THE ORIGIN OF THE PLATEAU AND LATE REBRIGHTENING IN THE AFTERGLOW OF GRB 120326A

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ABSTRACT

GRB 120326A is an unusual gamma-ray burst (GRB) that has a long plateau and a very late rebrightening in both X-ray and optical bands. The similar behavior of the optical and X-ray light curves suggests that they may share a common origin. The long plateau starts at several hundred seconds and ends at tens of thousands of seconds, and the peak time of the late rebrightening is about 30,000 s. We analyze the energy injection model by means of numerical and analytical solutions, considering both the wind environment and the interstellar medium for GRB afterglows. We particularly study the influence of the injection starting time, ending time, stellar wind density (or density of the circumburst environment), and injection luminosity on the shape of the afterglow light curves, respectively. In the wind model, we find that the light curve is largely affected by the parameters and that there is a “bump” in the late stage. In the wind environment, we found that the longer the energy is injected, the more obvious the rebrightening will be. We also find that the peak time of the bump is determined by the stellar wind density. We use the late continuous injection model to interpret the unusual afterglow of GRB 120326A. The model fits the observational data well; however, we find that the timescale of the injection must be higher than 10,000 s, which implies that the timescale of the central engine activity must also be more than 10,000 s. This information can give useful constraints on the central engines of GRBs—we consider a newborn millisecond pulsar with a strong magnetic field to be the central engine. On the other hand, our results suggest that the circumburst environment of GRB 120326A is very likely a stellar wind.

Key words: gamma-ray burst: individual (GRB 120326A) – ISM: jets and outflows – radiation mechanisms: non-thermal – stars: neutron

Online-only material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) are violent phenomena in the universe that radiate tremendous energy, about $10^{51}$–$10^{54}$ erg, between fractions of a second and tens of seconds. The widely accepted model is the fireball shock model (Goodman 1986; Rees & Mészáros 1992, 1994; Mészáros & Rees 1992; Piran 1999), through which it is believed that the electrons are accelerated by either internal shocks or external shocks. Internal shocks are likely developed near the site of optically thin fireballs (Rees & Mészáros 1994), which give birth to prompt emission due to shells colliding with each other. Soon after the burst, the relativistic ejecta continue to spread out to form an external shock, which sweeps up the interstellar medium (ISM; Blandford & McKee 1976; Piran et al. 1993; Sari et al. 1998), and is believed to produce X-ray, optical/IR, and radio emission, i.e., the afterglow.

The Swift satellite (Gehrels et al. 2004), which was launched by NASA on 2004 November 20, marked a new era for GRB research. The X-Ray Telescope (XRT; Burrows et al. 2005a) on board Swift has since detected several hundreds of X-ray afterglows with fruitful results (Mészáros 2006; Zhang 2007). To summarize the X-ray afterglow data, a canonical X-ray afterglow light curve includes five components (Zhang et al. 2006; Nousek et al. 2006): (1) a steep decay phase (Zhang et al. 2007, 2009), a shallow decay phase (Liang et al. 2007), a normal decay phase (Withillongale et al. 2007), a post-jet break phase (Liang et al. 2008), and X-ray flares (Burrows et al. 2005b; Dai et al. 2006). For many bursts, we do not observe all of the components simply because of inadequate observation conditions. Many GRB afterglows have only been seen during the normal decay phase and therefore consist of a single-power component (Liang et al. 2009). Recently, Zhang et al. (2013) studied the long-term central engine activities in an X-ray afterglow. Hou et al. (2014) studied a special sample, GRB 130925A, which showed a series of flares in the X-ray afterglow. Different samples show different temporal structures, increasing our perplexity. Meanwhile, Li et al. (2012) had systematically decomposed the optical afterglow light curves, indicating that the structure and composition of optical afterglows were more complex than those of X-ray afterglows.

