DELAYED ENERGY INJECTION MODEL FOR GAMMA-RAY BURST AFTERGLOWS

J. J. Gen1,2, X. F. Wu3,4,5, Y. F. Huang1,2, and Y. B. Yu1,2

1 Department of Astronomy, Nanjing University, Nanjing 210093, China; hyf@nju.edu.cn
2 Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, China
3 Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China; xfwu@pmo.ac.cn
4 Chinese Center for Antarctic Astronomy, Chinese Academy of Sciences, Nanjing 210008, China
5 Joint Center for Particle Nuclear Physics and Cosmology of Purple Mountain Observatory-Nanjing University, Chinese Academy of Sciences, Nanjing 210008, China

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ABSTRACT

The shallow decay phase and flares in the afterglows of gamma-ray bursts (GRBs) are widely believed to be associated with the later activation of the central engine. Some models of energy injection involve a continuous energy flow since the GRB trigger time, such as the magnetic dipole radiation from a magnetar. However, in the scenario involving a black hole accretion system, the energy flow from the fall-back accretion may be delayed for a fall-back time ∼t_fb. Thus, we propose a delayed energy injection model. The delayed energy would cause a notable rise to the Lorentz factor of the external shock, which will “generate” a bump in the multiple band afterglows. If the delayed time is very short, our model degenerates to the previous models. Our model can explain the significant re-brightening in the optical and infrared light curves of GRB 081029 and GRB 100621A. A considerable fall-back mass is needed to provide the later energy; this indicates that GRBs accompanied with fall-back material may be associated with a low energy supernova so that the fraction of the envelope can survive during eruption. The fall-back time can give meaningful information on the properties of GRB progenitor stars.

Key words: accretion, accretion disks – gamma-ray burst: individual (081029, 100621A) – methods: numerical

Online-only material: color figures

1. INTRODUCTION

The multi-wavelength observations of gamma-ray bursts (GRBs) by the Swift satellite have opened a new era for GRB studies (Gehrels et al. 2004). Many unexpected phenomena in the X-ray and optical light curves have been collected. In summarizing the X-ray band may consist of five components (Zhang et al. 2006), of which two segments draw much theoretical interest. The first is the shallow decay phase (we can refer to it as a plateau), and it usually lasts from 10^3 to 10^4 s, during which the flux declines slowly with time. The second is the sudden rise and precipitous drop features “superposed” on the power-law X-ray light curve, which are referred to as flares. Both these two segments deviate from the smooth power-law evolution predicted in the frame of standard external shock afterglow model (Piran et al. 1993; Meszaros & Rees 1997; Sari & Piran 1999a, 1999b). The late-time re-brightenings in some GRB optical afterglows also show this deviation (Nardini et al. 2011a, 2011b; Greiner et al. 2013). In the frame of an external shock fireball model, the optical re-brightening may be associated with the discontinuity in the external medium density profile (e.g., Dai & Wu 2003; Lazzati et al. 2002; Nakar & Piran 2003) or possible variations of the microphysical parameters of the fireball (Kong et al. 2010). However, numerical simulations have shown that even a sharp discontinuity with a strong increase in the density profile cannot produce a sharp bump in the light curve and only a smooth and diluted change can be observed (Nakar & Granot 2007).

The X-ray plateau and X-ray flares strongly indicate that the inner engines of GRBs should be active much longer than the prompt gamma-ray emission (Zhang 2007; Lazzati & Perna 2007), or the energy release can be restarted from the central engine for some mechanism (e.g., Proga & Zhang 2006). As many models of GRBs involve accretion onto a compact object, usually a black hole (Woosley 1993; MacFadyen & Woosley 1999; Popham et al. 1999; Narayan et al. 2001; Tutukov & Fedorova 2007), the late activities of the black hole (BH) may be sustained by the accretion of the fall-back material that fails to escape from the progenitor star (Perna et al. 2006; Kumar et al. 2008a). In the proto-magnetar model (Metzger et al. 2011), a rapidly spinning, strongly magnetized proto-neutron star produces outflows, which gives birth to the prompt emission. While the magnetar cools, the wind becomes ultra-relativistic and Poynting-flux dominated, which may continue to power the late time flaring or afterglow emission. If the assumption of later energy injection is true, the interaction between the injected flow and the external shock may explain the mysterious features of X-ray afterglows. For example, the pure electromagnetic injection model was initially proposed to interpret the X-ray plateau (Dai & Lu 1998a, 1998b; Fan & Xu 2006; Kong & Huang 2010; Xue et al. 2009). Zhang & Meszéros (2002) have shown the bumps in broadband as the injection signature due to the collision of kinetic-energy dominated shells. Zhang et al. (2006) considered the continuous energy injection into the fireball during the deceleration phase, and gave an analytical result of the temporal index if the central engine is long lasting, behaving as \( L(t) \propto t^{-3} \). A more physical version of the energy injection scenario of a pulsar assumes that the pulsar may continuously eject an ultrarelativistic electron-positron-pair wind. The wind will interact with the external medium, during which the reverse shock emission can account for plateaus in some GRBs (Dai 2004; Yu & Dai 2007; Mao et al. 2010). The later X-ray flares can also be explained by the later internal shock model (Wang & Cheng 2012; Zou et al. 2013), in which the long shock catching time “defers” the X-ray emission.
However, if the energy injection is somehow delayed (the activity of the central engine is suspended after the prompt emission and restarts again later; e.g., Proga & Zhang 2006; Lei et al. 2008), the shock dynamics may evolve from a non-injection phase to the injection-dominated phase. During this transition, a rapid change in the Lorentz factor $\gamma$ of the external shock will occur on a time scale, $\delta t < t$. Steep rise of $\gamma$ will naturally lead to a flux rise, corresponding to the flares in some X-ray or optical light curves. Thus, we propose a delayed energy injection model to interpret the bumps in the X-ray or optical band. In this model, we assume there exists a start time $t_s$ (in the observer frame) from which the energy flow begins to inject into the external shock produced before. The dynamics of the outflow are described by the equations in Huang et al. (1999, 2000a, 2000b) and the revised versions by Kong & Huang (2010) and Xue et al. (2009). We take the form of the energy flow as Poynting-flux; this is applicable since the numerical results from the Poynting-flux injection or the pair wind injection differ little with each other in the low energy band (Yu & Dai 2007). Soon after the injection, the shock dynamics will approach the track predicted by the normal injection models proposed before. So our model can also give an explanation for the plateau phase following the bump.

