Two types of softening detected in x-ray afterglows of Swift bursts: internal and external shock origins?

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Abstract. The softening process observed in the steep decay phase of early x-ray afterglows of Swift bursts has remained a puzzle since its discovery. The softening process can also be observed in the later phase of the bursts and its cause has also been unknown. Recently, it was suggested that, influenced by the curvature effect, emission from high latitudes would shift the Band function spectrum from a higher energy band to a lower band, and this would give rise to the observed softening process accompanied by a steep decay of the flux density. The curvature effect scenario predicts that the terminating time of the softening process would be correlated with the duration of the process. In this paper, on the basis of the data from the UNLV GRB (University of Nevada, Las Vegas, Gamma-Ray Burst) group web-site, we found an obvious correlation between the two quantities. In addition, we found that the softening process can be divided into two classes: the early type softening ($t_{s,max} \leq 4000$ s) and the late type softening ($t_{s,max} > 4000$ s). The two types of softening show different behaviors in the duration versus terminating time plot. In the relation between the variation rates of the flux density and spectral index during the softening process, a discrepancy between the two types of softening is also observed. According to their timescales and the discrepancy between them, we propose that the two types are of different
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origins: the early type is of internal shock origin and the late type is of external shock origin. The early softening is related to the steep decay just following the prompt emission, whereas for the late decay one typically conceives the transition from flat decay to late afterglow decay. We suspect that there might be a great difference in Lorentz factor between the two classes, which is responsible for the observed discrepancy.

Keywords: gamma ray bursts, gamma ray burst experiments

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1. Introduction

A newly discovered phenomenon, the spectral softening of gamma-ray bursts (GRBs) observed by the Swift instruments in their early x-ray afterglows [1]–[5], has not been predicted by any of the existing GRB models. Credit for this discovery goes to the Swift instruments, which can monitor x-ray emission of GRBs at quite early time after the trigger events. Soon after this discovery, the authors of [6] performed a systematic analysis of a selected sample of Swift bursts and found that \( \sim 75\% \) of the bursts (33 out of 44) show an obvious spectral softening process. Besides their papers, the UNLV (University of Nevada, Las Vegas) GRB group also presented temporal and spectral data for Swift bursts on their web-site\(^4\); these continue to accumulate as the number of Swift bursts keeps increasing. Their data show, besides the steep decay phase, that the softening can be observed in later phases as well (see our analysis below).

Most softening processes are detected in the steep decay phase in the early x-ray afterglows of GRBs. Since the steep decay phase promptly follows, and is smoothly connected to, the prompt emission phase, it is regarded as the prompt emission tail [7]–[10]. It is generally believed that this phenomenon is due to the high latitude emission of fireballs, in which the so-called curvature effect must play a role [6, 9], [11]–[18]. However, the steep decay tails are expected from the curvature effect but the softening process is not, which puzzled astronomers.

The curvature effect arises from the emission from the surface of a relativistically expanding fireball, where the delay of time, the shifting of the intrinsic spectrum due

\(^4\) http://swift.physics.unlv.edu/
to high latitude emission areas, as well as other relevant factors of expanding fireballs must be taken into account (for detailed explanation and analysis, see [17], [19]–[21]). Due to the great amount of energy release, relativistically expanding fireballs would be produced at a very early epoch of GRBs [22, 23]. The curvature effect is thus expected in the prompt gamma-ray emission phase. Investigations on the profile of the light curves of pulses, the spectral lags, the power-law relation between the pulse width and the energy, the evolution of the hardness ratio and the evolution of the peak energy in the prompt emission phase have been performed by various groups in the last decade [19]–[21], [24]–[34]. It was shown that the effect can also play an important role in the early afterglow period [11, 12, 17, 35].

There have only been a few attempts at interpreting the softening phenomenon, which indicate that the phenomenon is beyond the expectation of current or underlying models. The few attempts at interpretation include: cooling of the internal shock region might be responsible for strong softening [6]; at least in some bursts, the softening might be accounted for by the central engine, which is assumed to produce a soft and decaying afterglow emission [1, 6, 36]; both the temporal behavior and the spectral softening of bursts might be a consequence of the cannonball model of GRBs [37]; a hard-to-soft behavior lasting to the latest phases of the afterglow can be expected on the basis of the ‘fireshell’ model with a ‘canonical GRB’ light curve containing two sharply different components [38, 39]. One of the most remarkable investigations on this issue was performed by authors of [16]. They concluded that the early emission in >90% of early afterglows has a curved $\nu f_\nu$ spectrum and that $E_{\text{peak}}$ (peak energy) likely evolves from the $\gamma$-rays through the soft x-ray bands on timescales of $10^2$–$10^4$ s after the GRBs. Along with this is the discovery of [5]: the $E_{\text{peak}}$ of GRB 060614, which is one of the members of the sample of reference [6], decreases to as low as $\sim8$ keV at the beginning of the XRT observations. The same phenomenon was revealed in the literature as early as 2000 by the analysis of BeppoSAX data: the peak energy was found to evolve from the prompt to the afterglow phase of GRBs, decreasing from >700 keV to <3 keV for some bursts [40].

Motivated by the finding of reference [16], very recently, the author of [35] has shown that the curvature effect alone can produce both the softening and the decaying behavior observed in the early x-ray afterglow of the Swift bursts. It is due the shifting of the Band function spectrum [41] which gives rise to the softening along with the temporal decaying. Two factors of the curvature effect, the time delay and the variation of the Doppler effect of higher latitude emission from the fireball surface, cause the shifting of the Band function spectrum.