For X-ray afterglows, the shallow decay phase is still a puzzle (Zhang 2007). Broadband afterglows, which usually decay as a power-law function of time with an index of $\alpha \sim 1.2$ (normal decay phase), are believed to be associated with external shocks. If the external shocks are refreshed by continuous energy injection into the blast wave, a shallow decay phase prior to the normal decay phase could be observed. The shallow decay may be due to the following mechanisms: (1) energy injection, invoking a long-term central engine (Dai & Lu 1998; Zhang & Mészáros 2001; Zhang et al. 2006; Nousek et al. 2006; Fan & Piran 2006), (2) a late internal shock model (Zhang & Mészáros 2002; Zou et al. 2013), (3) an off-axis jet model (Eichler & Granot 2006; Toma et al. 2006), or (4) a central engine model (Kumar et al. 2008; Geng et al. 2013). We also notice that shallow decay phase can be interpreted as zero-time effect (Yamazaki 2009; Liang et al. 2009). To determine which one of these models is correct, we need more observational data.

A long plateau followed by a very late rebrightening is observed for the first time in the afterglow of GRB 120326A in both X-ray and optical bands. The feature of rebrightening behavior around 30,000 s is not easy to understand. The
phenomenon is so rare and interesting that many telescopes carried out observations. We collect a lot of observational data, including early and late afterglows in the optical band. These data can potentially help us to understand the underlying mechanism of this afterglow. Unlike common X-ray flares or prompt pulses, which are usually characterized by a rapid rise and an exponential decay (Kocevski et al. 2007; Norris et al. 2005; Chincarini et al. 2007, 2010; Margutti et al. 2011; Li et al. 2012), GRB 120326A shows a slight bump overlapping the afterglow light curve.

In this work, we use the energy injection model mainly in the wind environment to explain the particular phenomenon of GRB 120326A. In Section 2, we briefly describe the observation data. We review the energy injection model and fit the X-ray data in Section 3, and in Section 4, we present our conclusions and discussion. The cosmological parameters $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ have been adopted throughout our study.

2. DATA ANALYSIS

2.1. Prompt Emission

GRB 120326A was first detected at $T_0 = 01:20:29$ UT on 2012 March 26 by the Burst Alert Telescope (BAT) on board the Swift satellite and was located at a position of $\alpha = 18^h15^m42^s$, $\delta = +69^\circ15'37''$ (J2000), with a 90% containment radius of 4.1 (Siegel et al. 2012). It was also triggered and located by the Fermi Gamma-ray Burst Monitor (GBM; Collazzi 2012). The light curve of prompt emission was a single pulse with a duration ($T_0$) of about 12 s (50–300 keV; Barthelmy et al. 2012), shown in the left panel of Figure 1. The redshift of GRB 120326A was 1.798 (Kruehler et al. 2012; Tello et al. 2012).

We process the Fermi/GBM data using RMFIT. The time-averaged spectrum from $T_0 - 3.58$ s to $T_0 + 13.82$ s, as shown in the right panel of Figure 1, is fit well by the Band function, yielding a relatively low peak energy of $E_p = 64.42 \pm 7.54$ keV, a typical low energy photon index of $\alpha = -1.18 \pm 0.15$, and a soft high energy photon index of $\beta = -3.04 \pm 1.06$. The high-energy photon index is not confined very well. The reduced chi-squared of the fit is $\chi^2 = 239.8/211 = 1.14$. The total fluence of the prompt emission in the $10–1000$ keV band is $3.54 \pm 0.17 \times 10^{-6}$ erg cm$^{-2}$, which corresponds to an isotropic energy release of $E_{iso} = 1.96 \pm 0.17 \times 10^{51}$ erg. According to the empirical $\Gamma_0-E_{iso}$ relationship (Liang et al. 2010), the initial Lorentz factor can be estimated to be $\Gamma_0 \approx 120$.

