Afterglows from Jetted GRB Remnants

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Abstract

We have found that the conventional generic dynamical model for gamma-ray bursts (GRBs) cannot reproduce the Sedov solution in the non-relativistic limit. Based on our refined generic dynamical model, we investigate afterglows from jetted GRB remnants numerically. Many new results are reached. For example, we find no obvious break in the optical light curve during the relativistic phase itself. But an obvious break does exist at the transition from the relativistic phase to the non-relativistic phase, which typically occurs at time 10 to 30 days. It is very interesting that the break is affected by many parameters, such as the electron energy fraction, $\xi_e$, the magnetic energy fraction, $\xi_B^2$, the initial opening angle of the jet, $\theta_0$, and the medium density, $n$. We also find that afterglows from jetted GRB remnants are uniformly characterized by a quick decay during the non-relativistic phase, with power law timing index greater than 2.1. Afterglows from GRB 970228, 980326, 980519, 990123, 990510 and 991208 can be satisfactorily fitted if the corresponding GRB ejecta are highly collimated.

1 Introduction

The discovery of afterglows from some gamma-ray bursts (GRBs) has opened up a new era in the field (Costa et al. 1997; Galama et al. 1999). The so called fireball model (Meszáros & Rees 1992; Sari et al. 1996), which can successfully explain the major features of GRB afterglows (Vietri 1997; Waxman 1997; Tavani 1997; Wijers et al. 1997), becomes the most popular model (see Piran 1999 and van Paradijs et al. 2000 for recent reviews). Some GRBs localized by BeppoSAX satellite have implied isotropic energy release of more than $10^{54}$ ergs (Madsen et al. 1999; Harrison et al. 1999), this has forced many theorists to deduce that GRB radiation must be highly collimated (Groot et al. 1998; Owens et al. 1998; Halpern et al. 1999; Castro-Tirado et al. 1999; Sari et al. 1999; Wei & Lu 1999a, b).

To tell a jet from an isotropic fireball, it seems that we must resort to the afterglow light curves. When the bulk Lorentz factor of a jet drops to $\gamma < 1/\theta$, with $\theta$ the half opening angle, the edge of the jet becomes visible, the light curve will steepen by $t^{-3/4}$. This is called the edge effect (Meszáros & Rees 1999; Panaitescu & Meszáros 1999; Kulkarni et al. 1999). Additionally, the lateral expansion of a relativistic jet will make
the break even more precipitous (Rhoads 1999; Lamb 2000). So it is generally believed that afterglows from jetted GRBs are characterized by an obvious break in the light curve at the relativistic stage.

In this article, I use our refined dynamical model to study the jet effect on the afterglow light curves.

2 Our Refined Generic Model

The importance of the non-relativistic phase of fireball expansion has been stressed by Huang et al. (1998a, b; also see Wijers et al. 1997). In the literature, it is generally believed that the following equation can depict the evolution of GRB remnants (Chiang & Dermer 1999)

$$\frac{d\gamma}{dm} = -\gamma^2 - \frac{1}{M},$$

where $m$ is the rest mass of the swept-up medium, $M$ is the total mass in the co-moving frame, including internal energy. However, Huang et al. (1999) pointed out that during the non-relativistic phase of an adiabatic expansion, Eq. (1) cannot reproduce the familiar Sedov solution. This is clearly shown in Fig. 1.

Huang et al. (1999) have proposed a refined equation

$$\frac{d\gamma}{dm} = -\gamma^2 - \frac{1}{M_{ej} + \epsilon m + 2(1 - \epsilon)\gamma m},$$

where $M_{ej}$ is the initial baryon mass ejected from the GRB central engine, and $\epsilon$ is the radiative efficiency. For an adiabatic fireball, $\epsilon = 0$; and for a highly radiative one, $\epsilon = 1$. 

Figure 1: Velocity vs. radius for an isotropic adiabatic fireball. The dashed line is the familiar Sedov solution in the Newtonian phase. The dash-dotted line is drawn according to Eq. (1), which differs from the dashed line markedly. The solid line corresponds to our refined model (i.e., Eq. (2)), which is consistent with the Sedov solution.
Huang et al. (1999) have shown that Eq. (2) is correct for both radiative and adiabatic fireballs, and in both ultra-relativistic and non-relativistic phases (c.f. Fig. 1).