According to the curvature effect scenario, the start time of the softening is much smaller than the terminating time of the process, and thus it is expected that the softening duration must be correlated with its terminating time [35]. We will investigate statistically in the following whether the two quantities are correlated or not. At the same time, some other statistical properties will also be explored. We will not limit our analysis to the steep decay phase, but instead, any softening detected in the XRT light curve will be considered.

The paper is organized as follows: in section 2, we describe our sample of Swift data and the data reduction; in section 3, we discuss the statistical properties obtained from our analysis; conclusions of the present work are reported in the last section.
2. Data

The data (up to 23 May 2008) employed in our analysis on the relation between the duration and terminating time of the softening process are taken from the UNLV GRB group web-site (see footnote 4), where Swift/XRT time-resolved spectra of selected bursts are available (see [6] for selection criteria for the bursts). The softening is observed in some of the bursts and we selected only those bursts which have noticeable x-ray softening, i.e., those bursts which should contain at least three data points starting from a smaller spectral index and ending at a larger one (refer to the time intervals presented in table 1 and the corresponding spectral evolution figures presented on the UNLV GRB group web-site).

The start time \( t_{s,\text{min}} \) and the terminating time \( t_{s,\text{max}} \), together with the corresponding values of the spectral index \( \beta_{\text{min}} \) and \( \beta_{\text{max}} \), for the softening process of the selected bursts are listed in table 1. Here we divide the softening process into two distinct classes according to the corresponding terminating time: for class 1, \( t_{s,\text{max}} \leq 4000 \) s (called the early type softening); and for class 2, \( t_{s,\text{max}} > 4000 \) s (called the late type softening). Note that, for some bursts, there might exist both types of softening (see table 1).

An example of selecting the softening as well as the corresponding start time and terminating time is displayed in the lower panel of figure 1 (note that we employ index \( \beta \) instead of \( \Gamma \)), where the spectral evolution of GRB 070520B is shown. The light curve of this burst is displayed in the upper panel of the figure. The spectral and light curve data are taken from http://swift.physics.unlv.edu/ (spectra.txt and lc.txt files). We first selected \( t_{s,\text{min}} \) and \( t_{s,\text{max}} \) by viewing the \( \beta \) versus \( t \) plot (see the lower panel of figure 1 and the dash lines there), and then located them in the spectra.txt file of the burst, and then read and calculated (see the explanation below) their values as well as their uncertainties from this file. The data provided have been analyzed by the UNLV GRB group. The details of the analysis are described in [6]. The UNLV GRB group have developed a time filter for the time-resolved spectral analysis which can be automatically performed. Time intervals for analyzing the spectral index are determined by two criteria raised by them, and hence they are different from each other. For example, for GRB 070520B, the lower limit of the time interval associated with its \( \beta_{\text{min}} = 1.196 \pm 0.054 \) is \( t_1 = 125 \) s and the upper limit of this interval is \( t_2 = 195 \) s (see figure 1 and table 1, and also the spectra.txt file). This gives rise to a time interval of 70 s. According to the data format file, the mean time of this interval is \( t = (t_1 + t_2)/2 = 160 \) s and its error is \( \sigma_t = (t_2 - t_1)/2 = 35 \) s (see table 1). However, the lower limit of the time interval associated with \( \beta_{\text{max}} = 1.92 \pm 0.21 \) for this burst is \( t_1 = 308 \) s, and the upper limit of this interval is \( t_2 = 391 \) s. That measures the time interval as 83 s. The mean time of this interval is \( t = (t_1 + t_2)/2 = 349.5 \) s and its error is \( \sigma_t = (t_2 - t_1)/2 = 41.5 \) s (see table 1). The UNLV GRB group use different NH for different sources. They used the XSPEC spectral fitting model: a simple power law combined with the absorptions of both our Galaxy and the GRB host galaxy, \( \text{wabs}^{\text{Gal}} \times \text{wabs}^{\text{host}} \times \text{power law} \) (for bursts with known redshifts) or \( \text{wabs}^{\text{Gal}} \times \text{wabs}^{\text{host}} \times \text{power law} \) (for bursts whose redshifts are unknown; see [6]).
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Table 1. The minimum and maximum values of the spectral index ($\beta_{\text{min}}$ and $\beta_{\text{max}}$) and the corresponding times ($t_{s,\text{min}}$ and $t_{s,\text{max}}$), of the softening process of the selected bursts.

