ON THE LATE-TIME SPECTRAL SOFTENING FOUND IN X-RAY AFTERGLOWS OF GAMMA-RAY BURSTS

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ABSTRACT

Strong spectral softening has been revealed in the late X-ray afterglows of some gamma-ray bursts (GRBs). The scenario of X-ray scattering around the circumburst dusty medium has been greatly extended, especially in the X-ray wavelength. The overall light curves of X-ray afterglows have been revealed to be somewhat puzzling with diverse physical origins (e.g., Nousek et al. 2006; Zhang et al. 2006; Liang et al. 2007) especially when the optical afterglow is also taken into account (Panaiteescu et al. 2006; Liang et al. 2008). In general, the observed multiwavelength afterglows have been found consistent with the external forward shock models (e.g., Piran 2004; Mészáros 2006 for reviews). In contrast to the remarkable variations of the X-ray light curves, most spectra of X-ray afterglows show little variation (Butler & Kocevski 2007; Evans et al. 2009; Shao et al. 2010), which is consistent with the prediction of standard external forward shock models.

The first explicitly reported spectral variation was in the X-ray afterglow of an unusual X-ray flash, XRF 060218 (e.g., Fan et al. 2006; Soderberg et al. 2006; Butler 2007). Later an optically dark burst, GRB 090417B, showed significant softening after ~2 × 10^4 s since the burst trigger (Holland et al. 2010). Very recently a similar spectral softening was also reported in GRB 130925A (Evans et al. 2014; Zhao & Shao 2014). The X-ray afterglow of GRB 090417B and 130925A are both found to be consistent with the previously proposed X-ray scattering scenario regarding their light curves and spectra (Shao & Dai 2007; Shao et al. 2008). As pointed out by Evans et al. (2014), this spectral behavior has also been detected in several other bursts. In the literature, GRB 100316D has also showed the presence of very soft X-ray emission similar to that of XRF 060218 (Margutti et al. 2013).

In this paper we report on a sample of 12 bursts that showed a significant spectral softening at a late time since the burst trigger that were well-observed by the X-Ray Telescope (XRT) aboard Swift. We will show that the radiative features regarding their light curves and spectral evolution are very consistent with the X-ray scattering scenario. We will make an effort to study their time-resolved spectra by focusing on the radiative feature of this spectral softening. Our burst sample and data analysis is described in Section 2. The X-ray light curves and spectral evolution of these bursts are analyzed with the scattering model in Section 3. The time-resolved spectra are further analyzed and reproduced by the scattering model in Section 4. Discussions and the conclusion are given in Section 5.

1. INTRODUCTION

Thanks to the Swift satellite (Gehrels et al. 2004), which has been in service for over 10 years, our knowledge on gamma-ray bursts (GRBs) has been greatly extended, especially in the X-ray wavelength. The overall light curves of X-ray afterglows have been revealed to be somewhat puzzling with diverse physical origins (e.g., Nousek et al. 2006; Zhang et al. 2006; Liang et al. 2007) especially when the optical afterglow is also taken into account (Panaiteescu et al. 2006; Liang et al. 2008). In general, the observed multiwavelength afterglows have been found consistent with the external forward shock models (e.g., Piran 2004; Mészáros 2006 for reviews). In contrast to the remarkable variations of the X-ray light curves, most spectra of X-ray afterglows show little variation (Butler & Kocevski 2007; Evans et al. 2009; Shao et al. 2010), which is consistent with the prediction of standard external forward shock models.

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In this paper we report on a sample of 12 bursts that showed a significant spectral softening at a late time since the burst trigger that were well-observed by the X-Ray Telescope (XRT) aboard Swift. We will show that the radiative features regarding their light curves and spectral evolution are very consistent with the X-ray scattering scenario. We will make an effort to study their time-resolved spectra by focusing on the radiative feature of this spectral softening. Our burst sample and data analysis is described in Section 2. The X-ray light curves and spectral evolution of these bursts are analyzed with the scattering model in Section 3. The time-resolved spectra are further analyzed and reproduced by the scattering model in Section 4. Discussions and the conclusion are given in Section 5.

2. SAMPLE SELECTION AND DATA ANALYSIS

To select the bursts that show significant spectral evolution in the X-ray afterglow we made use of the Burst Analyzer data6 from the UK Swift Science Data Centre (Evans et al. 2010). To study the spectral details of late-time afterglow, the bursts we chose needed to last long enough and be bright enough to make time-sliced spectra. To satisfy this, the sample was selected and handled as follows.

First we checked the results of the Burst Analyzer displayed on the Swift UK site to find the evidence for late-time spectral evolution, i.e., the detectable changes of hardness ratios after 10^3 s (when most of the early X-ray flares have faded away). As a result we found 28 bursts to have this kind of behavior up to 2013 October which all showed hard-to-soft spectral evolution.

Next we used the server of the Swift UK site to extract a series of time-sliced spectra after 10^3 s (considered a late epoch in this work) for these 28 bursts. We adopted the scheme for slicing time bins introduced by Zhang et al. (2007). In most of the cases we wanted the time intervals of each burst to be equal in the logarithmic scale. For instance, the first time interval starts at 10,000 s and ends at 20,000 s. Then the spans of the following intervals form a geometric progression of

http://www.swift.ac.uk/burst_analyser/
\( \Delta T_i = 2^{-1} \Delta T_0 \) for each burst, where \( \Delta T_i \) is the span for time interval \( i \) and \( \Delta T_0 = 10,000 \) s. To perform reliable spectral fitting the total counts in each time interval should be greater than 100. If the total counts in one time interval were less than 100, we combined that interval with the next. We also extracted the time intervals of 100–10,000 s (considered early epoch) for each burst in the similar way.

