Effects of Environment and Energy Injection on Gamma-Ray Burst Afterglows

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Abstract

There is growing evidence that some long gamma-ray bursts (GRBs) arise from the core collapse of massive stars, and thus it is inevitable that the environments of these GRBs are pre-burst stellar winds or dense media. We studied, for the first time, the wind model for afterglows based on the Blandford-McKee self-similar solution of a relativistic shock, and suggested that GRB 970616 is an interactor with a stellar wind. We also proposed a dense medium model for some afterglows, e.g., the steepening in the light curve of the R-band afterglow of GRB 990123 may be caused by the adiabatic shock which has evolved from an ultrarelativistic phase to a nonrelativistic phase in a dense medium. We further discussed the dense medium model in more details, and investigated the effects of synchrotron self absorption and energy injection. A shock in a dense medium becomes nonrelativistic rapidly after a short relativistic phase. The afterglow from the shock at the nonrelativistic stage decays more rapidly than at the relativistic stage. Since some models for GRB energy sources predicted that a strongly magnetic millisecond pulsar may be born during GRB formation, we discussed the effect of such a pulsar on the evolution of the nonrelativistic shock through magnetic dipole radiation. We found that in the pulsar energy injection case, the dense medium model fits very well all the observational data of GRB 980519. Recently, we combined the dense medium model with the pulsar energy injection effect to provide a good fit to the optical afterglow data of GRB 000301C.

1 Introduction

In the standard afterglow shock model (for a review see [27,38]), a gamma-ray burst (GRB) afterglow is usually believed to be produced by synchrotron radiation or inverse Compton scattering in an ultrarelativistic shock wave expanding in a homogeneous medium. As more and more ambient matter is swept up, the shock gradually decelerates while the emission from such a shock fades down, dominating at the beginning in X-rays and progressively at optical to radio energy band. The standard model is based on four basic assumptions: (1) the total energy of the shock is released impulsively before its formation; (2) the medium swept up by the shock is homogeneous and its density ($n$) is the one of the interstellar medium $\sim 1 \, \text{cm}^{-3}$; (3) the electron and magnetic field energy fractions of the shocked medium and the index ($p$) in the accelerated electrons’ power-law distribution are constant during the whole evolution stage; and (4) the shock is spherical.

Each of these assumptions has been varied to discuss why some observed afterglows deviate from that expected by the standard afterglow model. For example, the R-band light curve of GRB 970508 afterglow peaks around two days after the burst, and there is a rather rapid rise before the peak which is followed by a long power-law decay. There are two models explaining
this special feature: (i) It was envisioned [28] that a postburst fireball may contain shells with a continuous distribution of Lorentz factors. As the external forward shock sweeps up ambient matter and decelerates, internal shells will catch up with the shock and supply energy into it. A detailed calculation shows that this model can explain well this special feature [26]. (ii) We considered continuous energy injection from a strongly magnetized millisecond pulsar into the shock through magnetic dipole radiation [8]. This model can also account for well the observations. It is very clear that these models don’t use basic assumption (1).

There are several models in the literature that discuss the effect of inhomogeneous media on afterglows [9,23,3,4], dropping the second assumption. Generally, an \( n \propto r^{-k} \) \((k > 0)\) medium is expected to steepen an afterglow’s temporal decay. We studied, for the first time, the wind model for afterglows based on the Blandford-McKee self-similar solution [1] of a relativistic adiabatic shock, and suggested that GRB 970616 is an interact with a stellar wind of \( n \propto r^{-2} \) [9]. It was found [3] that a Wolf-Rayet star wind likely leads to an \( n \propto r^{-2} \) medium, and thus if GRB 980519 resulted from the explosion of such a massive star, subsequent evolution of a relativistic shock in this medium is consistent with the steep decay in the R-band light curve of the afterglow from this burst. Another way of dropping the second assumption is that the density of an ambient medium is invoked to be as high as \( n \sim 10^6 \text{ cm}^{-3} \). The temporal decay of the R-band afterglow of GRB 990123 has been detected to steepen about 2.5 days after this burst [21,2,16]. We proposed a plausible model in which a shock expanding in a dense medium has evolved from a relativistic phase to a nonrelativistic phase [11]. We found that this model fits well the observational data if the medium density is about \( 3 \times 10^6 \text{ cm}^{-3} \). We further suggested that such a medium could be a supernova or supranova or hypernova ejecta.

