Could the Unusual Optical Afterglow of GRB 000301c Arise from a Non-relativistic Shock with Energy Injection?

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ABSTRACT

Recent observations on the GRB 000301c afterglow show that three breaks appear in the R-band light curve, and in particular the decay slope at late times is as steep as -3.0. This unusual afterglow is clearly inconsistent with the standard afterglow shock model. Here we propose a non-standard model for the unusual R-band afterglow of GRB 000301c. In this model, an ultra-relativistic shock in a dense medium ("dirty environment") rapidly evolved to the non-relativistic phase in initial 1 day. During such a phase, the shock happened to be caught up with by two energetic shells ejected from the central engine at two different times, and the shock was refreshed, leading to two flattenings of the light curve. After each interaction between the shock and shell, the afterglow decayed as $\propto t^{-3.0}$ if the electron distribution index of the shocked medium, $p \approx 3.4$, derived from the optical spectrum. Therefore, this model can provide an excellent explanation for the flattening and steepening features of the GRB 000301c optical afterglow light curve. We further point out that the energy injection shells ejected from the central engine at later times may be material shells (e.g., in the massive star progenitor models related to black holes) or radiation shells (e.g., in the millisecond pulsar progenitor models).

Subject headings: gamma-rays: bursts

1. Introduction

The standard model of gamma-ray burst (GRB) afterglows assumes that a relativistic fireball is decelerating due to interaction with the surrounding medium (for a review see Piran 1999). During such a deceleration, a relativistic forward shock forms and then produces an afterglow by synchrotron radiation and/or inverse Compton scattering. The simplest case of this model is that the surrounding medium is a homogeneous interstellar one with typical density of $\sim 1\,\mathrm{cm}^{-3}$. In this case, an optical afterglow light curve (e.g., GRB 970508) can be well fitted by a single power law until several months. However, this property, as we will see below, is clearly inconsistent with the peculiar optical afterglow of GRB 000301c.

GRB 000301c was independently detected by the All-Sky Monitor on the Rossi X-Ray Timing Explorer and by Ulysses and NEAR of the current Interplanetary Network on 2000 March 1.4108. The burst itself had a single peak lasting approximately 10 seconds (Smith, Hurley & Cline 2000). Its R-band afterglow on March 2.906 UT was first detected by UPSO (Masetti et al. 2000). This burst's redshift was measured as $z = 2.0335 \pm 0.0003$ (Castro et al. 2000) by identifying weak metal lines in the afterglow's optical spectrum. According to the published papers (Rhoads & Fruchter 2000; Masetti et al. 2000; Sagar et al. 2000), we can see the following features of the optical afterglow: the R-band afterglow light curve in about 4 days after the burst was fitted approximately by a power-law with an index of $\alpha_1 = -0.82 \pm 0.20$, and in later one day steepened based on another power law with an index of $\alpha_2 = -3.0 \pm 0.10$. However, during a period between the fifth and seventh days after the burst, the light curve flattened with the third temporal decay index of $\alpha_3 = -0.53 \pm 0.50$, and subsequently till March 14.60 UT (the lastly observed time), steepened again based on a decay index α_4 similar to α_2. In addition, the V-band and B-band afterglow could fade down almost simultaneously with the R-band one.

A successful scenario must explain the flattening and steepening features of the optical afterglow light curve of GRB 000301c. To our knowledge, four mechanisms have been proposed to account for steepening. First, as the emission comes from slow-cooling electrons to fast-cooling electrons accelerated behind a relativistic shock in a homogeneous medium, its decay index steepens by a factor of 0.25 (Sari, Piran & Narayan 1998), which is clearly inconsistent with the observational result. Second, as analyzed by many authors (Vietri 1997; Dai & Lu 1998a; Mészáros, Rees & Wijers 1998; Panaitescu, Mészáros & Rees 1998; Chevalier & Li 1999, 2000), the afterglow from a relativistic shock in the wind medium must decay more rapidly than in the interstellar medium (ISM). For an adiabatic relativistic shock in the wind case, an electron distribution index of $p \sim 4.3$ is required by a large decay index of the late-time afterglow of GRB 000301c, $\alpha_2 \approx \alpha_4 \sim -3.0$. This would lead to a spectral index of $\beta \sim -1.7$, which is steeper than the observed one, $\beta_{\rm obs} = -1.1 \pm 0.1$, derived from the spectrum taken on 2000 March 3.47 UT by Feng, Wang & Wheeler (2000) and on March 14.61 UT by Sagar et al. (2000), respectively. Third, the steepening of a late-time optical afterglow light curve may be caused by lateral spreading of a jet (Rhoads 1999; Sari, Piran & Halpern 1999). A difficulty for this mechanism is that the degree of steepening found by numerical studies (e.g., Panaitescu & Mészáros 1999; Moderski, Sikora & Bulik 2000; Huang, Dai & Lu 2000; Wei & Lu 2000) when two effects such as the equal-time surface and detailed dynamics of the jet are considered is much weaker than the one analytically predicted. Finally, we recently suggested that the evolution of a relativistic shock in a dense medium to the non-relativistic phase should lead to steepening of an afterglow light curve (Dai & Lu 1999). We found that this model is quite consistent with the observations on the GRB 990123 afterglow if the medium density is about $10^6\,\mathrm{cm}^{-3}$. Furthermore, as shown analytically and numerically by Dai & Lu (2000a) and Wang, Dai & Lu (2000), this model can also well fit all the GRB 980519 afterglow data.