The XSPEC ver.12.8.1 (Arnaud 1996) included in HEASOFT ver.6.14 was used to fit the spectrum of each time interval. We considered a simple power-law model combined with the absorption from the host galaxy and Milky Way respectively, i.e., PHABS*PHABS*Powerlaw for the bursts with redshifts detected and PHABS*PHABS*Powerlaw for the bursts whose redshifts are unknown. The first PHABS was fixed at the Galactic value for each burst. Considering the the intrinsic absorption might not be varying a lot during the appearance of a burst, the second PHABS was left free but constant within the same burst. The power-law index was free as was the normalization. All the spectra from the same burst and same epoch (early or late) were fitted simultaneously using W-statistic in the XSPEC. As suggested in Appendix B of the XSPEC manual, W-statistic might generate an uncalled-for wrong best fit for some weak sources and binning to ensure that every bin contains at least one count that would often fix the problem. As a conservative approach, we rebinned all of the data using grppha in Science Tools to >20 counts per bin for early-epoch spectra and to >5 counts per bin for late-epoch spectra, respectively (some bursts with low count rates were rebinned to >5 and >2 counts per bin for early and late epochs, respectively). The systematic uncertainty that might be introduced by this rebinning scheme is still uncertain and the best-fit results should be taken with caution.

Our aim for this data analysis is to collect the bursts with significant late-time spectral softening after 10⁷ s. We judge the presence of significant spectral softening by comparing the first and the last spectral indices derived from the preliminary spectral fitting. The softening is considered significant if the 90% of the confidence intervals for the two spectral indices do not overlap with each other and if the later turn out to be softer than the former. As a result we found 12 bursts that could meet these criteria and obtained a total of 111 spectra as listed in Table 1. Their light curves and the spectral power-law indices in different time intervals are shown in Figure 1.

3. MODELING LIGHT CURVES AND SPECTRAL EVOLUTION

The GRB afterglows are generally considered as being radiated by the relativistic electrons accelerated in the external shocks due to relativistic GRB ejecta propagating in the circumburst medium (e.g., Piran 2004; Mészáros 2006, for reviews). To successfully interpret the seemingly very complicated afterglow light curves, it would take great effort to develop the external shock models (e.g., Li et al. 2015; Wang et al. 2015). Alternatively, for the X-ray afterglows that have shallow decay in the light curves and softening in the spectra, an X-ray scattering scenario (Shao & Dai 2007) has been proposed to nicely reproduce both the light curves and spectral evolution (Shao et al. 2008; Holland et al. 2010; Evans et al. 2014; Zhao & Shao 2014). In this scenario a severe optical extinction would also be predicted (Shen et al. 2009).

In previous works, to better fit the light curves of GRB 090417B and 130925 (Holland et al. 2010; Zhao & Shao 2014) a smaller-sized upper limit (\( a_c \sim 0.3 \mu m \)) of the dust grains typically found in interstellar medium (ISM) was suggested. But to be consistent with the evolution of spectral indices, a relatively harder initial spectral index of the prompt emission in X-ray wavelength would be required, which may indicate the self-absorbing processes taking place in the prompt emission (Holland et al. 2010). Here we further investigate these physical parameters by fitting the light curves and spectral evolution of our extended sample with the dust-scattering model.

We adopt the algorithm introduced in Zhao & Shao (2014) to calculate the radiative flux of scattered X-ray photons of circumburst dust grains which loses the Rayleigh-Gans (RG) limit to allow dust grains of a larger size to be involved. To compare the spectral evolution predicted by the model with the observational data in the literature, it is straightforward to compute the photon index predicted by the model and compare it with the observational one (Shen et al. 2009; Holland et al. 2010; Zhao & Shao 2014). For simplicity we adopt the “pseudo” spectral index as introduced in Shen et al. (2009). The “pseudo” spectral index \( \Gamma \) is determined by fitting a power-law only with the two flux densities at the two ends of the spectrum, at 0.3 and 10 keV, respectively, for Swift/XRT.

In our convention the spectral shape of prompt X-ray emission from the GRBs has the form of \( S(E) \propto E^\alpha \) as in Equation (9) of Zhao & Shao (2014). The scattered X-ray emission that we receive in the detector would have the spectral shape, i.e., flux density \( F_E(t) \) at a given time \( t \) described by Equation (8) in Zhao & Shao (2014). For completeness we write down the form of \( F_E(t) \) as

\[
F_E(t) = \int_{a_c}^{a} S(E) \frac{dN}{da} \frac{c \pi a^2}{R} \left( \frac{2 \pi E a}{hc} \right)^2 |A(\hat{\rho}, \hat{\theta})|^2 da. \tag{1}
\]

