X-RAYING EXTENDED EMISSION AND RAPID DECAY OF SHORT GAMMA-RAY BURSTS

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ABSTRACT

Extended emission in short gamma-ray bursts (SGRBs) is a mystery. By conducting time-resolved spectral analyses of the nine brightest events observed by the Swift-XRT, we classify the early X-ray emission of SGRBs into two types. One is the extended emission with exponentially rapid decay, which shows significant spectral softening for hundreds of seconds after the SGRB trigger and is also detected by the Swift-BAT. The other is a dim afterglow that only shows power-law decay over 10^3 s. The correlations between the temporal decay and spectral indices of the extended emissions are inconsistent with the α–β correlation expected for the high-latitude curvature emission from a uniform jet. The observed too-rapid decay suggests that the emission is from a photosphere or a patchy surface, and manifests the stopping via a central engine such as magnetic reconnection at the black hole.

Key words: gamma-ray burst: general – gravitational waves

1. INTRODUCTION

Short gamma-ray bursts (SGRBs) are a sub-category of gamma-ray burst (GRB) phenomena. The SGRB light curve is composed of an intense prompt emission with a short time duration of less than 2 s and an extended soft X-ray emission lasting about 100 s in some cases. The integrated energy of both emissions is almost comparable, which motivates us to make detailed studies of the X-ray properties.

The origin of SGRBs is still in debate. A major candidate is a coalescence of compact objects, such as neutron stars and black holes (Paczynski 1986; Eichler et al. 1989). Recently, in the afterglow of GRB 130603B, rebrightening in the red or near-infrared bands, a so-called macronova (or kilonova), was observed, and its physical interpretation is discussed as nuclear decay of neutron-rich r-process (rapid-process) elements synthesized in the ejecta of a neutron star binary coalescence (Berger et al. 2013; Tanvir et al. 2013; Berger 2014). It is also possible that the macronova is energized by the extended activity of the central engine (Kisaka et al. 2015) and/or dust emission (Takami et al. 2014).

In the compact merger scenario, the SGRB prompt emission is powered by a relativistic jet launched from the remnant compact object surrounded by a massive disk. The central engine could be black holes (Fan et al. 2005; Rosswog 2007; Lee et al. 2009; Barkov & Pozanenko 2011; Nakamura et al. 2014; Kisaka & Ioka 2015) or rapidly spinning strongly magnetized neutron stars (millisecond magnetars; Usov 1992; Zhang & Mészáros 2001; Gao & Fan 2006; Metzger et al. 2008; Bucciantini et al. 2012; Gompertz et al. 2013; Zhang 2013), depending on the type of coalescing binaries and the equation of state of the neutron star matter (Hotokezaka et al. 2011; Kyutoku et al. 2013, 2015). The origin of the extended emission is rather puzzling; the observed duration is longer than the typical accretion time of the disk. It has been proposed that the longer activity can be powered by a fallback accretion of tidally stripped matter (Lee et al. 2009; Kisaka & Ioka 2015) or a spin-down of magnetars (Metzger et al. 2008).

If the compact merger scenario is the case, we expect to detect strong gravitational waves via the second-generation gravitational wave observatories, Advanced-LIGO, Advanced-VIRGO, and KAGRA. To pioneer the gravitational wave astronomy, synchronized observations of electromagnetic counterparts in multi-wavelengths are required. Wide field monitoring in the X-ray band is an important method for discovering the prompt emission and extended soft X-ray emission of SGRBs accompanying the gravitational wave detection.

This paper is constructed as follows. In the next section, we systematically investigate the X-ray properties of nine bright SGRBs. Particularly, we perform time-resolved spectral analyses for the extended soft X-ray emission and X-ray afterglows. We show that strong spectral evolution is a common property of the rapid decay phase that follows the extended emission of SGRBs. Finally, in Section 3, we discuss the association between the extended soft X-ray emission and the rapid decay, and their spectral and temporal properties. We find that the decay is more rapid than the simple high-latitude emission and discuss interesting implications. Moreover, we discuss population statistics showing bright extended emissions.

