*R*esearch in
*A*stronomy and
*A*strophysics

X-ray afterglow of GRB 050712: multiple energy injections into the external shock [*]

Liang-Duan Liu[1,2] and A-Ming Chen[1]

[1] Institute of Astrophysics, Central China Normal University, Wuhan 430079, China;
    liuliangduan@gmail.com
[2] School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China

Abstract As indicated by observed X-ray flares, a great amount of energy can be intermittently released from the postburst central engine of gamma-ray bursts (GRBs). As a natural consequence, the GRB's external shock could be repeatedly energized. With such a multiple energy injection model, we explore the unique X-ray afterglow light curve of GRB 050712, which exhibits four shallow decay plateaus. Together with three early X-ray flares, the central engine of GRB 050712 is believed to have released energy at least seven times after the burst. Furthermore, we find that the energies released during the four plateaus are all on the same order of magnitude, but the luminosity significantly decreased with time. These results may provide some interesting implications for the GRB central engine.

Key words: gamma rays: bursts — individual: GRB 050712

1 INTRODUCTION

The successful launch and operation of the *Swift* satellite have significantly improved our understanding of the physical origin of gamma-ray bursts (GRBs). The X-ray Telescope (XRT) onboard *Swift* has revealed many unexpected features in X-ray afterglows (Zhang et al. 2006), which include: (1) steep decay phase (Zhang et al. 2007, 2009), (2) shallow decay phase (Liang et al. 2007), (3) missing jet breaks in some GRBs (Liang et al. 2008; Racusin et al. 2009), and (4) X-ray flares (Falcone et al. 2007; Swenson & Roming 2013). Specifically, the shallow decay segments have commonly been seen in about 60% of the X-ray afterglows detected by *Swift*, and the flares appear in roughly 1/3 of them (Gehrels et al. 2009; Grupe et al. 2013). It seems difficult to explain these phenomena with the standard external shock model (Meszaros & Rees 1997; Sari et al. 1998; Zhang 2007; Liang et al. 2007), where a simple power-law decay with a temporal index around 1.2 is predicted in the X-ray light curves.

X-ray flares share many similarities with GRB prompt emission, which indicates that the flares might have similar physical processes with the prompt emission, including the dynamics and radiation mechanisms (Fan & Wei 2005; Zhang et al. 2006; Yu & Dai 2009). At the same time, it is widely accepted that the shallow decay afterglows could be due to an energy injection into the external shock (Dai & Lu 1998a,b; Rees & Meszaros 1998; Zhang & Mészáros 2001; Fan & Xu 2006;
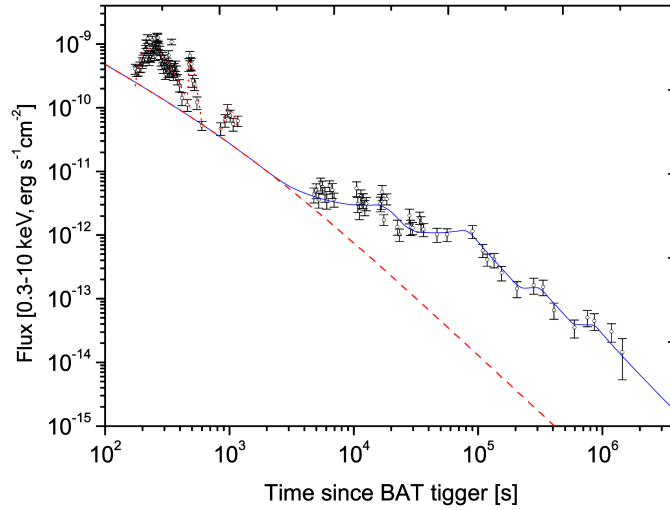

Fig. 1 Fitting to the X-ray afterglow of GRB 050712 with multiple energy injections (*solid line*), where the case without energy injection is also presented for comparison (*dashed line*). The three early flares are fitted by the empirical Norris function (*dotted line*). The observational data are taken from *http://www.swift.ac.uk/xrt_curves/00145581/*.