| Type | Burst | $t_{s,\text{min}}$ (s) | $\beta_{\text{min}}$ | $t_{s,\text{max}}$ (s) | $\beta_{\text{max}}$ |
|------|-------|------------------------|-----------------------|------------------------|-----------------------|
| Early | 050315 | 91.0 ± 7.0 | 1.02 ± 0.27 | 620 ± 230 | 1.58 ± 0.45 |
|       | 050421 | 124.0 ± 9.0 | −0.23 ± 0.32 | 247 ± 44 | 1.35 ± 0.36 |
|       | 050502B | 340 ± 270 | 0.972 ± 0.053 | 1200 ± 150 | 2.29 ± 0.26 |
|       | 050714B | 188 ± 31 | 4.80 ± 0.20 | 474 ± 73 | 6.06 ± 0.40 |
|       | 050716 | 114 ± 10 | −0.13 ± 0.12 | 396 ± 88 | 1.019 ± 0.084 |
|       | 050717 | 94.0 ± 3.0 | 0.08 ± 0.24 | 247 ± 32 | 0.90 ± 0.20 |
|       | 050724 | 87.9 ± 4.3 | 0.38 ± 0.10 | 318 ± 16 | 2.24 ± 0.31 |
|       | 050726 | 366 ± 32 | 0.72 ± 0.26 | 689 ± 58 | 1.02 ± 0.26 |
|       | 050730 | 145 ± 12 | 0.245 ± 0.089 | 729 ± 66 | 0.962 ± 0.062 |
|       | 050814 | 173.1 ± 8.1 | 0.885 ± 0.091 | 358 ± 26 | 1.88 ± 0.25 |
|       | 050904 | 182 ± 13 | 0.043 ± 0.072 | 533 ± 48 | 0.977 ± 0.093 |
|       | 050922B | 673 ± 17 | 0.93 ± 0.29 | 1460 ± 220 | 2.21 ± 0.41 |
|       | 051117A | 153 ± 40 | 0.722 ± 0.028 | 1560 ± 170 | 1.268 ± 0.027 |
|       | 051227 | 112 ± 11 | 0.21 ± 0.20 | 340 ± 140 | 0.91 ± 0.31 |
|       | 060115 | 126.7 ± 4.5 | 0.71 ± 0.14 | 810 ± 290 | 1.60 ± 0.31 |
|       | 060124 | 559 ± 31 | 0.032 ± 0.023 | 871 ± 49 | 1.591 ± 0.087 |
|       | 060210 | 113.0 ± 9.6 | 0.472 ± 0.093 | 500 ± 120 | 1.503 ± 0.049 |
|       | 060211A | 202 ± 16 | 0.689 ± 0.058 | 351 ± 29 | 1.30 ± 0.20 |
|       | 060218 | 1013 ± 13 | 0.424 ± 0.087 | 2122 ± 27 | 1.057 ± 0.072 |
|       | 060413 | 132 ± 11 | 0.626 ± 0.099 | 278 ± 31 | 1.25 ± 0.21 |
|       | 060510B | 291 ± 11 | 0.214 ± 0.060 | 417 ± 16 | 1.32 ± 0.18 |
|       | 060522 | 160 ± 11 | 0.40 ± 0.24 | 390 ± 190 | 0.98 ± 0.16 |
|       | 060526 | 285 ± 30 | 0.640 ± 0.037 | 420 ± 44 | 1.89 ± 0.13 |
|       | 060607A | 97 ± 10 | 0.428 ± 0.073 | 140 ± 16 | 1.12 ± 0.11 |
|       | 060607A | 220 ± 24 | 0.560 ± 0.061 | 353 ± 38 | 1.114 ± 0.088 |
|       | 060614 | 104.3 ± 5.5 | 0.070 ± 0.042 | 451 ± 25 | 2.09 ± 0.13 |
|       | 060707 | 213 ± 49 | 0.72 ± 0.15 | 970 ± 470 | 0.96 ± 0.14 |
|       | 060714 | 116.5 ± 7.5 | 0.361 ± 0.083 | 223 ± 28 | 2.13 ± 0.17 |
|       | 060729 | 132.09 ± 0.50 | 0.94 ± 0.20 | 2868 ± 7.5 | 4.90 ± 0.47 |
|       | 060814A | 83.3 ± 4.8 | 0.241 ± 0.074 | 377 ± 36 | 1.51 ± 0.12 |
|       | 060904A | 76.2 ± 3.0 | 0.036 ± 0.079 | 228 ± 14 | 2.19 ± 0.21 |
|       | 061007 | 106 ± 18 | 0.847 ± 0.032 | 252 ± 57 | 0.967 ± 0.029 |
|       | 061110A | 80.4 ± 3.0 | 1.57 ± 0.14 | 210 ± 15 | 3.23 ± 0.21 |
|       | 061121 | 71.7 ± 2.0 | −0.455 ± 0.062 | 1558 ± 5.3 | 1.68 ± 0.31 |
|       | 061222A | 108.8 ± 2.3 | 0.80 ± 0.20 | 177.8 ± 9.6 | 2.05 ± 0.35 |
|       | 070110 | 111 ± 10 | 0.79 ± 0.11 | 245 ± 25 | 1.32 ± 0.26 |
|       | 070129 | 299 ± 46 | 0.250 ± 0.030 | 1030 ± 150 | 2.36 ± 0.44 |
|       | 070223 | 121.0 ± 3.0 | −0.22 ± 0.26 | 218 ± 22 | 1.17 ± 0.13 |
|       | 070318 | 174 ± 22 | 0.19 ± 0.12 | 397 ± 89 | 0.924 ± 0.069 |
|       | 070330 | 141 ± 54 | 0.43 ± 0.27 | 540 ± 230 | 0.76 ± 0.20 |
|       | 070419B | 106 ± 17 | 0.569 ± 0.047 | 333 ± 25 | 1.144 ± 0.076 |
|       | 070518 | 101 ± 22 | 1.147 ± 0.093 | 226 ± 31 | 1.99 ± 0.15 |
|       | 070520B | 160 ± 35 | 1.196 ± 0.054 | 350 ± 42 | 1.92 ± 0.21 |
|       | 070616 | 204 ± 65 | −0.060 ± 0.028 | 1100 ± 100 | 0.72 ± 0.15 |
|       | 070621 | 122.0 ± 2.0 | 1.18 ± 0.21 | 235 ± 39 | 1.56 ± 0.16 |
|       | 070704 | 252 ± 57 | 0.385 ± 0.084 | 511 ± 26 | 1.07 ± 0.25 |
|       | 070714B | 74.0 ± 4.0 | −0.11 ± 0.22 | 396 ± 88 | 1.13 ± 0.33 |
|       | 070721B | 265 ± 44 | 0.08 ± 0.16 | 930 ± 160 | 0.50 ± 0.17 |
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\textbf{Table 1.} (Continued.)