In our study, we select GRB 081029 and GRB 100621A as examples of the high-quality multi-wavelength observation data. GRB 081029 and GRB 100621A are both characterized by the fast re-brightening in the optical afterglow (Nardini et al. 2011a, 2011b; Greiner et al. 2013). Within our model, the afterglow can be well fitted. Our paper is organized as follows. In Section 2, we describe our delayed energy injection model and some numerical results are shown. In Section 3, we describe the observations of these two GRBs and apply our model to interpret them. Our conclusions are summarized in Section 4.

2. DELAYED ENERGY INJECTION MODEL

2.1. Shock Hydrodynamics

A generic dynamical model of GRB outflow was proposed by Huang et al. (1999, 2000a) and has been widely used to interpret the afterglow light curves (e.g., He et al. 2009; Xu & Huang 2010). 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). The results generally did not deviate too much from those of Huang et al. (1999, 2000a). Here, for simplicity, we still use Huang et al.’s equations. When the Poynting-flux energy injection is taken into account, the basic equation for GRB outflow dynamics during the afterglow phase proposed by Huang et al. (2000a) can be modified to be (also see Kong & Huang 2010; Liu et al. 2010)

$$\frac{d\gamma}{dm} = \frac{(\gamma^2 - 1) - \frac{1 - \beta^2}{\gamma} \Omega_j L(t - R/c)}{M_{ej} + 2(1 - \epsilon)\gamma m + \epsilon m},$$

where $\gamma = 1/\sqrt{1 - \beta^2}$ is the bulk Lorentz factor of the shocked medium, $\Omega_j = (1 - \cos \theta_j)/2$ is the beaming factor of the GRB outflow, $\theta_j$ is the half-opening angle of the jet, $M_{ej}$ is the initial mass of the jet, $m$ is the swept-up mass by the shock, $\epsilon$ is the radiative efficiency, and $R$ is the radius. The forward shock may be continuously refreshed with the additional luminosity $L$, and thus the emission from the electrons accelerated by the shock can decrease very slowly or even rise in some cases.

2.2. External Shock Radiation

We briefly describe the radiation process from the external forward shock based on the standard model (Sari et al. 1998) in this subsection. Here, we will use prime (‘) on variables to denote parameters in the shock comoving frame and characters without a prime to denote parameters in the observer frame. The distribution function, $dn_e'/d\nu_e'$, of the injected electrons is often taken as a power-law form with the index $-p$. Then the minimum Lorentz factor $\gamma_{m}'$ of shock accelerated electrons is

$$\gamma_m' = \frac{(p - 2)m_p}{(p - 1)m_e}(\gamma - 1),$$

and the cooling Lorentz factor $\gamma_c'$ is

$$\gamma_c' = \frac{6\pi m_e c}{\sigma_T B^2(1 + Y)t'},$$

where $\epsilon_B$ and $\epsilon_e$ are shock energy equipartition parameters for magnetic fields and electrons, $B'$ is the magnetic field strength in the plasma, and $Y$ is the energy ratio between the inverse Compton component and the synchrotron component.

