1998; Vietri 1997a, b). As usual we assume that the magnetic energy density in the co-moving frame is a fraction ξ_B^2 of the total thermal energy density ($B'^2/8\pi = \xi_B^2 e'$), and that electrons carry a fraction ξ_e of the proton energy. This means that the minimum Lorentz factor of the random motion of electrons in the co-moving frame is $\gamma_{e,\text{min}} = \xi_e(\gamma - 1)m_p(p - 2)/[m_e(p - 1)] + 1$, where p is the index characterizing the power-law energy distribution of electrons, and m_e is the electron mass. Our model also takes the electron cooling (Sari, Piran & Narayan 1998) and the equal arrival time surface effect (Panaitescu & Mészáros 1998) into account.

The most important advantage of this model is that it is appropriate for both adiabatic and radiative jets, no matter whether their expansion is highly relativistic or Newtonian.

3. Numerical results

Based on the model described above, Huang, Dai & Lu (2000b) have found that: (i) The optical light curve does not break during the relativistic phase, i.e., the time determined by $\gamma \sim 1/\theta$ is not a breaking point. (ii) An obvious break does appear within the relativistic-Newtonian transition region, but its existence depends on parameters such as ξ_e , ξ_B^2 , n , θ_0 . Increase of any of them to a large enough value will make the break disappear. (iii) Generally speaking, the Newtonian phase of the jet evolution is characterized by a rapid decay of optical afterglows ($\alpha \sim 1.8 - 2.1$).

In this section we use the model to study those GRBs whose optical afterglows decayed rapidly. They include GRB 970228, 980326, 980519, 990123, 990510 and 991208. We employ a standard Friedmann cosmology with $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.2$, $\Lambda = 0$ throughout.

3.1. GRB 990123

GRB 990123 was determined to be at a redshift $z = 1.6004 \pm 0.0008$ (Kulkarni et al. 1999), corresponding to a luminosity distance $D_L \approx 12 \text{ Gpc}$. An enormous isotropic γ -ray energy release of $E_\gamma \approx 3.4 \times 10^{54} \text{ ergs}$ was estimated (Kulkarni et al.

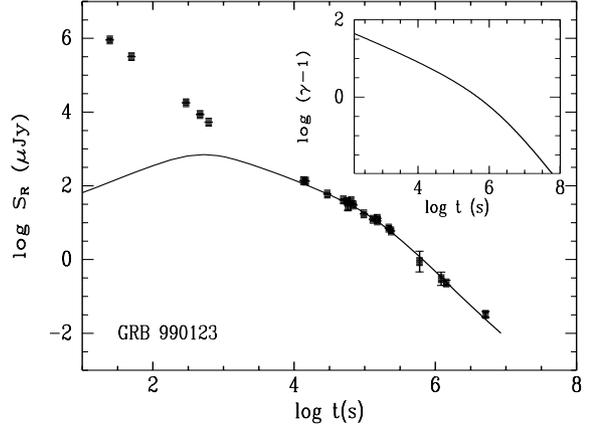


Fig. 1. Observed optical (R band) afterglow from GRB 990123 (Galama et al. 1999a; Kulkarni et al. 1999; Fruchter et al. 1999; GCN 354). The solid line is our best fit to it by employing a jet model. Inset shows the evolution of γ in our model

1999). R band observations made between 0.16 and 2.75 days after the GRB are well described by a power-law with index $\alpha = 1.09 \pm 0.05$ (Fruchter et al. 1999), and the light curve steepens greatly when $t \geq 4 \text{ d}$. Fig. 1 illustrates our best model fit to the R band light curve. We have taken the following initial values and parameters: initial energy per solid angle $(E/\Omega)_0 = 3.4 \times 10^{54} \text{ ergs}/4\pi$, $\gamma_0 = 300$, $n = 10^3 \text{ cm}^{-3}$, $\xi_e = 0.2$, $\xi_B^2 = 10^{-6}$, $\theta_0 = 0.13$, $p = 2.2$ and $D_L = 12 \text{ Gpc}$. In our calculation, the jet enters the sub-relativistic phase at time $t \sim 10^{5.5} \text{ s}$, leading to an obvious break in the light curve. We see that observed data points spanning from $t = 0.16 \text{ d}$ to $t = 59.5 \text{ d}$ can be well fitted.

3.2. GRB 990510

GRB 990510 lies at a redshift $z \geq 1.619 \pm 0.002$ (Vreeswijk et al. 1999), corresponding to $D_L \geq 12 \text{ Gpc}$. Adopting $D_L = 12 \text{ Gpc}$ implies an isotropic energy of $E_\gamma \approx 2.9 \times 10^{53} \text{ ergs}$ (Harrison et al. 1999). Fig. 2 illustrates R band afterglows reported in the literature, where the solid line is our model fit, taking: $(E/\Omega)_0 = 2.9 \times 10^{53} \text{ ergs}/4\pi$, $\gamma_0 = 300$, $n = 1 \text{ cm}^{-3}$, $\xi_e = 0.2$, $\xi_B^2 = 0.01$, $\theta_0 = 0.075$, $p = 2.6$ and $D_L = 12 \text{ Gpc}$. In our calculation, the ejecta enters the sub-relativistic phase at $t \sim 10^6 \text{ s}$. But due to relatively large values of ξ_e and ξ_B^2 , the theoretical light curve peaks very late (Huang, Dai & Lu 2000b), $t_{\text{peak}} \sim 10^4 \text{ s}$, so that observed data points before 10^5 s can be well fitted. For the same reason (also see Huang, Dai & Lu 2000b), theoretical flux decays rapidly during the mildly relativistic phase (i.e., from 10^5 s to 10^6 s), which just meets the observational requirements.

