The X-ray afterglow of GRB 081109A: clue to the wind bubble structure

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ABSTRACT

We present the prompt Burst Alert Telescope and afterglow X-ray Telescope data of Swift-discovered GRB 081109A up to \( \sim 5 \times 10^5\) s after the trigger, and the early ground-based optical followups. The temporal and spectral indices of the X-ray afterglow emission change remarkably. We interpret this as the gamma-ray burst jet first traversing the freely expanding supersonic stellar wind of the progenitor with density varying as \( \rho \propto r^{-2} \). Then, after approximately 300 s the jet traverses into a region of apparent constant density similar to that expected in the stalled-wind region of a stellar wind bubble or the interstellar medium. The optical afterglow data are generally consistent with such a scenario. Our best numerical model has a wind density parameter \( A_\nu \sim 0.02 \), a density of the stalled wind \( n \sim 0.12\) cm\(^{-3}\) and a transition radius \( \sim 4.5 \times 10^{17}\) cm. Such a transition radius is smaller than that predicted by numerical simulations of the stellar wind bubbles and may be due to a rapidly evolving wind of the progenitor close to the time of its core-collapse.

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

1 INTRODUCTION

Gamma-ray bursts (GRBs) are the most luminous explosions in the Universe. They feature extremely relativistic outflows with bulk Lorentz factors of \( 10^{3–5} \) and isotropic energies of \( 10^{44–52}\) erg. These energies are widely believed to be generated via the core-collapse of massive stars for conventional long-(duration) GRBs (e.g. Woosley 1993; Woosley & Bloom 2006) or the merger of compact star binaries for conventional short-(duration) GRBs (e.g. Eichler et al. 1989; Narayan, Paczyński & Piran 1992). In the standard fireball model, the prompt soft \( \gamma \)-ray emission is powered by the collision of the material shells within the relativistic outflow (i.e. the internal shocks); afterwards these material shells spread and merge into a single uniform outflow, continuing to move outwards; then, the long-lived X-ray, optical and radio afterglow emission is powered by the interaction of the overall outflow and the circumburst medium (e.g. Piran 1999; Mészáros 2002; Zhang & Mészáros 2004). Therefore, the temporal and spectral evolution of the multiwavelength afterglow can be used to diagnose the underlying radiation mechanism and the profile of the circumburst medium (e.g. Sari, Piran & Narayan 1998; Chevalier & Li 2000; Panaitescu & Kumar 2002).

For short GRBs, the circumburst medium is expected to be of the interstellar medium (ISM) type or even of the intergalactic medium type, for which the number density is roughly constant and much lower than unity, being consistent with the current afterglow modelling (see Nakar 2007 for a review). For long GRBs, Panaitescu & Kumar (2002) found that the afterglow modelling usually favours the constant density (CD) medium scenario, half of the cases in 10 bursts of a sample were better fitted by the CD medium while only one was better described by a free wind (FW) medium. However, Starling et al. (2008) found that in 10 bursts of a sample, four were clearly in the FW medium while only one was consistent with the CD medium. It seems that the circumburst environments are unlikely to be drawn from only one of the CD or FW profile for long bursts. This is not obviously consistent with the collapsar model in which an ideal FW circumburst medium would be created. The FW has a density profile \( \rho = 5 \times 10^{11} A_\nu r^{-2} \) g cm\(^{-3}\), where \( A_\nu = \left( \frac{M}{10^{-3} M_\odot} \right) \left( \frac{v_\nu}{c} \right)^{1/2} \) is the parameter reflecting the density of the wind. One potential solution is that the ideal FW medium profile has been modified before the GRB explosion. As is known, massive stars are believed to enter the Wolf–Rayet stage during their late evolution and have lost a major fraction of their
masses in the form of the stellar wind. The interaction between this stellar wind and the surrounding medium creates a bubble structure (e.g. Weaver et al. 1977; Ramirez-Ruiz et al. 2001; Wijers 2001; Dai & Wu 2003; Chevalier, Li & Fransson 2004; Eldridge et al. 2006; Pe’er & Wijers 2006; van Marle et al. 2006, 2007; van Marle et al. 2008; Eldridge 2007). In this scenario, the free expanding supersonic wind is terminated at a radius $R_c \sim 10^{18}$–$10^{20}$ cm, where the density jumps by a factor of 4 or more with the lower value expected for such an adiabatic shock. Beyond the wind termination shock is the roughly CD stalled wind, holding up to a rather large radius $R_{\text{ISM}} \sim 10^{20}$–$10^{21}$ cm; outside this radius is the very dense swept-up ISM (the number density $n \sim 10^{-6}$–$10^{-3}$ cm$^{-3}$) and then the ISM.

