Mem. S.A.It. Suppl. Vol. 21, 194

Memorie della
Supplementi

Early afterglow emission as a probe of the density profile of the medium surrounding gamma-ray bursts

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Abstract. The gamma-ray bursts (GRBs) with durations longer than 2 seconds, namely long gamma-ray bursts, are believed to have a massive star progenitor and should be born in the free stellar wind medium holding up to a radius $\geq 10^{17}$cm. We propose to constrain the density profile of the medium with the early afterglow data and find out that for the interstellar medium (ISM) an early rapid increase of the afterglow flux is possible while in the free wind medium there is no such a signature. For GRB 060418 and GRB 060607A we show that the data is well consistent with the ISM model and the number density is low. While for GRB 081109A, the X-ray and optical data are consistent with the forward shock emission of an ultra-relativistic ejecta expanding into a wind bubble, in which the free wind terminates at a radius $\sim 4.5\times10^{17}$cm, beyond which the medium is ISM-like. The implication of these results has been discussed.

Key words. gamma-rays: bursts - ISM: jets and outflows - radiation mechanisms: non-thermal

1. Introduction

GRBs are widely believed to be generated via the core-collapse of massive stars for conventional long bursts or the merger of compact star binaries for conventional short bursts. In the standard fireball model, the prompt soft γ-ray emission is powered by the collision of the material shells within the relativistic outflow (i.e. the internal shocks) and the afterglow emission is powered by the external forward shock driven by the outflow expanding into the circum-burst medium. The temporal and spectral evolution of the multi-wavelength afterglow, in principle, can be used to diagnose the profile of the circum-burst medium. For short

GRBs, the circumburst medium is expected to be of the interstellar medium (ISM) type or even of the intergalactic medium type. For long GRBs, the circumburst medium is plausibly free wind-like (Dai & Lu 1998; Chevalier & Li 2000) and the density drops with radius as $\rho = 5 \times 10^{11} A_* r^{-2}$g cm^{-1}, where A_* is the normalized parameter of wind density. In reality the density profile may be much more complicated. As is known, massive stars enter the Wolf-Rayet stage during their late evolution and have lost a considerable fraction of their masses in the form of the stellar wind. The interaction between this stellar wind and the surrounding medium creates a wind bubble structure (Weaver et al. 1977). In this scenario, the free expanding supersonic wind is terminated at a radius $R_t \sim 10^{18} - 10^{20}$cm, where the density jumps by a factor of 4 or more. Beyond the wind termination shock is the roughly constant density stalled wind, holding up to a rather large radius $R_{\rm ISM} \sim 10^{19} - 10^{21}$cm; outside this radius is the very dense swept-up ISM (the number density $n \sim 10^2 - 10^3$cm^{-3}) and then the ISM.

The early afterglow data in principle is able to pin down the medium profile. For the GRB outflow expanding into the ISM-like medium but has not get decelerated yet, the observed flux is ($\nu_m < \nu_{\rm obs} < \nu_c$)

$$F_{\rm obs} \propto F_{\nu,\rm max}(\nu_{\rm obs}/\nu_m)^{-(p-1)/2} \propto t^3, \quad (1)$$

where $\nu_{\rm m}$ is the typical synchrotron frequency, ν_c is the cooling frequency and $\nu_{\rm obs}$ is the observer's frequency (Sari et al. 1998). While for a free wind medium, the increase of the forward shock emission cannot be steeper than $t^{1/2}$, as long as the self-absorption effect can be ignored (Jin & Fan 2007). With the late time (i.e., the outflow gets decelerated) afterglow data, there are two ways to diagnose the number density profile of the medium with afterglow date (Jin et al. 2009):

(I) For $\nu_{\rm m} < \nu_{\rm opt} < \nu_{\rm c} < \nu_{\rm X}$, in the case of free wind medium the X-ray emission drops with time as $t^{(2-3p)/4}$ while the optical emission drops faster by a factor of 1/4. On the contrary, in the ISM-like medium the optical emission drops more slowly than the X-rays.

(II) In the case of $\nu_{\rm m} < \nu_{\rm X} < \nu_{\rm c}$, i.e., the X-ray emission is in the slow cooling phase, the temporal index α and spectral index β roughly satisfy $\alpha = (3\beta - 1)/2$ in the free wind medium. We can conclude the surrounding medium is free wind, if we find this relation in the afterglow and no other observation is against it.