2.2. X-Ray and Optical Afterglows

The XRT started to observe GRB 120326A from 59.5 s after the BAT trigger (Kennea et al. 2012). The X-ray light curve of GRB 120326A, which is taken from the UK Swift Science Data Centre at the University of Leicester (Evans et al. 2007, 2009), is shown in Figure 2. It has a steep decay, of which the decay index is about 3.4, and lasts from 52 s to 268 s after the BAT trigger. Then, there is a data gap until about $T_0 + 3700$ s due to the first earth occultation. A plateau emerges either in or before the second orbit observation and ends at about 20 ks after the BAT trigger. After the plateau, the light curve shows a rebrightening that peaks at about 30 ks–40 ks after the BAT trigger with a rising slope of $\sim 2.22$. It is not like the common X-ray flares or the prompt pulses. This phenomenon is very peculiar and this is the first time that it has been observed so obviously in the afterglow. We use the Web-based analysis system4 for the XRT data analysis (Evans et al. 2007, 2009). An average spectrum is obtained from 3700 s to 80 ks, during which the energy injection is thought to play a role. The spectrum can be fitted with an absorbed power law with a photon index of $1.89 \pm 0.06$. The best fit is achieved with an absorption column density of $4.5 \pm 1.2 \times 10^{21}$ cm$^{-2}$.

In spite of the very dim optical afterglow, GRB 120326A was observed by many ground-based telescopes (e.g., Klotz et al. 2012a; Zhao et al. 2012). We collect the optical data from the Gamma-ray Coordination Network (GCN). Considering the different filters of these observations, we select the $R$- and $r$-band data, which are represented by black dots in Figure 2. By combining the data from the GCNs 13111, 13119, and 13192, which are unfiltered observations (Guidorzi 2012; Hentunen et al. 2012; Quadri et al. 2012) represented by the black open circles in Figure 2, we can get a well-limited light curve of the optical emission. From Figure 2, we can see that the optical afterglow light curve is composed of three parts: a decay from about 1000 s to 2000 s, a plateau from about 2000 s to 10 ks (may be more longer), and a brightening from 10 ks to dozens of thousands of seconds. The detailed optical data are listed in Table 1.

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4 http://www.swift.ac.uk/
Table 1
GRB 120326A Optical Observations Collected from GCN

| Time (s) | Exposure Time (s) | Magnitude (mag) | Mag Error (mag) | Filters | References |
|---------|------------------|----------------|----------------|---------|------------|
| 163     | 59.4             | 18.2           |                | R       | 1          |
| 473     | 945              | 19.1           |                | R       | 1          |
| 846     | 30               | 19.1           | 0.2            | r       | 2          |
| 2688    | 120              | 19.6           | 0.1            | r       | 2          |
| 440     | 60               | 18.51          | 0.2            | R       | 3          |
| 507     | 60               | 19.07          | 0.2            | R       | 3          |
| 574     | 60               | 19.21          | 0.3            | R       | 3          |
| 641     | 60               | 19.75          | 0.4            | R       | 3          |
| 708     | 60               | 19.63          | 0.6            | R       | 3          |
| 775     | 60               | 19.1           | 0.2            | R       | 3          |
| 842     | 60               | 19.48          | 0.3            | R       | 3          |
| 909     | 60               | 19.19          | 0.2            | R       | 3          |
| 976     | 60               | 19.77          | 0.4            | R       | 3          |
| 1043    | 60               | 19.01          | 0.2            | R       | 3          |
| 1110    | 60               | 19.11          | 0.2            | R       | 3          |
| 1177    | 60               | 19.18          | 0.2            | R       | 3          |
| 1244    | 60               | 19.62          | 0.3            | R       | 3          |
| 1311    | 60               | 20.02          | 0.5            | R       | 3          |
| 1379    | 60               | 19.35          | 0.3            | R       | 3          |
| 1446    | 60               | 19.79          | 0.4            | R       | 3          |
| 1513    | 60               | 19.38          | 0.3            | R       | 3          |
| 1580    | 60               | 18.97          | 0.2            | R       | 3          |
| 1647    | 60               | 19.42          | 0.3            | R       | 3          |
| 1714    | 60               | 19.82          | 0.4            | R       | 3          |
| 6125    | 720              | 19             | 0.2            | Unfiltered | 4 |
| 63720   | 300              | 18.7           | 0.1            | R       | 5          |
| 64800   | 300              | 18.8           | 0.1            | R       | 5          |
| 72720   | 3600             | 18.6           | 0.1            | R       | 6          |
| 70020   | 300              | 18.56          |                | R       | 7          |
| 27639   | 300              | 17.63          | 0.06           | R       | 8          |
| 27964   | 300              | 17.53          | 0.04           | R       | 8          |
| 28282   | 300              | 17.61          | 0.04           | R       | 8          |
| 28601   | 300              | 17.84          | 0.03           | R       | 8          |
| 28915   | 300              | 17.9           | 0.03           | R       | 8          |
| 29239   | 300              | 18.08          | 0.03           | R       | 8          |
| 157320  | 300              | 19.32          |                | R       | 9          |
| 164070  | 1500             | 19.68          | 0.07           | R       | 10         |
| 76781   | 120              | 18.75          |                | Unfiltered | 11     |
| 78675   | 120              | 18.7           |                | Unfiltered | 11     |
| 80570   | 120              | 18.7           |                | Unfiltered | 11     |
| 82468   | 120              | 18.8           |                | Unfiltered | 11     |
| 84363   | 120              | 18.7           |                | Unfiltered | 11     |
| 86260   | 120              | 18.8           |                | Unfiltered | 11     |
| 88158   | 120              | 18.85          |                | Unfiltered | 11     |
| 90244   | 120              | 18.95          |                | Unfiltered | 11     |
| 170707  | 120              | 19.3           |                | Unfiltered | 11     |
| 172603  | 120              | 19.48          |                | Unfiltered | 11     |
| 172604  | 120              | 19.41          |                | Unfiltered | 11     |
| 174501  | 120              | 19.52          |                | Unfiltered | 11     |
| 258684  | 120              | 19.77          |                | Unfiltered | 11     |
| 258667  | 120              | 19.91          |                | Unfiltered | 11     |
| 260619  | 120              | 19.93          |                | Unfiltered | 11     |
| 262582  | 120              | 20             |                | Unfiltered | 11     |
| 263298  | 120              | 19.98          |                | Unfiltered | 11     |