Nousek et al. 2006; Granot & Kumar 2006; Sollerman et al. 2007; Geng et al. 2013). Both the X-ray plateaus and flares suggest that the GRB central engine (an accreting black hole or millisecond magnetar) has not switched off immediately after the prompt emission. For a black hole surrounded by an accretion disk, the late activities could be powered by the accretion of fall-back materials, where the spin energy of the black hole can be released by the Blandford-Znajek mechanism (Blandford & Znajek 1977). On the other hand, if the central engine is a millisecond magnetar, it will lose its rotational energy by some braking mechanism (e.g., magnetic dipole radiation).

Long GRB 050712 with a duration of $T_{90} = 48 \pm 2\,\mathrm{s}$ was detected by the BAT onboard *Swift* at 14:00:28 UT on 2005 July 12, with coordinates observed by XRT of $\mathrm{RA(J2000)} = 05^\mathrm{h}10^\mathrm{m}48^\mathrm{s}$, $\mathrm{Dec(J2000)} = 64°55'48.2''$ and an error circle with a $6''$ radius. Its peak flux measured in the $15-150\,\mathrm{keV}$ band was $(1.10 \pm 0.07) \times 10^{-6}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The XRT observation in the $0.3-10\,\mathrm{keV}$ band started about $160\,\mathrm{s}$ after the trigger. The observed X-ray light curve exhibited a unique temporal behavior. Firstly, three flares happened at 174, 455 and 861 s (Swenson & Roming 2013) after the BAT trigger respectively. Such early flares are normal in GRBs observed by *Swift* (Falcone et al. 2007; Zhang et al. 2006). However, after these flares occur, the afterglow emission shows a tiered decline (i.e., step by step; see Fig. 1), which is completely different from the normal single-power-law decay or a single plateau followed by a power-law decay. Furthermore, the rise and decline of these steps are very slow, so they cannot be late flares. Obviously, such a tiered light curve cannot be explained by the traditional energy injection model where energy is continuously injected. Alternatively, in this paper we suggest that the afterglow emission of GRB 050712 could indicate several intermittent, multiple energy injections.

2 MODEL

In the standard model of GRBs (Zhang 2007; Gehrels et al. 2009), the GRB central engine drives an energetic fireball or Poynting-flux-dominated ejecta, which could be accelerated to a high relativistic

speed. Then the internal dissipations in the ejecta (e.g. internal shocks and magnetic reconnections) lead to the prompt gamma-ray emission. Subsequently, the interaction between the GRB ejecta and the ambient medium gives rise to a relativistic external shock, which could produce long-lasting multi-wavelength afterglow emission. Therefore, the temporal behavior of the afterglow emission should basically be determined by the dynamical evolution of the external shock. A generic dynamical model which describes dynamics of both the ultra-relativistic and non-relativistic shock was given by Huang et al. (1999, 2000). The fundamental dynamical equation can be written as

$$\frac{d\Gamma}{dm_{\text{sw}}} = -\frac{\Gamma^2 - 1}{M_{\text{ej}} + 2\Gamma m_{\text{sw}}}, \tag{1}$$

where Γ is the bulk Lorentz factor of the external shock, m_{sw} is the mass of the swept-up medium and M_{ej} is the mass of the GRB ejecta.

The post-burst energy injection into the external shock could significantly slow down the deceleration rate of the shock or even lead to a short-term acceleration (Dai & Liu 2012). The dynamical equation can be derived from the energy conservation law. The total energy of the GRB ejecta and the shocked medium can be written as $E_k = \Gamma M_{\text{ej}} c^2 + (\Gamma^2 - 1) m_{\text{sw}} c^2$, where the shock jump condition is used to calculate the internal energy. Then we can obtain $dE_k = (\Gamma^2 - 1) c^2 dm_{\text{sw}} + (M_{\text{ej}} + 2\Gamma m_{\text{sw}}) c^2 d\Gamma = L(t) dt$, where L is the luminosity of the post-burst energy flow released from the central engine and $t = t_{\text{obs}}/(1+z)$ with t_{obs} being the time measured in the observer's frame and redshift z (Fan & Xu 2006). Therefore, we can revise the dynamical equation as follows

$$\frac{d\Gamma}{dm_{\text{sw}}} = -\frac{1}{M_{\text{ej}} + 2\Gamma m_{\text{sw}}} \left[\Gamma^2 - 1 - \frac{L(t)}{c^2} \frac{dt}{dm_{\text{sw}}} \right]. \tag{2}$$