In the standard model, the main radiation mechanism for the outflow is the synchrotron radiation from electrons (Sari et al. 1998; Sari & Piran 1999a, 1999b). In this context, the synchrotron emission from electrons can be approximated by a broken power-law spectrum with two characteristic break frequencies corresponding to the characteristic electron Lorentz factor: $\nu_m = 1.5\gamma\gamma_m'\nu_c/(1 + z)$ and $\nu_c = 1.5\gamma\gamma_m'\nu_c^L/(1 + z)$, where $\nu_c^L$ is the Larmor frequency. The evolution of $\nu_m$ and $\nu_c$ determines the evolution of the radiation spectrum, and then the light curve can be obtained. If the circumstance is homogeneous interstellar medium (ISM), the typical synchrotron frequency and the cooling frequency are $\nu_m \propto \epsilon_B^{1/2}\epsilon_e^{1/2}t^{-3/2}$ and $\nu_c \propto (1 + Y)^{-2}\epsilon_B^{-1/2}t^{-1/2}$ in the “standard” case (adiabatic evolution with prompt injection of energy). While in the wind type environment, $\nu_m \propto \epsilon_B^{1/2}\epsilon_e^{1/2}t^{-3/2}$, $\nu_c \propto (1 + Y)^{-2}\epsilon_B^{-3/2}t^{1/2}$. As we will see below, the delayed energy injection will modify the normal evolution of $\gamma$, so that $\nu_m$ and $\nu_c$ will experience a sharp transition between two phases. It is this transition that finally gives a consequence of X-ray and optical bump.

2.3. Numerical Results

In previous work, a Poynting flux power luminosity, $L = L_0(1 + t/T)^{-2}$, is often assumed to be continuously injected into the shock (Dai & Lu 1998a; Zhang & Mészáros 2001; Yú & Dai 2007), where $L_0$ is the initial luminosity at $t = 0$, and $T$ is the characteristic spin-down timescale of the magnetar. However, this continuous injection can only cause a mild deviation from canonical afterglow. For the violent bumps, a delayed injection may be needed. In the context of the collapse of a massive star for long GRBs, the fall-back accretion of the stellar envelope seems reasonable and can give additional consequences (Kumar et al. 2008a, 2008b; Cannizzo et al. 2011; Wu et al. 2013). Since we know little information about the process of fall-back accretion, the injected luminosity may be of various forms. Here, we focus on two possible modes: “top-hat” mode and broken-power-law mode; a detailed description of these modes and the corresponding consequences are given below.

2.3.1. “Top-hat” Mode

This mode refers to a constant injection mode shown in the left panel of Figure 1. The injected power continues to be
a constant from \( t_i \) to \( t_e \) (in the observer frame). The simulation result from Kumar (2008b) shows a plateau of luminosity produced by a continuous fall-back of matter, so this mode seems applicable to the cases with a plateau phase in the afterglow. By taking \( L = L_0 \) (defined in the local frame) in Equation (1), we can calculate the evolution of the Lorentz factor in our model, then calculate the afterglow emission. In our calculations, the typical values (e.g., Huang et al. 2000b; Freedman & Waxman 2001; Wu et al. 2003) adopted for parameters of the afterglow model are \( E_{K, iso} = 1.0 \times 10^{52} \) erg, \( \theta_j = 0.1 \) rad, \( p = 2.3 \), \( \epsilon_e = 0.1 \), \( \epsilon_B = 0.01 \), \( \Gamma_0 = 300 \), and \( n = 1.0 \) cm\(^{-3} \) for the ISM case, where \( E_{K, iso} \) is the isotropic explosion kinetic energy, \( \Gamma_0 \) and \( \theta_j \) are the initial Lorentz factor and half-opening angle of the jet, and \( n \) is the density of the circumburst environment. If the environment is wind type, the density is characterized by the parameter \( A_w = 0.5 \) (\( n = 3 \times 10^{33} A_w/r^2 \) cm\(^{-3} \)) in our calculation. For the injection process, we take \( L_0 = 1.0 \times 10^{50} \) erg s\(^{-1} \) (isotropic), the start time of injection period \( t_s = 5000 \) s, and the end time \( t_e = 6000 \) s.

Figure 2 shows the numerical results by taking the parameters above. The left panel and right panel correspond to the ISM case and wind case, and the upper panel and lower panel correspond to the evolution of characteristic frequencies and afterglows in two observable bands (4.0 \( \times 10^{14} \) Hz as optical band and 0.3 keV as soft X-ray band), respectively. In the upper left panel of Figure 2, \( \nu_m \propto t^{-3/2} \) and \( \nu_c \propto t^{-1/2} \) before the energy injection, then \( \nu_m \) and \( \nu_c \) experience a quick evolution when the later energy begins to change the shock dynamics. They then slowly transit to a new trajectory like the canonical one before. Therefore there is a period where these two characteristic frequencies transit from the normal evolving phase to the phase dominated by injected energy. This period corresponds to later re-brightening of afterglows shown in the lower left panel. In this case, \( \nu_c \) goes across the optical band and gets higher again during the injection period, and the optical spectral index should become softer due to the injection and soon begin to harden. This can provide an interpretation of the possible spectrum evolution within the bump. For the wind case in the upper right panel of Figure 2, the characteristic frequencies behave in the same way as that in the upper left panel during the injection period, though the primary evolution of \( \nu_c \) is different. If \( \nu_X > \max (\nu_m, \nu_c) \), the X-ray light curve in the wind case would not be significantly different from that in the ISM case. This is consistent with the comparison of the lower left and lower right panel. However, the shape of the optical light curve during the injection period may be different for different circumburst environments. With the specific parameters used in Figure 2, the optical frequency is in the slow cooling regime in the ISM case, then \( F_s \propto (\nu/\nu_m)^{-(p-1)/2} \), while \( F_s \propto (\nu/\nu_m)^{-(p-1)/2}(\nu_c/\nu)^{1/2} \) for the fast cooling in the wind case at the beginning of the injection. As can be seen in the lower panel, the bump in the ISM case is steeper than that in the wind case, this is caused by the decreasing factor \( \nu_c/\nu \) during the injection period.

