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X-Ray Afterglows of GRBs 050318 and 060124 and their External Shock Origin *

Jin Zhang[1,4], Yi-Ping Qin[2,3], Fu-Wen Zhang[1,4] and Bin-Bin Zhang[1,4]

[1] National Astronomical Observatories / Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011; *jinzhang@ynao.ac.cn*
[2] Center for Astrophysics of Guangzhou University, Guangzhou 510006
[3] Physics Department, Guangxi University, Nanning 530004
[4] Graduate School of Chinese Academy of Sciences, Beijing 100049

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Abstract The observations with *Swift* X-ray telescope (XRT) challenge the conventional gamma-ray burst model in many aspects. The XRT light curves are generally composed of four consecutive segments, i.e., a steep decay segment, a shallow decay segment, a normal decay segment, a jet-like steep decay segment, and sometimes erratic flares as well. The physical origin of the X-ray emission is highly debatable. We focus here on the physical origin of the X-ray emissions of GRBs 050318 and 060124. We present the XRT light curves and spectra of the two bursts. The light curve decay slopes of the two bursts are normal, and their relations to the spectral indices are consistent with the prediction of the standard forward shock model. The multi-wavelength light curves at 0.5 keV, 1.0 keV, 2.0 keV and 4.0 keV can be reproduced by this model with an isotropic kinetic energy $E_{\rm k} = 2.2 \times 10^{52}$ erg, $\epsilon_{\rm e} = 0.04$, $\epsilon_B = 0.01$ for GRB 050318 and $E_{\rm k} = 4.2 \times 10^{53}$ erg, $\epsilon_{\rm e} = 0.05$, $\epsilon_B = 0.01$ for GRB 060124. These facts suggest that the normal decay phases of the X-rays for the two bursts are of the forward shock origin.

Key words: gamma-rays — bursts-individual: GRB 050318, GRB 060124

1 INTRODUCTION

The *Swift* Gamma-Ray Burst (GRB) Explorer (Gehrels et al. 2004) has revolutionized GRB observations in many aspects during its first two years of operation (Zhang 2007). The *Swift* X-ray telescope (XRT) reveals that the X-ray light curves following prompt gamma-rays are generally composed of four consecutive segments, i.e., a steep decay segment, a shallow decay segment, a normal decay segment, a jet-like steep decay segment, and sometimes erratic flares as well (Zhang et al. 2006; Panaitescu et al. 2006; O'Brien et al. 2006). It has been suggested that the first decay segment is of internal origin due to the curvature effect (Zhang et al. 2006; Liang et al. 2006a), caused by the time delay of photons radiated at higher latitudes of the fireball than the line of sight (Kumar & Panaitescu 2000; Qin et al. 2004; Shen et al. 2005), and/or due to the internal shock afterglows during the cooling of the plasma after the GRB prompt emission phase (Zhang, Liang & Zhang 2007), or due to the cooling of a hot cocoon surrounding the GRB jet (Pe'er et al. 2006).

The physical origin of the shallow decay phase is hotly debated. Various models, such as energy injection (Rees & Mészáros 1998; Dai & Lu 1998a,b; Zhang & Mészáros et al. 2001; Granot & Kumar 2006), two-component jet (Granot et al. 2006; Jin et al. 2007; Panaitescu et al. 2006), delayed energy transferring

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to the forward shock (Kobayashi & Zhang 2007) and scattering by dust (Shao & Dai 2007) have been proposed (see more details in recent review by Zhang (2007) and references therein). Most recently, Ghisellini et al. (2007) suggested that the shallow decay segment is produced by the late internal shocks, and Troja et al. (2007) argued that the shallow decay component of GRB 070110 may be of internal origin. However, a comprehensive analysis with a large sample of the XRT data for this segment shows that this segment is generally consistent with the scenario of refreshed shocks by the long lasting energy injection for most the *Swift* GRBs (Liang et al. 2007). Generally, the normal decay component and the following jet-like steep decay segment are believed to be explained by the standard external forward shock model (Rees & Mészáros 1994; Paczyński & Rhoads 1993; Mészáros & Rees 1997; Cheng & Lu 2001; Mészáros 2002; Zhang & Mészáros 2004; Piran 2005) and the jet model (Rhoads 1997; Sari et al. 1999). The erratic flares are thought to be produced by the late internal shocks (Zhang et al. 2006; Liang et al. 2006a; Wu et al. 2006; Zou et al. 2006) due to the late central engine activities (Burrows et al. 2005; Dai et al. 2006; King et al. 2005; Fan & Wei 2005; Perna et al. 2006; Proga & Zhang 2006; Gao & Fan 2006).