| Type | Burst        | $t_{s,\text{min}}$ (s) | $\beta_{\text{min}}$ | $t_{s,\text{max}}$ (s) | $\beta_{\text{max}}$ |
|------|--------------|-------------------------|-----------------------|-------------------------|-----------------------|
| Late | 050315       | 40 000 ± 18 000         | 0.99 ± 0.10           | 400 000 ± 130 000       | 1.31 ± 0.23           |
|      | 050721       | 830 ± 97                | 0.55 ± 0.22           | 20 400 ± 4100           | 1.16 ± 0.50           |
|      | 050726       | 4850 ± 900              | 0.95 ± 0.11           | 19 300 ± 4100           | 1.25 ± 0.30           |
|      | 050730       | 4580 ± 570              | 0.434 ± 0.049         | 22 600 ± 1300           | 0.714 ± 0.080         |
|      | 050803       | 9800 ± 3300             | 0.879 ± 0.088         | 60 000 ± 30 000         | 1.29 ± 0.20           |
|      | 050826       | 210 ± 95                | 0.63 ± 0.30           | 84 000 ± 54 000         | 1.64 ± 0.54           |
|      | 050904       | 17 800 ± 1300           | 0.730 ± 0.063         | 45 000 ± 15 000         | 1.28 ± 0.12           |
|      | 051109A      | 4070 ± 570              | 0.720 ± 0.093         | 56 800 ± 6200           | 1.11 ± 0.18           |
|      | 060105       | 4820 ± 180              | 0.92 ± 0.15           | 81 000 ± 24 000         | 1.44 ± 0.19           |
|      | 060204B      | 530 ± 140               | 1.03 ± 0.26           | 13 800 ± 4100           | 1.63 ± 0.16           |
|      | 060306       | 135 ± 38                | 1.00 ± 0.16           | 12 500 ± 6500           | 1.39 ± 0.14           |
|      | 060313       | 175 ± 65                | 0.42 ± 0.16           | 7100 ± 2900             | 1.01 ± 0.14           |
|      | 060714       | 980 ± 220               | 0.78 ± 0.19           | 6750 ± 650              | 1.19 ± 0.21           |
|      | 060807       | 4960 ± 480              | 1.09 ± 0.15           | 17 400 ± 1300           | 1.39 ± 0.20           |
|      | 070220       | 397 ± 87                | 0.23 ± 0.20           | 12 100 ± 1300           | 0.80 ± 0.20           |
|      | 070318       | 990 ± 220               | 0.55 ± 0.11           | 12 480 ± 890            | 1.01 ± 0.27           |
|      | 070419B      | 5970 ± 180              | 0.50 ± 0.15           | 28 100 ± 1200           | 0.82 ± 0.11           |
|      | 070508       | 1600 ± 270              | 0.55 ± 0.12           | 57 000 ± 23 000         | 1.31 ± 0.19           |
|      | 070721B      | 5020 ± 770              | 0.43 ± 0.11           | 10 610 ± 530            | 0.68 ± 0.27           |
|      | 071020       | 630 ± 140               | 0.53 ± 0.11           | 17 000 ± 1500           | 1.38 ± 0.69           |
|      | 071025       | 174 ± 22                | 0.412 ± 0.049         | 13 400 ± 2100           | 1.39 ± 0.30           |
|      | 080207       | 5260 ± 530              | 1.69 ± 0.23           | 17 500 ± 1400           | 2.03 ± 0.42           |
|      | 080319C      | 650 ± 190               | 0.535 ± 0.079         | 30 190 ± 970            | 1.30 ± 0.31           |
|      | 080328       | 5590 ± 200              | 0.57 ± 0.26           | 18 200 ± 1200           | 1.33 ± 0.20           |
|      | 080413B      | 7000 ± 1000             | 0.79 ± 0.10           | 18 800 ± 1300           | 1.18 ± 0.18           |
|      | 080430       | 6490 ± 910              | 0.75 ± 0.16           | 26 000 ± 4000           | 0.90 ± 0.15           |