In our calculations, the effect of equal-arrive-time surface (EATS; e.g., Waxman 1997; Granot et al. 1999) has been considered, and the light curve seems to be relatively smooth rather than very sharp. Another consequence of EATS is that the peak time of the high energy band and the low energy band is different (Huang et al. 2007). This will also be shown in Section 3. One should notice that in the wind case, if the parameters are “selected” appropriately so that \( \nu_m \) and \( \nu_c \) cross each other shortly after the bump, there will be a short plateau or even small bump following the previous “big” bump. This is because the cooling Lorentz factor is calculated with different equations before and after the crossing time due to the synchrotron self-Compton (SSC; e.g., Sari & Esin 2001) process. \( \nu_c \) will change slightly after the crossing time. This result can potentially be used to interpret the small structure after the bump. It is also noticeable that a relative lower kinetic energy \( E_{K, iso} \) is essential to ensure the notable change of \( \gamma \) during the injection of a limited luminosity. This indicates that the effect of energy injection would be significant only for low-luminosity GRBs, otherwise the fall-back energy should be large enough.

In principle, the spectrum of the afterglows can be modified markedly at \( t_i \) in our delayed energy injection model, by affecting the evolution of \( \nu_m \) and \( \nu_c \) before (using the fireball parameters) and after (using the injection parameters) \( t_i \). So these parameters can be constrained from the spectrum evolution around \( t_i \) if detailed observations are available.

### 2.3.2. Broken-power-law Mode

This mode refers to a more realistic case in which the luminosity rises and declines with time. We assume the fall-back accretion starts at a fall-back time, \( t_f = t_{fb} \) (defined in the observer frame). According to previous work (MacFadyen et al. 2001; Zhang et al. 2008; Dai & Liu 2012; Wu et al. 2013), during the fall-back accretion process, the fall-back accretion rate \( \dot{M} \) evolves with time as \( \dot{M} \propto t^{1/2} \) before the peak time \( t_p \), and \( \dot{M} \propto t^{-5/3} \) in the late time. To convert the \( \dot{M} \) to the
output power $L$, one needs to know details about the mechanism of relativistic jet launch. For the BH accretion system as the central engine of GRBs, the jet power is mainly from two methods: the magnetic processes through the Blandford–Znajek (Blandford & Znajek 1977; Lee et al. 2000) mechanism, the Blandford–Payne (Blandford & Payne 1982) mechanism, or the disk magnetic reconnection (Yuan & Zhang 2012); and the annihilation of neutrinos and anti-neutrinos in the neutrino-dominated accretion flows (Narayan et al. 2001). Many authors have attempted to investigate these processes (e.g., Popham et al. 1999; Xie et al. 2009; Lei et al. 2009, 2013). However, the jet efficiency $\eta = L/\dot{M}c^2$ has remained a mystery up to now (McKinney 2005; Narayan et al. 2013).

Here, for simplicity, we assume the late energy release is proportional to $\dot{M}$. We then obtain the luminosity profile of the fallback power,

$$L = L_p \left[ \frac{1}{2} \left( \frac{t - t_s}{t_p - t_s} \right)^{-\alpha_r} + \frac{1}{2} \left( \frac{t - t_s}{t_p - t_s} \right)^{-\alpha_d} \right]^{-1/s}, \quad (4)$$

where $L_p$ is the peak luminosity at the peak time $t_p$, $\alpha_r$ and $\alpha_d$ are the rising and decreasing index, respectively, and $s$ denotes the sharpness of the peak. This kind of profile is shown in the right panel of Figure 1. For the realistic case, the injected power should depend on more physical variables (such as the BH spin parameter $a$, the magnetic field $B$ around the BH). However, the realistic luminosity profile should essentially include a rising and a decreasing segment, and our simplification can roughly describe the jet luminosity during the fallback accretion.