The complex amplitude function of \( A(\hat{\rho}, \hat{\theta}) \) has been introduced by van de Hulst (1957) and further addressed in Zhao & Shao (2014). For completeness we rewrite it here with a little rearrangement of the symbols as

\[
A(\hat{\rho}, \hat{\theta}) = \int_{0}^{\frac{\pi}{2}} (1 - e^{-i \hat{\rho} \sin \tau}) J_0(\hat{\theta} \cos \tau) \cos \tau \sin \tau d\tau, \tag{2}
\]

where the item \( \hat{\rho} \) is the phase shift of the photon with energy \( E \) in the dust grain with a size \( a \) as given by

\[
\hat{\rho} \simeq 3 \times \left( 1 + \frac{z}{2} \right)^{-1} \left( \frac{E}{1 \text{ keV}} \right)^{-1} \left( \frac{a}{1 \mu \text{m}} \right), \tag{3}
\]

and the item \( \hat{\theta} \) is the dimensionless scattering angle for dust grains located at the distance \( R \) from the GRB source as given by

\[
\hat{\theta} = \frac{2 \pi E a}{hc} \sqrt{\frac{2(1 + z)c}{R}}, \tag{4}
\]

where \( h \) is the Planck constant and \( c \) is the speed of light in the vacuum. The light curve would then be determined by the integral \( F(t) = \int F_E(t) dE \) in a given wavelength range, e.g., 0.3–10 keV for XRT.
| GRB   | Interval | Epoch | $\Gamma$ | Intrinsic $N_H$ | Redshift | w_statistic/bins |
|-------|----------|-------|---------|----------------|----------|------------------|
| 060105 | 0.1–0.2  | Early | 2.08 $^{+0.04}_{-0.04}$ | 0.36 $^{+0.01}_{-0.01}$ | –         | 1164.58/1123   |
|       | 0.2–0.4  |       | 1.96 $^{+0.04}_{-0.04}$ | –               | –         |                  |
|       | 0.4–0.8  |       | 1.94 $^{+0.04}_{-0.04}$ | –               | –         |                  |
|       | 0.8–1.4  |       | 1.87 $^{+0.04}_{-0.04}$ | –               | –         |                  |
|       | 4.6–7.2  |       | 1.92 $^{+0.08}_{-0.08}$ | –               | –         |                  |
|       | 10–20    | Late   | 1.83 $^{+0.12}_{-0.12}$ | 0.09 $^{+0.04}_{-0.04}$ | –         | 301.8/372       |
| 060218 | 0.1–0.2  | Early | 1.50 $^{+0.07}_{-0.07}$ | 0.26 $^{+0.01}_{-0.01}$ | 0.033     | 4703.16/2355    |
|       | 0.2–0.4  |       | 1.47 $^{+0.03}_{-0.03}$ | –               | –         |                  |
|       | 0.4–0.8  |       | 1.40 $^{+0.02}_{-0.02}$ | –               | –         |                  |
|       | 0.8–1.6  |       | 1.64 $^{+0.01}_{-0.01}$ | –               | –         |                  |
|       | 1.6–2.8  |       | 2.28 $^{+0.02}_{-0.02}$ | –               | –         |                  |
|       | 5.9–8.6  |       | 3.04 $^{+0.12}_{-0.12}$ | –               | –         |                  |
|       | 10–20    | Late   | 3.96 $^{+0.43}_{-0.38}$ | 0.51 $^{+0.10}_{-0.08}$ | –         | 293.99/265      |
|       | 20–80    |       | 4.41 $^{+0.06}_{-0.06}$ | –               | –         |                  |
|       | 80–1880  |       | 5.34 $^{+0.53}_{-0.53}$ | –               | –         |                  |
| 080207 | 0.1–0.2  | Early | 1.31 $^{+0.09}_{-0.09}$ | 1.06 $^{+0.10}_{-0.10}$ | 2.0858    | 325.45/327      |
|       | 4.7–0.4  |       | 2.61 $^{+0.20}_{-0.20}$ | –               | –         |                  |
|       | 10–0.8   | Late   | 2.31 $^{+0.22}_{-0.24}$ | 0.68 $^{+0.12}_{-0.12}$ | –         | 142.70/122      |
|       | 20–1.4   |       | 3.03 $^{+0.39}_{-0.36}$ | –               | –         |                  |
| 081221 | 0.1–0.2  | Early | 2.23 $^{+0.04}_{-0.04}$ | 3.32 $^{+0.17}_{-0.16}$ | 2.36      | 794.65/556      |
|       | 0.2–0.4  |       | 2.31 $^{+0.06}_{-0.06}$ | –               | –         |                  |