Energy injection from the GRB central engine to its postburst shock has been widely argued to be a plausible scenario causing flattening of an afterglow light curve. This scenario can be realized by two different mechanisms: (1) The central engine may eject some shells with different Lorentz factors at different times. As the outer shells move outward, they begin to interact with the surrouding medium and decelerate, forming a forward shock (blast wave). Eventually the slower inner shells catch up with the outer shells. The interaction of slow shells with faster shells that have been slowed down implies refreshment of the shock, leading to a flattening of the afterglow light curve (Rees & Mészáros 1998; Panaitescu et al. 1998; Kumar & Piran 2000; Sari & Mészáros 2000). (2) If the GRB central engine is a strongly magnetized millisecond pulsar, its rotational energy input to the postburst shock through magnetic dipole radiation also results in a flattening of the afterglow light curve (Dai & Lu 1998b, 1998c, 2000a). In this Letter we argue that combination of our dense medium model with such an energy injection scenario can provide an excellent explanation for the peculiar optical afterglow light curve of GRB 000301c.

2. The Model

The dense ("dirty") environment of GRBs has been discussed in the literature. For example, collisions of relativistic nucleons with a dense cloud is suggested by Katz (1994) to explain the delayed hard photons from GRB 940217. The presence of an iron emission line in the X-ray afterglow spectrum of GRB 970508 and GRB 970828 reported by Piro et al. (1999) and Yoshida et al. (1999) requires that the ambient medium of these bursts is rather dense (Lazzati, Campana & Ghisellini 1999). The steepening of the light curves of some optical afterglows (e.g., GRB 990123 and GRB 980519) may be due to the transition to the non-relativistic phase. This also requires that the medium density is as high as $10^6\,\mathrm{cm}^{-3}$ (Dai & Lu 1999, 2000a). The medium with a similar density is invoked by Dermer & Böttcher (2000) to resolve the "line-of-death" objection to the GRB synchrotron shock model. This work is guided by the optical observations of η Carinae (a best-studied massive star), whose environment is a dense cloud (Davidson & Humphrey 1997). In addition, dense media may appear in some energy source models, e.g., failed supernovae (Woosley 1993), hypernovae (Paczyński 1998), supranovae (Vietri & Stella 1998), phase transitions of neutron stars to strange stars (Dai & Lu 1998b; Wang et al. 2000), and anisotropic supernovae (Wheeler et al. 2000).

Based on these motivations, we here assume that the surrounding medium is dense and perhaps at different times the central engine ejects several shells, some of which are relativistic and others are non-relativistic. It is widely believed that a slow shell contains more energy than a faster shell which is ejected at an earlier time. Collisions between shells with large Lorentz factors give rise to internal shocks which are expected to produce GRBs. After then, these merging shells decelerate, leading to a forward shock (blast wave), as they sweep up the dense medium. The shock can be thought to be adiabatic unless the electron energy fraction of the shocked medium is as large as ~ 1 (Dai, Huang & Lu 1999). The Blandford-McKee (1976) self-similar solution gives the Lorentz factor of an adiabatic relativistic shock: $\gamma = 1.0 E_{52}^{1/8} n_5^{-1/8} t_{\rm day}^{-3/8} [(1+z)/2]^{3/8}$, where $E_{52} \times 10^{52}$ergs is the total isotropic energy, $n = n_5 \times 10^5\,{\rm cm}^{-3}$ is the medium density, $t_{\rm day} = t/1\,{\rm day}$ is the observer time, and z is the the redshift of the source. This equation implies that, at time

$$t_{\rm nr} = 0.7 E_{52}^{1/3} \left(\frac{n}{10^6 {\rm cm}^{-3}}\right)^{-1/3} \left(\frac{1+z}{3}\right) {\rm days}, \tag{1}$$

the shock begins to enter the non-relativistic phase.

