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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 gamma-ray burst (GRB) 000301c afterglow show that one sharp break appears in the global optical/IR light curves, and in particular the decay slope at late times is as steep as about −3.0. This unusual feature is clearly inconsistent with the standard afterglow shock model. Here we propose a non-standard model for the afterglow of GRB 000301c, in which an initial ultra-relativistic shock in a dense medium ("dirty environment") rapidly evolved to the non-relativistic phase in 1 day after the burst. During such a phase, the shock was refreshed by a strongly magnetized millisecond pulsar through magnetic dipole radiation. This refreshment led to flattening of the light curves. After the energy injection, 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, our model can provide a plausible explanation for the peculiar optical/IR afterglow light curves of GRB 000301c.

Key words. gamma-rays: bursts – shock waves

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 s (Smith et al. 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) and $z = 2.0404 \pm 0.0008$ (Jensen et al. 2000) by identifying metal and CIV lines in the afterglow's optical spectrum. In an early paper on this GRB afterglow (Rhoads & Fruchter 2000), the optical/IR data have been fit independently by two different singly-broken power laws. However, subsequent papers by Masetti et al. (2000) and Sagar et al. (2000) pointed out that there are unusual flux density variations (∼30%) on timescales as short as a few hours, which are superposed on the overall steepening of the optical/IR light curves. A recent paper by Berger et al. (2000) took a different approach, in which the optical/IR data are modelled by one singly-broken power law. In this global model, there is the following feature of the optical/IR light curves: the time index is $\alpha_1 = -1.28$ before the break time $t_{\rm br} = 7.5 \pm 0.5$ days and $\alpha_2 = -2.7$ after the break time. However, the global fit of Berger et al. (2000) is not statistically acceptable ($\chi^2 = 450$). The fits of the other studies give $t_{\rm br} = 6.3$ days, $\alpha_1 = -0.92$, and $\alpha_2 = -3.11$ (Rhoads & Fruchter 2000), $t_{\rm br} = 7.51 \pm 0.63$ days, $\alpha_1 = -1.18 \pm 0.14$, and $\alpha_2 = -3.01 \pm 0.53$ (Sagar et al. 2000), and $t_{\rm br} = 4.49 \pm 1.52$ days, $\alpha_1 = -0.72 \pm 0.34$, and $\alpha_2 = -2.29 \pm 1.00$ (Jensen et al. 2000). It is clear that the late-time afterglow of GRB 000301c is the most rapidly fading one among all the detected afterglows. The observed variations in the global optical/IR light curves may result from a non-uniform ambient density (Berger et al. 2000) or a microlensing event (Garnavich et al. 2000).

A successful scenario must explain the sharp break and steepening in the optical/IR light curves 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, the resultant time slope steepens by a factor of 0.25 (Sari et al. 1998), which is clearly inconsistent with the observational result. Second, as analyzed by many authors (Vietri 1997; Dai & Lu 1998a; Mészáros et al. 1998; Panaitescu et al. 1998; Chevalier & Li 1999, 2000), the afterglow from

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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, $\alpha_2 \sim -3.0$. This would lead to a spectral index of $\beta \sim -1.7$, which is slightly 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 et al. (2000) and on March 14.61 UT by Sagar et al. (2000), respectively. In this mechanism, no break appears in an afterglow light curve. Third, the steepening of a late-time optical afterglow light curve may be caused by lateral spreading of a jet, as analytically shown by Rhoads (1999) and Sari et al. (1999). Thus, the global optical/IR light curves of the GRB 000301c afterglow have been widely suggested to be due to lateral spreading of a jet (Rhoads & Fruchter 2000; Sagar et al. 2000; Berger et al. 2000; Jensen et al. 2000). However, a difficulty for this mechanism is that the degree of steepening found by numerical studies (e.g., Panaitescu & Mészáros 1999; Moderski et al. 2000; Huang et al. 2000; Kumar & Panaitescu 2000a; Wei & Lu 2000) when two effects such as the equal-time surface and detailed dynamics of the jet are considered is much weaker than that predicted analytically. 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 $10^6\,{\rm cm}^{-3}$. Furthermore, as shown analytically and numerically by Dai & Lu (2000) and Wang et al. (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. As suggested by Dai & Lu (1998b,c, 2000), if the GRB central engine is a strongly magnetized millisecond pulsar, its rotational energy input to the postburst shock through magnetic dipole radiation may result in flattening of the afterglow light curve. In this paper we argue that a combination of our dense medium model with this energy injection can provide an explanation for the global optical/IR afterglow light curves of GRB 000301c.