2. OBSERVATIONS AND DATA ANALYSES

2.1. Data Selection

We first select 79 SGRBs with a time duration of T_{90} < 2.0 s from the Swift GRB catalog, selecting data up until the end of

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2014. Here \(T_{90}\) is measured as the duration of the time interval during which 90% of the total observed counts have been detected. However, considering that several SGRBs show extended soft X-ray emission lasting \(\sim 100\) s just after the short prompt emission, the above criterion may be insufficient for selecting samples of interest. We check the individual light curves and pick up events with an initial spike of prompt emission followed by a rather gradual time sequence. Then, we additionally include 13 possible SGRB candidates that were reported in GCN circulars.\(^{11}\)

We use the data of X-ray afterglows and/or extended X-ray emission observed by the Burst Alert Telescope (BAT) and the X-ray telescope (XRT) on board Swift to investigate the X-ray properties of SGRBs. For our purposes, we need a high enough number of X-ray photons to perform time-resolved spectral analyses. Thus, we adopt a selection criterion of \(F \geq 10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\) in the 2–10 keV band at the XRT observation start time. Hereafter, we treat the selected nine samples, GRBs 050724, 051221A, 060313, 070714B, 080503, 090510, 100702A, 120804A, and 130603B.

### 2.2. Swift-BAT Light curves

In Figure 1, we show the SGRB light curves observed with the BAT. In Figure 1, each panel shows two kinds of information, i.e., the main panels show the initial spike of prompt emission, with a 128 ms time resolution in the 15–150 keV band, and the inserted panels show the following hard X-ray emission up to 200 s since the SGRB trigger time, with an 8 s time resolution in the 15–25 keV band.

We adopted a null-flux constant model for the data, with an 8 s time bin in a time between 8–200 s since the SGRB trigger time (except for the first 8 s to avoid the contribution from prompt emission). We summarized the fitting results in Table 1. As also seen in Figure 1, the extended X-ray emission is detected in three of the sampled GRBs, 050724, 070714B, and 080503, with a \(T_{90}\) duration of 98.7 s, 65.2 s, and 274.9 s, respectively.

According to these analyses, the other six events are fully consistent, with no bright extended X-ray emission after the initial spike in the BAT data. We searched the extended X-ray emission with several time durations from 8 s since the trigger time. However, we failed to detect any obvious indication of extended X-ray emission in these six events.

### 2.3. Spectral Analyses of the XRT Data

At first, we extracted an X-ray signal within the image region of \(40 \times 30\) rectangular pixels, with a rotation angle of the spacecraft for windowed timing (WT) mode data, and 20 pixels in the radius (corresponding to \(\sim 47\) arcsec) for photon counting (PC) mode data. These are recommended region sizes described in the Swift-XRT software guide. We extracted a background signal from the image region with no X-ray sources (under the sensitivity of the XRT). The region size is rectangular, with \(30 \times 30\) pixels for WT mode data, and the circle is as large as possible (at least 20 pixels) for the PC mode data. The source and background regions do not overlap with each other.

After that, we performed time-resolved spectral analyses for both the WT and PC data of the nine selected SGRBs. To conserve the uniform statistical uncertainty for each spectrum, we divided the entire data set into several time bins to keep the same number of photons (about 512 photons for WT mode, and 256 photons for PC mode). Then we obtained at least four spectra for each SGRB.

We adopted two kinds of spectral models, i.e., a power law (PL) and a blackbody function. We include galactic and extra-galactic column densities (“phabs”) for each time-resolved datum. The exact formulas are as follows:

\[
N(E) = \exp \left( -\left( N_{H}^{gal} + N_{H}^{ext} \right) \sigma(E) \right) \times K \left( \frac{E}{1\ \text{keV}} \right)^{-\Gamma},
\]

for the PL model, and

\[
N(E) = \exp \left( -\left( N_{H}^{gal} + N_{H}^{ext} \right) \sigma(E) \right) \times \left( K \times 8.0525E^{-2}dE \right) \left[ \exp(E/kT) - 1 \right],
\]

for the blackbody model, respectively. Here, \(N(E)\) is in units of photons cm\(^{-2}\)s\(^{-1}\)keV\(^{-1}\). \(N_{H}^{gal}\) and \(N_{H}^{ext}\) are a galactic and an extra-galactic hydrogen column density, in units of \(10^{20}\) atoms cm\(^{-2}\), respectively, and \(\sigma(E)\) is a photoelectric cross-section (not including Thomson scattering). \(\Gamma\) is a photon index and \(kT\) is a temperature in units of keV. The parameters \(K\) in both functions are normalization.