In this paper, we focus on the normal decay segments of GRBs 050318 and 060124. Ghisellini et al. (2007) suggested that the shallow decay segment is produced by the late internal shocks and the break between the shallow decay segment and the normal decay segment is due to the jet opening angle being smaller than the inverse of the bulk Lorentz factor. In this scenario, the normal decay segment should be also of internal origin. We examine whether the typical normal decay segments observed in the two GRBs are consistent with the expectations of the standard external shock model. The details of the observations of the two bursts have been presented by Perri et al. (2005) and Romano et al. (2006). We re-present the XRT light curves and spectra of the two bursts from the XRT data, and examine the close correlation between the spectral index and the light curve decay slope predicted by the standard forward shock model (Sect. 2). The XRT light curve decay slopes of the two bursts are normal, and their relation to the spectral indices are well consistent with the prediction of the standard forward shock model. Using the XRT data we extract multi-wavelength light curves at 0.5 keV, 1.0 keV, 2.0 keV and 4.0 keV, and examine if these light curves can be produced by this model (Sect. 3). Discussion and conclusions are presented in Section 4.

2 XRT DATA REDUCTION

The XRT data of GRB 050318 began to be recorded with the *Swift*/XRT on 2005 March 18 at 16:39:11 UT. The data reduction is conducted with the standard XRT tools. The details of the data reduction and corrections are given in Liang et al. (2006b) and Zhang, Liang & Zhang (2007). The source region is taken to be a circle of 30-pixel radius, and the background is selected from a nearby source-free circular region of 30-pixel radius. We extract the light curve and the spectrum observed between ~ 3400 s to ~ 18000 s since the GRB trigger time, which corresponds to the normal decay phase with a temporal decay slope $\alpha = 1.12 \pm 0.06$. We fit the spectrum with an absorbed power law model ($f_\nu \propto \nu^{-\Gamma}$) and obtain $\Gamma = 2.01^{+0.07}_{-0.06}$ with reduced $\chi^2 = 1.01$ for 58 degrees of freedom (d.o.f.). These results are consistent with that reported by Perri et al. (2005) within the errors.

The *Swift*/XRT began to observe the X-ray afterglow of GRB 060124 on 2006 January 24 at 15:56:36 UT, 104 s after the trigger time. We focus on the normal decay phase from $\sim 1.1 \times 10^4$ s to $\sim 1.0 \times 10^5$ s after the trigger, which spans two observation sequences labelled 001 and 002. During 001 the PC mode data are affected by the pile-up effect. Considering this effect, the source data are extracted in an annulus with a 35-pixel outer radius and a 3-pixel inner radius. The source data of observation sequence 002 are extracted within a circle of 30-pixel radius. The backgrounds are selected nearby source-free regions with the same size as the source regions for the sequences 001 and 002. We fit the spectra with an absorbed power law model, which yields $\Gamma = 2.12 \pm 0.05$ with reduced $\chi^2 = 1.22$ (61 d.o.f) for sequence 001 and $\Gamma = 2.05 \pm 0.05$ with reduced $\chi^2 = 0.91$ (89 d.o.f.) for sequence 002. We find that the spectra of the two sequences are mutually consistent. The light curve is well fitted with a simple power law with decay slope $\alpha = 1.36 \pm 0.05$. These results agree with that presented by Romano et al. (2006).

The XRT effective energy band is 0.2–10 keV. We present semi multi-wavelength light curves to test the forward shock model, although this energy band is not broad enough to constrain the model parameters. We extracted four monochromatic light curves at 0.5 keV, 1 keV, 2 keV and 4 keV for the two X-ray afterglows (see Figs. 1 and 2).