In our calculations, the typical values of the fireball model parameters are the same as those in the “top-hat” mode. For the injection process, we take $L_p = 1.0 \times 10^{50} \text{ erg s}^{-1}$, $t_s = 5000 \text{ s}$, $t_p = 5200 \text{ s}$, $t_e = 5600 \text{ s}$, $\alpha_r = 0.5$, $\alpha_d = -1.2$, and $s = 0.5$. Figure 3 shows the numerical results in the broken-power-law mode. It can be seen that the result of this mode differs little from that in the “top-hat” mode. This is mainly because both of these two modes lead to the same evolution of $\gamma$. The shape of the bump in the ISM case is also steeper than that in the wind case, which can be explained by the same reason mentioned in the previous subsection.

3. APPLICATION TO GRBs

3.1. GRB 081029

GRB 081029, detected by the Swift satellite at 01:43:56 UT on 2008 October 29, is a long-soft burst with a redshift of $z = 3.8479$ (D’Elia et al. 2008). The X-Ray Telescope (XRT, Burrows et al. 2005) began observing the field of GRB 081029 2.7 ks after the BAT trigger. Figure 4 shows the overall temporal evolution of the afterglow in X-ray and optical band. The X-ray light curve can be modeled by a broken power law ($f(t) \propto t^{-\alpha}$). The best fit gives decay indices of $\alpha_{X,1} = 0.56 \pm 0.03$ and $\alpha_{X,2} = 2.56 \pm 0.09$, with a break time of $t_{X,b} = 18230 \pm 346 \text{ s}$ (Holland et al. 2012). The initial X-ray light curve shows evidence of possible flares between 2550 s and 5000 s after the trigger time. However, the lack of X-ray data during this period...
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Figure 3. Results in the broken-power-law mode. The upper left panel shows the evolution of two frequencies, $\nu_m$ (dashed line) and $\nu_c$ (solid line) in the ISM case. The two straight lines note the two typical bands ($4.0 \times 10^{14}$ Hz as optical band and 0.3 keV as soft X-ray band) in which the afterglows are calculated. The lower left panel shows the afterglows in these two bands (redshift $z=1$ is assumed). The upper right panel and lower right panel show the similar plots as left panels, but the environment is wind type. (A color version of this figure is available in the online journal.)

missed the possible flares. The X-ray spectrum can be fitted by a power-law with $\beta_X = 0.98 \pm 0.08$ ($f_\nu \propto \nu^{-\beta}$). The optical and infrared data are from the observations of the Gamma-Ray burst Optical and Near-infrared Detector (GROND). Between about 3000 s and 5000 s, the optical and infrared light curves rise rapidly (clearly seen in the GROND data; Nardini et al. 2011b); the rising index is $\alpha \simeq -8$ during this period. The rise of the optical re-brightening is so steep that one can nearly rule out the explanations of the discontinuity in the external medium density profile and the two component jet model (Filgas et al. 2012). A later reactivation of the central engine is preferred (Nardini et al. 2011b). Yu & Huang (2013) have given a numerical fitting to the afterglow of GRB 081029 using a two-step injection model. However, they have only fitted the light curves in two bands and the SSC process and the synchrotron self-absorption by electrons have not been considered in their calculations.

Since our model can produce giant bumps in the optical bands as shown in Figures 2 and 3, we now apply the model to fit the multi-wavelength afterglow of GRB 081029. The shallow decay and small bump after the peak of the bump strongly indicate that the circumstance should be wind type according to the comparison in Figures 2 and 3. Although we can “construct” one case in which $\nu_m$ crosses $\nu_c$ just after the peak time so that one small bump (at 8000 s in the afterglow) would emerge naturally in the wind case, it causes a technical problem to adjust this small numerical bump to the data to get a good fitting. At last, we attribute this small feature to some other physical process (e.g., the variability of the injected power due to some instabilities in the central engine) and use two injection processes in the ISM case to interpret the observations.

The fitting results are shown in Figure 4. We do not include the data in the $g'$ and $r'$ bands since they may be strongly affected by the Lyman break at $z = 3.8$ (Nardini et al. 2011b). The first injection is assumed to be in broken-power-law mode starting from 3300 s, and the second injection is assumed to be the “top-hat” mode starting from 10000 s. Other parameters of the double injection are summarized in Table 1. The reduced chi-square $\chi^2/\nu$ of the X-ray fitting in the bottom panel of Figure 4 is 1.87. The $\chi^2/\nu$ of fitting for the other five bands are all larger than 10 due to the small structures of the light curves and the small error bars of the observations. However, our main purpose is to reproduce the giant bump, and we realize it in this fitting. One consequence when taking the effect of EATS into consideration is that the peak times of bumps in different bands are actually slightly different (Huang et al. 2007), which can be seen clearly in the middle panel of Figure 4. It is due to the fact that the refreshed shock with an increasing $\gamma$ would prefer emitting higher energy photons. This effect should also hold for the models involving refreshed shock based on external shock models.