3.3. GRB 980519

GRB 980519 had a rapid fading in optical as well as in X-ray band. Its optical afterglow is consistent with $t^{-2.05 \pm 0.04}$ (Halpern et al. 1999). No redshift was determined. Here we assume a typical value of $z \sim 1.4$ for it, corresponding to $D_L \approx$

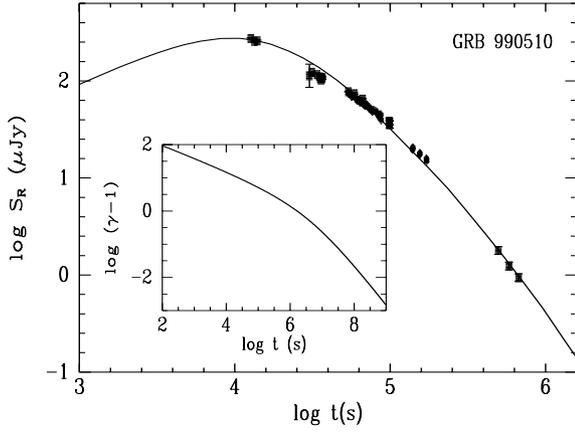


Fig. 2. Observed R band light curve of GRB 990510 and our model fit to it. Data points were taken from GCN 310, 313, 315, 321, 323, 325, 329 and 332 (also see Stanek et al. 1999; Harrison et al. 1999). Inset shows the evolution of γ in our model

10 Gpc. Then the BATSE measured γ -ray fluence of $(2.54 \pm 0.41) \times 10^{-5}$ ergs cm^{-2} implies an isotropic energy of $E_\gamma \sim 10^{53}$ ergs. Taking $(E/\Omega)_0 = 1 \times 10^{53}$ ergs/ 4π , $\gamma_0 = 300$, $n = 100 \text{ cm}^{-3}$, $\xi_e = 0.1$, $\xi_B^2 = 0.01$, $\theta_0 = 0.1$, $p = 2.6$ and $D_L = 10$ Gpc, we give our model fit to the R band light curve in Fig. 3. In our calculation, due to the relatively large ISM density, the jet becomes sub-relativistic at $t \sim 10^5$ s, so the theoretical afterglow decays rapidly after $t \sim 10^4$ s. It is clear that the rapid fading of GRB 980519 can be reasonably explained in our model.

3.4. GRB 991208

GRB 991208 was localized by the Interplanetary Network. Beginning on 1999 Dec. 10.27 UT, the observed optical afterglow is consistent with a rapid decay of $t^{-2.5}$. A redshift of $z \approx 0.71$ was measured (Dodonov et al. 1999), corresponding to $D_L \approx 4$ Gpc. The implied γ -ray energy is $E_\gamma \sim 10^{53}$ ergs. We give our model fit to the R band afterglows in Fig. 4, where we have taken: $(E/\Omega)_0 = 1 \times 10^{53}$ ergs/ 4π , $\gamma_0 = 300$, $n = 10 \text{ cm}^{-3}$, $\xi_e = 0.2$, $\xi_B^2 = 0.01$, $\theta_0 = 0.1$, $p = 2.8$ and $D_L = 4$ Gpc. Due to the relatively large values of n , ξ_e and ξ_B^2 , the theoretical light curve peaks at $\sim 10^4$ s, and it turns into a single line when $t \geq 10^5$ s. We see that the observed data points can be well fitted.

3.5. GRB 970228 and 980326

GRB 970228 is the first GRB that an optical counterpart was observed. Recently, evidence for a supernova was found in the reanalyzed optical and near-infrared images. Galama et al. (1999b) argued that the afterglow observations are well explained by an initial power-law decay with $\alpha = 1.73^{+0.12}_{-0.09}$, modified at later times by a type-Ic supernova light curve. Here we suggest that the initial rapid decay of $t^{-1.73}$ (beginning at $t \sim 5.5 \times 10^4$ s) can be easily explained if a jet model was