If the above picture is a good approximation of the circumburst medium, it may be possible to observe afterglow signatures caused by the medium transition at $\sim R_c$ or even at $\sim R_{\text{ISM}}$. In Section 2, we describe the signatures in GRB afterglows for the first transition which is more easily observed and more of interest with respect to the second one. Such a transition is possibly evident in GRB 050904 (Kamble, Resmi & Misra 2007) and GRB 081109A (Gendre et al. 2007). In Section 3, we present the X-ray afterglow observations of GRB 081109A which leads to reach the conclusion that the FW–CD transition is quite clear in this event. The optical afterglow data are generally consistent with such a scenario. Throughout this work, we use the notation $F(t, \nu) \propto t^{-\beta} \nu^{\alpha}$ for the afterglow monochromatic flux as a function of time, where $\nu$ represents the observer’s frequency, $\alpha$ is the monochromatic decay index and $\beta$ is the energy spectrum index. The convention $Q_p = Q/10^p$ has been adopted in cgs units.

2 THE AFTERGLOW SIGNATURES OF THE MEDIUM TRANSITION

The GRB afterglow emission in the CD or FW scenarios has been extensively discussed (see Zhang & Meszaros 2004 for a review). We use the standard fireball afterglow theory with the simple microphysical assumptions of constant energy fractions imparted to the swept-up electrons, $e_e$, and to the generated magnetic field, $e_B$, respectively. The typical synchrotron radiation frequency, $\nu_m$, and the cooling frequency, $\nu_c$, are calculated in the standard way (Sari et al. 1998). Both scenarios lead to the afterglow closure relations made of the temporal decay index, $\alpha$, and the spectral index, $\beta$, depending upon the spectral segment and the energy distribution index of $p \sim 2$–3 of the swept-up electrons. Usually the synchrotron self-absorption frequency, $\nu_a$, is much lower than the optical band and thus neglected unless radio observation is invoked. Therefore, with good-quality temporal and spectral data, the circumburst medium profile can be reliably constrained. We summarize the closure relation in Table 1, apart from the $\nu < \nu_c$ cases (see also Pe’er & Wijers 2006).

For the X-ray afterglow of our interest, there are following two ways to diagnose the number density profile of the medium.

(I) When $\nu_m < \nu_{\text{opt}} < \nu_c < \nu_X$, occurs, in the FW scenario the X-ray emission drops with time as $t^{3/2-3\beta/4}$ while the optical emission drops faster by a factor of $1/4$. On the contrary, in the CD scenario the optical emission drops more slowly than the X-rays.

(II) In the case of $\nu_m < \nu_X < \nu_c$, i.e. the X-ray emission is in the slow cooling phase, the temporal and spectral indices roughly satisfy $\alpha = (3\beta - 1)/2$ in the FW scenario.

Table 1. Temporal index $\alpha$ and spectral index $\beta$ in the cases that the medium profile can be constrained, where the convention $F(t, \nu) \propto t^{-\beta} \nu^{\alpha}$ is adopted. $\nu_m$ is the power-law index of the swept-up electrons, and $\nu_c$, $\nu_a$, and $\nu_{\text{opt}}$ are the self-absorption frequency, the cooling frequency and the characteristic frequency in the synchrotron radiation, respectively (Sari et al. 1998; Chevalier & Li 2000).

| Case | $\beta$ | $\alpha$ (CD) | $\alpha$ (FW) |
|------|--------|--------------|--------------|
| $\nu_m < \nu < \nu_c < \nu_{\text{opt}}$ | 1/3 | 1/6 | -2/3 |
| $\nu_m < \nu < \nu_m < \nu_c$ | 1/3 | 1/2 | 0 |
| $\max\{\nu_m, \nu_{\text{opt}}\} < \nu < \nu_c$ | $-3/4$ | $3/4$ | $1-3\nu$ |
| $\nu_c < \nu$ | $-4$ | $2-3\nu$ | $1-3\nu$ |