According to equation (1), therefore, we find that if GRB 000301c was in a dense medium with density of $\sim 10^6\,{\rm cm}^{-3}$, its postburst shock would be non-relativistic at a time less than 1 day after the burst. If, during such a period, this shock happened to be caught up with by an energetic homogeneous shell which had been ejected from the central source at some time, then the shock would be refreshed and its energy evolved based on

$$E_{\rm shock} = E_0 + \left(\frac{1}{1+z}\right) \int_{t_0}^{t} L(t) dt, \tag{2}$$

where E_0 is the initial energy of the shock, t_0 is the time at which the shell started to inject energy, and $L(t)$ is the injection luminosity. Assuming that the shell's velocity, energy and width are $v_{\rm shell}$, $E_{\rm shell}$ and ΔR, and the shock's velocity is $v_{\rm shock}$, we can write the injection luminosity approximately as

$$L(t) \approx \frac{v_{\rm shell} - v_{\rm shock}}{\Delta R} E_{\rm shell} \approx \frac{v_{\rm shell}}{\Delta R} E_{\rm shell}. \tag{3}$$

In writing the second expression, we have assumed $v_{\rm shell} \gg v_{\rm shock}$. The energy of the non-relativistic shocked medium can be approximated by

$$E_{\rm shock} \approx \frac{2\pi}{3} v_{\rm shock}^2 R_{\rm shock}^3 n m_p \propto v_{\rm shock}^2 R_{\rm shock}^3, \tag{4}$$

where $R_{\rm shock}$ is the shock's radius, m_p is the proton mass and c is the speed of light. Assuming that $E_{\rm shell} \gg E_0$ and the energy which the shock had obtained from the shell is much larger than E_0 when $t \gg t_0$, combination of equation (2) with equations (3) and (4) leads to

$$v_{\rm shock}^2 R_{\rm shock}^3 \propto t. \tag{5}$$

Because $R_{\rm shock} \propto v_{\rm shock} t$, we easily find

$$v_{\rm shock} \propto t^{-2/5}. \tag{6}$$

In the following we consider only synchrotron radiation from the shock and ignore synchrotron self absorption. To analyze the spectrum and light curve, one needs to know two crucial frequencies: the synchrotron peak frequency (ν_m) and the cooling frequency (ν_c). Unfortunately, these frequencies are dependent on two unknown parameters: the electron energy fraction (ϵ_e) and the magnetic energy fraction (ϵ_B) of the shocked medium. Even so, the optical-band frequency is usually much higher than the ν_m of a late-time afterglow. From equation (6), we find the shock's radius $R_{\rm shock} \approx (5/3) v_{\rm shock} t/(1+z) \propto t^{3/5}$ and the internal field strength $B = (4\pi\epsilon_B n m_p v_{\rm shock}^2)^{1/2} \propto t^{-2/5}$. The typical electron Lorentz factor $\gamma_m \approx [m_p/(2m_e)]\epsilon_e (v_{\rm shock}/c)^2 \propto t^{-4/5}$ and the synchrotron peak frequency $\nu_m = \gamma_m^2 (eB)/[(1+z)2\pi m_e c] \propto t^{-2}$. The cooling Lorentz factor $\gamma_c = 6\pi m_e c(1+z)/(\sigma_T B^2 t) \propto B^{-2} t^{-1}$ with σ_T being the Thomson scattering cross section (Sari, Piran & Narayan 1998) and the cooling frequency $\nu_c = \gamma_c^2 (eB)/[(1+z)2\pi m_e c] \propto B^{-3} t^{-2} \propto t^{-4/5}$. The synchrotron peak flux decays as $F_{\nu_m} = (1+z) N_e P_{\nu_m}/(4\pi D_L^2) \propto R^3 B \propto t^{7/5}$, where $N_e = (4\pi/3)R^3 n$ is the total number of swept-up electrons in the postshock fluid, $P_{\nu_m} = m_e c^2 \sigma_T B/(3e)$ is the power radiated per electron per unit frequency and D_L is the luminosiy distance from the source. According to these scaling laws, we further derive the spectrum and light curve of the afterglow