In basic assumption (3), the electron and magnetic field energy fractions of the shocked medium may not be varied during whole evolution, as argued in [34], where all the observational data including both the prompt optical flash and the afterglow of GRB 990123 were analyzed.

The steepening in the light curves of the afterglows of some bursts may also be due to lateral spreading of a jet, as analyzed in [29,31] when the jet expands in a homogeneous interstellar medium (ISM). This in fact drops basic assumption (4). However, numerical studies of [24,20,36,37] show that the break of the light curve is weaker and smoother than the one analytically predicted when the light travel effects related to the lateral size of the jet and a realistic expression of the lateral expansion speed are taken into account. In the case of a jet expanding in a wind, the calculated light curve is even much weaker and smoother than the analytical one [22,17]. We recently calculated light curves for GRB afterglows when anisotropic jets \( (dE/d\Omega \propto \theta^{-k}) \) expand both in the interstellar medium and in the wind medium [5]. We found that in each type of medium, one break appears in the late-time afterglow light curve for small \( k \) but becomes weaker and smoother as \( k \) increases. When \( k \geq 2 \), the break seems to disappear but the afterglow decays rapidly. Thus, we expect that the emission from expanding, highly anisotropic jets provides a plausible explanation for some rapidly fading afterglows whose light curves seem to have no break.

We discussed the dense medium model in more details [12], by taking into account both the synchrotron self-absorption effect in the shocked medium and the energy injection effect of [8,10]. Recently, we combined the dense medium model with the pulsar energy injection effect to provide a good fit to the optical afterglow data of GRB 000301C [13]. Here we want to give a brief review of some of our studies on GRB afterglows.


2 Shock Evolution

It is well known that the evolution of a partially radiative shock depends on both the efficiency with which the shock transfers its bulk kinetic energy to electrons and magnetic fields and on the efficiency with which the electrons radiate their energy. In 1998, we proposed, for the first time, a unified model for dynamical evolution of a partially radiative shock [6]. This model is not only valid during the whole evolution stage including the Sedov phase for an adiabatic shock, but also can describe well an adiabatic shock as well as a highly radiative shock. This model was later re-investigated and referred to as a generic one in [19]. For simplicity, we here assume that a relativistic shock expanding in a dense medium is adiabatic. This assumption is correct particularly for a low electron energy density fraction in the shocked medium [6,7]. The Blandford-McKee self-similar solution [1] gives the Lorentz factor of an adiabatic relativistic shock,

\[
\gamma = \frac{1}{4} \left[ \frac{17E_0(1+z)^3}{\pi^n m_p^2 n_0^2} \right]^{1/8} = 1 \times 10^{18} n_5^{-1/8} t_5^{-3/8} [(1+z)/2]^{3/8},
\]

where \( E_0 = 52 \times 10^{52} \) ergs is the total isotropic energy, \( n_5 = n/10^{5} \text{ cm}^{-3} \), \( t_5 \) is the observer’s time since the gamma-ray trigger in units of 1 day, \( z \) is the the redshift of the source generating this shock, and \( m_p \) is the proton mass. We assume \( \gamma = 1 \) when \( t_5 = t_b \). This implies

\[
n_5 = E_5 t_b^{-3} [(1+z)/2]^3.
\]

For \( t_5 > t_b \), the shock will be in a nonrelativistic phase. In the following we will discuss the spectrum and light curve during the non-relativistic phase.