After this paper was submitted, the other two models have been proposed to explain the afterglow of GRB 000301c. First, Kumar & Panaitescu (2000b) suggest that the steepening of the R-band light curve may be due to a sudden, large drop in the density of the ambient medium into which the GRB blast wave propagates. Initially, the light curve steepens continuously as the blast wave expands freely, which leads to a constant decay rate when the observed flux is dominated by the emission from the high-latitude parts of the blast wave away from the line of sight to the explosion center. Second, Li & Chevalier (2000) attribute the steepening of GRB 000301c to a sudden increase in the power-law index of the electron distribution. These two models are similar because they invoke a *sudden* change in either the ambient density or the electron energy distribution. But our model invokes a *natural* disappearance of energy injection from a pulsar.

2. Energy injection from a pulsar

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 et al. 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 $10^6\,{\rm cm}^{-3}$ (Dai & Lu 1999, 2000). 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), R-mode-induced explosions in low-mass X-ray binaries (Spruit 1999), and anisotropic supernovae (Wheeler et al. 2000).

Based on these motivations, we here assume that the surrounding medium is dense and the central object is a strongly magnetized millisecond pulsar. An ultra-relativistic fireball may form during the birth of this pulsar through the following models: accretion-induced collapses of magnetized white dwarfs (Usov 1992; Blackman et al. 1996; Ruderman et al. 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; Wang et al. 2000), R-mode-induced explosions in low-mass X-ray binaries (Spruit 1999), and anisotropic supernovae (Wheeler et al. 2000). Such a fireball may contain several shells. It is widely believed that collisions between the shells give rise to internal shocks, which are expected to produce long-duration GRBs. After then, the fireball decelerates as it sweeps up the dense medium, leading to a forward shock (blast wave). The relativistic electrons accelerated behind the shock may be in the fast cooling regime at early times (Böttcher & Dermer 2000), but they are likely to be slow cooling at late times even if the electron energy fraction of the shocked medium is $\sim$1 (Dai et al. 1998, 1999). In fact, this fraction may be smaller than unity (Freedman & Waxman 2000). So, it is reasonable to assume that the shock is adiabatic. 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 $E_{52}\ 10^{52}$ ergs is the total isotropic energy, $n = n_5\ 10^5\,{\rm cm}^{-3}$ 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

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

the shock begins to enter the non-relativistic phase.

According to Eq. (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. We next discuss what happened if a strongly magnetized millisecond pulsar was the central engine of this GRB. It is well known that such a pulsar would lose its rotational energy through magnetic dipole radiation, whose power is given by

$$\begin{aligned} L &= \frac{2}{3c^3}\left(\frac{2\pi}{P}\right)^4 B_{\rm s}^2 R^6 \\ &= 4\ 10^{45} \left(\frac{B_{\rm s}}{10^{13}\ {\rm G}}\right)^2 \left(\frac{P}{1\,{\rm ms}}\right)^{-4} \\ &\quad \times \left(\frac{R}{10^6\ {\rm cm}}\right)^6 {\rm ergs\,s^{-1}}, \end{aligned} \quad (2)$$

where P is the pulsar period, $B_{\rm s}$ is the surface magnetic field strength, R is the pulsar radius, and the angle between the magnetic axis and rotation axis has been assumed to be $\pi/2$. Because of magnetic dipole radiation, such a power would vary with time as $L(t) \propto (1+t/T)^{-2}$, where T is the initial spin-down timescale in the observer frame,

$$\begin{aligned} T = 174 &\left(\frac{B_{\rm s}}{10^{13}\ {\rm G}}\right)^{-2} \left(\frac{P_0}{1\,{\rm ms}}\right)^2 \left(\frac{I}{10^{45}\ {\rm g\,cm}^2}\right) \\ &\times \left(\frac{R}{10^6\ {\rm cm}}\right)^{-6} \left(\frac{1+z}{3}\right) {\rm days} \end{aligned} \quad (3)$$