Notes:
- From left to right: time since burst, exposure time, magnitude, magnitude error, filters, and references.

References:
1. Klotz et al. 2012b; 2. Guidorzi 2012; 3. Dintinjana & Mikuz 2012; 4. Hentunen et al. 2012; 5. Zhao et al. 2012; 6. Soulier 2012; 7. Xin et al. 2012a; 8. Jang et al. 2012; 9. Xin et al. 2012b; 10. Sahu et al. 2012; 11. Quadri et al. 2012.

3. MODELING THE AFTERGLOW OF GRB 120326A

A shallow decay phase is often observed in X-ray and optical afterglows (Liang et al. 2007). The temporal decay slope is about 0.5, which is flatter than the temporal slope of normal decay (∼1.2), and the shallow decay slope cannot be explained by the standard afterglow model (Mészáros & Rees 1997; Sari et al. 1998; Chevalier & Li 2000; Sari & Esin 2001). This phenomenon is difficult to understand. For some bursts, no spectral evolution is observed during the phase transition, which rules out the crossing of spectral break frequencies in the observing band (Zhang 2007). The energy injection model is still a preferred model used to explain the shallow decay phase. In the framework of the fireball shock model, all of the shells merge into a thick shell that continues to move forward and interact with the surrounding medium to form the external shock after the prompt emission. The external shock accelerates electrons to relativistic speed. Therefore, a fraction of shock energy will be transported to the swept-up medium as internal energy. The synchrotron radiation from the relativistic electrons contributes to the afterglow in X-ray, optical, and radio bands. However, after the prompt emission, a new millisecond pulsar (or black hole) with a strong magnetic field and rapid rotation can be born. It can produce a Poynting-flux-dominated wind (Dai & Lu 1998). The strong Poynting flow can be injected directly into the external shock and its energy may be much larger than the initial energy of the external shock. This so-called energy injection process is used to interpret the plateau or “bump” features in X-ray and optical afterglow light curves.
3.1. Shock Dynamics and Synchrotron Radiation

