A&A 368, 464–470 (2001)
DOI: 10.1051/0004-6361:20000352

Astronomy & Astrophysics

Gamma-ray burst afterglows from jetted shocks in wind environments

L. J. Gou[1], Z. G. Dai[1,2], Y. F. Huang[1,3], and T. Lu[1,2]

[1] Department of Astronomy, Nanjing University, Nanjing 210093, PR China
e-mail: daizigao@public1.ptt.js.cn
[2] IHEP, Chinese Academy of Sciences, Beijing 100039, PR China
[3] Astronomical and Astrophysical Center of East China, Nanjing University, Nanjing 210093, PR China

Received 6 June 2000 / Accepted 22 September 2000

Abstract. Gamma-ray bursts with long durations are widely thought to arise from the collapse of massive stars, where the wind environment is unavoidable. It is also believed that γ-ray bursts come from jets. Considering these two points in this paper, we calculate the evolution of a highly collimated jet that expands in a stellar wind environment and the expected afterglow from such a jet. We use a set of refined dynamical equations and a realistic lateral speed of the jet, and find: (1) There is no observable break at the time when the Lorentz factor of the jet is equal to the inverse of its initial half-opening angle. (2) No obvious break appears at the time when the blast wave transits from the relativistic to the non-relativistic phase. (3) For the wind case, there is no flattening tendency even up to 10^9 s. (4) Compared with the homogeneous medium case, our calculated flux is weaker in the stellar wind case. Finally, we find that two kinds of GRB models (neutron star mergers and massive star collapses) may be discriminated in our numerical results.

Key words. gamma-rays: bursts – ISM: jets and outflows – stars: mass loss – shock waves

1. Introduction

Since the discovery of the GRB 970228 afterglow by BeppoSAX, research on gamma-ray bursts (GRBs) has evolved. Now we know that GRBs are one of the most energetic phenomena at the cosmological distance. Optical afterglows have been observed from about a dozen GRBs (Klose 2000), most of which concentrate at the distance scale of $z \sim 1$, corresponding to the luminosity distance of about 3.0 Gpc. In addition, some GRBs' host galaxies have been discovered. All these discoveries leave no doubt that GRBs, the origins of which had puzzled people since their discovery more than 30 years ago, are of cosmological origin.

Whether a jet exists or not in GRBs is fundamental. We believe that jets should exist based on the following facts: (1) The isotropic energy release per GRB is generally in the range of 10^{51}–10^{52} ergs. It can be explained well by a stellar-mass progenitor. However for two GRBs, GRB 990123 (Kulkarni et al. 1999a) and GRB 990510 (Harrison et al. 1999), the isotropic energy is so enormous that it is difficult to explain it by any stellar progenitor model, which forces some theorists to deduce that the radiation must be highly collimated in these cases. (2) The steepening of some afterglow light curves observed at the optical band is argued as evidence that jets exist in GRB radiation (Kulkarni et al. 1999a; Harrison et al. 1999; Stanek et al. 1999; Huang et al. 2000a). Rhoads (1997a, 1999), Sari et al. (1999), Mészáros & Rees (1999b) have shown that the lateral expansion of a relativistic jet will lead to a more rapid deceleration, causing a sharp break in the afterglow light curve. For GRB 990123, the power law index of the afterglow light curve is $\alpha = 1.0 \pm 0.03$ in the 2 days after the burst. After 2 days, there is a sudden steepening in the light curve (Kulkarni et al. 1999b). Similarly, for GRB 990510 the power law index changes from $\alpha = 0.76$ to $\alpha = 2.4 \pm 0.02$ after $t = 1.0$ day (Stanek et al. 1999). Recently, a rapid decay with $\alpha = 1.73$ was found in GRB 970228 (Galama et al. 2000). All these breaks may be due to the lateral expansion of jets (Huang et al. 2000a). (3) The observed radio flare may provide an independent and excellent indication of a jet-like geometry in GRBs (Harrison et al. 1999; Kulkarni et al. 1999). As argued by Waxman et al. (1998), the radio afterglow from a spherical fireball must rise to a peak flux on a timescale of a few weeks, but because of lateral expansion, the radio afterglow from the forward shock of a jet must fade a few days after the burst. Therefore, the relative faintness of the observed late-time radio emission implies the existence of a jet (Sari & Piran 1998a). GRB 990510 may be

Send offprint requests to: L. J. Gou,
e-mail: tlu@nju.edu.cn

a good example: its radio radiation began to decline one day after the burst (Harrison et al. 1999). (4) The polarization observed in the afterglows may also be evidence for jets. Gruzinov (1999) has argued that optical afterglows from jets can be strongly polarized, in principle up to tens of percents, if co-moving magnetic fields parallel and perpendicular to the jet have different strengths and if we observe the afterglows at a right viewing angle. However, Sari (1999) argued that even if the magnetic fields had a well-defined orientation relative to the direction of the shock, the polarization is unlikely to exceed 20%. Furthermore, taking into account the dynamics of jets, the polarization first rises to the peak around the jet break time and then decays. (5) Observed light curves of some GRBs steepen simultaneously at different bands. This may be further evidence that there is collimated ejecta in GRB radiation (Harrison et al. 1999). (6) Observational characteristics of some GRBs are similar to those of BL Lacs, in which jets are unavoidably involved (Paczyński 1993; Dermer & Chiang 1999; Cheng et al. 1999). This implies that GRBs may arise from jets.