with P_0 and I being the initial period and the moment of inertia of the pulsar respectively. Therefore, $L(t)$ could approximately be a constant for $t < T$ and decayed as $\propto t^{-2}$ for $t \gg T$. The power was radiated away mainly through electromagnetic (EM) waves with frequency of $\omega = 2\pi/P$. Once the EM waves propagated in the shocked medium, they would be absorbed because the ω is much smaller than the plasma frequency of the shocked medium, as shown by Dai & Lu (1998b,c). This implies that the pulsar could continuously pump its rotational energy into the shocked medium and thus the bulk kinetic energy of the shock would increase. The present case is similar to that discussed by Pacini (1967), who proposed that a supernova remnant may be refreshed due to magnetic dipole radiation of its central pulsar. Therefore, the energy of the shock evolved based on

$$E_{\rm sh} = E_0 + \left(\frac{1}{1+z}\right)\int_0^t L(t){\rm d}t, \quad (4)$$

where E_0 is the initial energy of the shock. The energy of the non-relativistic shocked medium could be approximated by

$$E_{\rm sh} \approx \frac{2\pi}{3} v_{\rm sh}^2 R_{\rm sh}^3 n m_{\rm p} \propto v_{\rm sh}^2 R_{\rm sh}^3, \quad (5)$$

where $v_{\rm sh}$ is the shock's velocity, $R_{\rm sh}$ is the shock's radius, $m_{\rm p}$ is the proton mass and c is the speed of light. Equation (5) has assumed that the energy input refreshing the shock was transformed into bulk kinetic energy. In fact, as argued above, the low-frequency EM waves would be absorbed primarily by the electrons in the shocked medium. But, the jump conditions for the shock require that most of the energy input would be transformed subsequently into bulk kinetic energy in the presence of a strong proton-electron coupling. Thus, the direct electron heating and acceleration due to the low-frequency EM waves might be a minor effect on the afterglow. We further assume that the energy which the shock had obtained from the pulsar is much larger than E_0, which in fact constrains the pulsar's parameters (period and magnetic field) as discussed below. From Eqs. (4) and (5), we can see

$$v_{\rm sh}^2 R_{\rm sh}^3 \propto t, \quad (6)$$

when $t < T$. Because $R_{\rm sh} \propto v_{\rm sh} t$, we further find

$$v_{\rm sh} \propto t^{-2/5}. \quad (7)$$

In the following we consider only synchrotron radiation from the shock and ignore synchrotron self absorption and inverse Compton scattering. To analyze the spectrum and light curve, one needs to know two crucial frequencies: the synchrotron peak frequency ($\nu_{\rm m}$) and the cooling frequency ($\nu_{\rm c}$). Unfortunately, these frequencies are dependent on two unknown parameters: the electron energy fraction ($\epsilon_{\rm e}$) and the magnetic energy fraction ($\epsilon_{\rm B}$) of the shocked medium. Even so, the optical-band frequency is usually much higher than the $\nu_{\rm m}$ of a late-time afterglow. From Eq. (7), we find the shock's radius $R_{\rm sh} \approx (5/3) v_{\rm sh} t/(1+z) \propto t^{3/5}$ and the internal field strength $B = (4\pi\epsilon_{\rm B} n m_{\rm p} v_{\rm sh}^2)^{1/2} \propto t^{-2/5}$. The typical electron Lorentz factor $\gamma_{\rm m} \approx [m_{\rm p}/(2m_{\rm e})]\epsilon_{\rm e}(v_{\rm sh}/c)^2 \propto t^{-4/5}$ and the synchrotron peak frequency $\nu_{\rm m} = \gamma_{\rm m}^2(eB)/[(1+z)2\pi m_{\rm e} c] \propto t^{-2}$. The cooling Lorentz factor $\gamma_{\rm c} = 6\pi m_{\rm e} c(1+z)/(\sigma_{\rm T} B^2 t) \propto B^{-2} t^{-1}$ with $\sigma_{\rm T}$ being the Thomson scattering cross section (Sari et al. 1998) and the cooling frequency $\nu_{\rm c} = \gamma_{\rm c}^2(eB)/[(1+z)2\pi m_{\rm e} c] \propto B^{-3} t^{-2} \propto t^{-4/5}$. The synchrotron peak flux decays as $F_{\nu_{\rm m}} = (1+z) N_{\rm e} P_{\nu_{\rm m}}/(4\pi D_{\rm L}^2) \propto R_{\rm sh}^3 B \propto t^{7/5}$, where $N_{\rm e} = (4\pi/3) R_{\rm sh}^3 n$ is the total number of swept-up electrons in the postshock fluid, $P_{\nu_{\rm m}} = m_{\rm e} c^2 \sigma_{\rm T} B/(3e)$ is the power radiated per electron per unit frequency and $D_{\rm L}$ is the luminosiy distance from the source. According to these scaling laws, we further derive the spectrum and light curve of the afterglow