A generic dynamical model for GRB outflows was proposed by Huang et al. (1999, 2000), and it has been widely used to calculate the afterglow light curves. Recently, the effects of some subtle factors such as the adiabatic pressure and radiative losses on the dynamics were further studied (van Eerten et al. 2010; Pe’er 2012; Nava et al. 2013). When Poynting-flux energy injection is taken into account, the basic equation for GRB outflow dynamics during the afterglow phase can be modified as (also see Kong & Huang 2010; Liu et al. 2010)

$$\frac{d\gamma}{dm} = -\left(\frac{\gamma^2 - 1}{\gamma^2 - 1 - \frac{1}{c^2} 1/m \gamma dm + \epsilon m \gamma dm}\right) \frac{R(t) - \epsilon R}{m c^2},$$

where $\beta$ and $\gamma = 1/\sqrt{1 - \beta^2}$ are the bulk velocity and Lorentz factor of the shocked medium, $m$ is the mass of the surrounding medium swept up by the shock, $\Omega_j = (1 - \cos \theta_j)/2$ is the beaming factor of the GRB outflows, $\theta_j$ is the half-opening angle of the jet, $M_0$ is the initial mass of the jet, $\epsilon$ is the radiative efficiency, $R$ is the radius, $c$ is the speed of light, and $L$ is the luminosity of the additional energy injection into the forward shock.

If the central engine is a magnetar, the Poynting-flux power evolves over time as $L = L_0(1 + t/T)^{-2}$, where $L_0$ is the initial luminosity at $t = 0$ and $T$ is the characteristic spin-down timescale. We assume that the magnetar has an initial spin period, $P$, a surface magnetic field strength, $B$, a moment of inertia, $I$, a radius, $R_0$, and an angle between the rotation axis and magnetic dipole moment, $\theta$. The typical initial luminosity, $L_0$, and timescale, $T$, depend on the parameters of the magnetar (Dai 2004; Dai & Liu 2012): $L_0 = 4 \times 10^{57} B^2_{14} R_6^6 / P^2_{-3}$ erg s$^{-1}$ and $T = 5 \times 10^3 B_{14}^2 R_6^6 / I_{51}$ s, where $B_{14} = B \sin \theta / (10^{14} \text{ G})$, $R_{6} = R / (10^6 \text{ cm})$, $P_{-3} = P / (10^{-3} \text{ s})$ and $I_{51} = I / (10^{51} \text{ g cm}^2)$. The afterglow photons mainly come from the synchrotron radiation of electrons accelerated by the external shock (Sari et al. 1998; Sari & Piran 1999a, 1999b; Gao et al. 2013). The electron distribution is assumed as: $n_e = n_0 \gamma^{-\beta} (\nu_m \leq \gamma \leq \gamma_{\max})$ after shock acceleration, where $\beta$ is the power-law index of electron energy distribution, $\gamma_{\max} = \epsilon_n (p - 2)/(p - 1) (m_0/m_\gamma)(\gamma - 1)$ is the minimum Lorentz factor of the electrons, $\gamma_{\max} = (8\pi q_c/\gamma \Omega \sqrt{B(1 + \gamma)})^{1/2}$ is the maximum Lorentz factor of the electrons, $\gamma_e$ is the energy ratio between the inverse Compton component and the synchrotron component, $\epsilon_e$ is the shock energy equipartition parameter for electrons, and $\sigma_T$ is the Thomson cross section. The cooling Lorentz factor of electrons is $\gamma_c = (6\pi \rho c (1 + z) / \sigma_T \gamma^{2/3})^{1/2}$.

In general, there are two types of medium surrounding a massive star: homogeneous ISM and wind. Liang et al. (2013) argued that the medium surrounding some GRBs evolved from the wind case to the ISM case at a certain radius. However, Yi et al. (2013) suggested that the environment was neither a wind case nor an ISM case. For simplicity, we use the wind + ISM model, respectively. The synchrotron frequency scales as $\nu_m \propto t^{-1/3}$, the synchrotron cooling frequency scales as $\nu_c \propto t^{-1/2}$, and the peak flux densities scales as $F_{\nu,\max} \propto t^{-3/2}$ (Zhang et al. 2006). Therefore, the synchrotron radiation flux density at the observing frequency, $\nu$, (for simplicity, we only consider the optical and X-ray emission) is

$$F_\nu = \begin{cases} \left(\frac{\nu}{\nu_m}\right)^{-1/3} F_{\nu,\max}, & \nu_c < \nu < \nu_m, \\ \left(\frac{\nu}{\nu_m}\right)^{-3/2} F_{\nu,\max}, & \nu_m < \nu < \nu_c, \\ \nu^{0.5} \nu_{\max}^{1/2} \nu_{\nu,\max}^{1/2} \nu^{-2/3} F_{\nu,\max}, & \text{max} \{\nu_m, \nu_c\} < \nu < \nu_{\max}. \end{cases}$$

As we can see, the evolution of $\nu_m$, $\nu_c$, and $F_{\nu,\max}$ actually determine the temporal evolution of the afterglow light curve.