|       | 0.4–0.8  |       | 2.04 $^{+0.05}_{-0.05}$ | –               | –         |                  |
|       | 4.8–6.6  |       | 1.94 $^{+0.10}_{-0.10}$ | –               | –         |                  |
|       | 10–20    | Late   | 2.22 $^{+0.15}_{-0.14}$ | 4.97 $^{+0.64}_{-0.63}$ | –         | 289.12/281      |
|       | 20–40    |       | 2.36 $^{+0.15}_{-0.16}$ | –               | –         |                  |
|       | 40–80    |       | 2.58 $^{+0.32}_{-0.31}$ | –               | –         |                  |
|       | 80–600   |       | 3.49 $^{+0.31}_{-0.29}$ | –               | –         |                  |
| 090201 | 3.6–10   | Early | 2.00 $^{+0.15}_{-0.15}$ | 0.47 $^{+0.08}_{-0.07}$ | –         | 59.97/54        |
|       | 10–20    | Late   | 2.02 $^{+0.15}_{-0.14}$ | 0.41 $^{+0.04}_{-0.04}$ | –         | 447.78/407      |
|       | 20–40    |       | 2.14 $^{+0.15}_{-0.15}$ | –               | –         |                  |
|       | 40–80    |       | 2.39 $^{+0.17}_{-0.17}$ | –               | –         |                  |
|       | 80–160   |       | 2.65 $^{+0.25}_{-0.24}$ | –               | –         |                  |
|       | 160–320  |       | 2.95 $^{+0.36}_{-0.34}$ | –               | –         |                  |
|       | 320–885  |       | 3.36 $^{+0.50}_{-0.47}$ | –               | –         |                  |
| 090404 | 0.1–0.2  | Early | 2.90 $^{+0.07}_{-0.07}$ | 0.35 $^{+0.02}_{-0.02}$ | –         | 652.57/347      |
|       | 0.2–0.8  |       | 2.75 $^{+0.05}_{-0.04}$ | –               | –         |                  |
|       | 0.8–1.25 |       | 2.69 $^{+0.04}_{-0.04}$ | –               | –         |                  |
|       | 4.5–7.1  |       | 2.42 $^{+0.15}_{-0.16}$ | –               | –         |                  |
|       | 10–20    | Late   | 2.54 $^{+0.19}_{-0.18}$ | 0.41 $^{+0.05}_{-0.05}$ | –         | 290.26/280      |
|       | 20–40    |       | 2.43 $^{+0.20}_{-0.20}$ | –               | –         |                  |
|       | 40–80    |       | 2.94 $^{+0.29}_{-0.28}$ | –               | –         |                  |
|       | 80–160   |       | 3.20 $^{+0.31}_{-0.30}$ | –               | –         |                  |
|       | 160–320  |       | 3.67 $^{+0.39}_{-0.38}$ | –               | –         |                  |
|       | 320–2000 |       | 4.05 $^{+0.44}_{-0.46}$ | –               | –         |                  |
| 100621 | 0.1–0.2  | Early | 2.75 $^{+0.06}_{-0.06}$ | 1.74 $^{+0.08}_{-0.07}$ | 0.542     | 938.77/638      |
|       | 0.2–0.4  |       | 2.53 $^{+0.09}_{-0.09}$ | –               | –         |                  |
|       | 0.4–0.8  |       | 1.75 $^{+0.19}_{-0.18}$ | –               | –         |                  |
|       | 0.8–2.35 |       | 2.06 $^{+0.15}_{-0.15}$ | –               | –         |                  |
|       | 5.66–8.13|       | 2.01 $^{+0.15}_{-0.15}$ | –               | –         |                  |
|       | 10–20    | Late   | 2.17 $^{+0.16}_{-0.16}$ | 1.85 $^{+0.19}_{-0.18}$ | –         | 453.51/457      |
|       | 20–40    |       | 2.61 $^{+0.17}_{-0.16}$ | –               | –         |                  |
|       | 40–80    |       | 2.59 $^{+0.17}_{-0.16}$ | –               | –         |                  |
|       | 80–160   |       | 2.78 $^{+0.26}_{-0.25}$ | –               | –         |                  |
|       | 160–320  |       | 3.26 $^{+0.38}_{-0.38}$ | –               | –         |                  |
|       | 320–2000 |       | 3.38 $^{+0.34}_{-0.34}$ | –               | –         |                  |
Table 1
(Continued)