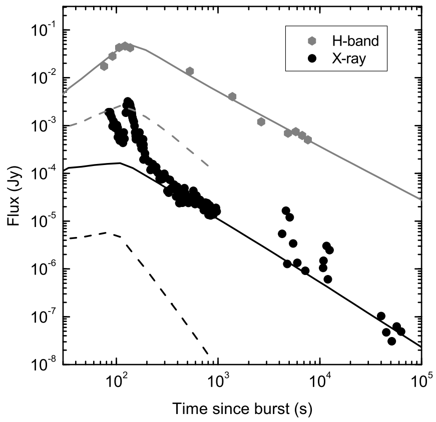

Fig. 1. Numerical fit to the GRB 060418 afterglow. The the circles (black) and hexagons (grey) are X-ray and H-band observations. The solid and dashed lines are our fit to the emission from the forward and reverse shock(from Jin & Fan 2007).

Below we report what we found in past years by taking the early afterglow emission as a probe of the density profile of the circumburst medium.

2. Constant density medium surrounding long GRBs

Molinari et al. (2007) reported the high-quality very early IR afterglow data of GRB 060418 and GRB 060607A. The infrared (IR) afterglow lightcurves are characterized by a sharp rise ($\sim t^3$) and then a normal decline ($\sim t^{-1.3}$), though the simultaneous X-ray lightcurves are highly variable. The smooth joint before and after the peak time in the IR band strongly suggests a very weak reverse shock emission. For GRB 060418 and GRB 060607A, their sharp increase of the very early H-band afterglow light curve has ruled out a wind-like medium.

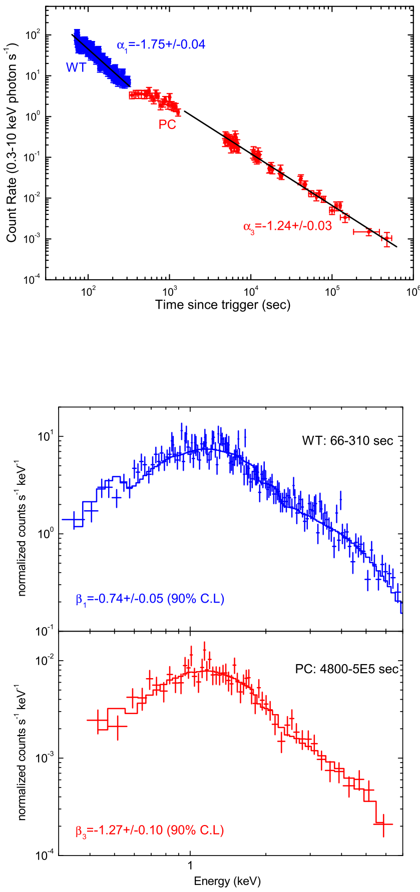

Fig. 2. The X-ray afterglow light curve and spectra of GRB 081109A (from Jin et al. 2009).

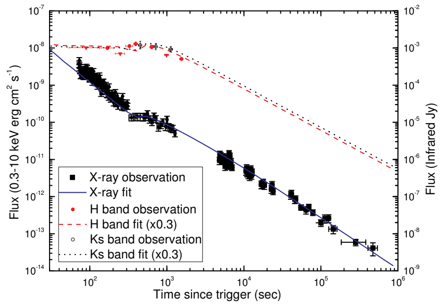

Fig. 3. Numerical fit to the afterglow of GRB 081109A. The lower circles and squares are X-ray observations, and the solid line is our fit. The upper circles(triangles) are H and Ks band observations(upper limits) with Rapid Eye Mount telescope. The dashed and dotted lines are our fit to H- and Ks-band data respectively (from Jin et al. 2009).

The density profile of the medium around long GRBs, in principle, could vary over radius due to the interaction between the stellar wind and the ISM. For $R < R_{\rm t} \sim$ several times $10^{16}-10^{17}$ cm, the medium may be wind-like. At larger R, the stalled wind material may be ISM-like. Assuming that GRB 060418 has such a density profile, we can estimate $R_{\rm t}$ as follows. For the current data it is required that the outflow has not got decelerated at $R_{\rm t}$. Such a fact suggests that $3.8\times10^{36}A_*\Gamma^2 m_{\rm p}c^2 R_{\rm t} < E_{\rm k}/2$, where $E_{\rm k}$ is the isotropic equivalent kinetic energy of the outflow. On the other hand, a $\Gamma\sim 200$ for this burst is likely (Molinari et al. 2007), we thus have(Jin & Fan 2007):

$$R_{\rm t} < 2\times10^{15}{\rm cm}E_{\rm k,54}A_*^{-1}, \qquad (2)$$

here and throughout this work the convention $Q_{\rm x} = Q/10^{\rm x}$ has been adopted. As shown in Fig.1, the ISM-like medium model works nicely and the best fit parameters are $(E_{\rm k,53}, n, \epsilon_e, \epsilon_B, p, \Gamma_0) \sim (300, 1, 0.005, 0.0002, 2.5, 600)$, where $\epsilon_{\rm e}$ ($\epsilon_{\rm B}$) is the fraction of shock energy given to the electrons (magnetic field), p is the power-law index of the accelerated electrons and Γ_0 is the initial Lorentz factor of the outflow.