In the ISM case, the typical synchrotron frequency, the cooling frequency, and the maximum peak flux density are $\nu_m \approx 1 \times 10^{13} \nu_{14}^{1/2} \nu_{B,14} \approx E_{52}^{1/3} \nu_{t,day,14}^{1/3} \text{ Hz}$, $\nu_c \approx 8.2 \times 10^{11} \nu_{14}^{3/2} \nu_{B,14} \approx E_{52}^{1/3} \nu_{t,day,14}^{1/3} \text{ Hz}$, and $F_{\nu,\max} \approx 8.2 \times 10^{14} \nu_{14}^{1/2} \nu_{B,14} \approx E_{52}^{1/3} \nu_{t,day,14}^{1/3} \text{ \mu Jy}$, respectively, where $\nu_{t,day,14} = (\nu_{t,day} / (14 \text{ G})$. Here, the synchrotron radiation flux density at the observing frequency, $\nu$, can also be described by Equation (2).

3.2. Parameter Effects of the Energy Injection Model

The energy injection should be carried out within a period of time, starting at $T_{\text{start}}$ and ending at $T_{\text{end}}$. For simplicity, we only consider a constant injection luminosity, i.e.,

$$L(t) \approx L_0, \quad T_{\text{start}} \leq t \leq T_{\text{end}}.$$  

Combining Equation (3) and Equation (1), we can calculate the evolution of the external shock that is subjected to the energy injection from a strongly magnetized millisecond pulsar. Following the procedure described in Huang et al. (2000), we can calculate both X-ray and optical afterglows using any set of model parameter values. Our numerical code has also included the effect of equal arrival time surface (see Huang et al. 2007) and the effect of synchrotron self-absorption by electrons, which might be important for optical emission during the early phase (Wu et al. 2003).

Here, we analyze the afterglow light curves in the wind model and ISM model, respectively. In the wind model, we investigate the effects of the wind parameter, $A_\text{w}$, the starting time, $T_{\text{start}}$, and the ending time, $T_{\text{end}}$, of energy injection, and the injection luminosity, $L_0$, on the light curves of the afterglow through numerical calculations. To explore the effect of one of the above model parameters, we fix the values of the other three parameters. In our calculations, the standard values of these parameters are $A_\text{w} = 0.1, T_{\text{start}} = 100 \text{ s}, T_{\text{end}} = 10 \text{ ks}$ (the only exception is when investigating the effect of $A_\text{w}$, $T_{\text{end}} = 30 \text{ ks}$ is adopted), and $L_0 = 1.87 \times 10^{50} \text{ erg s}^{-1}$. The typical values adopted for the remaining model parameters of the afterglow are $\Gamma_0 = 300$, $E_{K,iso} = 2.0 \times 10^{51} \text{ erg}$, $\theta_1 = 0.05$, $\rho = 2.3$, $\epsilon_B = 0.01$, and $\epsilon_e = 0.1$, where $\Gamma_0$ is the initial...
Figure 3. Effects of various parameters on the X-ray afterglow light curve in the wind model. Panels (a), (b), (c), and (d) show the effects of the wind parameter, $A_\ast$, the starting time, $T_{\text{start}}$, and ending time, $T_{\text{end}}$, of energy injection, and the injection luminosity, $L_0$, respectively. In our calculations, the standard values of these parameters are $A_\ast = 0.1$, $T_{\text{start}} = 100 \text{ s}$, $L_0 = 1.87 \times 10^{49} \text{ erg s}^{-1}$, and $T_{\text{end}} = 10 \text{ ks}$ (the only exception is when we investigate the effect of $A_\ast$, where $T_{\text{end}} = 30 \text{ ks}$ is adopted).