We show representative spectra of GRB 080503 in Figure 2. The left and right panels of Figure 2 show the best-fit results with the PL and blackbody models, respectively. The PL model can describe the entire shape of the observed spectrum well, while the blackbody model has large discrepancies between the data and the model around the low- and high-energy regions.

In Figure 3, we show reduced \(\chi^2\) distribution as a function of time since the GRB 080503 trigger. The reduced \(\chi^2\) values of the PL model (open and filled squares for WT and PC mode) and blackbody model (open and filled circles for WT and PC mode) systematically locate around 1 and 2 throughout the entire epoch, respectively. Therefore we can conclude that the observed spectra can be described by the PL model and the blackbody model is not suitable for the X-ray spectra after \(\sim 100\) s of SGRBs. In the other eight events, all spectra can be described by the PL model.

### 2.4. Spectral Softening

We summarized the fitting results of spectral parameters, the energy flux in units of \(10^{-12}\) erg cm\(^{-2}\)s\(^{-1}\) in the 2–10 keV band (top panel), the photon index \(\Gamma\) (middle panel), and the extra-galactic column density \(N_{H}^{ext}\) (bottom panel) in Figure 4. As shown in the figure, at least for five samples (GRBs 050724, 060313, 070714B, 080503, and 100702A), the photon indices drastically change as a function of time, especially in the early decay phase, while \(N_{H}\) is rather stable.

For example, the brightest case of GRB 050724 shows the spectral evolution from \(\Gamma \sim 1.2\) to 3.0 for 300 s since the SGRB trigger time. GRB 070714B, 080503, and 100702A also show rapid spectral softening during 200–500 s since each SGRB trigger. Only one case, that of GRB 060313, shows gradual softening over \(10^4\) s.

\(^{11}\) GRB 050724, 050911, 051227, 060717, 061006, 070714B, 080123, 080503, 090309, 100213A, 100816A, 130716A, and 130822A.
2.5. Decay Slopes of Light Curves

In Figure 4, the energy fluxes are estimated by the spectral fitting, although almost all previous works converted the photon flux to the energy flux with averaged spectral parameters. Then we investigated the temporal behavior with three models, i.e., single PL, broken PL (BPL), and exponential (EXP) functions. We summarize the fitting results in Table 2.

Because of small flaring activities or some fluctuations of the early X-ray afterglows, the reduced $\chi^2$ values are rather large. However, the PL model is acceptable for five SGRBs: GRBs 050724, 060313, 070714B, 120804A, and 130603B.

On the other hand, we could significantly improve the fitting results with the BPL and/or EXP models compared with the PL model for the other four SGRBs, GRBs 050724, 080503, 090510, and 100702A. For three events in particular (GRB 050724, 080503, and 100702A), their temporal indices after the break time are remarkably steep. In the remaining GRB, 090510, the BPL model is better than the PL model, but the

![Figure 1. Swift-BAT light curves of nine bright SGRBs. The main panels show the light curves of prompt emission, with a 128 ms time resolution in the 15–150 keV band. The inserted panels also show the following long-lasting X-ray emission up to 200 s since the SGRB trigger, with an 8 s time resolution in the 15–25 keV band. We can clearly confirm extended X-ray emission for three events (GRB 050724, 070714B, and 080503).](image)

### Table 1

| ID          | Redshift | $T_{90,\text{obs}}$ (s) | $\chi^2$(dof) of E. E. | Reference of Redshift |
|-------------|----------|-------------------------|------------------------|------------------------|
| GRB 050724  | 0.258    | 98.7                    | 105.3 (23)             | Prochaska et al. (2005) |
| GRB 051221A | 0.5465   | 1.4                     | 17.9 (23)              | Berger & Soderberg (2005) |
| GRB 060313  | ...      | 0.8                     | 21.9 (23)              | ...                    |
| GRB 070714B | 0.92     | 65.2                    | 59.9 (23)              | Graham et al. (2007)   |
| GRB 080503  | ...      | 274.9                   | 712.8 (23)             | ...                    |
| GRB 090510  | 0.903    | 0.4                     | 23.2 (23)              | Rau et al. (2009)      |
| GRB 100702A | ...      | 0.2                     | 18.3 (23)              | ...                    |
| GRB 120804A | ...      | 1.8                     | 23.2 (23)              | ...                    |
| GRB 130603B | 0.3586   | 0.18                    | 14.5 (23)              | Cucchiara et al. (2013) |
temporal index is gentle, $1.97 \pm 0.35$, even after the break, which is different from the previous three events. When we adopt the EXP model to the X-ray light curves of GRBs 050724, 080503, and 100702A, the time constant is obtained as $50 \sim 100$ s (see Table 2). The redshift is measured only for GRB 050724, as $z = 0.258$, and then the intrinsic time constant is $41.5 \pm 0.7$ s in this case.