Generally, the broken light curves of some afterglows are explained to be due to the expansion of jets into a homogeneous interstellar medium (Harrison et al. 1999; Stanek et al. 1999; Huang et al. 2000a). However, other explanations have also been proposed. For example, when a spherical fireball evolves in the Wolf-Rayet star wind, the light curve can also steepen (Chevalier & Li 1999, 2000; Mészáros et al. 1998; Frail et al. 1999a,b; Dai & Lu 1998a). Dai & Lu (1999, 2000a,b) suggested that when a shock in a dense medium transits from the relativistic phase to the non-relativistic phase, a break would occur in the light curve.

The most important problem in GRB research is the energy mechanism. It is widely believed that GRBs with long durations come from the collapse of massive stars (Fryer et al. 1998, 1999a,b; In't Zand 1998; Ruffert & Janka 1998, 1999; Woosley et al. 1999; Rees 1999; Mészáros & Rees 1999a). For a massive star at the end of its evolution, it throws away its envelope and the core collapses into a compact object, producing a jet. Then, due to interactions between different shells inside the jet and between the jet and its surrounding medium, a GRB and its afterglow are produced, respectively. The recently discovered connection between supernovae and GRBs provides strong support to such a collapsar model. At present, there are three GRBs which are most likely connected with supernovae: GRB 980425 (SN 1998bw) (Galama et al. 1998; Iwamoto et al. 1998), GRB 970228 (Galama et al. 2000; Reichart 1999), GRB 980326 (Bloom et al. 1999). Recently, two other GRBs were added, i.e. GRB 970514 (SN 1997cy) (Germany et al. 2000; Turatto et al. 2000) and GRB 980910a (SN 1999e) (Kulkarni & Frail 1999c; Thorsett & Hogg 1999).

Livio & Waxman (1999) recently discussed the evolution of a jet in the wind environment and gave an analytical result. They argued that at late stages (particularly after the break corresponding to $\gamma = 1/\theta_{\rm o}$), the light curve has a flattening tendency. In this paper, we use some refined equations to describe the evolution of jets. First, in the adiabatic case, when blast wave is extremely relativistic, its dynamical evolution satisfies the Blandford-Mckee (1976) solution. But when it reaches the non-relativistic phase, it satisfies the Sedov-Taylor self-similar solution. However, the conventional dynamical model can not transit correctly from the ultra-relativistic phase to the non-relativistic phase. This has been stressed by Huang et al. (1998a,b, 1999a,b). Here we use the refined dynamical equations proposed by Huang et al. (1999a,b, 2000b,c,d), which can describe the overall evolution of jets from the ultra-relativistic phase to the non-relativistic phase. Second, for the lateral expansion speed of jets, it is reasonable to assume that it is just the co-moving local sound speed $c_{\rm s}$. Usually, one has taken $c_{\rm s} = c$ or $c/\sqrt{3}$ (Rhoads 1997a,b, 1999; Sari et al. 1999), where c is the speed of light. In fact we expect $c_{\rm s}$ to vary with time, and especially it will by no means be c or $c/\sqrt{3}$ when the blast wave decelerates into the non-relativistic stage. Huang et al. (2000b,c,d) have given the proper lateral expansion speed which depends on the bulk speed of the blast wave.

Based on these considerations, we calculate the evolution of jets in the wind environment from the relativistic stage to the non-relativistic stage and compare numerical results with those of jet evolution in the homogeneous medium. We describe our model in Sect. 2. Our detailed numerical results are presented in Sect. 3. Section 4 is a brief discussion of our final results.

2. Model

2.1. Basic equations

The overall evolution of a jet can be described by the refined equations (Huang et al. 2000b,c,d)

$$\frac{\mathrm{d}\gamma}{\mathrm{d}t_\oplus} = -\frac{(\gamma^2-1)}{M_{\rm ej}+\epsilon m_{\rm sw}+2(1-\epsilon)\gamma m_{\rm sw}} \times 2\pi R^2(1-\cos\theta_{\rm j})\rho\beta c\gamma(\gamma+\sqrt{\gamma^2-1}), \quad (1)$$

$$\frac{\mathrm{d}m_{\rm sw}}{\mathrm{d}t_\oplus} = 2\pi R^2\,(1-\cos\theta_{\rm j})\,\rho\beta c\gamma\left(\gamma+\sqrt{\gamma^2-1}\right), \quad (2)$$

$$\frac{\mathrm{d}R}{\mathrm{d}t_\oplus} = \beta c\gamma\left(\gamma+\sqrt{\gamma^2-1}\right), \quad (3)$$