$$F_\nu = \begin{cases} (\nu/\nu_{\rm m})^{-(p-1)/2} F_{\nu_{\rm m}} \\ \propto \nu^{-(p-1)/2} t^{(12-5p)/5}, & \text{if } \nu \le \nu_{\rm c}; \\ (\nu_{\rm c}/\nu_{\rm m})^{-(p-1)/2} (\nu/\nu_{\rm c})^{-p/2} F_{\nu_{\rm m}} \\ \propto \nu^{-p/2} t^{2-p}, & \text{if } \nu > \nu_{\rm c}, \end{cases} \quad (8)$$

where p is the electron distribution index (Dai & Lu 2000). 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 in initial 7.5 days after the burst. These data indicate $\alpha_1 \sim -1.1$, which implies $\alpha_{\rm obs} \sim \beta_{\rm obs}$ 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.

When $t > T$, the power of the pulsar due to magnetic dipole radiation decayed as $\propto t^{-2}$, and thus the shock was hardly influenced by the stellar radiation. In this case, the shock's velocity evolved as $v_{\rm sh} \propto t^{-3/5}$ and thus the spectrum and light curve of the afterglow became

$$F_\nu \propto \begin{cases} \nu^{-(p-1)/2} t^{(21-15p)/10}, & \text{if } \nu \le \nu_{\rm c}; \\ \nu^{-p/2} t^{(4-3p)/2}, & \text{if } \nu > \nu_{\rm c}, \end{cases} \quad (9)$$

where the $\nu_{\rm c}$ is different from in Eq. (8) (Wijers et al. 1997; Dai & Lu 1999, 2000). We can see from this equation that in the case of $p = 3.4$, the model's time index $\alpha = (21 - 15p)/10 = -3.0$ is quite consistent with the observational data of the GRB 000301c R-band afterglow at late times, $\alpha_2 = -3.11$ (Rhoads & Fruchter 2000), $\alpha_2 = -3.01 \pm 0.53$ (Sagar et al. 2000), and $\alpha_2 = -2.29 \pm 1.00$ (Jensen et al. 2000).

We now turn to derive some constraints on the pulsar parameters. First, in our model, the afterglow first faded down based in Eq. (8) before the spin-down time and subsequently decayed based in Eq. (9) after the spin-down time. This implies the break time $t_{\rm br} \approx T$, that is

$$\left(\frac{B_{\rm s}}{10^{13}\ {\rm G}}\right) \left(\frac{P_0}{1\,{\rm ms}}\right)^{-1} \left(\frac{I}{10^{45}\ {\rm g\,cm^2}}\right)^{-1/2} \left(\frac{R}{10^6\ {\rm cm}}\right)^3 \times \left(\frac{1+z}{3}\right)^{-1/2} \left(\frac{t_{\rm br}}{7.5\,{\rm days}}\right)^{1/2} \approx 4.8. \quad (10)$$

Second, the necessary condition for the assumption that the energy which the shock had obtained from the pulsar is much larger than the initial energy of the shock is that the initial rotational energy of the pulsar, $(1/2)I(2\pi/P_0)^2$, is much larger than E_0, viz.,

$$\left(\frac{P_0}{1\,{\rm ms}}\right) \left(\frac{I}{10^{45}\ {\rm g\,cm^2}}\right)^{-1/2} \left(\frac{E_0}{10^{52}\ {\rm ergs}}\right)^{1/2} \ll 1.4. \quad (11)$$

According to these two constraints, we conclude that the central object of GRB 000301c might be a highly magnetic millisecond pulsar if this burst resulted from the birth of such a compact object.