As usual, only synchrotron radiation from the shock is considered. To analyze the spectrum and light curve, one needs to know three crucial frequencies: the synchrotron peak frequency \( (\nu_m) \), the cooling frequency \( (\nu_c) \), and the self-absorption frequency \( (\nu_a) \). We assume a power law distribution of the electrons accelerated by the shock: \( dn_e/d\gamma_e \propto \gamma_e^{-p} \) for \( \gamma_e \geq \gamma_{em} \), where \( \gamma_e \) is the electron Lorentz factor and \( \gamma_{em} = 610 \epsilon_e (\gamma - 1) \) is the minimum Lorentz factor. We further assume that \( \epsilon_e \) and \( \epsilon_B \) are the electron and magnetic energy density fractions of the shocked medium respectively. The \( \nu_m \) is the characteristic synchrotron frequency of an electron with Lorentz factor of \( \gamma_{em} \), while the \( \nu_c \) is the characteristic synchrotron frequency of an electron which cools on the dynamical age of the shock. According to Sari et al. [32], we have derived the synchrotron peak frequency, the cooling frequency and the synchrotron self-absorption frequency, measured in the observer’s frame [12]. They are correct for the whole evolution stage.

Now we give the spectrum and light curve of the afterglow during the non-relativistic phase. First, for the case without energy injection, the shock velocity decays as \( \propto t_5^{-3/5} \) and thus we have

\[
F_\nu = \begin{cases} 
(v_a/\nu_m)^{-p} \nu^{5/2} F_{\nu_m} \propto \nu^{5/2} t_5^{11/10} & \text{if } \nu < \nu_a \\
(\nu/\nu_m)^{-p} \nu^{5/2} F_{\nu_m} \propto \nu^{-p} t_5^{(21-15p)/10} & \text{if } \nu_a < \nu < \nu_c \\
(\nu_c/\nu_m)^{-p} \nu^{5/2} F_{\nu_m} \propto \nu^{-p} t_5^{(4-3p)/2} & \text{if } \nu > \nu_c.
\end{cases}
\]

We easily see that for high-frequency radiation the temporal decay index \( \alpha = (21 - 15p)/10 \) for emission from slow-cooling electrons or \( \alpha = (4 - 3p)/2 \) for emission from fast-cooling electrons. If \( p \approx 2.8 \), then \( \alpha \approx -2.1 \) or \(-2.2 \). Comparing this with the relativistic result, we conclude that the afterglow decay steepens at the nonrelativistic stage.
Some models for GRB energy sources (for a brief review see [10]) predict that during the formation of an ultrarelativistic fireball required by GRB, a strongly magnetized millisecond pulsar will be born. If so, the pulsar will continuously input its rotational energy into the forward shock of the postburst fireball through magnetic dipole radiation because electromagnetic waves radiated by the pulsar will be absorbed in the shocked medium [8,10]. Since an initially ultrarelativistic shock discussed in [12] rapidly becomes nonrelativistic in a dense medium, we next investigate the evolution of a nonrelativistic adiabatic shock with energy injection from a pulsar. The total energy of the shock is the sum of the initial energy and the energy which the shock has obtained from the pulsar:

\[ E_0 + \int_0^{t_\oplus} L dt_\oplus = E_{\text{tot}} \propto v^2 r^3, \]  

where \( L \) is the stellar spindown power \( \propto (1 + t_\oplus/T)^{-2} \) (\( T \) is the initial spindown time scale). The term on the right-hand side is consistent with the Sedov solution. Please note that \( L \) can be thought of as a constant for \( t_\oplus < T \), while \( L \) decays as \( \propto t_\oplus^{-2} \) for \( t_\oplus \gg T \). Because of this feature, we easily integrate the second term on the left-hand side of equation (17). We now define a time at which the shock has obtained energy \( \sim E_0 \) from the pulsar, \( t_c = E_0/L \), and assume \( t_c \ll T \). The evolution of the afterglow from such a shock can be divided into three stages.