If $L = 0$ (no energy injection), the above equation returns to Equation (1). For a general consideration, Zhang & Mészáros (2001) proposed a simple power-law form for the injected luminosity as $L(t) \propto t^{-q}$. Specifically, $q = 5/3$ is expected if the central object is a black hole surrounded by a fallback accretion disk. However, for $q > 1$, the energy injection is not important. On the other hand, for a millisecond magnetar, $q = 0$ or -2 can be found for traditional magnetic dipole radiation before/after the spin down timescale (Dai & Lu 1998a). Moreover, for a fallback-accreting magnetar, its spin down history could become much more complicated (Dai & Liu 2012) and then the value of q might evolve with time.

In most energy injection models, the energy release is usually assumed to be continuous. However, as indicated by X-ray flares, the energy release from the post-burst object could be intermittent. It seems that the central engine can be turned on after a period of energy accumulation. Therefore, it is reasonable to consider that the energy injection into the external shock might be intermittent. In this case, we have

$$L_i(t) = Q_i t^{q_i}, \qquad \text{for } t_{\text{start},i} < t < t_{\text{end},i}, \tag{3}$$

where the subscript "i" represents the ith energy injection, Q_i and q_i are constants in each injection, and the energy injection starts and ends at $t = t_{\text{start},i}$ and $t_{\text{end},i}$ respectively. As an example, Geng et al. (2013) used a two-step energy injection model to interpret the rebrightening of the multi-band afterglow of GRB 081029.

In order to solve Equation (2), the evolutions of the swept-up mass m_{sw} and the radius r of the shock should be described as (Huang et al. 1999, 2000)

$$\frac{dm_{\text{sw}}}{dr} = 2\pi r^2 (1 - \cos\theta_j) n m_{\text{p}}, \tag{4}$$

$$\frac{dr}{dt} = \frac{\beta c}{1 - \beta}, \tag{5}$$

Table 1 Parameters for the Energy Injections

ith injection	t_{start} (10^4 s)	t_{end} (10^4 s)	Q (10^{46} erg s^{-1})
1	0.3	1.4	15.0
2	2.0	7.3	5.0
3	19.0	28.0	1.1
4	55.0	75.0	1.2

where n is the ambient number density, θ_j the half opening angle of the jet, m_{p} the mass of a proton, and $\beta = \sqrt{1 - \Gamma^{-2}}$ the velocity in terms of the speed of light being unity. The distribution of the ambient medium plays an important role in determining the profile of the afterglow light curve. In contrast to the usually assumed homogenous interstellar medium (ISM), a wind-like case with $n \propto r^{-2}$ is also proposed by Dai & Lu (1998c) and Chevalier & Li (2000) by considering that long GRBs probably originate from the collapse of massive stars (Woosley 1993; MacFadyen & Woosley 1999).

As the external shock propagates, charged particles are accelerated and the stochastic magnetic field is amplified. The internal energy of the shocked medium is shared by magnetic fields and electrons with fractions ϵ_B and $\epsilon_e \sim \sqrt{\epsilon_B}$ (Medvedev 2006), respectively. The accelerated electrons are further assumed to be distributed as $n_{\gamma'} \propto \gamma'^{-p}$ (for $\gamma'_m \leq \gamma' \leq \gamma'_M$) with minimum and maximum electron Lorentz factors $\gamma'_m = \epsilon_e \frac{m_{\text{p}}(p-2)}{m_e(p-1)}(\Gamma - 1)$ and $\gamma'_M \sim q_e B' r/(m_e c^2)$ respectively, where the prime denotes that the quantities are measured in the comoving frame. The magnetic field strength B' can be calculated using the parameter ϵ_B. By considering the radiative cooling of the electrons and introducing a cooling Lorentz factor $\gamma'_c = 6\pi m_e c/(\sigma_{\text{T}} B'^2 \Gamma t)$, where σ_{T} is the Thomson cross section, a quasi-steady electron distribution can be written as (Huang et al. 2000)