| GRB   | Interval$^a$ | Epoch | $\Gamma$ | Intrinsic $N_H$$^b$ | Redshift | $w_{\text{statistic}}$/bins |
|-------|--------------|-------|----------|---------------------|----------|-----------------------------|
| 110709| 0.1–0.2      | Early | 2.23$^{+0.11}_{-0.12}$ | 0.74$^{+0.03}_{-0.05}$ | --       | 587.44/543 |
|       | 0.2–0.4      |       | 2.19$^{+0.11}_{-0.11}$ | --         | --       | --                          |
|       | 0.4–0.635    |       | 2.04$^{+0.12}_{-0.11}$ | --         | --       | --                          |
|       | 0.635–1      |       | 1.84$^{+0.17}_{-0.17}$ | --         | --       | --                          |
|       | 1–2          |       | 1.93$^{+0.13}_{-0.13}$ | --         | --       | --                          |
|       | 5.15–7.77    |       | 2.09$^{+0.12}_{-0.12}$ | --         | --       | --                          |
|       | 10–20        | Late  | 2.35$^{+0.23}_{-0.22}$ | 0.74$^{+0.11}_{-0.12}$ | --       | 114.64/125 |
|       | 80–300       |       | 4.23$^{+0.09}_{-0.08}$ | --         | --       | --                          |
| 111209| 0.425–0.8    | Early | 1.06$^{+0.02}_{-0.02}$ | 0.19$^{+0.01}_{-0.01}$ | 0.677    | 2859.51/2514 |
|       | 0.8–1.6      |       | 1.20$^{+0.01}_{-0.01}$ | --         | --       | --                          |
|       | 1.6–2.07     |       | 1.12$^{+0.01}_{-0.01}$ | --         | --       | --                          |
|       | 5.23–7.84    |       | 1.45$^{+0.01}_{-0.01}$ | --         | --       | --                          |
|       | 10–20        | Late  | 1.56$^{+0.02}_{-0.02}$ | 0.17$^{+0.01}_{-0.01}$ | --       | 1241.41/1300 |
|       | 20–40        |       | 1.68$^{+0.05}_{-0.05}$ | --         | --       | --                          |
|       | 40–80        |       | 2.00$^{+0.12}_{-0.12}$ | --         | --       | --                          |
|       | 80–160       |       | 2.31$^{+0.12}_{-0.12}$ | --         | --       | --                          |
|       | 160–320      |       | 2.46$^{+0.21}_{-0.20}$ | --         | --       | --                          |
|       | 320–2560     |       | 2.75$^{+0.21}_{-0.21}$ | --         | --       | --                          |
| 120308| 0.1–0.2      | Early | 2.80$^{+0.08}_{-0.08}$ | 0.10$^{+0.01}_{-0.01}$ | --       | 581.95/462 |
|       | 0.2–0.285    |       | 3.89$^{+0.16}_{-0.15}$ | --         | --       | --                          |
|       | 0.285–0.8    |       | 2.12$^{+0.15}_{-0.15}$ | --         | --       | --                          |
|       | 0.8–1.6      |       | 1.75$^{+0.13}_{-0.13}$ | --         | --       | --                          |
|       | 1.6–2.45     |       | 1.79$^{+0.13}_{-0.13}$ | --         | --       | --                          |
|       | 5.84–10      |       | 1.76$^{+0.12}_{-0.12}$ | --         | --       | --                          |
|       | 10–20        | Late  | 1.66$^{+0.19}_{-0.18}$ | 0.08$^{+0.05}_{-0.04}$ | --       | 145.08/133 |
|       | 20–40        |       | 1.93$^{+0.25}_{-0.24}$ | --         | --       | --                          |
|       | 40–300       |       | 2.25$^{+0.40}_{-0.38}$ | --         | --       | --                          |
| 130907| 0.1–0.2      | Early | 1.58$^{+0.04}_{-0.04}$ | 0.71$^{+0.02}_{-0.02}$ | 1.238    | 2558.14/1845 |
|       | 0.2–0.4      |       | 1.39$^{+0.02}_{-0.02}$ | --         | --       | --                          |
|       | 0.4–0.8      |       | 1.59$^{+0.02}_{-0.02}$ | --         | --       | --                          |
|       | 0.8–1.74     |       | 1.62$^{+0.01}_{-0.01}$ | --         | --       | --                          |
|       | 7.63–7.89    |       | 1.72$^{+0.14}_{-0.14}$ | --         | --       | --                          |
|       | 10–20        | Late  | 1.72$^{+0.06}_{-0.06}$ | 0.71$^{+0.06}_{-0.06}$ | --       | 1099.01/1121 |
|       | 20–40        |       | 1.79$^{+0.06}_{-0.06}$ | --         | --       | --                          |
|       | 40–80        |       | 1.88$^{+0.07}_{-0.07}$ | --         | --       | --                          |
|       | 80–160       |       | 2.08$^{+0.08}_{-0.08}$ | --         | --       | --                          |
|       | 160–320      |       | 2.55$^{+0.21}_{-0.20}$ | --         | --       | --                          |
|       | 320–640      |       | 2.66$^{+0.23}_{-0.23}$ | --         | --       | --                          |
|       | 640–2560     |       | 3.45$^{+0.27}_{-0.31}$ | --         | --       | --                          |
| 130925| 0.1–0.2      | Early | 1.89$^{+0.05}_{-0.05}$ | 1.73$^{+0.03}_{-0.03}$ | 0.347    | 3773.76/2879 |
|       | 0.2–0.4      |       | 1.79$^{+0.03}_{-0.03}$ | --         | --       | --                          |
|       | 0.4–0.8      |       | 1.77$^{+0.03}_{-0.03}$ | --         | --       | --                          |
|       | 0.8–1.5      |       | 1.76$^{+0.02}_{-0.02}$ | --         | --       | --                          |
|       | 4.75–5.5     |       | 1.98$^{+0.02}_{-0.02}$ | --         | --       | --                          |
|       | 6.68–7.27    |       | 1.59$^{+0.02}_{-0.02}$ | --         | --       | --                          |
|       | 10–20        | Late  | 2.53$^{+0.14}_{-0.14}$ | 2.07$^{+0.09}_{-0.09}$ | --       | 1200.25/1242 |
|       | 20–40        |       | 2.99$^{+0.14}_{-0.14}$ | --         | --       | --                          |
|       | 40–80        |       | 3.11$^{+0.11}_{-0.11}$ | --         | --       | --                          |
|       | 80–160       |       | 3.46$^{+0.12}_{-0.12}$ | --         | --       | --                          |
|       | 160–320      |       | 3.75$^{+0.12}_{-0.12}$ | --         | --       | --                          |
|       | 320–640      |       | 3.99$^{+0.17}_{-0.17}$ | --         | --       | --                          |
|       | 640–1280     |       | 4.33$^{+0.21}_{-0.20}$ | --         | --       | --                          |
|       | 1280–6000    |       | 3.72$^{+0.21}_{-0.21}$ | --         | --       | --                          |