Stage (i): \( t_\oplus \ll t_c \), viz., the second term on the left-hand side of equation (4) can be neglected. The evolution of the afterglow is the same as in the above case without any energy injection.

Stage (ii): for \( T > t_\oplus \gg t_c \), the term \( E_0 \) in equation (4) can be neglected. At this stage, the shock’s velocity \( v \propto t_\oplus^{-2/5} \), we have derived the spectrum and light curve of the afterglow [12]

\[ F_\nu = \begin{cases} 
(\nu_a/\nu_m)^{-(p-1)/2}(\nu/\nu_a)^{5/2} F_{\nu_m} \propto \nu^{5/2} t_\oplus^{7/5} & \text{if } \nu < \nu_a \\
(\nu/\nu_m)^{-(p-1)/2} F_{\nu_m} \propto \nu^{-(p-1)/2} t_\oplus^{12-5p/5} & \text{if } \nu_a < \nu < \nu_c \\
(\nu_c/\nu_m)^{-(p-1)/2}(\nu_c/\nu)\nu^{-p/2} F_{\nu_m} \propto \nu^{-p/2} t_\oplus^{2-p} & \text{if } \nu > \nu_c.
\end{cases} \]  

(5)

It can be seen that for high-frequency radiation the temporal decay index \( \alpha = (12-5p)/5 \approx -0.4 \) for emission from slow-cooling electrons or \( \alpha = 2 - p \approx -0.8 \) for emission from fast-cooling electrons if \( p \approx 2.8 \). This shows that the afterglow decay may significantly flatten due to the effect of the pulsar.

Stage (iii): for \( t_\oplus \gg T \), the power of the pulsar due to magnetic dipole radiation rapidly decreases as \( L \propto t_\oplus^{-2} \), and the evolution of the shock is hardly affected by the stellar radiation. Thus, the evolution of the afterglow at this stage will be the same as in the above case without any energy injection.

In summary, as an adiabatic shock expands in a dense medium from an ultrarelativistic phase to a nonrelativistic phase, the decay of radiation from such a shock will steepen, subsequently may flatten if a strongly magnetic millisecond pulsar continuously inputs its rotational energy into the shock through magnetic dipole radiation, and finally the decay will steepen again due to disappearance of the stellar effect. In the next section, we will see how to explain some unusual afterglows based on the above conclusion.

3 Some Unusual Afterglows
3.1 GRB 980519

The optical afterglow \( \sim 8.5 \) hours after GRB 980519 decayed as \( \propto \tau^{-2.05 \pm 0.04} \) in \( BVRI \) [18], while the power-law decay index of the X-ray afterglow \( \alpha_X = 2.07 \pm 0.11 \) [25], in agreement with the optical. The spectrum in optical band alone is well fitted by a power law \( \nu^{-1.20 \pm 0.25} \), while the optical and X-ray spectra together can also be fitted by a single power law of the form \( \nu^{-1.05 \pm 0.10} \). In addition, the radio afterglow of this burst was observed by the VLA at 8.3 GHz, and its temporal evolution \( \propto t_{\text{obs}}^{0.9 \pm 0.3} \) between 1998 May 19.8UT and 22.3UT [14].

We now analyze the observed afterglow data of GRB 980519 based on our model. We assume that for this burst, the forward shock evolved from an ultrarelativistic phase to a non-relativistic phase in a dense medium at \( \sim 8 \) hr after the burst. So, the detected afterglow, in fact, was the radiation from a nonrelativistic shock. This implies \( \gamma \sim 1 \) at \( t_b \approx 1/3 \) days. From equation (2), therefore, we find

\[
n_5 \sim 27E_{52}[(1 + z)/2]^3. \tag{6}
\]

If \( p \approx 2.8 \), and if the observed optical afterglow was emitted by slow-cooling electrons and the X-ray afterglow from fast-cooling electrons, then according to equation (3), the decay index \( \alpha_R = (21 - 15p)/10 \approx -2.1 \) and \( \alpha_X = (4 - 3p)/2 \approx -2.2 \), in excellent agreement with observations. Furthermore, the model spectral index at the optical to X-ray band and the decay index at the radio band, \( \beta = -(p - 1)/2 \approx -0.9 \) and \( \alpha = 1.1 \), are quite consistent with the observed ones, \(-1.05 \pm 0.10 \) and \( 0.9 \pm 0.3 \), respectively.