3. Results

3.1. Relation between the duration and terminating time of the softening process

The duration of the softening is calculated using $\Delta t_s = t_{s,\text{max}} - t_{s,\text{min}}$. The relation between $\Delta t_s$ and $t_{s,\text{max}}$ for these bursts is displayed in figure 2. We find that the data $(t_{s,\text{max}}, \Delta t_s)$ for the selected bursts are distributed mainly within the area confined by the lines represented by $\Delta t_s = t_{s,\text{max}}$ and $\Delta t_s = t_{s,\text{max}}/2$. We observed a difference between the two types of softening: the $(t_{s,\text{max}}, \Delta t_s)$ data for the late type softening are well within the aforementioned area, while some of the data for the early type softening dropped out the aforementioned area (especially when $t_{s,\text{max}}$ is relatively small).
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We performed a Spearman correlation analysis and obtained: for the early type softening, \( \log \Delta t_s = (1.172 \pm 0.051) \log t_{s,\text{max}} - (0.69 \pm 0.14) \), and the fitting parameters are \( R = 0.951 \) (the correlation coefficient), \( N = 57 \) (the number of data points), and \( P = 8.64 \times 10^{-30} \) (the chance probability); for the late type softening, \( \log \Delta t_s = (1.026 \pm 0.040) \log t_{s,\text{max}} - (0.19 \pm 0.18) \), with \( R = 0.982 \), \( N = 26 \), and \( P = 7.51 \times 10^{-19} \). This is in good agreement with the prediction made from the curvature effect [35]. In addition, the results show that the correlation between the two quantities for the late type softening follows well the trend of the identical curve, while in some extent it departs from the identical curve for the early type softening (see also figure 2). The cause of this difference is currently not known.

3.2. Two types of softening distinguished in other aspects

In addition to the duration and terminating time of the softening process, we also measured the variations of the spectral index and the flux density during this period.
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Figure 2. Relation between the duration $\Delta t_s$ and the terminating time $t_{s,\text{max}}$ of the softening process observed in the x-ray afterglows of the selected bursts. The upper and lower solid lines are drawn as $\Delta t_s = t_{s,\text{max}}$ and $\Delta t_s = t_{s,\text{max}}/2$, respectively. Open circles and open circles with dots represent the early type softening and the late type softening, respectively.

The period of the softening is confined by the lower limit ($t_1$) of the interval that measures $\beta_{\text{min}}$ and the upper limit ($t_2$) of the interval that measures $\beta_{\text{max}}$. For example, for GRB 070520B, the lower limit of the time interval associated with its $\beta_{\text{min}} = 1.196 \pm 0.054$ is $t_2 = 125$ s, and the upper limit of the time interval associated with its $\beta_{\text{max}} = 1.92 \pm 0.21$ is $t_2 = 391$ s (see section 4), and thus the softening period of this burst is the time interval from 125 to 391 s. Within this period, we search for the minimum and maximum of the flux $f_\nu$ from the lc.txt file of GRB 070520B. The two extreme values of the flux are denoted by $f_{\nu,\text{min}}$ and $f_{\nu,\text{max}}$ respectively, and the corresponding times are denoted by $t_{f,\text{min}}$ and $t_{f,\text{max}}$ respectively. The values of $t_{f,\text{min}}$ and $t_{f,\text{max}}$ and their uncertainties are estimated in the same way as was adopted in measuring $t_{s,\text{min}}$ and $t_{s,\text{max}}$ and their uncertainties (see section 4). For GRB 070520B, we found $f_{\nu,\text{max}} = (52.7 \pm 3.9) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, $f_{\nu,\text{min}} = (10.5 \pm 6.1) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, $t_{f,\text{max}} = 181.6 \pm 1.0$ s, and $t_{f,\text{min}} = 353.6 \pm 1.0$ s (see table 2). One might observe that for this burst $t_{f,\text{max}}$ is different from $t_{s,\text{min}}$ and $t_{f,\text{min}}$ is different from $t_{s,\text{max}}$. Two facts cause this difference. The first is that time intervals for measuring the flux are generally smaller than those for measuring the spectral index (see figure 1, where the number of data points of the flux within the softening period is much larger than that of the spectral index). The second is that in the softening process some bursts undergo a rise phase and then a decay phase in the light curve, and close to the lower limit of the softening we measure the peak of the flux instead of the flux at the very beginning of the softening process (see also figure 1). (Note that we identified a softening process according to the spectral index but not the flux.)

In table 2, we listed the maximum and minimum values of the flux density detected during the softening process. We calculated the variation rates of the two quantities using $\Delta \beta/\Delta t_s = (\beta_{\text{max}} - \beta_{\text{min}})/\Delta t_s$ and $\Delta \log f_\nu/\Delta t_f = (\log f_{\nu,\text{max}} - \log f_{\nu,\text{min}})/\Delta t_f$, where $\Delta t_f = t_{f,\text{min}} - t_{f,\text{max}}$ is the time interval between $f_{\nu,\text{max}}$ and $f_{\nu,\text{min}}$, which can be different from $\Delta t_s$ (see table 2).
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Table 2. The maximum and minimum values of the flux density (\(f_{\nu,\text{max}}\) and \(f_{\nu,\text{min}}\)) and the corresponding times (\(t_{f,\text{max}}\) and \(t_{f,\text{min}}\)), detected during the softening process.