Notes. All of the errors in this work indicate 90% confidence intervals.

$^a$ In the unit of 10$^3$ s since the BAT trigger.

$^b$ In the unit of 10$^{22}$ cm$^{-2}$. 


Figure 1. X-ray light curves (upper panels) and the evolution of spectral indices (lower panels) of 11 GRBs detected by Swift/XRT. The solid lines are the simultaneous best-fit results of dust-scattering model.
Figure 1. (Continued.)
As shown in Figure 1, most of the bursts\(^8\) have a significant hard-to-soft evolution almost right after \(\sim 10^4\) s. Many of them even become very soft with a change in spectral index of \(\Delta\Gamma > 2\). These features at late time violate the prediction of standard external shock models, which consider the afterglow as the synchrotron radiation by relativistic electrons accelerated in external shocks. The simultaneous fitting for the time intervals before \(10^3\) s was not successful. Most of earlier X-ray emission may come from the early “steep decay” phase of the prompt emission with strong spectra evolution due to the curvature effect (Zhang et al. 2007) or from the abnormal early X-ray flares (Chincarini et al. 2010).

As in Zhao & Shao (2014) we fit the light curves and spectral evolution simultaneously with the dust-scattering model for the data after \(\sim 10^4\) s. The best-fit model parameters are given in Table 2. Some physical parameters that would not change considerably during the fitting are given fixed values: \(a_\ast = 0.005\ \mu m\) and \(\beta = -3.5\). For the afterglows without known redshifts we assume that \(z = 1\). As an interesting result, while the location of the dusty shell appears to be quite different for these bursts, the characteristic sizes of dust grains turn out to be typical (\(\sim 0.3\ \mu m\)) as in the ISM. The only burst that has significantly larger dust grains is GRB/XRF 060218, which is a low-luminosity burst and has an association with a type-Ic supernova (e.g., Pian et al. 2006). However, there appears to be a degeneracy between the model parameters, especially between the location of the dusty shell \(R\) and the maximum radius of dust grains \(a_\ast\), as has been pointed out by Irwin & Chevalier (2015). Those authors proposed that a typical Galactic distribution of dust grain would also give a reasonably good fit to the data of GRB/XRF 060218 even though they made a small modification to the model by assuming a different source spectrum of the prompt emission.

Though most of the light curves can be well-consistent with the models, we can see that some evolution of the spectral indices are not well-reproduced. There might be a couple of issues that need to be mentioned. The first one is the difficulty in calculating these model light curves and spectral indices since multiple integrals over a series expansion are involved (Zhao & Shao 2014). In this work we have only obtained the maximum likelihood for model parameters by searching for the minimum chi-square in a manually chosen and evenly sampled parameter space instead of using a more sophisticated fitting scheme such as a Markov chain Monte Carlo (MCMC) method. Given that the model parameters also appear to have a degeneracy and the parameter space cannot be fully explored due to the fact that the process of the model evaluating is unavoidably timing-consuming, a true best fitting might be missed for some bursts. Therefore, what we have obtained here for these best-fit model parameters should be taken with caution. Nevertheless, the simultaneous fitting to both the light curve and spectral evolution is very promising and the resulting physical parameters might show valuable information about the circumburst medium. Further studies on the grain size and location of the dusty shells will provide much information on the GRB progenitors (e.g., Ramirez-Ruiz et al. 2001; Weingartner & Draine 2001). As suggested by the results of Zhao & Shao (2014), if the size distribution of dust grains around GRB can be confirmed to be as typical as in the ISM, the evaluation scheme of the original model adopting the RG approximation (Shao & Dai 2007; Shao et al. 2008) would be much simpler and a more powerful fitting scheme such as MCMC method would be helpful to constrain the model parameters.

### Table 2

| GRB        | \(a_\ast (\mu m)\) | \(R (pc)\) | \(\delta\) | Redshift |
|------------|-------------------|-------------|------------|----------|
| 060105     | 0.31              | 30          | 2.0        | ...      |
| 060218     | 0.95              | 150         | -1.0       | 0.0331   |
| 080207     | 0.33              | 20          | 1.8        | 2.0858   |
| 081221     | 0.28              | 200         | 0.0         | 2.26     |
| 090201     | 0.29              | 100         | 1.4        | ...      |
| 090404     | 0.33              | 300         | 0.5        | ...      |
| 090417B\(^b\) | 0.25            | 30–80       | 2.0        | 0.345    |
| 100621     | 0.28              | 300         | 0.6        | 0.542    |
| 110709     | 0.31              | 50          | 0.6        | ...      |
| 111209     | 0.30              | 100         | 1.8        | 0.677    |
| 120308     | 0.31              | 50          | 1.9        | ...      |
| 130907     | 0.28              | 50          | 1.9        | 1.238    |
| 130925\(^c\) | 0.40            | 600         | -0.3       | 0.347    |

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\(^8\) See Zhao & Shao (2014) for the plot of GRB 130925.
Table 3
The Best-fit Parameters for Time-resolved Spectral Fitting

| GRB    | Interval | \(a_s(\mu m)\) | \(R(\text{pc})\) | Redshift | \(N_H(10^{22}\text{cm}^{-2})\) | \(\delta^b\) |
|--------|----------|---------------|----------------|----------|--------------------------------|------------|
| 060218 | 10–20    | 0.95          | 150            | 0.0331   | 0.2                            | 0          |
|        | 20–80    | ...           | ...            | ...      | ...                            | ...        |
|        | 80–1880  | ...           | ...            | ...      | ...                            | ...        |
| 081221 | 10–20    | 0.28          | 200            | 2.26     | 2.5                            | 1.6        |
|        | 20–40    | ...           | ...            | ...      | ...                            | ...        |
|        | 40–80    | ...           | ...            | ...      | ...                            | ...        |
|        | 80–600   | ...           | ...            | ...      | ...                            | ...        |
| 100621 | 10–20    | 0.28          | 300            | 0.542    | 0.7                            | 1.5        |
|        | 20–40    | ...           | ...            | ...      | ...                            | ...        |
|        | 40–80    | ...           | ...            | ...      | ...                            | ...        |
|        | 80–160   | ...           | ...            | ...      | ...                            | ...        |
|        | 160–320  | ...           | ...            | ...      | ...                            | ...        |
|        | 320–2000 | ...           | ...            | ...      | ...                            | ...        |
| 111209 | 80–160   | 0.30          | 100            | 0.677    | 0.01                           | 2.6        |
|        | 160–320  | ...           | ...            | ...      | ...                            | ...        |
|        | 320–2560 | ...           | ...            | ...      | ...                            | ...        |
| 130907 | 10–20    | 0.28          | 50             | 1.238    | 0.4                            | 2.4        |
|        | 20–40    | ...           | ...            | ...      | ...                            | ...        |
|        | 40–80    | ...           | ...            | ...      | ...                            | ...        |
|        | 80–160   | ...           | ...            | ...      | ...                            | ...        |
|        | 160–320  | ...           | ...            | ...      | ...                            | ...        |
|        | 320–640  | ...           | ...            | ...      | ...                            | ...        |
|        | 640–2560 | ...           | ...            | ...      | ...                            | ...        |
| 130925 | 20–40    | 0.30          | 1500           | 0.347    | 0.8                            | 1          |
|        | 40–80    | ...           | ...            | ...      | ...                            | ...        |
|        | 80–160   | ...           | ...            | ...      | ...                            | ...        |
|        | 160–320  | ...           | ...            | ...      | ...                            | ...        |
|        | 320–640  | ...           | ...            | ...      | ...                            | ...        |
|        | 640–1280 | ...           | ...            | ...      | ...                            | ...        |