$$\frac{\mathrm{d}\theta_{\rm j}}{\mathrm{d}t_\oplus} = \frac{1}{R}c_{\rm s}\left(\gamma+\sqrt{\gamma^2-1}\right), \quad (4)$$

where γ is the Lorentz factor of the jet, $m_{\rm sw}$ is the total mass of the swept-up medium, R is the radius, $\theta_{\rm j}$ is the half opening angle of the jet, $t_\oplus$ is the observed time, ρ is the mass density of the interstellar medium, $M_{\rm ej}$ is the initial mass of the jet, and ϵ is the radiation efficiency of the jet. Equations (1)–(4) describe the overall dynamical evolution. However before evaluating them numerically, we should give the expressions for $c_{\rm s}, \epsilon$, and ρ.

2.2. Sound speed

The lateral expansion is determined by the co-moving sound speed. The simple assumption of $c_\mathrm{s} = c/\sqrt{3}$ is unreasonable in the present paper. Huang et al. (2000b,c,d) give the proper sound speed which depends on the bulk Lorentz factor. Here we give a brief derivation. Kirk & Duffy (1999) have derived

$$c_\mathrm{s}^2 = \frac{\hat{\gamma} p'}{\rho'} \left[\frac{(\hat{\gamma}-1)\rho'}{(\hat{\gamma}-1)\rho' + \hat{\gamma} p'} \right] c^2, \tag{5}$$

where ρ' and p' are the co-moving mass density and pressure, respectively, and $\hat{\gamma}$ is the adiabatic index. Dai et al. (1998, 1999) obtained a simple and useful expression for $\hat{\gamma}$, $\hat{\gamma} = (4\gamma+1)/(3\gamma)$. Since $e' = \gamma\rho' c^2$ and $p' = (\hat{\gamma}-1)(e' - \rho' c^2)$, it is easy to get (Huang et al. 2000b,c,d)

$$c_\mathrm{s}^2 = \hat{\gamma}(\hat{\gamma}-1)(\gamma-1)\frac{1}{1+\hat{\gamma}(\gamma-1)} c^2. \tag{6}$$

In the ultra-relativistic limit ($\gamma \gg 1, \hat{\gamma} \approx 4/3$), Eq. (6) becomes $c_\mathrm{s}^2 = c^2/3$; and in the non-relativistic limit ($\gamma \sim 1, \hat{\gamma} \approx 5/3$), we simply get $c_\mathrm{s}^2 = 5\beta^2 c^2/9$. So, Eq. (6) is a reasonable expression and will be used in our model.

2.3. Radiative efficiency

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 (Dai et al. 1998, 1999)

$$\frac{B'^2}{8\pi} = \xi_\mathrm{B}^2 \frac{\hat{\gamma}\gamma+1}{\hat{\gamma}-1}(\gamma-1) n m_\mathrm{p} c^2. \tag{7}$$

Generally, the afterglow comes from synchrotron radiation of the electrons accelerated behind the shock (Sari et al. 1998; Wijers et al. 1997). The contribution of the inverse Compton-scattering emission is always neglected, because it is unimportant particularly at late times (Waxman 1997). So we only consider synchrotron emission from the electrons. Assume that the accelerated electrons carry a fraction ξ_e of the proton energy. This implies that the minimum Lorentz factor of the random motion of electrons in the co-moving frame is

$$\gamma_\mathrm{e,min} = \xi_\mathrm{e}(\gamma-1)\left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)\left(\frac{p-2}{p-1}\right) + 1, \tag{8}$$

where m_e is the electron mass, p is the index characterizing the power law energy distribution of electrons, and m_p is the proton mass. Considering only the synchrotron radiation, Dai et al. (1998, 1999) derived the radiative efficiency of the jet

$$\epsilon = \xi_\mathrm{e} \frac{t'^{-1}_\mathrm{syn}}{t'^{-1}_\mathrm{syn} + t'^{-1}_\mathrm{ex}}, \tag{9}$$

where $t'_\mathrm{syn} = 6\pi m_\mathrm{e} c/(\sigma_\mathrm{T} B'^2 \gamma_\mathrm{e,min})$ is the synchrotron cooling time with σ_T being the Thompson scattering cross section, and $t'_\mathrm{ex} = R/\gamma c$ is the co-moving frame expansion time. For the highly radiative expansion, $\xi_\mathrm{e} \approx 1$ and $t'_\mathrm{syn} \ll t'_\mathrm{ex}$ we have $\epsilon \approx 1$. The early evolution of the jet might be in this regime. For the adiabatic expansion, $\xi_\mathrm{e} \ll 1$ or $t'_\mathrm{syn} \gg t'_\mathrm{ex}$, we get $\epsilon \approx 0$. The late evolution of the jet is believed to be in this regime. In this paper, we consider the latter case, i.e. adiabatic expansion.