$$n_{\gamma'} = \frac{n'_e}{\gamma'_l} \begin{cases} \left(\frac{\gamma'}{\gamma'_l}\right)^{-x}, & \gamma'_l \leq \gamma' \leq \gamma'_h, \\ \left(\frac{\gamma'_h}{\gamma'_l}\right)^{-x}\left(\frac{\gamma'}{\gamma'_h}\right)^{-p-1}, & \gamma'_h < \gamma' \leq \gamma'_M. \end{cases} \tag{6}$$

For $\gamma'_c > \gamma'_m$ (slow cooling), we have $x = p$, $\gamma'_l = \gamma'_m$ and $\gamma'_h = \gamma'_c$, whereas $x = 2$, $\gamma'_l = \gamma'_c$ and $\gamma'_h = \gamma'_m$ for $\gamma'_m > \gamma'_c$ (fast cooling). The comoving synchrotron emission coefficient at frequency ν' can be given by (Rybicki & Lightman 1979)

$$j'_{\nu'} = \frac{1}{4\pi} \frac{\sqrt{3} q_e^3 B'}{m_e c^2} \int_{\gamma'_l}^{\gamma'_M} n'_{\gamma'} \left[\frac{\nu'}{\nu'_0} \int_{\frac{\nu'}{\nu'_0}}^{\infty} K_{5/3}(t) dt\right] d\gamma', \tag{7}$$

where $\nu'_0 = 3 q_e B' \gamma'^2/(4\pi m_e c)$ and $K_{5/3}(t)$ is the Bessel function. Then the synchrotron flux density received by the observers can be calculated as

$$F_\nu(t) = \frac{(1+z)}{d_{\text{L}}^2} \int_0^{\theta_j} \frac{j'_{\nu'} V'}{\Gamma^3 (1 - \beta \cos \theta)^3} \frac{\sin \theta}{2} \cos \theta d\theta, \tag{8}$$

where $\nu = \nu'/[\Gamma(1 - \beta \cos \theta)]$ is the observational frequency, d_{L} is the luminosity distance of the GRB and V' is the comoving volume of the emission region. Additionally, the effect of the equal arrival time surface has also been taken into account in our calculation.

3 NUMERICAL RESULTS

We use the model described above to reproduce the light curve of the X-ray afterglow of GRB 050712. A comparison between the numerical result and the observational data is presented in
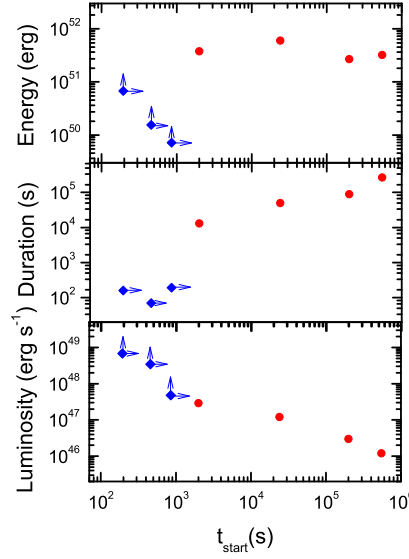
Fig. 2 The energy (*top*), duration (*middle*) and luminosity (*bottom*) of the energy releases by the central engine during three flares (*diamonds*) and the four plateaus (*circles*).

Figure 1. As shown, the unusual tiered X-ray light curve requires four independent energy injections into the external shock. The reduced chi-square χ^2/ν of the fitting is 1.253. The model parameters are taken as follows:

(1) GRB ejecta parameters: the initial isotropic-equivalent kinetic energy $E_0 = 2.5 \times 10^{51}$ erg, the initial Lorentz factor $\Gamma_0 = 125$ and the half opening angle $\theta_j = 0.1$;
(2) Microphysical parameters: $\epsilon_B = 0.04$, $\epsilon_e = 0.2$ and $p = 2.3$;
(3) The parameter describing the wind: $A = 3 \times 10^{35}$, where a wind-like condition is taken because too high of a value for p is required in the ISM case, which is inconsistent with the observed spectral index;
(4) Energy injection parameters: as listed in Table 1, where $q = 0$ is adopted in all of the four injections;
(5) Redshift: $z = 1$, where the average value of the Swift GRBs is taken because there is no redshift measurement for GRB 050712.