(A color version of this figure is available in the online journal.)

Lorentz factor of the jet. With these parameters, we calculate the afterglow light curves under different conditions, as shown in Figures 3 and 4.

We briefly describe the effects of the different parameters on the X-ray light curves—Figure 3(a) shows the light curves for different wind parameters, $A_\ast$. We set $T_{\text{end}} = 30 \text{ ks}$ and find that when $A_\ast = 0.05$, the peak time of the “bump” is about $3 \text{ ks}$, and when $A_\ast = 0.2$, the peak time of the “bump” is about $10 \text{ ks}$. For a smaller $A_\ast$, the peak time is earlier and the peak flux is larger. In addition, the peak time is always less than $T_{\text{end}}$. When $A_\ast$ is small enough, there will be a plateau/shallow decay after the peak of the “bump” (e.g., $A_\ast = 0.1$). When $A_\ast$ is large enough, there will be a shallow decay prior to the peak (e.g., $A_\ast = 0.4$). These phenomena reveal that the wind parameter, $A_\ast$, determines the peak time of the “bump.” They also prove that the medium density plays a very important role in shaping the afterglow light curves in the energy injection model. The calculated light curve, showing early shallow decay and late narrow “bump”/rebrightening, is a novel prediction by the energy injection model with a wind environment. As we will show in the next subsection, such a specific model can interpret the peculiar X-ray and optical afterglows of GRB 120326A quite well.

$T_{\text{end}}$ corresponds to the injection of more energy into the external shock. Figure 3(c) shows the effect of the energy injection starting time, $T_{\text{start}}$. We find that the later the energy injection begins, the more obvious the rebrightening will be. This is in fact the zero-time effect. We also note that the $T_{\text{start}}$ affects the peak time and the peak flux of the “bump.” The later the $T_{\text{start}}$ is (causing less energy to be injected into the external shock), the later the peak time will be, and the smaller the peak flux will be. Figure 3(d) shows the effect of the energy injection luminosity $L_0$. From Figure 3(d), we can see that an obvious rebrightening is positively correlated with the $L_0$. The larger the $L_0$ is, the more obvious the rebrightening will be. The parameter effects on the optical afterglow light curves (Figure 4) are quite similar to those on the corresponding X-ray light curves.

In the ISM model. Similar to our investigation of the wind model, we study the effects of the density of the circumburst environment, $n_0$, the starting time, $T_{\text{start}}$, and ending time, $T_{\text{end}}$, of energy injection, and the injection luminosity, $L_0$, on the light curves of the afterglow through numerical calculations. When we study the effect of one of these model parameters, we use the standard parameters: $n_0 = 1.0 \text{ cm}^{-3}$, $T_{\text{start}} = 100 \text{ s}$, $T_{\text{end}} = 30 \text{ ks}$, and $L_0 = 1.87 \times 10^{49} \text{ erg s}^{-1}$, respectively. We find that although the light curve is also affected by these parameters, there is not a “bump” at the late time in the light curve that resembles the shape of GRB 120326A (see Figures 5 and 6, corresponding to X-ray and optical light curves, respectively). In the same case, when the starting time $T_{\text{start}}$ is relatively later and the injection luminosity $L_0$ is relatively larger, there is also
3.3. Fitting to the Afterglow of GRB 120326A

The simultaneous long plateau and very late rebrightening of GRB 120326A in X-ray and optical bands provide a template for testing the energy injection + wind model that is almost ideal. This phenomenon may help us to reveal the details of the underlying energy injection and circumburst environment. Note that we only consider the forward shock emission provided in our modeling and assume that the injection energy is purely in the form of Poynting flux.