$\nu_m$ decays with time as $t^{-3/2}$ in both CD and FW scenarios. However, the cooling frequency $\nu_c$ evolves very differently. In the FW scenario it increases as $t^{1/2}$, but in the CD scenario it declines as $t^{-1/2}$. Therefore, the following observational signatures would be evident before and after the transition. In Case I, the decline of the X-ray emission remains unchanged while the optical decay becomes shallower by a factor of $t^{1/4}$ as long as the optical band is still below $\nu_c$. In Case II, the X-ray decay will get flattened by a factor of $t^{1/4}$ as long as the X-ray band is still below $\nu_c$. Afterwards, when $\nu_c$ drops below the X-ray band, the X-ray decay steepens by a factor of $t^{-1/4}$. As we shall show in the next section, the X-ray afterglow of GRB 081109A fits Case II.

3 THE FW–CD TRANSITION IN GRB 081109A

3.1 Observation and data reduction of GRB 081109A

GRB 081109A was triggered and located by Burst Alert Telescope (BAT) onboard Swift at 07:02:06 UT (trigger 334112), 2008 November 9 (see Immler et al. 2008). We downloaded the raw data from the UK Swift data archive and processed them in a standard way with HEASOFT 6.6. The BAT light curve in the 15–350 keV band was processed with the BATGRBPRODUCT task. This burst has $T_{90}$ of about 61 s in 15–350 keV, classified as a long GRB. The duration value is consistent with the duration measurement of 45 s in 8–1000 keV by the Gamma-ray Burst Monitor (GBM) onboard Fermi (von Kienlin 2008). Also, the time-averaged GBM spectrum is best fit by a power-law function with an exponential high-energy cutoff. The power-law index is $-1.28 \pm 0.09$ and the cut-off energy, parametrized as $E_{\nu_p}$, is $240 \pm 60$ keV ($\chi^2 = 510$ for 479 degrees of freedom). The fluence in 8–1000 keV is $6.35 \pm 0.43 \times 10^{-6}$ erg cm$^{-2}$. Fig. 1 shows the prompt light curves of GRB 081109A in 15–25, 25–50 and 50–100 keV with 1 s time binning. Spectral lag between different energy bands cannot be well measured for this event due to relatively low signal-to-noise ratio.

The Swift X-ray Telescope observations began at 65.6 s after the BAT trigger and discovered a bright and fading X-ray afterglow. Observations continued during the following hours and days and in several return visits, with windowed timing (WT) mode for $\sim 300$ s after the trigger and photon counting (PC) mode afterwards. Throughout the X-ray observation, spectral softening is evident. There is no need for pileup correction to WT data as the highest count rate is less than $\sim 150$ count s$^{-1}$, but such correction should be applied to early PC data when the count rate is higher than $\sim 0.6$ count s$^{-1}$ in order to get correct X-ray light curve and spectra. We made this correction by fitting a King function profile to the point spread function (PSF) to determine the radial point at which the measured PSF deviates from the model. The counts were
The X-ray afterglow of GRB 081109A

Figure 1. The prompt light curves of GRB 081109A in 15–25, 25–50 and 50–100 keV with 1 s binning. Spectral lag between different energy bands cannot be well measured for this event due to relatively low signal-to-noise ratio.

Figure 2. The X-ray afterglow light curve of GRB 081109A in 0.3–10 keV. Also marked are the fitting temporal indices for the WT and late PC segments of the light curve.

extracted using an annular aperture that excluded the affected ∼4 pixel core of the PSF, and the count rate was corrected according to the model. We also considered the most recent calibration and exposure maps. Fig. 2 shows the 0.3–10 keV X-ray light curve, which can be well modelled with a doubly broken power law which is equivalent to a broken power law with a jump transition at ∼500s. For a doubly broken power law, the fitted parameters are $\alpha_1 = -1.75 \pm 0.04$ ($\chi^2 = 152.4$ for 119), $t_{b1} \sim 310$ s, $\alpha_2 = -0.70 \pm 0.13$ ($\chi^2 = 13.7$ for 18), $t_{b2} \sim 2.9 \times 10^3$ s and $\alpha_3 = -1.24 \pm 0.03$ ($\chi^2 = 38.9$ for 54). The integrated spectra of the above first and third segments are shown in Fig. 3. In detail, the spectral power-law indices are $\beta_1 = -0.74 \pm 0.05$, $\beta_3 = -1.27 \pm 0.10$, and $\beta_2$ is in the middle.