Notes.

a Intervals for time-resolved spectral analysis with a unit of \(10^3\) s.
b Derived from time-resolved spectral fitting.

complicated problem, especially in the ISM around the vicinity of GRBs (e.g., Greiner et al. 2011; Littlejohns et al. 2015). For an approximate evaluation that makes our model self-consistent, we adopt the form

\[
\sigma(E) = \sigma_0 \left(\frac{E(1+z)}{1\text{ keV}}\right)^{-\gamma},
\]

where we have \(\sigma_0 \approx 10^{-21.5}\text{ cm}^2\) and \(\gamma \approx 2.5\) as suggested by Wilms et al. (2000) for the accumulative absorption by the ISM with a same chemical composition as in our Galaxy, and \(z\) is the redshift of the GRB source. Here only the total hydrogen column density \(N_H\) is taken as a free parameter when interpreting the absorption in observed spectra, which is very similar to selecting the parameter \(zPHABS\) for the redshifted photoelectric absorption when using XSPEC for evaluating the spectral indices as introduced above.

Since the redshift is a major parameter in determining the quantitative spectrum, especially in a narrow energy range less than two orders of magnitude, we now only interpret the time-resolved spectra of the bursts with known redshifts. This leads to seven bursts in our sample: GRB 060218 (\(z = 0.0331\); Mirabal & Halpern 2006), GRB 080207 (\(z = 2.0858\); Hjorth et al. 2012), GRB 081221 (\(z = 2.26\); Salvaterra et al. 2012), GRB 100621 (\(z = 0.542\); Milvang-Jensen et al. 2010), GRB 111209 (\(z = 0.677\); Vreeswijk et al. 2011), GRB 130907 (\(z = 1.238\); de Ugarte Postigo et al. 2013), and GRB 130925 (\(z = 0.347\); Vreeswijk et al. 2013; Sudilovsky et al. 2013). However, GRB 080207 is not considered in our spectral fitting. There are too few photons in the late-time spectra which therefore have very low signal-to-noise ratios (S/N) and would provide useless information on the model parameters. For a more convincing comparison between our model and the observational data we now focus on the six bursts as listed in Table 3 which all have well-determined time-resolved late-time spectra.

The time-resolved spectra of the six bursts are shown in Figure 2. The data access and analysis has been introduced in Section 2. For each burst with a redshift \(z\), all the spectra at different time \(t\) were fitted simultaneously according to the following formula:

\[
F_E(t; z; N_H, a_\pm, \delta, R) \propto \exp\left[-\sigma(E)N_H\right] \times \int_{a_-}^{a_+} \frac{E^2 + \delta 0.5}{R} |A(\hat{\rho}, \hat{\theta})|^2 da.
\]

In this formula the photoionization cross section \(\sigma(E)\) is given above by Equation (5). For each burst an constant coefficient at the beginning of the right-hand side of Equation (6) is assumed and taken as a free parameter. Therefore, \(t\) and \(z\) all have predetermined values for each spectrum in a given time interval. The minimum grain size \(a_-\) is not important and set as \(a_- = 0.005 \mu m\). Therefore, together with the constant coefficient the neutral hydrogen column density \(N_H\), the maximum grain size \(a_+\), the initial spectral index of prompt emission in
X-ray band δ, and the dust distance R are also taken as free parameters. The constant coefficient determines the absolute flux level of the spectra group and the other four parameters determine the relative flux level between each time-sliced spectra in the group of each burst. The best fits provided by Equation (6) for the time-resolved spectra of these bursts are shown in Figure 2 from early to late (top to bottom) by solid lines in different colors. The corresponding time intervals for these spectra and the best-fit model parameters are listed in Table 3. All the time-resolved spectra of these six bursts can be well-reproduced by the scattering model. The best-fit parameters here are in general consistent with those introduced in Section 3 based on light curves and spectral indices except that the spectral power-law index δ is slightly larger (harder) in the case of time-resolved spectral fitting. Based on the best-fit parameters we confirm that the size of circumburst dust grains tends to be as small as in the typical ISM. The distance between the central source and dusty shell is about 100 pc, which is typical for the swept-up wind bubble surrounding late massive stars (Castor et al. 1975; Ramirez-Ruiz et al. 2001; Mirabal et al. 2003).