| Type     | Burst   | \(t_{f,\text{max}}\) (s) | \(f_{\nu,\text{max}}\) | \(t_{f,\text{min}}\) (s) | \(f_{\nu,\text{min}}\) |
|----------|---------|---------------------------|-------------------------|---------------------------|-------------------------|
| Early    | 050315  | 88.0 ± 1.5                | \((8.6 ± 1.4) \times 10^{-10}\) | 620 ± 77                  | \((12.8 ± 2.3) \times 10^{-12}\) |
|          | 050421  | 130.4 ± 1.0               | \((17.1 ± 3.4) \times 10^{-10}\) | 285.0 ± 4.7               | \((9.6 ± 4.5) \times 10^{-11}\) |
|          | 050502B | 743.2 ± 1.0               | \((66.6 ± 4.6) \times 10^{-10}\) | 1277 ± 26                 | \((29.5 ± 9.8) \times 10^{-12}\) |
|          | 050714B | 162.4 ± 1.0               | \((19.2 ± 2.6) \times 10^{-8}\) | 273.2 ± 3.5               | \((2.2 ± 1.5) \times 10^{-9}\) |
|          | 050716  | 109.0 ± 1.0               | \((25.1 ± 3.1) \times 10^{-10}\) | 457.0 ± 1.0               | \((9.0 ± 4.5) \times 10^{-11}\) |
|          | 050717  | 96.0 ± 1.0                | \((32.2 ± 3.9) \times 10^{-10}\) | 202.0 ± 1.0               | \((15.1 ± 9.2) \times 10^{-11}\) |
|          | 050724  | 79.94 ± 0.25              | \((18.6 ± 2.1) \times 10^{-9}\) | 312.0 ± 1.1               | \((7.6 ± 2.4) \times 10^{-10}\) |
|          | 050726  | 382.3 ± 6.9               | \((17.3 ± 2.9) \times 10^{-11}\) | 6178.8 ± 8.6              | \((5.9 ± 1.4) \times 10^{-11}\) |
|          | 050730  | 139.6 ± 1.0               | \((20.5 ± 2.4) \times 10^{-10}\) | 603.6 ± 1.0               | \((22.4 ± 6.7) \times 10^{-11}\) |
|          | 050814  | 167.09 ± 0.30             | \((24.6 ± 4.1) \times 10^{-10}\) | 363.7 ± 2.9               | \((17.0 ± 3.2) \times 10^{-11}\) |
|          | 050904  | 175.0 ± 1.0               | \((34.6 ± 3.4) \times 10^{-10}\) | 566.0 ± 1.0               | \((14.8 ± 5.6) \times 10^{-11}\) |
|          | 050922B | 755.6 ± 1.6               | \((5.7 ± 1.0) \times 10^{-9}\) | 1426 ± 12                 | \((19.1 ± 8.6) \times 10^{-12}\) |
|          | 051117A | 134.0 ± 1.0               | \((87.3 ± 5.7) \times 10^{-10}\) | 1257.7 ± 1.1              | \((41.5 ± 9.3) \times 10^{-11}\) |

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Table 2. (Continued.)

| Type | Burst   | $t_{f,\text{max}}$ (s) | $f_{\nu,\text{max}}$ $^a$ | $t_{f,\text{min}}$ (s) | $f_{\nu,\text{min}}$ $^a$ |
|------|---------|-------------------------|---------------------------|-------------------------|---------------------------|
| Late |         |                         |                           |                          |                           |
| 050315 | 23810 ± 270 | (9.7 ± 1.1) × 10$^{-12}$ | 432 400 ± 9400 | (40.8 ± 7.4) × 10$^{-14}$ |
| 050721 | 7770 ± 50 | (14.1 ± 3.4) × 10$^{-11}$ | 23 530 ± 190 | (8.8 ± 6.2) × 10$^{-13}$ |
| 050726 | 4001 ± 53 | (27.3 ± 6.6) × 10$^{-12}$ | 23 010 ± 380 | (10.7 ± 2.9) × 10$^{-13}$ |
| 050730 | 43701 ± 3.7 | (5.2 ± 1.0) × 10$^{-10}$ | 23 912 ± 28 | (7.2 ± 2.9) × 10$^{-12}$ |
| 050803 | 10 502 ± 53 | (5.7 ± 4.0) × 10$^{-11}$ | 83 100 ± 5500 | (9.7 ± 1.4) × 10$^{-13}$ |
| 050826 | 169.7 ± 5.0 | (20.8 ± 5.1) × 10$^{-11}$ | 111 000 ± 12 000 | (10.4 ± 6.8) × 10$^{-14}$ |
| 050904 | 18 5828 ± 8.9 | (8.6 ± 1.8) × 10$^{-11}$ | 47 020 ± 120 | (4.9 ± 3.4) × 10$^{-13}$ |
| 051109A | 4185 ± 32 | (61.0 ± 8.3) × 10$^{-12}$ | 57 940 ± 670 | (27.2 ± 5.3) × 10$^{-13}$ |
| 060105 | 55712 ± 3.4 | (24.4 ± 5.7) × 10$^{-11}$ | 87 600 ± 300 | (12.6 ± 4.8) × 10$^{-12}$ |
| 060204B | 411 ± 17 | (11.6 ± 1.9) × 10$^{-11}$ | 16 720 ± 110 | (2.1 ± 1.1) × 10$^{-12}$ |
| 060306 | 102.4 ± 1.7 | (10.3 ± 1.5) × 10$^{-10}$ | 16 970 ± 220 | (40.3 ± 9.5) × 10$^{-13}$ |
| 060313 | 149.4 ± 2.4 | (27.2 ± 6.1) × 10$^{-11}$ | 4500 ± 17 | (3.0 ± 2.1) × 10$^{-12}$ |
| 060714 | 880 ± 10 | (8.4 ± 1.8) × 10$^{-11}$ | 6860 ± 28 | (3.7 ± 2.1) × 10$^{-12}$ |
| 060807 | 4743 ± 53 | (36.6 ± 4.9) × 10$^{-12}$ | 17 850 ± 250 | (62.4 ± 9.5) × 10$^{-13}$ |
| 070220 | 542.5 ± 3.5 | (41.0 ± 8.0) × 10$^{-11}$ | 12 786 ± 53 | (4.1 ± 2.5) × 10$^{-12}$ |
| 070318 | 789.1 ± 4.1 | (15.8 ± 3.8) × 10$^{-11}$ | 7584 ± 39 | (2.8 ± 2.0) × 10$^{-12}$ |
| 070419B | 5807.5 ± 3.8 | (17.3 ± 4.3) × 10$^{-11}$ | 29 245 ± 19 | (6.1 ± 4.6) × 10$^{-12}$ |
| 070508 | 1583.3 ± 2.4 | (8.0 ± 2.1) × 10$^{-10}$ | 53 632 ± 269 | (11.7 ± 8.3) × 10$^{-13}$ |
| 070721B | 4438 ± 15 | (40.4 ± 9.5) × 10$^{-12}$ | 10 501 ± 38 | (5.1 ± 2.4) × 10$^{-12}$ |
| 071020 | 566.6 ± 2.9 | (31.4 ± 6.8) × 10$^{-11}$ | 17 000 ± 1500 | (11.4 ± 3.6) × 10$^{-13}$ |
| 071025 | 159.0 ± 1.0 | (100.8 ± 7.5) × 10$^{-10}$ | 10 866 ± 39 | (2.3 ± 1.3) × 10$^{-12}$ |
| 080207 | 4751 ± 19 | (17.3 ± 4.1) × 10$^{-11}$ | 18 230 ± 100 | (9.8 ± 4.6) × 10$^{-12}$ |
| 080319C | 505.1 ± 7.7 | (44.9 ± 6.0) × 10$^{-11}$ | 30 511 ± 35 | (1.8 ± 1.3) × 10$^{-12}$ |
| 080328 | 5517 ± 14 | (15.0 ± 3.4) × 10$^{-11}$ | 18 298 ± 43 | (4.9 ± 3.0) × 10$^{-12}$ |
| 080413B | 8541 ± 53 | (3.5 ± 1.4) × 10$^{-11}$ | 12 367 ± 53 | (2.1 ± 1.5) × 10$^{-12}$ |
| 080430 | 5965 ± 35 | (14.2 ± 3.5) × 10$^{-12}$ | 29 943 ± 57 | (2.2 ± 1.1) × 10$^{-12}$ |