3 Evolution of Jetted GRB Remnants

Using our refined dynamical model, the evolution of the beamed ejecta can be described by (Huang et al. 2000a, b, c, d):

$$\frac{dR}{dt} = \beta c \gamma (\gamma + \sqrt{\gamma^2 - 1}),$$  

(3)

$$\frac{dm}{dR} = 2\pi R^2 (1 - \cos \theta) n m_p,$$  

(4)

$$\frac{d\theta}{dt} = \frac{c_s (\gamma + \sqrt{\gamma^2 - 1})}{R},$$  

(5)

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_{ej} + \epsilon m + 2(1 - \epsilon)\gamma m},$$  

(6)

$$c_s^2 = \dot{\gamma}(\gamma - 1)(\gamma - 1) \frac{1}{1 + \dot{\gamma}(\gamma - 1)} c^2,$$  

(7)

where $m_p$ is the proton mass, $c_s$ is the co-moving sound speed, $\dot{\gamma} \approx (4\gamma + 1)/(3\gamma)$ is the adiabatic index, and $c$ is the speed of light. Below we will consider only adiabatic jets, for which $\epsilon \equiv 0$).

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.
As usual we assume that the magnetic energy density in the co-moving frame is a fraction \( \xi_B^2 \) of the total thermal energy density \((B'^2/8\pi = \xi_B^2 e')\), and that electrons carry a fraction \( \xi_e \) 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.

### 4 Numerical Results

For convenience, let us define the following initial values or parameters as a set of “standard” parameters: initial energy per solid angle \( E_0/\Omega_0 = 10^{54} \) ergs/4\( \pi \), \( \gamma_0 = 300 \), \( n = 1 \) cm\(^{-3} \), \( \xi_B^2 = 0.01 \), \( p = 2.5 \), \( \xi_e = 0.1 \), \( \theta_0 = 0.2 \), \( \theta_{\text{obs}} = 0 \), \( D_L = 10^6 \) kpc, where \( \theta_{\text{obs}} \) is the angle between the line of sight and the jet axis, and \( D_L \) is the luminosity distance.

We have followed the evolution of jetted GRB remnants numerically and calculated their afterglows (Huang et al. 2000a, c, d). Fig. 2 shows the evolution of \( \gamma \) for some exemplary jets. We see that the ejecta will cease to be highly relativistic at time \( t \sim 10^5 - 10^6 \) s. This gives strong support to our previous argument that we should be careful in discussing the fireball evolution under the simple assumption of ultra-relativistic limit (Huang et al. 1998a, b, 1999, 2000a, b, c, d).

Fig. 3 illustrates the effect of \( \xi_e \) on the optical (R-band) light curves. In no case could we observe the theoretically predicted light curve steepening (with the break point determined by \( \gamma \sim 1/\theta \)) during the relativistic stage itself. The reason is: at time of \( \gamma \sim 1/\theta \), the jet is already in its mildly relativistic phase and it will become non-relativistic.
soon after that, so the break due to the edge effect and the lateral expansion effect does not have time to emerge during the relativistic phase (Huang et al. 2000a, c). Furthermore, since $\gamma$ is no longer much larger than 1, conventional theoretical analyses (under the assumption of $\gamma \gg 1$) are not proper. However, when $\xi_e$ is small, an obvious break does appear in the light curve, but it is clearly due to the relativistic-Newtonian transition. The simulation by Moderski et al. (2000) does not reveal such breaks, because their model is not appropriate for Newtonian expansion. When $\xi_e$ is large, the break disappears. This is not difficult to understand. According to the analysis in the ultra-relativistic limit, the time that the light curve peaks scales as $t_m \propto \xi_e^{4/3}(\xi_B^2)^{1/3}$. Fig. 3 shows this trend qualitatively. In the case of $\xi_e = 1.0$, $t_m$ is as large as $\sim 10^5$ s, then we can not see the initial power law decay (with timing index $\alpha \sim 1.1$) in the relativistic phase, it is hidden by the peak. So the break disappears. We should also note that in all cases, light curves during the non-relativistic phase are characterized by quick decays, with $\alpha \geq 2.1$. This is quite different from isotropic fireballs, whose light curves steepen only slightly after entering the Newtonian phase (i.e., $\alpha \sim 1.3$).