### 3. DISCUSSION

We systematically studied the X-ray properties of SGRBs for the nine brightest events observed by the *Swift*-XRT. We performed time-resolved spectral analyses for all events, and measured energy fluxes, taking the spectral parameters into account in each time bin. In this section, we discuss the observed X-ray properties of SGRBs, and classify them into two types.

#### 3.1. Connection Between Extended X-Ray Emission and Rapid Decay

Comparing Figures 1 and 4, three SGRBs with extended X-ray emission in the *Swift*-BAT light curves (GRBs 050724, 070714B, and 080503) have strong spectral softening and two also show rapid decay (GRBs 050724 and 080503). GRB 100702A did not have strong extended emission in the BAT light curve, though it does show spectral softening. The extended emission of GRB 100702A is most likely under the sensitivity of the *Swift*-BAT since the X-ray flux in the *Swift*-XRT is dimmer than the other three events in Figure 4. These results are summarized in Table 3.

On the other hand, the remaining five events without extended emission in the *Swift*-BAT light curves (GRBs 051221A, 060313, 090510, 120804A, and 130603B) do not show the rapid decay phase, and their X-ray light curves are almost fully consistent with the single PL decay in the *Swift*-XRT observations. Therefore we conclude that the extended X-ray emission in BAT light curves has the same origin as the rapid decay in XRT light curves, which have the PL spectral shape and also show rapid spectral softening, with a timescale of 100–1000 s.

#### 3.2. Exponential Decay in the Early Phase

In Section 2.5, we adopt both BPL and EXP functions for the light curves of the rapid decay phase. According to the reduced $\chi^2$ values in Table 2, it is difficult to distinguish which model is a more appropriate function for describing the rapid decay phase. This is because, in general, the XRT starts the follow-up observations after $\sim 100$ s since GRB triggers and hence the light curves are already steeply declining. Moreover, small flaring activities disturb the baseline shape of the early decay phase.

In the BPL model, the best-fit temporal index is $-5 \sim -6$ after the break time. In the standard afterglow model, i.e., synchrotron radiation from high-energy electrons accelerated by a relativistic shock, the steepest temporal index is $-3p/4$, corresponding to the temporal evolution in the highest-energy spectral segment (Piran 1999). Here the parameter $p$ is the PL index of the energy distribution of accelerated electrons. If we
assume temporal indices of $-5$ and $-6$, the corresponding indices are $p = \frac{22}{3}$ and $p = \frac{26}{3}$, respectively. These are too soft to realize in the usual particle acceleration. Therefore we should include an additional idea to describe the steep decay.

On the other hand, in the EXP model, the observed time constant seems to be 50–100 s for all events with the rapid decay phase. In the case of long GRBs, the light curves of the early X-ray decay phase can be described by the EXP model (O’Brien et al. 2006; Sakamoto et al. 2007; Willingale et al. 2010; Nathanail et al. 2014; Imatani et al. 2015). Imatani et al. (2015) first reported evidence of the exponential decay from the prompt emission to the following rapid decay (prompt tail) phase of GRB 100418A in the 0.7–7.0 keV energy band combined with MAXI-SSC and Swift-BAT data. Its decay constant of $31.8 \pm 1.6$ s is similar to the timescale of the SGRBs shown in this paper. Therefore, because of the analogies between long and short GRBs, the EXP model may be appropriate for describing the time behavior of rapid decay in SGRBs.

Yonetoku et al. (2008) and Moretti et al. (2008) reported a similar rapid decline in time with strong spectral evolution in long GRBs. In particular, Yonetoku et al. (2008) interpreted the temporal and spectral behavior as a dynamic evolution of a spectral model, i.e., a spectral model of a broken PL with an exponential cutoff moves through the observational energy window of the XRT during the rapid decay phase. Here the physical interpretation of the break energy and the cutoff energy is the $E_{peak}$ corresponding to the minimum energy of accelerated electrons and the synchrotron cutoff, respectively. In this paper, we cannot investigate similar and detailed analyses because of limited photon fluxes, but the dynamic spectral evolution may be a possible explanation for the observed temporal and spectral evolution in SGRBs.