$^a$ In units of erg cm$^{-2}$ s$^{-1}$.
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Figure 3. Relation between the variation rates of the flux density and spectral index, $\Delta \log f_\nu / \Delta t_f$ and $\Delta \beta / \Delta t_s$, during the softening process observed in the x-ray afterglows of the selected bursts. Solid lines from top to the bottom represent the $\Delta \log f_\nu / \Delta t_f = k \Delta \beta / \Delta t_s$ lines with $k = 6, 2, 1,$ and $0.5$, respectively. The open circles represent the early type softening while the open circles with dots represent the late type softening.

In figure 3, we present the relation between the two variation rates. It shows that the two types of softening do have distinct behaviors in the variation rate. Data for the late type softening are distributed within the $\Delta \log f_\nu / \Delta t_f = 2 \Delta \beta / \Delta t_s$ and $\Delta \log f_\nu / \Delta t_f = 6 \Delta \beta / \Delta t_s$ curves, which follow well the trend of the identical curve. For the early type softening, the data are scattered in a wider area confined by the $\Delta \log f_\nu / \Delta t_f = 0.5 \Delta \beta / \Delta t_s$ and $\Delta \log f_\nu / \Delta t_f = 6 \Delta \beta / \Delta t_s$ curves. The trend of the early type is obviously deviated from that of the identical curve.

A Spearman correlation analysis for the two variation rates was also performed. For the early type softening we got $\log \Delta \log f_\nu / \Delta t_f = (0.556 \pm 0.045) \log \Delta \beta / \Delta t_s - (0.85 \pm 0.11)$, with $R = 0.857$, $N = 57$, and $P = 1.84 \times 10^{-17}$, and for the late type softening we obtained $\log \Delta \log f_\nu / \Delta t_f = (0.987 \pm 0.071) \log \Delta \beta / \Delta t_s + (0.51 \pm 0.33)$, with $R = 0.943$, $N = 26$, and $P = 5.49 \times 10^{-13}$. The correlation must be owing to the fact that the softening scope (represented by $\Delta \beta$) and the decaying scale (described by $\Delta \log f_\nu$) vary mildly for different sources, but the time intervals of the process differ significantly. The two types of softening occupy distinct areas in the plot due to the large difference in softening duration between them. But why the trends of the relation for the two types are so different remains unclear.

4. Discussion and conclusions

In the present work, we studied the relation between the duration and terminating time of the softening process observed in the x-ray afterglows of the Swift bursts. We found that these two quantities are obviously correlated, as expected from the curvature effect. The analysis reveals that the softening can be divided into two classes merely on the basis of...
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the corresponding terminating time: the early type softening \((t_{s,\text{max}} \leq 4000\text{ s})\) and the late type softening \((t_{s,\text{max}} > 4000\text{ s})\). The two types of softening show different behaviors in their duration and the terminating time plot. We also investigated the relation between the variation rates of the flux density and the spectral index during the softening process. In this respect, more obvious discrepancy is observed between the two types of softening.