It should be noted that the goodness of fit here is only judged by eye, but not by a precise statistical criterion, as has usually been done in GRB afterglow modelings, so the error bars of the parameters cannot be given. This is because too many parameters are involved and a more precise fitting is actually not more informative. In any case, the main features of the light curve have been captured by our fitting. Additionally, three early flares are fitted by a function defined by Norris as

$$f(t) = C \exp\left[-\tau_1/(t - t_0) - (t - t_0)/\tau_2 \right],$$

where C is the intensity, t_0 is the beginning time, and τ_1 and τ_2 are the rise and decay timescales, respectively (Norris et al. 2005). The obtained luminosity and integrated energy of the flares can be regarded as a lower limit because the emission efficiencies of the flares are unknown.

The three early flares and the following four energy injections indicate that the central engine of GRB 050712 released energy at least seven times after the burst. The energy, duration and luminosity of these energy releases are displayed in Figure 2, where the energy and luminosity during the flares are represented. Swenson & Roming (2013) gave the lower limit of the start time for the flares in GRB 050712. As can be seen, the injection of energy at different times is comparable to each other on the order of magnitude of 3×10^{51} erg. The duration ($t_{\mathrm{end},i} - t_{\mathrm{start},i}$) of the energy released increases with time and thus the luminosity(Q_i) declines. These features could have important implications for the properties of the central engine.

4 SUMMARY AND DISCUSSION

GRB 050712 is one of the most interesting GRBs detected by *Swift*, whose X-ray afterglow has four apparent shallow decay plateaus. In this paper, we numerically calculated the dynamical evolution and the radiation of the GRB external shock with multiple energy injections. The model can explain the light curve of the X-ray afterglow for GRB 050712 well, which indicates that the central engine of GRB 050712 released energy at least seven intermittent times after the burst, and the first three directly produced X-ray flares via internal dissipation and the latter four resulted in four plateaus by injecting energy into the external shock. The energies released during these four plateaus are similar, but the luminosity decreased significantly with increasing duration. Because of the close connection between the energy injections and the late activities of the central engine, our result demonstrates that the GRBs with multiple energy injections can be used to explore the properties of the GRB central engine. At least, our result indicates that the GRB central engine can last much longer than previously thought, which is related to the topic of t_{burst} discussed in Zhang et al. (2013). In addition, such a multiple energy injection model may also have further implications for supernovae powered by a central object (Kasen & Bildsten 2010) and mergernovae (Yu et al. 2013).

For a single or a few plateaus, the plateau emission can in principle be ascribed to a reverse shock propagating into the slow tail of GRB ejecta (e.g., Uhm et al. 2012; Gao et al. 2013). The tiered X-ray afterglow of GRB 050712 presented here unambiguously breaks the degeneracy between the reverse shock model and the energy injection model. Nevertheless, in this paper, we simply assumed that the released energy is completely injected into the GRB external shock. The energy released from the central engine is probably initially in the form of Poynting flux, which could be accelerated and thermalized before it catches up with the GRB's external shock. Therefore, the internal dissipation of the energy flow could directly produces some afterglow emission such as the so-called internal-origin afterglow (Yu et al. 2010; Zhang 2013). The internal dissipation may arise from turbulent magnetic reconnection (Zhang & Yan 2011) or from the termination shock of the injected flow arising from the collision between the injected flow and the GRB ejecta (Dai 2004; Yu & Dai 2007; Yu et al. 2007; Mao et al. 2010; Dai & Liu 2012).