We additionally study a possibility that the start time of extended emission is different from the trigger time of short prompt emission. As shown in Figure 1, the peak times of

![Figure 4](image-url)
Table 2
Temporal Properties of Early X-Ray Emission (Extended Emission or Afterglow) of SGRBs

| ID         | Model | Index $\alpha_1$ | Break Time $t_b$ | Index $\alpha_2$ | Time Const. $\tau$ | $\chi^2$ | dof |
|------------|-------|------------------|------------------|------------------|--------------------|--------|-----|
| GRB 050724 | PL    | ±2.63 ± 0.19     | ...              | ...              | ...                | 280    | 19  |
|           | BPL   | ±2.03 ± 0.07     | 187              | ±5.90 ± 0.53     | ...                | 55.2   | 17  |
|           | EXP   | ...              | ...              | ...              | 52.2 ± 0.9         | 81.7   | 19  |
| GRB 051221A | PL    | ±0.77 ± 0.04     | ...              | ...              | ...                | 4.0    | 2   |
|           | BPL   | ±0.66 ± 0.03     | 25700            | ±1.47 ± 0.24     | ...                | 0.3    | 0   |
|           | EXP   | ...              | ...              | ...              | 192 ± 39           | 103    | 2   |
| GRB 060313 | PL    | ±1.11 ± 0.04     | ...              | ...              | ...                | 5.5    | 4   |
|           | BPL   | ±1.07 ± 0.03     | 20100            | ±2.07 ± 0.37     | ...                | 4.9    | 2   |
|           | EXP   | ...              | ...              | ...              | 305 ± 60           | 93.7   | 4   |
| GRB 070714B | PL    | ±2.33 ± 0.06     | ...              | ...              | ...                | 76.2   | 6   |
|           | BPL   | ±1.58 ± 0.17     | 117              | ±2.64 ± 0.14     | ...                | 67.7   | 4   |
|           | EXP   | ...              | ...              | ...              | 68.3 ± 4.0         | 100    | 6   |
| GRB 080503 | PL    | ±3.34 ± 0.22     | ...              | ...              | ...                | 143    | 11  |
|           | BPL   | ±2.27 ± 0.12     | 179              | ±5.06 ± 0.29     | ...                | 24.4   | 9   |
|           | EXP   | ...              | ...              | ...              | 51.9 ± 1.3         | 18.3   | 11  |
| GRB 090510 | PL    | ±1.17 ± 0.03     | ...              | ...              | ...                | 19.0   | 6   |
|           | BPL   | ±0.93 ± 0.01     | 10200            | ±1.97 ± 0.35     | ...                | 4.7    | 4   |
|           | EXP   | ...              | ...              | ...              | 706 ± 87           | 39.1   | 6   |
| GRB 100702A | PL    | ±1.72 ± 0.16     | ...              | ...              | ...                | 13.2   | 2   |
|           | BPL   | ±0.74 ± 0.05     | 192              | ±6.13 ± 0.30     | ...                | 0.002  | 0   |
|           | EXP   | ...              | ...              | ...              | 91.1 ± 8.6         | 8.0    | 2   |
| GRB 120804A | PL    | ±0.93 ± 0.04     | ...              | ...              | ...                | 8.9    | 2   |
|           | BPL   | ±0.78 ± 0.03     | 14800            | ±1.91 ± 0.24     | ...                | 5.3    | 0   |
|           | EXP   | ...              | ...              | ...              | 1260 ± 140         | 46.2   | 2   |
| GRB 130603B | PL    | ±0.83 ± 0.05     | ...              | ...              | ...                | 4.72   | 2   |
|           | BPL   | ±0.75 ± 0.02     | 8880             | ±1.89 ± 0.33     | ...                | 1.57   | 0   |
|           | EXP   | ...              | ...              | ...              | 2130 ± 300         | 31.7   | 2   |

Table 3
Status of Early X-Ray Properties of SGRBs

| ID          | Extended Emission | Rapid Decay | Spectral Evolution |
|-------------|-------------------|-------------|-------------------|
| GRB 050724  | YES               | YES         | YES               |
| GRB 051221A | NO                | NO          | YES               |
| GRB 060313  | NO                | NO          | YES               |
| GRB 070714B | YES               | YES         | YES               |
| GRB 080503  | YES               | YES         | YES               |
| GRB 090510  | NO*               | NO          | NO                |
| GRB 100702A | NO                | NO          | YES               |
| GRB 120804A | NO                | NO          | NO                |
| GRB 130603B | NO                | NO          | NO                |

Note.
* The flux level of extended emission may be under the sensitivity of the BAT.