For the normal afterglows in non-injection cases, the model parameters can be roughly estimated from the analytical results according to the multi-band observations (e.g., Liu et al. 2013). However, in GRB 120326A, the model is unable to analytically constrain all of the parameters from the light curves of only two bands. In fact, the energy injection process will make the justification even more difficult since the evolution of $\nu_c$ and $\nu_m$ also depends on the injection luminosity. In our model, there are 10 parameters, some of which are set as the following typical values (Freedman & Waxman 2001; Wu et al. 2003): $p = 2.2$, $\epsilon_e = 0.1$, $\epsilon_B = 0.01$. $p = 2.2$ is consistent with the photon index, 1.89, of the spectrum from 3700 s to 80 ks if $\nu_X > \nu_{\text{opt}} > \nu_m > \nu_c$. We set the half-opening angle at a typical value of $\theta_j = 0.05$ rad (Frail et al. 2001; Lu et al. 2012), and $E_{K,\text{iso}}$ and $\Gamma_0$ are estimated from Section 2.1. The plateau of the optical light curve indicates that the injection starting time is around 600 s, though the data seems scattered, thus we set $T_{\text{start}} \simeq 600$ s. On the basis of the rebrightening of the optical and X-ray light curve, we set $T_{\text{end}} \simeq 30$ ks. When $A_*$ is large enough, there will be a shallow decay prior to the peak. These phenomena reveal that the wind parameter, $A_*$, determines the peak time of the “bump,” which is discussed in Section 3.2.

GRB 120326A is just an example of this case. Through the $T_{\text{end}} \simeq 30$ ks, we can get the $A_* \geq 0.4$. Then there are only two parameters, $L_0$ and $A_*$, that need to be determined by fitting the observations. There is a relatively large scattering in the plateau phase of the optical data, which makes it difficult for us to search the best parameters during the parameter space. Note that we want to address in this article is the origin of the plateau and rebrightening in GRB 120326A. After some trials, the rough fitting result is shown in Figure 2, in which $L_0 = 1.70 \times 10^{59}$ erg s$^{-1}$ and $A_* = 0.45$ are adopted. Two points should be emphasized in the fitting process. First, we only consider the $R$ and $r$ bands to be optical data and the unfiltered band data are only used for reference. Second, we are mainly concerned with the plateau and rebrightening stage.

Figure 7 shows the evolution of $\nu_c$, $\nu_m$, and $\gamma$ with time. The left panel shows that the evolution of these two frequencies differs slightly from the analytical ones since a transition period from the non-injection case to the full injection case exists. This kind of evolution rests with the evolution of $\gamma$, given in the right
Figure 5. Effects of various parameters on the X-ray afterglow light curve in the ISM model. Panels (a), (b), (c), and (d) show the effects of the density of the circumburst environment, $n_0$, the starting time, $T_{\text{start}}$, and ending time, $T_{\text{end}}$, of energy injection, and the injection luminosity, $L_0$, respectively. In our calculations, the standard choice of the parameters are $n_0 = 1.0 \times 10^{-3}$, $T_{\text{start}} = 100$ s, $T_{\text{end}} = 30$ ks, and $L_0 = 1.87 \times 10^{49}$ erg s$^{-1}$.

(A color version of this figure is available in the online journal.)
Figure 6. Effects of various parameters on the optical afterglow light curve in the ISM model. Panels (a), (b), (c), and (d) show the effects of the density of the circumburst environment, $n_0$, the starting time, $T_{\text{start}}$, and ending time, $T_{\text{end}}$, of energy injection, and the injection luminosity, $L_0$, respectively. In our calculations, the standard parameters are $n_0 = 1.0 \, \text{cm}^{-3}$, $T_{\text{start}} = 100 \, \text{s}$, $T_{\text{end}} = 30 \, \text{ks}$, and $L_0 = 1.87 \times 10^{49} \, \text{erg s}^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 7. Evolution of $\nu_c$ (dashed line), $\nu_m$ (solid line), and $\gamma$ with time for the case of GRB 120326A afterglow. Two vertical dashed lines indicate the starting time and ending time of energy injection, respectively.

(A color version of this figure is available in the online journal.)

an ideal template. Our results suggest that the circumburst environment of GRB 120326A is very likely a stellar wind. With reasonable parameter values, we give a good fitting to the X-ray and optical afterglow light curves of GRB 120326A (see Figure 2). The model parameters from our fits are $A_* = 0.45$, $T_{\text{start}} = 600 \, \text{s}$, $T_{\text{end}} = 3 \times 10^4 \, \text{s}$, and $L_0 = 1.70 \times 10^{49} \, \text{erg s}^{-1}$.

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