2.4. Mass density

Huang et al. (2000b,c,d) have considered the case that a jet evolves in the homogeneous interstellar medium (ISM). In this paper, we consider the case that a jet expands in the preburst stellar wind. For massive stars, particularly Wolf-Rayet stars, the typical wind-loss rate is $\dot{M} \approx 10^{-5} - 10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$, and their typical speed is $V_\mathrm{w} \approx 1000{-}25\,000\ \mathrm{km\,s^{-1}}$ (Willis 1991). According to $4\pi R^2 \rho V_\mathrm{w} = \dot{M}$, we can easily get

$$\rho = 5.02\ 10^{-18}\ \mathrm{g\ cm^{-3}} \left(\frac{R}{10^{15}\,\mathrm{cm}}\right)^{-2} \times \left(\frac{\dot{M}}{10^{-4}\ M_\odot\ \mathrm{yr}^{-1}}\right)\left(\frac{V_\mathrm{w}}{1000\ \mathrm{km\ s^{-1}}}\right). \tag{10}$$

We will use this kind of mass density structure in the paper.

2.5. Electron energy distribution

In the absence of radiation loss, the distribution of the shock accelerated electrons behind the blast wave is usually assumed to be a power law function of electron energy,

$$\frac{\mathrm{d}N'_\mathrm{e}}{\mathrm{d}\gamma_\mathrm{e}} \propto \gamma_\mathrm{e}^{-p}, \quad (\gamma_\mathrm{e,min} \le \gamma_\mathrm{e} \le \gamma_\mathrm{e,max}), \tag{11}$$

where $\gamma_\mathrm{e,max}$ is the maximum Lorentz factor, $\gamma_\mathrm{e,max} = 10^8 (B'/1\mathrm{G})^{-1/2}$ (Dai et al. 1998, 1999), and p usually varies between 2 and 3. However, radiation loss may play an important role in the process. Electrons with different Lorentz factors have different radiation efficiencies. Sari et al. (1998) have derived an equation for the critical electron Lorentz factor, γ_c, above which synchrotron radiation is significant,

$$\gamma_\mathrm{c} = \frac{6\pi m_\mathrm{e} c}{\sigma_\mathrm{T} \gamma B'^2 t}. \tag{12}$$

Electrons with Lorentz factors below γ_c are adiabatic, and electrons above γ_c are highly radiative.

In the presence of a steady injection of electrons accelerated by the shock, the distribution of radiative electrons becomes another power law function with an index of $p+1$ (Rybicki & Lightman 1979), but the distribution of adiabatic electrons is unchanged. Then the actual distribution should be given according to the following cases (Dai et al. 1998d, 1999):

(1) For $\gamma_c \le \gamma_{e,\min}$,

$$\frac{dN'_e}{d\gamma_e} = C_1 \gamma_e^{-(p+1)}, \quad (\gamma_{e,\min} \le \gamma_e \le \gamma_{e,\max}), \tag{13}$$

$$C_1 = \frac{p}{\gamma_{e,\min}^{-p} - \gamma_{e,\max}^{-p}} N_{ele}, \tag{14}$$

where N_{ele} is the number of radiating electrons in a ring between θ and $\theta + d\theta$ with θ being the angle between the velocity of emitting material and the line of sight.

(2) For $\gamma_{e,\min} < \gamma_c \le \gamma_{e,\max}$,

$$\frac{dN'_e}{d\gamma_e} = \begin{cases} C_2 \gamma_e^{-p}, & (\gamma_{e,\min} \le \gamma_e \le \gamma_c), \\ C_3 \gamma_e^{-(p+1)}, & (\gamma_c < \gamma_e \le \gamma_{e,\max}), \end{cases} \tag{15}$$

where

$$C_2 = C_3/\gamma_c, \tag{16}$$

$$C_3 = \left[\frac{\gamma_{e,\min}^{1-p} - \gamma_c^{1-p}}{\gamma_c (p-1)} + \frac{\gamma_c^{-p} - \gamma_{e,\max}^{-p}}{p} \right]^{-1} N_{ele}. \tag{17}$$

(3) For $\gamma_c > \gamma_{e,\max}$,

$$\frac{dN'_e}{d\gamma_e} = C_4 \gamma_e^{-p}, \quad (\gamma_{e,\min} \le \gamma_e \le \gamma_{e,\max}), \tag{18}$$

where

$$C_4 = \frac{p-1}{\gamma_{e,\min}^{1-p} - \gamma_{e,\max}^{1-p}} N_{ele}. \tag{19}$$