References

Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433

Chevalier, R. A., & Li, Z.-Y. 2000, ApJ, 536, 195

Dai, Z. G. 2004, ApJ, 606, 1000

Dai, Z. G., & Liu, R.-Y. 2012, ApJ, 759, 58

Dai, Z. G., & Lu, T. 1998a, A&A, 333, L87

Dai, Z. G., & Lu, T. 1998b, Physical Review Letters, 81, 4301

Dai, Z. G., & Lu, T. 1998c, MNRAS, 298, 87

Falcone, A. D., Morris, D., Racusin, J., et al. 2007, ApJ, 671, 1921

Fan, Y. Z., & Wei, D. M. 2005, MNRAS, 364, L42

Fan, Y.-Z., & Xu, D. 2006, MNRAS, 372, L19

Gao, H., Lei, W.-H., Zou, Y.-C., Wu, X.-F., & Zhang, B. 2013, New Astron. Rev., 57, 141

Gehrels, N., Ramirez-Ruiz, E., & Fox, D. B. 2009, ARA&A, 47, 567

Geng, J. J., Wu, X. F., Huang, Y. F., & Yu, Y. B. 2013, ApJ, 779, 28

Granot, J., & Kumar, P. 2006, MNRAS, 366, L13

Grupe, D., Nousek, J. A., Veres, P., Zhang, B.-B., & Gehrels, N. 2013, ApJS, 209, 20

Huang, Y. F., Dai, Z. G., & Lu, T. 1999, MNRAS, 309, 513

Huang, Y. F., Gou, L. J., Dai, Z. G., & Lu, T. 2000, ApJ, 543, 90

Kasen, D., & Bildsten, L. 2010, ApJ, 717, 245

Liang, E.-W., Zhang, B.-B., & Zhang, B. 2007, ApJ, 670, 565

Liang, E.-W., Racusin, J. L., Zhang, B., Zhang, B.-B., & Burrows, D. N. 2008, ApJ, 675, 528

MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262

Mao, Z., Yu, Y. W., Dai, Z. G., Pi, C. M., & Zheng, X. P. 2010, A&A, 518, A27

Medvedev, M. V. 2006, ApJ, 651, L9

Meszaros, P., & Rees, M. J. 1997, ApJ, 476, 232

Norris, J. P., Bonnell, J. T., Kazanas, D., et al. 2005, ApJ, 627, 324

Nousek, J. A., Kouveliotou, C., Grupe, D., et al. 2006, ApJ, 642, 389

Racusin, J. L., Liang, E. W., Burrows, D. N., et al. 2009, ApJ, 698, 43

Rees, M. J., & Meszaros, P. 1998, ApJ, 496, L1

Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley-Interscience), 393

Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17

Sollerman, J., Fynbo, J. P. U., Gorosabel, J., et al. 2007, A&A, 466, 839

Swenson, C. A., & Roming, P. W. A. 2013, arXiv:1310.2628

Uhm, Z. L., Zhang, B., Hascoët, R., et al. 2012, ApJ, 761, 147

Woosley, S. E. 1993, ApJ, 405, 273

Yu, Y. W., & Dai, Z. G. 2007, A&A, 470, 119

Yu, Y. W., Liu, X. W., & Dai, Z. G. 2007, ApJ, 671, 637

Yu, Y. W., & Dai, Z. G. 2009, ApJ, 692, 133

Yu, Y.-W., Cheng, K. S., & Cao, X.-F. 2010, ApJ, 715, 477

Yu, Y.-W., Zhang, B., & Gao, H. 2013, ApJ, 776, L40

Zhang, B. 2007, ChJAA (Chin. J. Astron. Astrophys.), 7, 1

Zhang, B. 2013, ApJ, 763, L22

Zhang, B., & Mészáros, P. 2001, ApJ, 552, L35

Zhang, B., Fan, Y. Z., Dyks, J., et al. 2006, ApJ, 642, 354

Zhang, B.-B., Liang, E.-W., & Zhang, B. 2007, ApJ, 666, 1002

Zhang, B.-B., Zhang, B., Liang, E.-W., & Wang, X.-Y. 2009, ApJ, 690, L10

Zhang, B., & Yan, H. 2011, ApJ, 726, 90

Zhang, B.-B., Zhang, B., Murase, K., Connaughton, V., & Briggs, M. S. 2013, arXiv:1310.2540