The Swift Ultraviolet and Optical Telescope (UVOT) began observing at ∼150 s after the trigger and found no optical counterpart down to ∼18 mag (Immler et al. 2008). Ground-based observations of the afterglow of GRB 081109A were carried out with the Rapid Eye Mount (REM) telescope at La Silla (Zerbi et al. 2001; Chincarini et al. 2003; Covino et al. 2004) equipped with the REM Optical Slitless Spectrograph (ROSS) optical spectrograph/imager and the NIR camera of the automatic REM (REMIR) near-infrared (NIR) camera on 2008 November 09, starting about 52 s after the burst (D’Avanzo et al. 2008). The night was clear, with a seeing of about 2.0 arcsec. We collected images with typical exposures times from 10 to 120 s, covering a time interval of about 0.5 hours. Image reduction was carried out by following the standard procedures. Astrometry was performed using the United States Naval Observatory B1.01 and the Two-Micron All-Sky Survey2 catalogues. We performed aperture photometry for the afterglow and comparison of stars. The afterglow was not detected in the optical. In the NIR, it was detected only in the H and Ks bands. Results for the photometry are reported in Table 2. The Gamma-Ray Burst

Table 2. Optical photometry for GRB 081109A. Upper limits are at 3σ confidence level.

| Filter | Time since trigger (s) | Time integral (s) | Magnitude |
|--------|------------------------|------------------|-----------|
| H      | 89.4                   | 71.3             | >15.0     |
| H      | 168.9                  | 72.2             | 15.017 ± 0.115 |
| H      | 248.4                  | 71.3             | >15.4     |
| H      | 327.0                  | 71.3             | 14.893 ± 0.109 |
| H      | 394.4                  | 47.3             | 14.747 ± 0.128 |
| H      | 636.3                  | 71.3             | 14.963 ± 0.114 |
| H      | 990.6                  | 121.1            | >15.5     |
| H      | 1545.3                 | 171.7            | 15.763 ± 0.101 |
| K      | 450.6                  | 45.6             | 14.365 ± 0.259 |
| K      | 718.4                  | 72.2             | 14.465 ± 0.207 |
| K      | 1122.8                 | 121.1            | 14.645 ± 0.188 |

1 http://www.nofs.navy.nmii/data/fchpix/
2 http://www.ipac.caltech.edu/2mass/
3.2 Analytical investigation of the afterglow of GRB 081109A

For $t < t_{b1}$, the temporal index $\alpha_1 = -1.75 \pm 0.04$ and the spectral index $\beta_1 = -0.74 \pm 0.05$ are related by $\alpha = -3\beta/2 \approx -0.5$, being consistent with the forward-shock emission in the FW medium as long as $v_{\text{m}} < v_\nu < v_c$. For $t > t_{b2}$, the temporal index $\alpha_3 = -1.24 \pm 0.03$ and the spectral index $\beta_3 = -1.27 \pm 0.10$ are related by $\alpha = -3\beta/2 \approx -0.5$, suggesting that the medium can be either FW or CD given $v_\nu > \nu_{300}$ (Zhang & Mészáros 2004). If the FW scenario holds from the very beginning, we have $v_c(t_{h2}) > v_c(t_{h1}) > v_\nu$ because of $v_c \propto t^{1/2}$. One can, of course, assume that either $A_e$ or $\epsilon_B$ has increased abruptly and then get a $v_c(t_{h2}) < v_c(t_{h1})$. However, such a treatment lacks any solid physical background and is thus artificial. On the other hand, if we assume that $t > t_{b1}$ there comes the FW to CD transition, the forward-shock emission light curve will get flattened by a factor of $t_\nu^{1/2}$, roughly consistent with the data (please note that $\alpha_2$ is only poorly constrained). In this scenario, the steepening at $t \geq t_{b2}$ implies $v_c(t_{h2}) > v_c$. Below we present our quantitative estimates.