Meanwhile, by fitting the X-ray spectra especially for the softer part, we can more directly obtain the value of $N_H$ self-consistently within the model. GRB 100621 was reported to have an intrinsic host extinction of $A_V = 3.6$ mag and an X-ray absorbing column of $N_H = 0.65 \times 10^{22}$ cm$^{-2}$ (Greiner et al. 2013). We have a similar $N_H = 0.6 \times 10^{22}$ cm$^{-2}$ based on our model-dependent fitting simultaneously to all the time-resolved spectra as in Table 3. The X-ray absorbing column of the host galaxy of GRB 130907A has been estimated as $N_H = (0.98 \pm 0.11) \times 10^{22}$ cm$^{-2}$ (Veres et al. 2015), which is close to our value of $0.4 \times 10^{22}$ cm$^{-2}$. Both bursts have suffered from significant dust extinction based on their values of $A_V$. We have not evaluated the value of $A_V$ for each burst in this work since it is more complicated and would involve more theoretical work on the dust extinction. For a pioneering work on the effect of dust extinction on optical afterglows see Lü et al. (2011). Melandri et al. (2012) classified GRB 081221 as a “dark” burst according to the slope of the spectral energy distribution between the optical and the X-ray band. The light curve of GRB 111209 is dominated by prompt, high-latitude flaring emission until around $10^5$ s after the trigger. The spectra can be fitted by the scattering model if we only focus on the X-ray afterglow after $10^5$ s, which may indicate that there is a long-lasting additional component before that.
5. CONCLUSION

In this paper we find that the late-time X-ray afterglows of the bursts in our sample appear to be overall consistent temporally and spectrally with the scattering scenario where the observed late-time X-ray emission comes from the scattering of early prompt X-ray emission off the circumburst dust grains. The information on the circumburst dusty medium can be determined by fitting the light curves and the evolution of spectral indices with the scattering model first proposed by Shao & Dai (2007) and further improved by Zhao & Shao (2014). We have not tried to constrain the model parameters with a sophisticated fitting scheme such as a MCMC method since the evaluation of the scattered emission is relatively time-consuming and not appropriate for the MCMC method. Our best-fitting results indicate that almost all of the bursts in our sample have a relatively small size distribution of dust grains as is typical in the ISM. This result is a little confusing since the grain size has been expected to be larger in the denser medium around GRBs (e.g., Weingartner & Draine 2001). Our results also indicate that the distance of the dusty shells is very close to the dense wind bubble around late massive stars such as a carbon-rich Wolf–Rayet star (e.g., Marston 1997; Chu et al. 1999).

The major features predicted by the dust-scattering model are the X-ray spectral softening and significant dust extinction in the optical (Shen et al. 2009). In our sample all the GRBs have significant late-time spectral softening which is consistent with the first prediction. Most of them also tend to have indications of extra dust extinction in case the optical observation has been carried out which appears to be consistent with the second prediction (e.g., Evans et al. 2014). We have shown that the X-ray afterglows of these bursts in our sample are very consistent with one dominant radiative component. If some other radiative processes such as the synchrotron radiation from the external shocks exist in these bursts, they might be suppressed for some reason. The late-time spectral softening as in GRB 130925 were also proposed to be related with a blackbody component in addition to the typical power-law spectrum (Piro et al. 2014). By time-resolved spectral analysis of the Swift/XRT data, we have not found any significant indication of a blackbody component at least before ∼10^5 s of this burst. However, the last time interval of GRB 130925A after ∼10^5 s did have a hardening spectral index (Zhao & Shao 2014) which might need further inspection and requires some other explanation.

The significant late-time softening in the X-ray afterglows would have raised a great challenge to the external shock...
The light curves of most normal non-softening GRBs have been exclusively explained by the well-studied external shock models (e.g., Liang et al. 2007, 2008, 2009; Li et al. 2015; Wang et al. 2015). In principle the dust scattering takes place at a distance of approximately a hundred parsecs, while the internal and external shocks would be produced at less than a parsec. Currently we still have difficulties in having both the scattering model and the shock model working together in one single burst event based on available observational data. Evans et al. (2014) has made an effort with a detailed discussion. The basic concern is that the circumburst medium within one parsec would be relatively attenuated after being swept up by the massive stellar wind. The resulting circumburst medium would be wind-like instead of uniform as is typical as in the ISM. This would also raise an open issue for the circumburst medium of GRBs especially taking into account the unexpected ISM-like size distribution of dust grains as we have found in this paper. While this work was in preparation, Margutti et al. (2015) studied a sample of GRBs with a soft ($\Gamma > 3$) X-ray afterglow and identified a connection between the X-ray photon index $\Gamma$, the X-ray absorbing column density $N_{\text{H}}$, and the burst duration $T_{90}$. They proposed that the bursts with significant soft X-ray afterglows appeared to have a significantly larger $N_{\text{H}}$ and significantly longer prompt duration. This also raises an interesting concern to the radiative mechanism of the prompt emission.

In this work we have made an effort to reproduce the time-resolved spectra of six bursts from Swift/XRT data with the dust-scattering model without utilizing XSPEC or similar advanced software. To take into account the effect of X-ray absorption from the circumburst medium, we have adopted a simple form for the total photonionization crosssection as given in our Equation (5) which is an analytical approximation to the numerical work by Wilms (2000). As we have shown above, we can nicely reproduce the shape of the time-resolved spectra in different time intervals within the dust-scattering scenario assuming a constant hydrogen column density of $N_{\text{H}}$. It appears that while the softening of the X-ray afterglow from dust scattering has been widely proposed in the literature, the high-energy spectral index of the output spectrum does not vary much at all, e.g., this has been explicitly shown by Figure 4 of Shao & Dai (2007). The spectral softening is mainly manifested by the spectral peak energy continually moving to the soft end. The X-ray absorption from the circumburst medium may have played an import role in shaping the spectra. We will further investigate this issue in our following work.
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