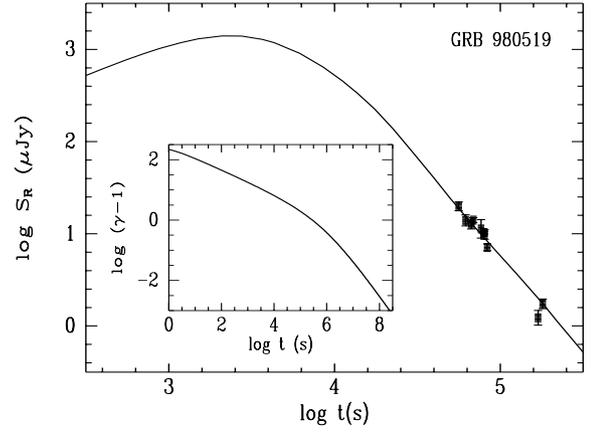


Fig. 3. Observed R band light curve of GRB 980519 and our model fit to it. Data points were taken from GCN 82, 83, 87, 88, 91, 148, 149 (also see Halpern et al. 1999). Inset shows the evolution of γ in our model

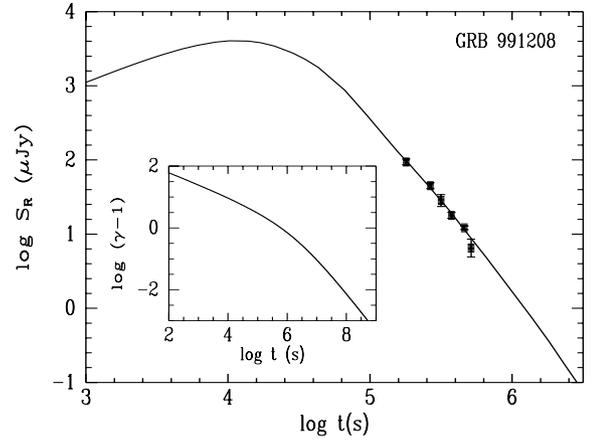


Fig. 4. Observed R band light curve of GRB 991208 and our model fit to it. Data points were taken from GCN 452, 454, 456, 458, 461 and IAU Circ. 7332. Inset shows the evolution of γ in our model

employed. This can be clearly seen from our calculations in Sects. 3.1 — 3.4.

GRB 980326 provides the most strong evidence for GRB/Supernova connection. Its optical afterglow has two distinct contributions: a power-law decaying component ($\alpha \sim 2.1$, Groot et al. 1998) and emission from the underlying supernova (Bloom et al. 1999). Similarly we suggest that the rapidly decaying afterglow component (beginning at $t \leq 3.6 \times 10^4$ s) is produced by beamed GRB ejecta.

4. Discussion and conclusions

Determining the existence of beaming in GRBs will be helpful to our understanding of the GRB “central engines”. Based on our refined dynamical model for beamed GRB remnants (Huang et al. 2000a), we have examined those GRBs with rapidly decaying optical afterglows closely. Detailed numerical results show that afterglows from GRB 970228, 980326, 980519, 990123, 990510 and 991208 can be satisfactorily fitted: the obvious

break in the optical light curve of GRB 990123 is due to the relativistic-Newtonian transition of the beamed ejecta, and the rapid fading of afterglows from other GRBs is due to the relatively large values of ξ_e , ξ_B^2 and n . We thus strongly suggest that these GRBs be highly collimated. Note that in all cases, synchrotron radiation during the mildly relativistic and non-relativistic phases plays an important role in explaining the rapid decaying of optical afterglows.

In our calculations, the ξ_e values distribute in a narrow range, i.e., between 0.1 and 0.2. This has given some support to Freedman & Waxman's (1999) suggestion that ξ_e has a universal value of $\sim 1/3$. However our results do not support their proposal that p has a universal value of 2.2. Our θ_0 values distributed in a narrow range, $\theta_0 \sim 0.1$. This may provide important clues to our understanding of the central engine. We note that Woosley et al. (1999) have obtained such a small value of θ_0 after numerically studying the collapsar models of GRBs. The range of our n values ($n \sim 1 - 1000 \text{ cm}^{-3}$) indicates that some GRBs may be in gaseous environments, also giving some hints on GRB central engines.

The jet model greatly relaxes the energy crisis for GRB 990123 and 990510. However, we should keep in mind that other GRBs such as GRB 970508, 971214, 980329 and 980703 do not have rapidly fading afterglows. They should not be highly collimated (Huang, Dai & Lu 2000b). Then the energy crisis is really a problem: GRB 971214 and 980703 have indicated isotropic γ -ray energies of $\sim 0.17 M_\odot c^2$ and $\sim 0.06 M_\odot c^2$ respectively!

The rapid fading of afterglows from GRB 970228, 980326, 980519 has also been explained as being due to the interaction of an isotropic blastwave with a wind environment (Dai & Lu 1998; Chevalier & Li 1999). However the wind environment model could not explain the light curve break observed for GRB 990123 and 990510. As has been shown clearly in this paper, the jet model can naturally explain all these bursts, and should be more reasonable.

Another possibility was proposed recently by Dai & Lu (1999, 2000). They suggested that the light curve break is due to the relativistic-Newtonian transition of an isotropic blastwave in a dense medium ($n \sim 10^6 \text{ cm}^{-3}$), and the rapidly fading afterglows can be explained as emissions in the non-relativistic phase. It is obviously an interesting proposition and should also be paid attention to.

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