2.6. Formulae of synchrotron spectrum

In the co-moving frame, the synchrotron radiation power at frequency ν' from electrons is given by (Rybicki & Lightman 1979)

$$P'(\nu') = \frac{\sqrt{3} e^3 B'}{m_e c^2} \int_{\gamma_{e,\min}}^{\gamma_{e,\max}} \left(\frac{dN'_e}{d\gamma_e} \right) F\left(\frac{\nu'}{\nu'_c} \right) d\gamma_e, \tag{20}$$

where e is electron charge, $\nu'_c = 3\gamma_e^2 e B'/(4\pi m_e c)$, and

$$F(x) = x \int_x^{+\infty} K_{5/3}(k) dk, \tag{21}$$

with $K_{5/3}(k)$ being the Bessel function. We assume that this power is radiated isotropically in the comoving frame,

$$\frac{dP'(\nu')}{d\Omega'} = \frac{P'(\nu')}{4\pi}. \tag{22}$$

Defining $\mu = \cos\theta$, we can derive the differential power in the observer's frame (Rybicki & Lightman 1979; Huang et al. 2000b,d),

$$\frac{dP(\nu)}{d\Omega} = \frac{1}{\gamma^3 (1-\beta\mu)^3} \frac{dP'(\nu')}{d\Omega'} = \frac{1}{\gamma^3 (1-\beta\mu)^3} \frac{P'(\nu')}{4\pi}, \tag{23}$$

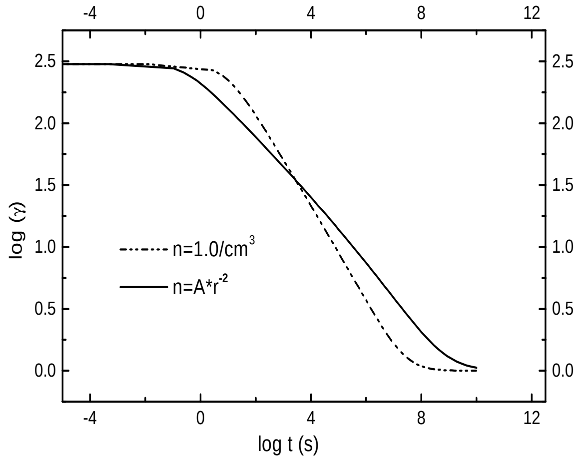

Fig. 1. Evolution of the Lorentz factor. We have taken the "standard" parameters: $E_0/\Omega_0 = 1\ 10^{54}$ ergs/4π, $\gamma_0 = 300$ (i.e. $M_{ej}/\Omega_0 = 0.002\ M_\odot/4\pi$), $\xi_B^2 = 0.02$, $p = 2.5$, $\xi_e = 0.1$, $\theta_0 = 0.2$. The solid line corresponds to the wind environment ($\dot{M} = 10^{-5}\ M_\odot\,yr^{-1}$ and $V_w = 10^3\ km\,s^{-1}$), and the dashed line to the homogeneous ISM ($n = 1\,cm^{-3}$). The time that $\gamma = 2$ is about 6 10^6 s in the ISM case, and 10^8 s in the wind case

$$\nu = \frac{\nu'}{\gamma(1-\mu\beta)}. \tag{24}$$

Here quantities with prime are measured in the comoving frame, and quantities without prime are in the observer's frame. Then the observed flux density at frequency ν at certain angle is

$$\begin{aligned} s_\nu(\mu) &= \frac{1}{A_s} \left(\frac{dP(\nu)}{d\Omega} \frac{A_s}{D_L^2} \right) \\ &= \frac{1}{\gamma^3 (1-\beta\mu)^3} \frac{1}{4\pi D_L^2} P'(\gamma(1-\mu\beta)\nu), \end{aligned} \tag{25}$$

where A_s is the area of the detector and D_L is the luminosity distance. The observed flux density at a given frequency is obtained by integrating over the shock front within the jet boundary θ_j.

3. Numerical results

In our model, we use the following initial values or parameters as a set of "standard" parameters: $E_0/\Omega_0 = 1\ 10^{54}$ ergs/4π, $\gamma_0 = 300$ (i.e. $M_{ej}/\Omega_0 = 0.002\ M_\odot/4\pi$), $\xi_B^2 = 0.02$, $p = 2.5$, $\xi_e = 0.1$, $\theta_0 = 0.2$. For simplicity, we assume that the expansion during the whole stage is adiabatic, i.e. $\epsilon \equiv 0$.

Figure 1 shows the evolution of the Lorentz factor. We see that the bulk Lorentz factor changes very slowly at late times in the wind case, compared with that in the homogeneous ISM case. For the wind case, using the standard parameters, we see that at 10^8 s, the blast wave decelerates into the non-relativistic stage (here we let $\gamma = 2$ be the critical point between the relativistic and non-relativistic phases). In the homogeneous ISM case,

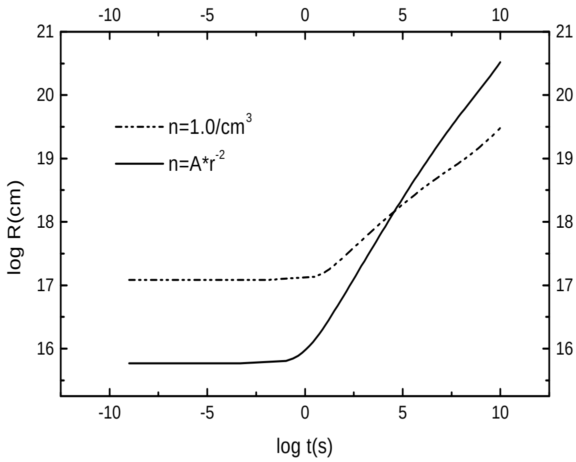

Fig. 2. Evolution of the shock radius (R). Parameters and line styles are the same as in Fig. 1