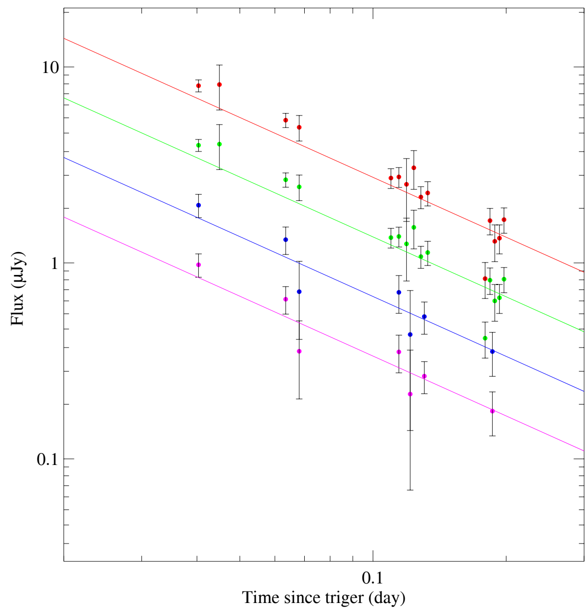

Fig. 1 XRT 0.5 keV, 1 keV, 2 keV and 4 keV light curves (from the top to the bottom) of the afterglow of GRB 050318.

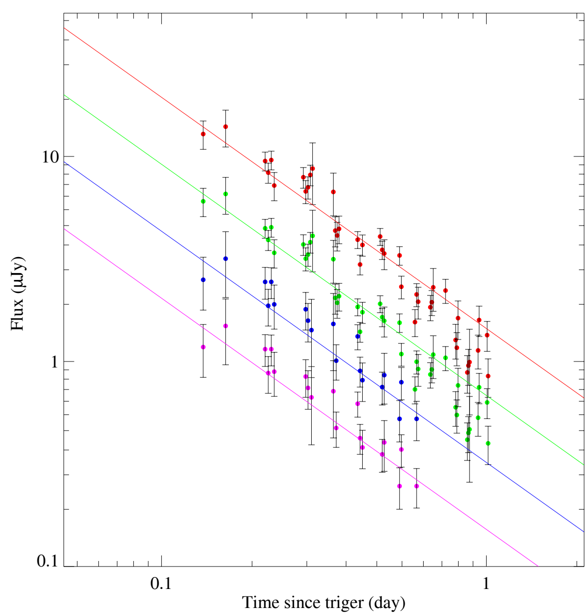

Fig. 2 XRT 0.5 keV, 1 keV, 2 keV and 4 keV light curves of the afterglow of GRB 060124. The symbols are the same as in Fig. 1.

3 EXAMINATION OF THE STANDARD FORWARD SHOCK MODEL

We adopt the parameterized forward shock model described by Sari et al. (1998), which reads,

$$F_\nu = \begin{cases} (\nu/\nu_c)^{1/3} F_{\nu,\max}, & \nu_c > \nu, \\ (\nu/\nu_c)^{-1/2} F_{\nu,\max}, & \nu_m > \nu > \nu_c, \\ (\nu_m/\nu_c)^{-1/2} (\nu/\nu_m)^{-p/2} F_{\nu,\max}, & \nu > \nu_m, \end{cases} \tag{1}$$

for the observed flux density in case of fast cooling and

$$F_\nu = \begin{cases} (\nu/\nu_m)^{1/3} F_{\nu,\max}, & \nu_m > \nu, \\ (\nu/\nu_m)^{-(p-1)/2} F_{\nu,\max}, & \nu_c > \nu > \nu_m, \\ (\nu_c/\nu_m)^{-(p-1)/2} (\nu/\nu_c)^{-p/2} F_{\nu,\max}, & \nu > \nu_c, \end{cases} \tag{2}$$

for the case of slow cooling. For an adiabatic evolution,

$$\nu_c = 2.7 \times 10^{12} \epsilon_B^{-3/2} E_{52}^{-1/2} n^{-1} t_{\rm d}^{-1/2} \ {\rm Hz}, \tag{3}$$

$$\nu_m = 5.7 \times 10^{14} \epsilon_B^{1/2} \epsilon_{\rm e}^2 E_{52}^{1/2} t_{\rm d}^{-3/2} \ {\rm Hz}, \tag{4}$$