Fig. 4 illustrates the effect of $\xi_B^2$ on the optical light curves. Interestingly but not surprisingly, we see that $\xi_B^2$ has an effect similar to $\xi_e$: for small $\xi_B^2$ values, there are obvious breaks at the relativistic-Newtonian transition points; but for large $\xi_B^2$ values, the break disappears, we could only observe a single steep line with $\alpha \geq 2.1$. This is also due to the dependence of $t_m$ on $\xi_B^2$ (Huang et al. 2000c).

We have also investigated the effects of other parameters such as $\theta_0$, $n$, $p$ on the optical light curves (Huang et al. 2000c). When $\theta_0 \geq 0.4$, the light curve becomes very similar to that of an isotropic fireball and no steep break exists. In the case of a dense medium ($n \geq 10^3$ cm$^{-3}$), the expansion becomes non-relativistic quickly, so that the break also disappears and we could only observe a quick decay with $\alpha \geq 2.1$. But generally speaking, $p$ does not affect the break notably.

In Fig. 5, we show the effects of $\xi_e$, $\xi_B^2$ and $\theta_0$ on the X-ray afterglow light curves. Again we see that a large value of any of these parameters will make the relativistic-Newtonian break disappear. X-ray afterglows from GRB 980519 decayed very quickly, with $\alpha \approx 1.83 \pm 0.3$. We suggest that they may be produced by a jet with a large $\xi_B^2$ or a large $\xi_e$ (Huang et al. 2000d).

5 Comparison with Observations

Optical afterglows from GRB 990123, 990510 are characterized by an obvious break in the light curve, and afterglows from GRB 970228, 980326, 980519, 991208 faded rapidly. We suggest that these phenomena are due to beaming effects. We have fitted these afterglows based on our refined jet model and find that the observations can be reproduced easily with a universal initial half opening angle $\theta_0 \sim 0.1$ (Fig. 6). The obvious light curve break in GRB 990123 is due to the relativistic-Newtonian transition of the beamed ejecta, and the rapidly fading afterglows come from synchrotron emissions during the mildly relativistic and non-relativistic phases. We thus strongly suggest that the rapid fading of afterglows currently observed in some GRBs is evidence for beaming in these cases.
6 Discussion and Conclusions

To conclude, in this article, we try to answer the following question: does the jet effect lead to any breaks in the afterglow light curve? We have shown clearly that the theoretically predicted light curve steepen due to the edge effect and the lateral expansion effect in fact does not exist, consistent with recent numerical results by some other researchers (Moderski et al. 2000). Our new finding is that a striking break does appear in the light curve at the relativistic-Newtonian transition point. However, this break is affected by many parameters, such as $\xi_e, \xi_B, \theta_0$ and also $n$. Increase of any of them to a large enough value will make the break disappear. So, although a sharp break in the light curve is a good indicator for jet (note that this break is due to the relativistic-Newtonian transition, as pointed out above), the jet effect does not definitely lead to sharp breaks in the afterglow light curves. This seems to make the task of distinguishing jets from isotropic fireballs even more difficult.

Fortunately we have another helpful tool. Although whether the break appears or not depends on parameters, afterglows from jetted GRB remnants are uniformly characterized by a quick decay during the non-relativistic phase, with $\alpha \geq 2.1$. This is quite different
from isotropic fireballs. We strongly suggest that it can be regarded as a fundamental characteristic of jet and may be used to judge the degree of beaming observationally. For example, the rapid fading of optical afterglows from GRB 970228, 980326, 980519, 990123, 990510 and 991208 has been argued as evidence for beaming in these GRBs (Huang et al. 2000b).

Showing only a single flat line (with $\alpha \sim 1.1$) in the optical light curve, radiation from GRB 971214 and GRB 980703 is not likely be highly collimated. Since they have indicated isotropic energies of $\sim 0.17 M_\odot c^2$ and $\sim 0.06 M_\odot c^2$ respectively (Kulkarni et al. 1998; Bloom et al. 1998), which could hardly be met by any kind of compact stellar objects, we see that the energy crisis is really a problem.

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