It is worth pointing out that though the multi-wavelength afterglow modeling of many other bursts has found ISM-like medium surrounding long GRBs (Panaitescu & Kumar 2001; Sollerman et al. 2007), these works were based on the late-time afterglow data. Consequently their results are only valid for medium at larger radius. In GRB 060418 and GRB 060607, we find out that the medium surrounding the center engine is ISM-like for $R \geq 2\times10^{15}{\rm cm}E_{\rm k,54}A_*^{-1}$, which is a very interesting issue on progenitor evolution of long GRBs.

3. Wind bubble surrounding GRB 081109A

The temporal and spectral indices of the X-ray afterglow of GRB 081109A change remarkably. The X-ray afterglow light curve can be well modeled with a doubly broken power law, the fitted parameters are: $\alpha_1 = -1.75 \pm 0.04$, $t_{b1} \sim 310$ s, $\alpha_2 = -0.70 \pm 0.13$, $t_{b2} \sim 2.9 \times 10^3$ s, $\alpha_3 = -1.24 \pm 0.03$, the spectral power-law indices are $\beta_1 = -0.74 \pm 0.05$, $\beta_3 = -1.27 \pm 0.10$ and β_2 in the middle, as shown in Fig. 2. Such behaviors can be self-consistently interpreted as the following. The GRB jet first traverses the freely expanding supersonic wind (FW) of the progenitor with density varying as $\rho \propto r^{-2}$. Then after approximately 300 seconds the jet traverses into a region of apparent constant density (CD) similar to that expected in the stalled-wind region of a stellar wind bubble or the ISM. The optical afterglow data are generally consistent with such a scenario.

Assuming a FW to CD medium transition, we find out that the observation data can be reasonably reproduced with the following parameters (see Fig. 3): $E_k = 4 \times 10^{54}$erg, $\Gamma_0 = 500$, $A_* = 0.02$, $n = 0.12$ cm^{-3}, $R_t = 4.5 \times 10^{17}$cm, $\epsilon_e = 0.02$, $p = 2.5$, $\epsilon_{B,FW} = 0.0002$ and $\epsilon_{B,CD} = 0.001$. The notable parameter is the rather small R_t, which implies a small wind parameter A_* and a large $\bar{p}/k$ since

$$R_t = 5.7 \times 10^{17} \left(\frac{v_w}{10^3 \text{ km s}^{-1}}\right)\left(\frac{\bar{p}/k}{10^6 \text{cm}^3 \text{ K}}\right)^{-1/2} A_{*,-2}^{1/2} \text{ cm}, \quad (3)$$

where v_w is the velocity of the stellar wind, $\bar{p}$ is the pressure in the shocked wind and k is the Boltzmann constant (Chevalier, et al. 2004).

4. Conclusions

The early afterglow data is valuable to constrain the medium profile surrounding the progenitor. For GRB 060418 and GRB 060607A, the sharp increase of the very early H-band afterglow light curve has ruled out a wind-like medium, at a distance very close to the central engine. This conclusion is further supported by the late time X-ray and IR afterglow data of GRB 060418. This rather robust argument is inconsistent with the canonical collapsar model, in which a dense stellar wind medium is expected. More fruitful very early IR/optical data are needed to draw a more general conclusion.

For GRB 081009A, we find it has been breed in a wind bubble environment. The temporal and spectral evolutions of the X-ray afterglow imply a medium transition from FW to CD at the radius $R_t \sim 4.5 \times 10^{17}$ cm. Although some bursts were found born in free stellar wind medium (e.g., Panaitescu & Kumar 2002; Starling et al. 2008), most others were likely born in the medium with a constant number density (even for some bursts associated with bright supernovae, see Fan 2008, and the references therein), which may indicate that GRB outflows expand into the wind bubble rather than the ideal free stellar wind. As shown in Section 3, in some cases the X-ray afterglow data could shed light on the wind bubble structure. Therefore the X-ray afterglow observation since the early time is required to pin down the profile of the circum-burst medium. However, in many *Swift* GRB cases the early X-ray afterglow deviates from the standard afterglow model significantly. For instance, the prolonged activity of GRB central engines would generate energetic X-ray flares that have outshone the regular forward shock emission (e.g., Fan & Wei 2005; Fan et al. 2005). Fortunately, in GRB 081109A there is no flare accompanying the early X-ray afterglow.

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