$$F_\nu = \begin{cases} (\nu/\nu_m)^{-(p-1)/2} F_{\nu_m} \propto \nu^{-(p-1)/2} t^{(12-5p)/5} & \text{if} \;\; \nu \le \nu_c \\ (\nu_c/\nu_m)^{-(p-1)/2} (\nu/\nu_c)^{-p/2} F_{\nu_m} \propto \nu^{-p/2} t^{2-p} & \text{if} \;\; \nu > \nu_c, \end{cases} \tag{7}$$

where p is the electron distribution index (Dai & Lu 2000a). We note that if $p = 3.4$, then $\alpha = (12-5p)/5 = -1.0$ and $\beta = -(p-1)/2 = -1.2$ are consistent with the GRB 000301c R-band afterglow data both in initial 4 days and during a period between the fifth and seventh days after the burst. These data indicate $\alpha_1 = -0.82 \pm 0.20$, $\alpha_3 = -0.53 \pm 0.50$ and $\beta_{\rm obs} = -1.1 \pm 0.1$, which imply $\alpha_{\rm obs} \approx 5\beta_{\rm obs}/6$. 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.

After the shell had input all its energy to the shock, from equations (2) and (4), the shock's velocity evolved as $v_{\rm shock} \propto t^{-3/5}$ and thus the spectrum and light curve of the afterglow became

$$F_\nu \propto \begin{cases} \nu^{-(p-1)/2} t^{(21-15p)/10} & \text{if} \quad \nu \le \nu_c \\ \nu^{-p/2} t^{(4-3p)/2} & \text{if} \quad \nu > \nu_c, \end{cases} \tag{8}$$

where the ν_c is different from that in equation (7) (Wijers, Rees & Mészáros 1997; Dai & Lu 1999, 2000a). We can see from this equation that in the case of $p = 3.4$, the model's decay index $\alpha = (21 - 15p)/10 = -3.0$ is quite consistent with the observational data of the GRB 000301c R-band afterglow both during a period between the fourth and fifth days after the burst and at later times, $\alpha_2 \approx \alpha_4 = -3.0 \pm 0.1$.

3. Discussion

We have shown that our dense medium model combined with the energy injection scenario can provide a plausible explanation for the unusual optical afterglow of GRB 000301c. Now we want to discuss the two energy injection mechanisms in some details. In the first mechanism, the shells which input their energy into the shock are *material shells*, whose energy source may be the core collapse of massive stars to black holes. As the shock decelerates, such a shell eventually catches up with the shock. During such an interaction, two additional shocks (a forward shock and a reverse shock) might form and perhaps give rise to some observational effects on afterglows. Kumar & Piran (2000) analyzed such effects of ultra-relativistic shocks. We will make a detailed analysis for non-relativistic shocks and discuss their possible effects on afterglows in a future paper (Dai & Lu 2000b). It is interesting to note that a small but discernible variability appears in the GRB 000301c optical afterglow light curve in initial 4 days, which could be due to these additional shocks.

In the second mechanism, the shells which input their energy into the shock may arise from a strongly magnetized millisecond pulsar. In this case, $t_0 \approx 0$ in equation (2) and $v_{\rm shell} = c$ in equation (3). Because the magnetic dipole radiation luminosity $L(t) \propto (1 + t/T)^{-2}$, where T is the characteristic spin-down age, $L(t)$ can be thought of as a constant for $t < T$ while $L(t)$ decays as $\propto t^{-2}$ for $t \gg T$. In addition, we define a timescale $t_{\rm cr}$ based on $t_{\rm cr} = E_0/L$. As found by Dai & Lu (1998b, 1998c), the pulsar energy input effect can be neglected for both $t < t_{\rm cr}$ and $t > T$, but the pulsar inputs its rotational energy into the shock at an approximately constant rate for $t_{\rm cr} < t < T$. This further implies $\Delta R \approx c(T - t_{\rm cr})$ in equation (3). Therefore, the energy injection shells in this case are *radiation shells*. It should be pointed out that the GRB source models involving strongly magnetized millisecond pulsars include accretion-induced collapses of magnetized white dwarfs (Usov 1992; Blackman, Yi & Field 1996; Ruderman, Tao, & Kluźniak 2000), mergers of two neutron stars if the equation of state for neutron matter is moderately stiff to stiff (Kluźniak & Ruderman 1998), phase transitions of neutron stars (Dai & Lu 1998b), R-mode-induced explosions in low-mass X-ray binaries (Spruit 1999), and anisotropic supernovae (Wheeler et al. 2000). All these models have been proposed to possibly produce GRBs with long durations, which are consistent with GRB 000301c.