3.3. Correlation between Temporal and Spectral Indices

According to the previous sub-sections of Sections 2.3 and 2.4, both temporal and spectral indices vary as a function of time. When we describe the energy flux as $F_{\gamma} \propto \Gamma^{\alpha - \beta}$, there is a well-known correlation between $\alpha$ and $\beta$ as $\alpha = \beta + 2$. Therefore we frequently obtain an unrealistic temporal index because of the rapid decay phase. When we describe the energy flux as $F_{\gamma} \propto \Gamma^{\alpha - \beta}$, there is a well-known correlation between $\alpha$ and $\beta$ as $\alpha = \beta + 2$. Therefore we directly estimate the temporal index from light curve data, and apply the power-law function to the time-resolved pseudo light curve. By doing this, we can avoid the disturbance from small flares and estimate the basic trend of the rapid decay phase. If we directly estimate the temporal index from light curve data, we frequently obtain unrealistic temporal index because of the rattle shape of light curves.)

extended emission in BAT light curves are about 80 s and 50 s for GRB 050724 and GRB 080503, respectively. Therefore we redefine the origin of start time to these peak times and measure the temporal index of the rapid decay phase. When we adopt the BPL model to the time-shifted light curves, we obtain the temporal index of $\alpha_1 = 0.32 \pm 0.01$, $\alpha_2 = 3.72 \pm 0.14$, and the break time of $t_b \sim 94$ s for GRB 050724, and $\alpha_1 = 1.22 \pm 0.07$, $\alpha_2 = 4.03 \pm 0.21$, and $t_b \sim 125$ s for GRB 080503. We can recognize that these temporal indices are still steeper than the general GRB afterglow phenomena, and conclude that the extended emission really shows the rapid decay in time.

Note.
* The flux level of extended emission may be under the sensitivity of the BAT.
points in the observed light curve. The solid line is the expected function of $\alpha = \beta + 2$ for high-latitude emission from a uniform jet (Kumar & Panaitescu 2000). The dashed lines are the best-fit function for each SGRB.

The best-fit function is $\beta + 2 = (0.5 \pm 0.1)\alpha + (1.6 \pm 0.3)$ for GRB 050724, $\beta + 2 = (0.3 \pm 0.1)\alpha + (1.6 \pm 0.2)$ for GRB 080503, and $\beta + 2 = (0.4 \pm 0.4)\alpha + (2.3 \pm 0.7)$ for GRB 100702A, respectively. In these results, the slopes of the linear fits are similar to each other, and inconsistent with the high-latitude emission of the slope 1 with a statistical level of more than $3\sigma$. The intercept values of the linear fits are different from each other.

Finally, let us argue the possible implications of the observed $\alpha$–$\beta$ correlation for the SGRB models. The extended emission is most likely caused by the long-lasting activity of the central engine because the rapid decay is very steep, while the external shock emission cannot generally produce such large variabilities in the afterglow light curves (Ioka et al. 2005). Then the rapid decay phase at $\delta t \sim 100$ s signals the quenching of the jet from the central engine. The important point of our finding is that the temporal decay of the extended emission becomes even faster than those produced by the high-latitude emission from quenching uniform jets, as one can see from Figure 5. This means that the contribution from the high-latitude emission is smaller than that of a uniform jet. Therefore the emission geometry of the jet should not be uniform; the brightness declines significantly outside the solid angle of $\theta_{\text{jet}} \gtrsim 1/\Gamma \sim 0.01$ on the line of sight, where $\Gamma$ is the bulk Lorentz factor of the jet and is larger than $\sim 100$ to avoid the compactness problem. Although this may imply the jet opening angle is small or patchy in the extended emission and rapid decay phase (Yamazaki et al. 2004), a typical opening angle of a SGRB jet is usually $\theta \sim 0.1$, much larger than $1/\Gamma$ (Mizuta & Ioka 2013; Fong et al. 2014; Nagakura et al. 2014; Nakamura et al. 2014). A natural solution to this inconsistency may be that the emission comes from a photosphere (Rees & Mészáros 2005; Ioka et al. 2007; Pe’er et al. 2012). The photospheric radius becomes large outside the viewing angle of $1/\Gamma$ for a relativistic jet because the photosphere is concave for $v/c > 2/3$ while it is convex for $v/c < 2/3$, as shown by (Abramowicz et al. 1991). Therefore the high-latitude emission from the photosphere is suppressed even if the jet is uniform.