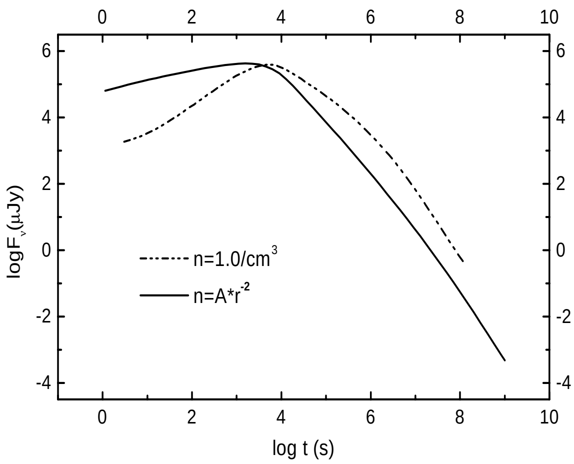

Fig. 4. R band afterglow light curves. The thick solid line corresponds to a jet with "standard" parameters, and viewing angle $\theta_{\rm obs} = 0$

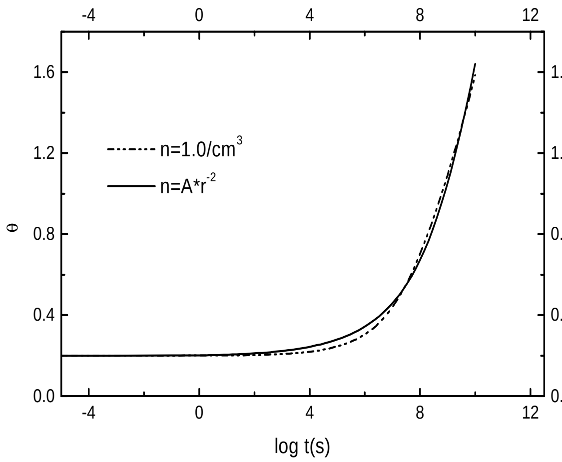

Fig. 3. Evolution of the half opening angle (θ). Parameters and line styles are the same as in Fig. 1

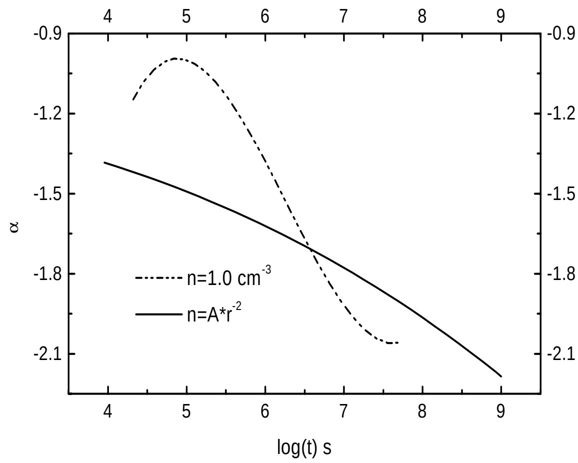

Fig. 5. The evolution of the time index of the afterglow light curve at the R band. Parameters and line styles are the same as in Fig. 1

the blast wave evolves into the non-relativistic stage at about 10^7 s. Figure 2 illustrates the time dependence of the shock radius.

In Fig. 3 we present the evolution of the jet opening angle. During the ultra-relativistic phase the angle increases only slightly, because at this time, lateral expansion speed can be thoroughly neglected when compared with the blast wave speed itself. However at the Newtonian stage, θ increases quickly from 0.6 to 1.4.

In Fig. 4, we show the R-band light curve. Please note that at the end point of each curve the average electron Lorentz factor is already as small as $\gamma_{\rm e,min} = 5$, corresponding to a bulk Lorentz factor of $\gamma = 1.05$, which implies that the jet is completely in the Newtonian regime. Rhoads (1999) as well as Livio & Waxman (1999) has predicted that the light curve will show a break when the bulk Lorentz factor is $\gamma \approx 1/\theta_0$ (here the blast wave is still at the relativistic stage). In Fig. 5, we give the evolution of the time index of the afterglow. We expect that the break in the wind case is less obvious than that found by Huang et al. (2000a,b,c,d) in the homogeneous ISM. Our numerical results verify this expectation.

Combining Fig. 4 with Fig. 1, we can see that both in the wind environment and in the homogeneous ISM environment there is no observable break during the relativistic stage, which is consistent with the results of Panaitescu & Mészáros (1998), Moderski et al. (2000), Huang et al. (2000a–d), and Wei & Lu (2000). We expected that there would be an obvious break during the trans-relativistic stage, i.e. transition from the relativistic stage to the non-relativistic stage. We don't find such a break but a rather smooth curve, which can be seen clearly in Fig. 5. In a uniform density medium the increase of the index in the power-law of the light curve is 1.07 during about two and a half decades in time. For a pre-ejected stellar wind α increases by 0.8 over 5 decades. Therefore, as argued by Kumar & Panaitescu (2000), a break in the light curve for a jet in a wind model is unlikely to be detected.