Note that some of the parameters derived from our best fit are different from those derived by Yu & Huang (2013). The difference may partly be due to the inclusion of SSC in our calculation. However, the more important factor may be that they include $r'$-band data in their fit, but we do not.
is shown in Figure 5. The optical overall temporal evolution of X-ray and optical This afterglow is more unusual than that of GRB 081029. The curves of GRB 100621A were obtained with XRT in X-rays at 230 s after the trigger. Since the early rise of on-axis canonical X-ray is usually \( t^2 \) or \( t^3 \) (Xue et al. 2009), this early rise is likely dominated by a flare (Greiner et al. 2013). Like GRB 081029, a steep rise during 4000–5000 s is also observed in the GROND band. Here, we would apply our delayed energy injection model to interpret this intensive jump. The emission beyond 100 ks is stronger than the extrapolation of the decay after the jump, which indicates that there exists another component which dominates at the later time. If we attribute the distortion to a second injection like GRB 081029, there is a problem for the injection time. From the X-ray emission in the bottom panel of Figure 5, it can be derived that the second injection would become dominant at 20 ks. However, the two observational points at about 28 ks in the K and H bands in the middle panel are still on the extrapolation of the decreasing shock after the bump, which is irreconcilable with the X-ray emission in the twice injection scenario. So we explain this distortion as an off-axis afterglow component emerging very late.

The curvature in the GROND spectrum illustrates the strong extinction of the afterglow light in the host galaxy. Also, we have assumed the spectrum of early flare as \( f_{\nu} \propto \nu^{-1.3} \) and used the “Norris function” (Norris et al. 2005) to describe the profile of the flare. Our fitting results are shown in Figure 5. The injection of the on-axis jet is assumed to be in broken-power-law mode starting from 3600 s. Detailed parameters of the afterglow and the injection are summarized in Table 2, and the dust extinction value of the seven bands we used is listed in Table 3. The flux of 6 Norris et al. (2005) have used the function \( f(t) = C \exp(-t_i/(t - t_0) - (t - t_i)/\tau_2) \) to fit the pulse shape of the light curve, where \( C \) represents the intensity, \( t_0 \) is the time when the flare begins to rise, and \( t_1 \) and \( t_2 \) are rise and decay timescales, respectively. In our fitting results, we obtain \( C = 6.0 \times 10^{-25} \) erg cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\) at K band, \( t_0 = 80 \) s, \( t_1 = 350 \) s, and \( t_2 = 400 \) s.

### Table 1

| Fireball Parameter | Value | Injection Parameter | Broken-power-law Mode | “Top-hat” Mode |
|-------------------|-------|---------------------|-----------------------|----------------|
| \( \theta_j \) (rad) | 0.03  | \( L_p \) (erg s\(^{-1}\)) | 4.5 \times 10\(^{50}\) | 4.0 \times 10\(^{50}\) |
| \( \Gamma_0 \) | 400   | \( L_0 \) (erg s\(^{-1}\)) | 3300.0 | 10000.0 |
| \( E_{K,\text{iso}} \) (erg) | 1.2 \times 10\(^{52}\) | \( \tau_i \) (s) | 3700.0 |
| \( \rho \) | 2.4   | \( \tau_p \) (s) | 3900.0 |
| \( \epsilon_e \) | 0.028 | \( \epsilon_e \) | 11000.0 |
| \( \epsilon_B \) | 0.5   | 0.5 | |
| \( n \) (cm\(^{-3}\)) | 10.0  | \( \alpha_d \) | -1.3 |
| \( z \) | 3.8479 | \( s \) | 0.5 |

**Notes.** We use the injection of broken-power-law mode to interpret the giant bump. The second injection of “top-hat” mode corresponds to the flat tail. The time parameters are all defined in the observer frame, whereas the isotropic luminosity parameters \( (L_p, L_0) \) are defined in the local frame.

### Table 2

| Fireball Parameter | Off-axis Jet | On-axis Jet | Injection Parameter | Broken-power-law Mode |
|-------------------|--------------|-------------|---------------------|-----------------------|
| \( \theta_{\text{obs}} \) (rad) | 0.24 | 0.0 | \( L_p \) (erg s\(^{-1}\)) | 5.0 \times 10\(^{59}\) |
| \( \theta_j \) (rad) | 0.2 | 0.04 | \( \tau_i \) (s) | 3600.0 |
| \( \Gamma_0 \) | 100 | 70 | \( \tau_p \) (s) | 4100.0 |
| \( E_{K,\text{iso}} \) (erg) | 5.0 \times 10\(^{52}\) | 1.0 \times 10\(^{52}\) | \( \epsilon_e \) | 4600.0 |
| \( \rho \) | 2.1 | 2.2 | \( \alpha_d \) | -1.2 |
| \( \epsilon_e \) | 0.04 | 0.04 | \( s \) | 0.5 |
| \( \epsilon_B \) | 0.1 | 0.06 | |
| \( n \) (cm\(^{-3}\)) | 2.0 | 2.0 | |
| \( z \) | 0.542 | 0.542 | |

**Notes.** We use the on-axis jet with an injection of broken-power-law mode to interpret the intensive jump at \( \sim 4.5 \) ks, while the off-axis jet can explain the slow decreasing flux at the later time. The time parameters are all defined in the observer frame, whereas the isotropic luminosity parameter \( (L_p) \) is defined in the local frame.