Additionally, we investigate the $\alpha$–$\beta$ correlation for the time-shifted light curve of GRB 050724 and GRB 080503. We exclude GRB 100702 because it does not show the obvious extended emission in the BAT light curve and we cannot determine its start time as shown in Figure 1. Then we estimated the temporal index of $\alpha$ with the same method as explained above except for the time shift of 80 s and 50 s for GRBs 050724 and 080503, respectively.

In Figure 6, we again show the $\alpha$–$\beta$ correlation for the time-shifted data. The best-fit function is $\beta + 2 = (0.5 \pm 0.1)\alpha + (2.3 \pm 0.2)$ for GRB 050724, and $\beta + 2 = (0.3 \pm 0.1)\alpha + (1.8 \pm 0.1)$ for GRB 080503. The slopes of these results are consistent with the previous ones before the time shift, and still inconsistent with the slope of 1 that is expected from the high-latitude emission. Even if we consider the time-shifted light curves, at least one data point is still clearly in the region of $\alpha > \beta + 2$, as shown in Figure 6. Therefore the above discussions may also be adopted in this case.

The observed $\alpha$–$\beta$ correlation may reflect the angular structure of the photosphere. It is an interesting problem to study whether the $\alpha$–$\beta$ correlation is reproduced in the photosphere model or not. Alternatively, the observed $\alpha$–$\beta$ correlation may be directly produced by the declining jet emission. In the black hole model with fallback accretion, the Blandford–Znajek process is the most likely mechanism for launching a relativistic jet (Blandford & Znajek 1977) and the rapid decay in X-ray emission corresponds to the magnetic field decay via reconnection at the black hole, which reduces the energy extraction from the rotating black hole (Kisaka & Ioka 2015). Although we currently cannot predict the spectral evolution, our observations should give a clue to the unknown mechanism of the jet emission.
3.4. Population Statistics of Extended Emission

In this paper, we selected the nine brightest SGRBs in early X-ray flux observed by the Swift-XRT. Eight of them are also the brightest events in the fluence of the BAT observations, including the extended emission if it exists, except for three SGRBs with observation start times of $\sim$200 s, which are later than usual. These eight events are satisfied with the criteria of BAT fluence of $>3.4 \times 10^{-7}$ erg cm$^{-2}$ and XRT flux of $>10^{-11}$ erg cm$^{-2}$ s$^{-1}$ from 92 selected SGRB candidates. In our sample, only GRB 100702A is the outlier of dimmer fluence in BAT observations, but brighter in XRT.

Focusing on these eight events, the ratio of SGRBs with extended emission is 37.5%. Bostanci et al. (2013) found that 7% of SGRBs have the extended emission in BATSE data, and Norris et al. (2010) and Sakamoto et al. (2011) reported 25% and 2% in the BAT data, respectively. These statistical values should not be directly compared because our criteria differ. But in this paper we found that the early X-ray flux observed by the XRT is strongly affected by the long-lasting tail of extended emission. Therefore, including the early X-ray flux, which was one of criteria, will be important for future investigations.

3.5. Conclusions

In conclusion, we find the following properties of SGRBs.

1. The spectra of the extended soft X-ray emission and following rapid decay phase can be described by a PL function with spectral softening. We can exclude a simple thermal blackbody function.

2. The rapid decay phase usually follows the extended X-ray emission.

3. The X-ray light curve from the extended emission to the rapid decay phase can be fitted by the exponential function with a time constant of 50–100 s.

4. The high-latitude emission cannot explain the temporal and spectral behavior of the extended emission and rapid decay because the observations do not follow the expected $\alpha-\beta$ correlation ($\alpha = \beta + 2$).

5. The extended X-ray emission may be observed in 37.5% of bright SGRBs using the selection criteria of BAT fluence of $>3.4 \times 10^{-7}$ erg cm$^{-2}$ and XRT flux of $>10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

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$^{13}$ GRB 101219A, 140930B, and 080426 are excluded.

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