4. Discussion

Following Huang et al. (2000a–d), who considered the evolution of a jet in a homogeneous ISM environment, we investigated the detailed dynamical evolution of jets and their afterglows for the wind case from the ultra-relativistic stage to the non-relativistic stage. Recently, Kumar & Panaitescu (2000) considered the evolution of a jet in stratified media. Compared with their studies, our model is refined in the following aspects: (1) Kumar & Panaitescu (2000) considered the evolution of an adiabatic jet, while we study the expansion of a partially radiative realistic jet. Furthermore, the dynamics presented are applicable to both ultra-relativistic and Newtonian jets, so we could follow the overall evolution of a jet using a set of differential equations. (2) Similarly, Kumar & Panaitescu (2000) did not consider the variation of sound velocity with time. We describe the lateral expansion of jets with a refined and more reasonable sound speed expression, which varies with the bulk Lorentz factor (Huang et al. 2000b,d).

In addition, we considered the evolution of electron distribution with time. Despite these differences, one of our results is similar to that of Kumar & Panaitescu (2000): there seems no observable break around the time of $\gamma = 1/\theta_0$, which conflicts with Rhoads' (1999) and Livio & Waxman's (1999) expectations. Furthermore, we also find that:

1. Livio & Waxman (1999) predicted that a light curve flattening would occur when the blast wave evolves into the non-relativistic stage. For the wind case, we calculated up to 10^9 s (corresponding to a Lorentz factor of 1.05), when the blast wave has completely evolved into the non-relativistic stage. We do not find any flattening tendency in the light curve.

2. The transition from the ultra-relativistic phase to the non-relativistic phase is also very smooth; the expected obvious break does not appear. This is very similar to the behaviour of isotropic fireballs (Wijers et al. 1997; Huang et al. 2000b).

3. If we use the same parameters (except for the differences in number density for the wind case and for the homogeneous ISM), we find that the flux density in the wind case is obviously weaker than that in the homogeneous ISM case. This property is consistent with Chevalier & Li's (2000) result.

Two currently popular models for GRB progenitors are the mergers of compact objects (neutron stars or black holes) and the explosions of massive stars. It is widely believed that GRBs produced by the former model occur in the ISM with density $n \sim 1$ cm^{-3} and GRBs produced by the latter model occur in the preburst stellar wind enviroment with mass density $\rho \propto R^{-2}$. As argued by Chevalier & Li (2000) and Livio & Waxman (1999), both ISM and wind cases should show the same emission feature during the lateral spreading phase, and in particular, on a timescale of days, the wind density is similar to typical ISM densities so that an interaction with the wind would give results that are not different from the ISM case. If GRBs are beamed, thus, their optical afterglow emission could not be used to discriminate the massive prognitor model from the compact binary progenitor model. However, our numerical results show that their optical afterglow emissions are different, particularly several days after the burst. Thus, it may be used to discriminate the two models from each other, and further observations may verify our numerical results.

Acknowledgements. We are very grateful to Z. Li, Z. X. Ma and X. Y. Wang for useful comments. This work was partially supported by the National Natural Science Foundation of China (grants 19773007, 19973003, 19825109 and 10003001), the National Project of Fundmental Researches (973 Project) and the Special Funds for Major State Basic Research Projects.