\( \theta_{\text{obs}} \) is defined as the angle between the line of sight and the jet axis.

### Table 3

| Band | \( g' \) | \( r' \) | \( i' \) | \( z' \) | \( J \) | \( H \) | \( K \) |
|------|--------|--------|--------|--------|------|------|------|
| \( A \) (mag) | 6.51 | 5.20 | 4.13 | 3.31 | 1.95 | 1.19 | 0.86 |

### 3.2. GRB 100621A

GRB 100621A triggered the BAT on the Swift satellite on 2010 June 21 at 03:03:32 UT (Ukwatta et al. 2010). Its redshift is \( z = 0.542 \) (Milvang-Jensen et al. 2010). The afterglow light curves of GRB 100621A were obtained with XRT in X-rays and GROND in its seven filter bands (Greiner et al. 2013). This afterglow is more unusual than that of GRB 081029. The overall temporal evolution of X-ray and optical/NIR afterglow is shown in Figure 5. The optical/NIR light curves show a rapid rise with \( \alpha \approx -4.0 \) at 230 s after the trigger. Since the early rise of on-axis canonical X-ray is usually \( t^2 \) or \( t^3 \) (Xue et al. 2009), this early rise is likely dominated by a flare (Greiner et al. 2013). Like GRB 081029, a steep rise during 4000–5000 s is also observed in the GROND band. Here, we would apply our delayed energy injection model to interpret this intensive jump. The emission beyond 100 ks is stronger than the extrapolation of the decay after the jump, which indicates that there exists another component which dominates at the later time. If we attribute the...
Figure 4. Our best fit to the multi-band afterglow of GRB 081029, by assuming two energy injections. The upper panel shows the evolution of $\nu_m$ (dashed line) and $\nu_c$ (solid line). The middle panel shows the fitting result in five optical and infrared bands (the value of four lower bands have been multiplied by four different factors to display better). The lower panel shows the fitting result in XRT band. The vertical solid line notes the starting time of the first injection, and the dashed line notes the starting time of the second injection. Detailed parameters are listed in Table 1. Observational data are taken from Nardini et al. (2011b).

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

Figure 5. Our best fit to the multi-band afterglow of GRB 100621A, by incorporating three components (a flare, an on-axis jet with delayed energy injection, and an off-axis jet). The upper panel shows the evolution of $\nu_m$ and $\nu_c$ of the on-axis jet. The middle panel shows the fitting results of seven bands of GROND, the dashed lines mark the flare, the dash-dotted lines mark the afterglow of on-axis jet, the short-dotted lines mark the afterglow of off-axis jet, and the solid lines show the total flux of these three components. The lower panel shows the fitting result in the XRT band. The vertical solid line notes the starting time of the injection. Detailed parameters are listed in Tables 2 and 3. GROND data are taken from Greiner et al. (2013).

(A color version of this figure is available in the online journal.)
the host galaxy is obtained using the later data, and it is added to the numerical results in our fitting.

4. DISCUSSION AND CONCLUSIONS

The fireball model can well explain the “clean” broken-power-law afterglows before the Swift era. However, many unexpected structures, like plateaus or bumps, have been observed in almost half of the long GRBs (Gehrels et al. 2009). Models to explain the plateaus or bumps always involve “finding” later energy sources that would dominate the later radiation. The Poynting-flux from magnetars (Metzger et al. 2011; Dai & Liu 2012; Bernardini et al. 2012) or BH accretion systems (Cannizzo et al. 2011; Lindner et al. 2012) can play this role. When the later reactivities of the central engines have to be considered, the later radiation may be modified in two ways: refreshing the external shock in the fireball frame or attributing the later light curve to the jet luminosity directly from the central engine. In this article, we consider the first case and give the numerical results based on two possible injection modes. Since we only consider the dynamic evolution of the forward shock changed by the later injection and other physical processes for photons streaming through the external shocks are neglected (Kumar et al. 2013), our model differs little from a “second” afterglow superposing on the original afterglow. However, this model can indeed explain the bumps in the later multiple-wavelength observations of GRB 081029 and GRB 100621A as shown in Section 3.