We have also carried out simulations of the evolution of a shock with energy injection from a pulsar and the resulting emission in more detail. In this numerical model, we adopt a more generic equation for evolution of the shock. This equation is valid during the whole evolution stage (from ultra-relativistic to non-relativistic phases) (Dai et al. 1998; Huang et al. 1999). Also, it can well describe a partially radiative shock. But, the present analytical model discusses only a non-relativistic adiabatic shock (see Eqs. (4) and (5)). Furthermore, in the numerical model, we use the integral formula for the synchrotron radiation power spectrum and the electron distribution derived by Dai et al. (1998, 1999). But, we adopt the anlytical formula for the synchrotron radiation power spectrum of Sari et al. (1998) in the analytical model. Although there are such differences, our numerical result indeed shows one sharp break in the late-time afterglow light curve and can give a good fitting to the R-band afterglow data of GRB 000301c. Figure 1 presents the R-band light curves: the solid line is the numerical result, the dashed line is the analytical result, and the observed data are taken from Rhoads & Fruchter (2000), Sagar et al. (2000) and Masetti et al. (2000). From this figure, we can see that the analytical result is quite consistent with the numerical one.

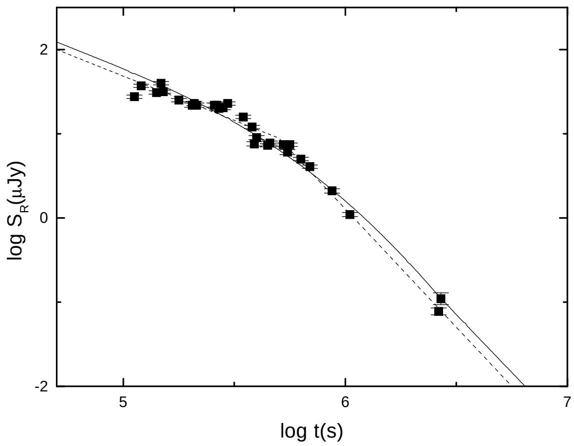

Fig. 1. R-band light curves: the solid line is the numerical result, the dashed line is the analytical result, and the observed data are taken from Rhoads & Fruchter (2000), Sagar et al. (2000) and Masetti et al. (2000). We fit these data (*solid line*) by considering a fireball with energy injection from a pulsar in a homogeneous dense medium: the baryon mass loading with the fireball $M_0 = 5.0\ 10^{-6}\,M_\odot$, $E_0 = 10^{51}$ ergs, $P_0 = 0.5$ ms, $n = 5\ 10^4\,{\rm cm^{-3}}$, $\epsilon_{\rm e} = 0.02$, $\epsilon_{\rm B} = 5.0\ 10^{-4}$, $B_{\rm s} = 3.0\ 10^{13}$ G, $p = 3.4$, and $D_{\rm L} = 13$ Gpc

3. Conclusions

Many optical afterglows can be well fitted by a single power-law decay, which supports the standard relativistic shock model. But, one sharp break appears in the global optical/IR afterglow light curve of GRB 000301c, and in particular the decay index at late times is as steep as about -3.0. This peculiar afterglow is clearly inconsistent with the standard model. Following Dai & Lu (1999, 2000), we have here proposed a non-standard shock model for the afterglow of GRB 000301c. In this model, an initial ultra-relativistic shock in a dense medium ("dirty environment") rapidly evolved to the non-relativistic phase in 1 day after the burst. During such a phase, the shock was refreshed by a strongly magnetized millisecond pulsar through magnetic dipole radiation. This refreshment led to flattening of the light curves. After such an energy injection was over, the shock evolved based on the Sedov-Taylor self-similar solution without energy injection and thus 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. This model can explain the observed global feature of the optical/IR afterglow light curves of GRB 000301c.

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