In an FW medium, we have $\alpha_1 = -3\beta/2$ and $\beta_1 = -2\beta/3$ in the case of $v_{\text{m}} < v_\nu < v_c$. In a CD medium, we have $\alpha_1 = -2\beta/3$ and $\beta_1 = -2\beta/3$ for $v_\nu < v_c \equiv \nu_{300}$. We find that $p = 2.5$ fits both the temporal and spectral slopes of GRB 081109A.

In an FW medium, we have (e.g. Chevalier & Li 2000)

$$F_{\nu,\text{max}} = 0.23 \text{ Jy} \left( \frac{1 + z}{2} \right)^{1/2} \epsilon_{2,-1} E_{k,53}^{1/2} A_{-1}^{1/2} t_{-1}^{1/2}$$

(1)

$$v_{\text{m}} = 1.8 \times 10^{16} \text{ Hz} C_p^2 \left( \frac{1 + z}{2} \right)^{1/2} \epsilon_{2,-1} E_{k,53}^{1/2} A_{-1}^{1/2} t_{-1}^{1/2}$$

(2)

$$v_c = 1.1 \times 10^{15} \text{ Hz} \left( \frac{1 + z}{2} \right)^{-3/2} \epsilon_{2,-1} E_{k,53} A_{-1}^{3/2} t_{-1}^{3/2}$$

(3)

where $E_k$ is the isotropic equivalent energy, $z$ is the redshift of the GRB, and $D_L$ is the corresponding luminosity distance, $t_d$ is the time in days since trigger in the observer’s frame and $C_p \equiv 13(p - 2)/[3(p - 1)]$.

In our model, at $t \sim 65.6$ s, $v_{\text{m}} < 0.3 \text{ keV}$, $v_c > 10 \text{ keV}$ and $F_{0.3\text{keV}} \sim 2.6 \times 10^{-3} \text{ Jy}$ are needed. So we have

$$\epsilon_{2,-1} E_{k,53} < 3 \quad (v_{\text{m}} < 0.3 \text{ keV})$$

(4)

$$\epsilon_{2,-1} E_{k,53} A_{-1} < 0.002 \quad (v_c < 10 \text{ keV})$$

(5)

$$\epsilon_{2,-1} E_{k,53} A_{-1}^{7/8} \sim 0.01$$

(6)

In a CD medium, we have (e.g. Sari et al. 1998)

$$F_{\nu,\text{max}} = 6.6 \text{ mJy} \left( \frac{1 + z}{2} \right) D_L^{2.28,38} E_{k,53} A_{-1}^{1/2} t_{-1}^{1/2}$$

(7)

$$v_{\text{m}} = 2.4 \times 10^{16} \text{ Hz} C_p^2 \left( \frac{1 + z}{2} \right)^{1/2} \epsilon_{2,-1} E_{k,53}^{1/2} A_{-1}^{1/2} t_{-1}^{1/2}$$

(8)

$$v_c = 4.4 \times 10^{16} \text{ Hz} \left( \frac{1 + z}{2} \right)^{-1/2} \epsilon_{2,-1} E_{k,53} A_{-1}^{1/2} t_{-1}^{1/2}$$

(9)

where $n$ is the density of CD medium.

Figure 4. Numerical fit to the afterglow of GRB 081109A. The solid circles and squares are X-ray observations, and the solid line is our numerical fit to X-ray. The circles on the top are H-band (empty) and Ks-band (solid) observations, the triangles are upper limits in the H band. The dashed and dotted lines are numerical fit to H- and Ks-band data, respectively.