The bumps in the later multiple-wavelength observations indicate the reactivity of the central engine. If this bump is truly due to the mass fall-back, the re-brightening time should correspond to the fall-back time $t_{fb} = t_s/(1 + z) \simeq (\pi^2 r_{hb}^2/8GM_{BH})^{1/2}$, where $r_{hb}$ is defined in the local frame and $M_{BH}$ is the BH mass. For GRB 081029, $t_s = 3300$ s. This suggests the minimum radius around which the matter starts to fall back is $r_{fb} \simeq 5.3 \times 10^{10}(M_{BH}/3M_{\odot})^{1/2}(r_{hb}/680 \text{ s})^{2/3}$ cm. In first principle, assuming the potential energy of the backfall matter is all converted to the jet power, we have $GM_{BH}M_{fb}/r_{fb} \simeq L_{pb}(t_p - t_s) + L_0(t_s - t_f)(1 - \cos \theta)/2.0/(1 + z)$. The total fall-back mass is $M_{fb} \simeq 3.5\times 10^3(M_{BH}/3M_{\odot})^{-2/3}$, which seems large according to some articles (Lindner et al. 2011; Cannizzo et al. 2011). However, the mass should be overestimated since the energy of the rotating BH and magnetic field around are also significant energy sources. On the other hand, the large luminosity needed may indicate that our model is an inefficient scheme to use the injected energy. While for GRB 100621A, $r_{fb} \simeq 1.2 \times 10^{11}(M_{BH}/3M_{\odot})^{1/2}(r_{hb}/2330 \text{ s})^{2/3}$ cm, the total fall-back mass is $M_{fb} \simeq 1.0\times 10^3(M_{BH}/3M_{\odot})^{-2/3}$.

For the golden sample of GRB-supernova association (GRBs 060218, 100316D, 091127, 120422A) in the Swift era (Zhang et al. 2012), three of them (except for GRB 120422A) lack X-ray plateaus. If some plateaus are the consequence of the fall-back accretion, then it can well explain the lacking plateaus with bright SN since the fall-back material cannot survive during the explosion. In our model, GRB 081029 and GRB 100621A might be accompanied by a low energy supernova, or even a failed supernova.

The later light curves, especially those with unusual features, can indeed help to us learn about the central engines. In the BH accretion system, the fall-back process seems plausible under some conditions. Based on this scenario (or other possible scenarios that can provide such a delayed energy), we propose the delayed energy injection model to interpret the later bump in the multi-band afterglows. However, we have only considered the simplified case. Some physical processes for photons streaming through the external shock may be considered later. Besides, the jet power from the fall-back accretion should depend on the spin evolution of the BH and the magnetic field around the BH. Our model can be tested using more afterglow samples with observations in more bands and detailed spectral evolution data.

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REFERENCES

Bernardini, M. G., Margutti, R., Mao, J., Zaninoni, E., & Chincarini, G. 2012, A&A, 539, A3
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, SSRv, 120, 165
Cannizzo, J. K., Troja, E., & Gehrels, N. 2011, ApJ, 734, 35
Dai, Z. G. 2004, ApJ, 606, 1000
Dai, Z. G., & Liu, R.-Y. 2010, MNRAS, 402, 409
D’Elia, V., Covino, S., & D’Avanzo, P. 2008, GCN, 8438, 1
Fan, Y.-Z., & Xu, D. 2006, MNRAS, 372, L19
Filgas, R., Greiner, J., Schady, P., et al. 2012, A&A, 546, A101
Freeland, D. M., & Waxman, E. 2001, ApJ, 547, 922
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Gehrels, N., Ramirez-Ruiz, E., & Fox, D. B. 2009, ARA&A, 47, 567
Granot, J., Piran, T., & Sari, R. 1999, ApJ, 513, 679
Greiner, J., Kührer, T., Nardini, M., et al. 2013, A&A, in press (arXiv:1304.5852)
He, H.-N., Wang, X.-Y., Yu, Y.-W., & Mészaros, P. 2009, ApJ, 706, 1152
Holland, S. T., De Pasquale, M., Mao, J., et al. 2012, ApJ, 745, 41
Huang, Y. F., Dai, Z. G., & Lu, T. 1999, MNRAS, 309, 513
Huang, Y. F., Dai, Z. G., & Lu, T. 2000a, MNRAS, 316, 943
Huang, Y. F., Gou, L. J., Dai, Z. G., & Lu, T. 2000b, ApJ, 543, 90
Huang, Y.-F., Lu, Y., Wong, A. Y. L., & Cheng, K. S. 2007, ChJAA, 5, 94
Kong, S., Huang, Y. 2010, SCIENCE, 325, 7
Kong, S. W., Huang, Y. 2010, ChJAA, 53, 94
Lee, H. K., Wijers, R. A. M. J., & Brown, G. E. 2000, PhR, 325, 83
Lei, W.-H., Wang, X.-Y., Zou, Y.-C., & Zhang, L. 2008, ChJAA, 8, 404
Lei, W.-H., Zhang, B., & Liang, E.-W. 2013, ApJ, 765, 125
Lindner, C. C., Milosavljević, M., Couch, S. M., & Kumar, P. 2010, ApJ, 713, 800
Lindner, C. C., Milosavljević, M., Shen, R., & Kumar, P. 2012, ApJ, 750, 163
Liu, X. W., Wu, X. F., & Lu, T. 2010, ScChG, 53, 262
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
MacFadyen, A. I., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 410
Mao, Z., Yu, Y. W., Dai, Z. G., Pi, C. M., & Zheng, X. P. 2010, A&A, 518, A27