There are two flattenings in the optical afterglow light curve of GRB 000301c. To interpret this, we require, in the first mechanism, only two energetic material shells which caught up with the shock at two different times. In the second mechanism, how did the central pulsar input its rotational energy into the shock twice? We envision that a strongly magnetized, rapidly rotating newborn neutron star first spun down through magnetic dipole radiation and thus input most of its rotational energy to the postburst shock, leading to the first flattening of the afterglow light curve. As the neutron star spun down to some extent, it would undergo a phase transition to become a more compact star (e.g., a strange star) (Dai & Lu 1998b; Wang et al. 2000). This case is somewhat similar to the one discussed by Vietri & Stella (1998), where as the neutron star spins down it will collapse to a black hole. Assuming that J is the angular momentum at the phase transition, and $I_{\rm NS}$ and $I_{\rm MCS}$ are the moments of inertia of the neutron star and the more compact star respectively, angular momentum conservation implies that the rotational energy of the post-transition star would significantly increase, that is, $E_{\rm MCS}=J^2/(2I_{\rm MCS})\gg E_{\rm NS}=J^2/(2I_{\rm NS})$ because $I_{\rm MCS}$ may be much less than $I_{\rm NS}$. The post-transition star would subsequently spin down through magnetic dipole radiation and inject its rotational energy to the postburst shock, possibly resulting in the second flattening of the afterglow light curve.

The infrared (2.1μm) light curve of the GRB 000301c afterglow is different from the R-band, B-band and V-band light curves. The latter present the flattening and steepening features but the former shows a well-sampled break in the decay index at $t\approx 3.5$ days after the burst. The early time index at infrared frequency is very shallow (~ -0.1), while the late time index is steep (-2.2) (Rhoads & Fruchter 2000). We here argue that such infrared and R-band emissions might result from different radiation mechanisms. Otherwise, (1) their temporal decay should be almost independent of frequency, which is contrary to the observational result; (2) the ratio of their fluxes should approximately be $(\nu_{\rm K'}/\nu_{\rm R})^{-(p-1)/2}\sim 3.7$ where $p=3.4$. However, this ratio derived from the observed data in about three days after the burst is about 10. Therefore, the infrared emission was unlikely to arise from the non-relativistic shock. In addition, the singly-broken power-law decay of the infrared emission is reminiscent of a relativistic jetted shock. However, as analytically shown by Rhoads (1999) and Sari et al. (1999), the time index of an afterglow from a lateral-spreading jet evolves from $\alpha=3(1-p)/4$ or $(2-3p)/4$ to $\alpha=-p$. The observed early-time index at infrared frequency ($\alpha \sim -0.1$) leads to $p \sim 1.1$ or 0.8, implying that the late-time index $\alpha \sim -1.1$ or -0.8, which is clearly inconsistent with the observations. Therefore, the infrared emission couldn't arise from a relativistic jetted shock. We note that for the GRB 990123 afterglow its infrared light curve is much different from that at R-hand frequency (Kulkarni et al. 1999). The observed infrared afterglow emission of GRB 000301c might be produced by dust sublimation (Waxman & Draine 2000; Esin & Blandford 2000). However, whether or not this possibility is correct needs further analytical and numerical studies.

4. Conclusions

Many optical afterglows can be well fitted by a single power-law decay, which supports the standard relativistic shock model. But, three breaks appear in the R-band afterglow light curve of GRB 000301c, and in particular the decay index at late times is as steep as -3.0. This unusual afterglow is clearly inconsistent with the standard model. Following Dai & Lu (1999, 2000a), we have here proposed a non-standard shock model for the unusual R-band afterglow of GRB 000301c. In this model, an ultra-relativistic shock in a dense medium ("dirty environment") rapidly evolved to the non-relativistic phase in initial 1 day. During such a transition, the shock was by chance caught up with by one energetic shell ejected from the central engine at a later time, and the shock was refreshed, leading to the first flattening of the light curve. Once the interaction between the shock and shell finished, the afterglow started to decay as $\propto t^{-3.0}$ if the electron distribution index of the shocked medium $p \approx 3.4$ derived from the optical spectrum. One day later, the shock was by chance caught up with by another more energetic shell, resulting in the second flattening of the light curve. After this interaction, the shock evolved based on the Sedov-Taylor self-similar solution without energy injection and the afterglow light curve steepened again. The energy injection shells ejected from the central engine at later times may be material shells (e.g., in the massive star progenitor models related to black holes) or radiation shells (e.g., in the millisecond pulsar progenitor models).

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