At $t \sim t_{b2} \sim 2900 \text{ s}$, our model suggests that $v_{\text{m}} < 0.3 \text{ keV}$, and $F_{0.3\text{keV}} \sim 5.7 \times 10^{-3} \text{ Jy}$. We then have

$$\epsilon_{2,-1} E_{k,53} A_{-1}^{1/2} t_{-1}^{1/2} \sim 310 \text{ s}$$

(13)

$$E_{k,53} A_{-1}^{1/2} t_{-1}^{1/2} \sim 0.06$$

(14)

For GRB 081109A, there is no self-consistent solution for equations (4)–(6), (10)–(12) and (14). The above observational constraints (5), (11) and (14) indicate that $v_{\nu} < \nu_{300}$ and $F_{0.3\text{keV}} > 5.7 \times 10^{-3} \text{ Jy}$, where the subscripts ‘CD’ and ‘FW’ represent the physical parameters measured in the CD and FW mediums, respectively. A similar assumption was needed in the modellings of the afterglow data of GRB 050904 (Gendre et al. 2007) and GRB 050319 (Kamble et al. 2007). The physical reason is that the CD medium has been heated by the termination reverse shock and then may be weakly magnetized.

The optical data, though rare comparing with the X-ray ones, provide us a reliable test of the current afterglow model. As shown in Fig. 4, the H-band light curve is distinguished by a flat at early time and then a rebrightening at $t \sim 400 \text{ s}$. These features are generally consistent with our FW to CD medium model. In the FW medium, a flat segment is expected if the observer’s frequency $v_{\nu,\text{obs}}$ is above the synchrotron self-absorption frequency $v_{\nu,\text{abs}}$ but below $v_{\nu,\text{m}}(v_c)$. In the CD medium, a rebrightening is present if the relation $v_\nu < v_{\nu,\text{abs}} < v_c$ still holds (e.g. Zhang & Mészáros 2004). The rebrightening peaks when $v_{\nu,\text{obs}}$ crosses the observer’s frequency. After that the flux will drop with time as $t^{3(1-p)/4}$ a little bit shallower than the simultaneous X-ray decline, as suggested by the H-band data.
Figure 5. Numerical fit to the spectrum evolution in GRB 081109A afterglow. In the X-ray band (0.3–10 keV), the spectrum between 65.6 and 310 s is a single power law $\beta_1 = 0.75$, and after ~4800 s is another single power law $\beta_3 = 1.25$.

3.3 Numerical fit of the afterglow of GRB 081109A

The code used here to fit the X-ray light curves has been developed by Yan, Wei & Fan (2007), with small changes to adapt a density transition in surrounding medium. Assuming an FW to CD medium transition, we find out that the observation data can be reasonably reproduced with the following parameters (see Figs 4 and 5): $E_k = 4 \times 10^{52}$ erg, the initial Lorentz factor $\gamma_0 = 500$, $A_s = 0.02$, $n = 0.12$ cm$^{-3}$, $R_t = 4.5 \times 10^{17}$ cm, $\epsilon_e = 0.02$, $p = 2.5$, $\epsilon_{B,\infty} = 0.0002$, and $\epsilon_{B,CD} = 0.001$. The source is assumed to be at a redshift $z = 1$. As shown in Fig. 5, a sudden increase of $\epsilon_{B}$ for $t > t_{hi}$ is required to account for the jump of $v_\perp$ inferred from the X-ray data. $A_s \sim 0.01$ and $R_t \sim 10^{17}$–$10^{18}$ cm is lower than the typical value found in numerical simulations and may be due to a rapidly evolving wind of the progenitor close to the time of its core-collapse (Eldridge et al. 2006; Eldridge 2007; van Marle et al. 2008). Assuming a redshift $z = 1$, the isotropic energy $E_v$ in the energy range of $1$–$10$ $000$ keV is about $5 \times 10^{52}$ erg. The corresponding GRB efficiency $E_v/(E_v + E_k)$ is $\sim 1$ per cent. Such a low efficiency, though not typical, is still reasonable, as found in previous estimates (e.g. Fan & Piran 2006; Jin & Fan 2007).

The observed optical flux is lower than the value extrapolated from X-ray observation, which implies that there is extinction in optical band. To agree with the optical observation, our numerical fit for the $H$ and $K_s$ band has been adjusted by a factor of 0.3, which requires about 1 mag extinction caused by the GRB host galaxy at the observed $H$ and $K_s$ band. They are about 1 $\mu$m at the GRB host galaxy. It essentially means $E(B-V) \sim 0.8$–0.9 assuming Milky Way or Small Magellanic Cloud extinction curves. With a Galactic dust-to-gas ratio it would correspond to $N_H \sim 5 \times 10^{21}$ cm$^{-2}$. The fit is shown in Fig. 4. The small differences around the termination radius may be due to the sharp density jump we have assumed.