$$F_{\nu,\max} = 1.1 \times 10^5 \epsilon_B^{1/2} E_{52} n^{1/2} D_{28}^{-2} \ \mu{\rm Jy}, \tag{5}$$

where $t_{\rm d}$ is the observed time in days, and D_{28} is the luminosity distance, p is the power-law index of electron distribution, and $\epsilon_{\rm e}$ and ϵ_B are the energy partitions of the electrons and the magnetic field, respectively. Numerical suffix n means the suffixed quantity is in 10^n cgs units. With these equations, one can obtain various correlations between the spectral index and the slopes in different spectral regimes (see Zhang & Mészáros 2004, table 1). For GRB 050318, $\alpha = 1.12 \pm 0.06$ and $\beta = 1.01^{+0.07}_{-0.06}$, they are well consistent with $\alpha = (3\beta - 1)/2$, indicating $\nu > \max(\nu_m, \nu_c)$ and $p = 2\beta = 2.02$ in the framework of this model. For GRB 060124, $\beta = 1.08$ (the average spectral index in the two sequences) and $\alpha = 1.36 \pm 0.05$, they also agree with $\alpha = (3\beta - 1)/2$, suggesting the normal decay phase of GRB 060124 is also in the spectral regime $\nu > \max(\nu_m, \nu_c)$ and $p = 2\beta = 2.16$.

According to our analysis above we reproduce the multi-wavelength light curves within the XRT band. The isotropic gamma-ray energies are $E_{\rm iso} = 2.2 \times 10^{52}$ erg (Perri et al. 2005) and $E_{\rm iso} = 4.2 \times 10^{53}$ erg (Romano et al. 2006) for GRB 050318 and GRB 060124, respectively. As reported by Zhang et al. (2007) with the *Swift* early XRT data for a large sample of *Swift* GRBs, the GRB efficiency ranges from a few percent to almost 100 percent. So we roughly take the GRB efficiency to be 50%. This suggests $E_{\rm k} = E_{\rm iso}$. We take $n = 1\,{\rm cm}^{-3}$, and then we leave both $\epsilon_{\rm e}$ and ϵ_B as free parameters and derive them from fitting the multi-wavelength light curves. The best fits yield $\epsilon_{\rm e} = 0.04$, $\epsilon_B = 0.01$ with reduced $\chi^2 = 1.62$ (42 d.o.f) for GRB 050318, and $\epsilon_{\rm e} = 0.05$, $\epsilon_B = 0.01$ with $\chi^2 = 2.26$ (116 d.o.f) for GRB 060124. The fitting curves are also shown in Figures 1 and 2. Both $\epsilon_{\rm e}$ and ϵ_B are roughly consistent with that derived from the multiple wavelength afterglow fittings (Panaitescu et al. 2001) and from the spectral energy properties (Liang et al. 2004; Wu et al. 2004). These results suggest that the observed XRT light curves can be explained by the conventional forward shock model with typical parameters.

4 DISCUSSION AND CONCLUSIONS

We have presented the XRT light curves and the spectra in the normal decay phases for GRBs 050318 and 060124. We examine whether or not the X-rays can be explained with the standard forward shock model. We find that the relations between the temporal decay slopes and the spectral indices are well consistent with the prediction of the standard forward shock model, and the multi-wavelength light curves at 0.5 keV, 1.0 keV, 2.0 keV and 4.0 keV are well reproduced by this model with an isotropic kinetic energy $E_{\rm k} = 2.2 \times 10^{52}$ erg, $\epsilon_{\rm e} = 0.04$, $\epsilon_B = 0.01$ for GRB 050318 and $E_{\rm k} = 4.2 \times 10^{53}$ erg, $\epsilon_{\rm e} = 0.05$, $\epsilon_B = 0.01$ for GRB 060124. These facts suggest that the normal decay phases of the X-rays for the two bursts originate in the forward shock.

The physical origin of the X-rays observed by *Swift*/XRT is hotly debated. Ghisellini et al. (2007) suggested that the shallow decay segment is produced by the late internal shocks and the normal decay segment is due to the jet effect. This scenario is completely different from the external shock model which suggests different physical origins for the X-ray and the optical afterglows. We show here that the normal decay phases of GRBs 050318 and 060124 are of the external shock origin.

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