References

Blandford, R. D., & McKee, C. F. 1976, Phys. Fluids, 19, 1130
Bloom, J. S., et al. 1999, Nature, 401, 453
Cheng, K. S., Fan, J. H., & Dai, Z. G. 1999 [astro-ph/9910540]
Chevalier, R. A., & Li, Z. Y. 1999, ApJ, 520, L29
Chevalier, R. A., & Li, Z. Y. 2000, ApJ, 536, 195 [astro-ph/9908272]
Dai, Z. G., Huang, Y. F., & Lu, T. 1998 [astro-ph/9806334]
Dai, Z. G., Huang, Y. F., & Lu, T. 1999, ApJ, 520, 634
Dai, Z. G., & Lu, T. 1998a, MNRAS, 298, 87
Dai, Z. G., & Lu, T. 1998b, A&A, 333, L87
Dai, Z. G., & Lu, T. 1998c, Phys. Rev. Lett., 81, 4301
Dai, Z. G., & Lu, T. 1999, ApJ, 519, L155
Dai, Z. G., & Lu, T. 2000a, ApJ, 537, 803 [astro-ph/9906109]
Dai, Z. G., & Lu, T. 2000b [astro-ph/0005417]
Dermer, C. D., & Chiang, J. 1999, High Energy Processes in Accreting Black Holes, ASP Conf. Ser., 161, ed. J. poutanen, & R. Svensson, 264 [astro-ph/9810222]
Frail, D. A., Kulkarni, S. R., Sari, R., et al. 1999a, ApJ, 534, 559 [astro-ph/9910060]
Frail, D. A., Waxman, E., & Kulkarni, S. R. 1999b, ApJ, 537, 191 [astro-ph/9910319]
Fryer, C. L., & Woosley, S. E. 1998, ApJ, 502, L9
Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 1999a, ApJ, 526, 152
Fryer, C. L., et al. 1999b, ApJ, 520, 650
Galama, T. J., et al. 1998, Nature, 395, 670
Galama, T. J., et al. 2000, ApJ, 536, 185 [astro-ph/9907264]
Germany, L. M., Reiss, D. J., & Schmidt, B. P., et al. 2000, ApJ, 533, 320
Gruzinov, A. 1999, ApJ, 525, L29
Harrison, F. A., Bloom, J. S., et al. 1999, ApJ, 523, L121 [astro-ph/9905306]
Huang, Y. F., Dai, Z. G., & Lu, T. 1998a, A&A, 336, L69
Huang, Y. F., Dai, Z. G., Wei, D. M., & Lu, T. 1998b, MNRAS, 298, 459
Huang, Y. F., Dai, Z. G., & Lu, T. 1999a, Chin. Phys. Lett., 16, 775
Huang, Y. F., Dai, Z. G., & Lu, T. 1999b, MNRAS, 309, 513
Huang, Y. F., Dai, Z. G., & Lu, T. 2000a, A&A, 355, L43
Huang, Y. F., Gou, L. J., Dai, Z. G., & Lu, T. 2000b, ApJ, 543, 90 [astro-ph/9910493]
Huang, Y. F., Dai, Z. G., & Lu, T. 2000c, Chin. Phys. Lett., 17, 778

Huang, Y. F., Dai, Z. G., & Lu, T. 2000d, MNRAS, 316, 943
In't Zand, J. J. M. 1998, ApJ, 503, L53
Iwamoto, K., et al. 1998, Nature, 395,672
Kirk, J. G., & Duffy, P. 1999, J. Phys. G: Nuclear and Particle Physics, 25, R163 [astro-ph/9905069]
Klose, S. 2000 [astro-ph/0001008]
Kulkarni, S. R., et al. 1999a, Nature, 398, 389
Kulkarni, S. R., et al. 1999b, ApJ, 522, 97
Kulkarni, S. R., & Frail, D. A. 1999c, GCN198
Kumar, P., & Panaitescu, A. 2000, ApJ, 541, L9 [astro-ph/0003264]
Livio, M., & Waxman, E. 1999, ApJ, 538, 187 [astro-ph/9911160]
Mészáros, P., Rees, M. J., & Wijers, R. A. M. J. 1998, ApJ, 499, 301
Mészáros, P., & Rees, M. J. 1999a, ApJ, 502, L105
Mészáros, P., & Rees, M. J. 1999b, MNRAS, 306, 39
Moderski, R., Sikora, M., & Bulik, T. 2000, ApJ, 529, 151
Paczyński, B. 1993, Ann. NY Acad. Sci., 688, 321
Panaitescu, A., & Mészáros, P. 1999, ApJ, 526, 707
Rees, M. J. 1999, A&AS, 138, 491
Reichart, D. E. 1999, ApJ, 521, L111
Rhoads, J. E. 1997, ApJ, 485, L57
Rhoads, J. E. 1997, in Gamma-Ray Bursts 4th Huntsville Symposium, ed. C. Meegan, R. Preece, & T. Koshut, AIP Conf. Proc. 428 (New York: AIP)
Rhoads, J. E. 1999, ApJ, 525, 737
Ruffert, M., & Janka, H. Th. 1998, A&A, 338, 535
Ruffert, M., & Janka, H. Th. 1999, A&A, 344, 573
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (Wiley, New York)
Sari, R., Piran, T., & Halpern, J. 1999, ApJ, 519, L17
Sari, R., & Piran, T. 1998a, ApJ, 517, L109
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Sari, R. 1999, ApJ, 524, L43
Stanek, K. Z., Garnavich, P. M., Kaluzny, J., et al. 1999, ApJ, 522, L39
Thorsett, S. E., & Hogg, D. W. 1999, GCN197
Turatto, M., Suzuki, T., & Mazzali, P. A. 2000, ApJ, 534, L57
Waxman, E. 1997, ApJ, 507, L45
Waxman, E., Kulkarni, S. R., & Frail, D. A. 1998, ApJ, 497, 288
Wei, D. M., & Lu, T. 2000, ApJ, 541, 203
Willis, A. J. 1991, in IAU Symp. 143, Wolf-Rayet Stars and Interactions with Other Massive Stars in Galaxies, ed. K. A. van der Hucht, & B. Hidayat (Dordrecht: Kluwer), 265
Wijers, R. A. M. J., Rees, M. J., & Mészáros, P. 1997, MNRAS, 288, 257
Woosley, S. E., MacFadyen, A. E., & Heger, A. 1999 [astro-ph/9909034]