Before the blast wave reaches $R_t$, its radius can be estimated as (Chevalier & Li 2000)

$$R = 3.5 \times 10^{17} \left( \frac{1+z}{2} \right)^{-1/2} E_k^{1/3} A_s^{-1/2} \epsilon_{B,\infty}^{1/2} \text{ cm.} \tag{15}$$

For $t(R_t) \sim 310$ s, with equation (5) we have $R = R_t > 10^{22}$ [(1 + z)/2]$^{-1/2} A_s^{3/2} \epsilon_{B,\infty}^{-1/2}$ cm. This implied that $R_t$ depends on the undetermined redshift $z$ weakly. A larger $A_s$ requires a smaller $\epsilon_{B,\infty}$ otherwise $R_t$ will be much smaller than a few $\times 10^{17}$ cm, the lowest value expected in the numerical simulation. Since the derived $\epsilon_{B,\infty}$ is already as low as $\sim 10^{-4}$, a smaller value is less likely. That is why we will not consider the case of an FW parameter $A_s \gg 0.01$.

When a GRB jet finally enters into the very dense swept-ISM region, strong reverse shock may be formed and an afterglow rebrightening is expected (Dai & Wu 2003; Pe’er & Wijers 2006). The X-ray observation for GRB 081109A lasted about $4.7 \times 10^4$ s after the trigger and did not find obvious flux enhancement. In our numerical fit, the jet front reached a radius $\sim 1.9 \times 10^{18}$ cm at such a late time, much smaller than $R_{\text{ISM}}$ estimated by numerical simulations (Eldridge et al. 2006; Eldridge 2007). So, the GRB outflow was still in the shocked wind material ejected in the Wolf–Rayet stage with an approximately CD (Weaver et al. 1977).

4 CONCLUSION AND DISCUSSION

Although some GRBs are inferred to occur in free stellar wind medium (e.g. Panaitescu & Kumar 2002; Starling et al. 2008), most are inferred to occur in a 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 2 of this work, 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 trace the profile of the circumburst medium. However, in many Swift GRB events the early X-ray afterglow deviates from the standard afterglow model significantly (Nousek et al. 2006; Zhang et al. 2006). 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; Nousek et al. 2006; Zhang et al. 2006). Fortunately, in GRB 081109A there is no flare accompanying the early X-ray afterglow. The temporal and spectral evolutions of the X-ray afterglow imply a medium transition at the radius $R_t \sim 4.5 \times 10^{17}$ cm (see Section 3). Such a small $R_t$ implies a small wind parameter $A_s$ and a large $\epsilon_{B,\infty}$ since

$$R_t = 5.7 \times 10^{17} \left( \frac{v_w}{10^4 \text{ km s}^{-1}} \right) \left( \frac{p}{10^6 \text{ cm}^3 \text{ K}} \right)^{-1/2} A_s^{-1/2} \text{ cm,}$$

where $p$ is the pressure in the shocked wind and $k$ is the Boltzmann constant (Chevalier et al. 2004). Indeed $A_s$ is found to be as small as $10^{-2}$ in our numerical fit, GRB 081109A is thus a good candidate of long GRBs born in wind bubble.

The rising behaviour of the very early afterglow light curves can play an important role in probing the density profile of the medium. This is particularly the case if the reverse shock optical emission is very weak. As shown in Jin & Fan (2007) and Xue, Fan & Wei (2009), in the FW scenario the very early optical rise is usually not expected to be faster than $t^{1/2}$ while in the CD medium the rise can be faster than $t^2$. Therefore, the $\sim t^{1/2}$-like rise in the early optical/infrared/X-ray afterglows of GRB 060418, GRB 060607A (Molnari et al. 2007), GRB 060801, GRB 060926, GRB 080319C, and GRB 080413B (Xue et al. 2009) rules out the FW medium for $R > 10^{16}$ cm. Thus, the absence of the FW signature in some GRB afterglows is still a puzzle. One possible solution is that the mass-loss rate due to the stellar wind before massive stars collapse is not a constant and might be much lower than previously assumed (Eldridge et al. 2006; Eldridge 2007).

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