We [12] took into account three observed data which correspond to the radio, R-band and X-ray frequencies respectively, and inferred intrinsic parameters of the shock and the redshift of the burst, \( \varepsilon_e \sim 0.16, \varepsilon_B \sim 2.8 \times 10^{-4}, E_{52} \sim 0.27, n_5 \sim 3.4 \), and \( z \sim 0.55 \). After considering these reasonable parameters, we numerically studied the trans-relativistic evolution of the shock [35] and found that our dense medium model can provide an excellent fit to all the observational data of the radio afterglow from GRB 980519 shown in [15].

3.2 GRB 000301C

The optical afterglow data of GRB 000301c were presented in [30]. In addition, the spectral index \( \beta = 1.1 \pm 0.1 \). We [13] combined the dense medium model with the pulsar energy injection effect to explain the unusual optical afterglow. For stage (ii), if \( p = 3.4 \), then \( \alpha = (12 - 5p)/5 \approx -1.0 \) and \( \beta = -(p - 1)/2 \approx -1.2 \) are consistent with the GRB 000301c R-band afterglow data in initial 7.5 days after the burst. These data indicate \( \alpha_1 \sim -1.1 \), which implies \( \alpha_{\text{obs}} \sim \beta_{\text{obs}} \) at early times. If the afterglow were radiated by fast-cooling electrons in the shocked medium, we would find \( \alpha = 2(1 - \beta) \), which is clearly inconsistent with the observational result. Therefore, the GRB 000301c R-band afterglow arose from those slow-cooling electrons in the shocked medium. For stage (iii), in the case of \( p = 3.4 \), the model’s time index \( \alpha = (21 - 15p)/10 \approx -3.0 \) is quite consistent with the observational data of the GRB 000301c R-band afterglow at late times, \( \alpha_2 = -3.01 \pm 0.53 \) [30]. We also carried out simulations of the evolution of a shock with energy injection from a pulsar and the resulting emission [33]. Our numerical results indeed show one sharp break in the late-time afterglow light curve and give a good fit to the R-band afterglow data of GRB 000301c.
4 Conclusions

We discussed the evolution of an adiabatic shock expanding in a dense medium from an ultrarelativistic phase to a nonrelativistic phase in more details in this paper. In particular, we discussed the effects of synchrotron self absorption and energy injection on the afterglow from this shock. In a dense medium, the shock becomes nonrelativistic rapidly after a short relativistic phase. This transition time varies from several hours to a few days when the medium density is from $10^5$ to a few $\times 10^6$ cm$^{-3}$, and the shock energy from $10^{51}$ to $10^{54}$ ergs. The afterglow from the shock at the nonrelativistic stage decays more rapidly than at the relativistic stage, while the decay index varies from $-1.35$ to $-2.1$ if the spectral index of the accelerated electron distribution, $p = 2.8$, and the radiation comes from those slow-cooling electrons. Since some models mentioned above predict that a strongly magnetic millisecond pulsar may be born during the formation of GRB, we also discuss the effect of such a pulsar on the evolution of a nonrelativistic shock through magnetic dipole radiation, in contrast to the case discussed in [8,10]. We found that after the energy which the shock obtains from the pulsar is much more than the initial energy of the shock, the afterglow decay will flatten significantly and the decay index will become $-0.4$. When the pulsar energy input effect disappears, the index will still be $-2.1$. These features are in excellent agreement with the afterglow of GRB 980519. Furthermore, our model fits very well all the observational data of GRB 980519 including all the radio data. Our model also provides a good fit to the R-band afterglow data of GRB 000301c.

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