As revealed in [35], the duration of the softening can be affected by three parameters: the Lorentz factor, the radius, and the intrinsic radiative peak energy concerned. As shown in [35] figure 6, for the same Lorentz factor \(\Gamma\) and radius \(R_c\), a smaller intrinsic peak energy \(E_{0,p}\) can lead to a smaller duration of the process, while the corresponding terminating time will be unchanged. It would give rise to the departure observed in figure 2. Why does this occur in the early type softening but not in the late type softening? We suspect that probably the early type softening is of internal shock origin while the late type softening is of external shock origin. In the former case the Lorentz factor is large and thus the curvature effect is sensitive to the fireball parameters, while in the latter case the Lorentz factor is small and hence the curvature effect is less sensitive to the fireball parameters. Is it due to the selection effect? This is unlikely, because if the earlier softening tends to have a relatively small duration due to the overlapping of its start time with other components of emission, then it will affect both variation rates of the flux density and spectral index in the same way and then the possible influence will be canceled. But figure 3 clearly shows that the early softening does have a different behavior relative to the rest.

The fact that the GRBs with lowest \(t_{s,\text{max}}\) tend to deviate from the \(\Delta t_s \sim t_{s,\text{max}}\) law may be partially due to the fact that \(\Delta t_s\) is defined as the difference of the linear quantities \(t_{s,\text{max}}\) and \(t_{s,\text{min}}\) and we take the logarithm of \(\Delta t_s\) and correlate it with the logarithm of \(t_{s,\text{max}}\). Is it better to use the ratio between \(t_{s,\text{max}}\) and \(t_{s,\text{min}}\) rather than \(\Delta t_s\)? The ratio, when passing to logarithms, becomes the difference between \(\log t_{s,\text{max}}\) and \(\log t_{s,\text{min}}\). Is it a more suitable quantity to correlate with \(\log t_{s,\text{max}}\)? We studied this issue by replacing \(\Delta t_s\) with \(t_{s,\text{max}}/t_{s,\text{min}}\) in figure 2. We found a weak correlation between \(\log(t_{s,\text{max}}/t_{s,\text{min}})\) and \(\log t_{s,\text{max}}\) (the plot is omitted). The data are quite scattered in the \(\log(t_{s,\text{max}}/t_{s,\text{min}})\) versus \(\log t_{s,\text{max}}\) plane. The analysis does not provide any information on the causes of the mentioned deviation. This must be due to the fact that \(\log(t_{s,\text{max}} - t_{s,\text{min}})\) is closer to \(\log t_{s,\text{max}}\) than \(\log t_{s,\text{max}} - \log t_{s,\text{min}}\) is, as long as the discrepancy between \(t_{s,\text{max}}\) and \(t_{s,\text{min}}\) is large enough (say, when \(t_{s,\text{max}}\) is one order of magnitude larger than \(t_{s,\text{min}}\)).

The strongest factor in favor of our suggestion of two types of origin might be that the two types of softening occur at very different timescales (the former appears much earlier and the latter emerges very late). In addition, we found that the early type softening is observed in the steep decay phase which is believed to be due to the high latitude emission of the prompt phase [6, 9], [11]–[18] and the late type softening is found in the normal afterglow phase which was believed to be due to the external shocks [42]–[44].

It should be pointed out that the softening process is divided into two classes empirically. If the two kinds of softening are associated with internal and external shock mechanisms, it might be more natural to divide them according to the start time of the process. By examining the data in tables 1 and 2, we roughly redivided the softening process into two classes according to \(t_{s,\text{min}}\) being less or larger than 500 s. Shown in figure 4 are the relations between the duration and the terminating time of the softening process for the newly defined early and late types. As expected, they do not dramatically affect the result. The two types are distributed in two distinguishable domains in the
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Figure 4. Relation between $\Delta t_s$ and $t_{s,\text{max}}$ for the newly defined two types of the softening process. Filled circles in the upper panel and open circles in the lower panel represent the process with $t_{s,\text{min}} > 500$ s (the newly defined late type softening process). Filled circles in the lower panel and open circles in the upper panel stand for the process with $t_{s,\text{min}} \leq 500$ s (the newly defined early type softening process). The two solid lines are the same as they are in figure 2.

$\Delta t_s$ versus $t_{s,\text{max}}$ plane. However, a slight overlapping between the two distributions is observed. We do not know whether this overlapping is due to the overlapping of physical parameters or merely the statistical fluctuation. One might notice that few of the new early type occupy the late type domain near the identical curve and few of the late type are located in the early type domain near the $\Delta t_s = t_{s,\text{max}}/2$ curve. Both seem to be a result of the extension of the two types. We therefore insist that this possibility cannot be ruled out with the current data. However, for an empirical analysis, we prefer the former division, i.e. dividing them according to $t_{s,\text{max}}$, since no overlapping is observed in this division scenario.

Studied in figure 3 is the relation between the variation rates of the flux density and spectral index during the softening process. How would it be if we simply studied the relation between $\Delta \log f_\nu$ and $\Delta \beta$? Shown in figure 5 is the result. One finds that the two types seem to have different distributions of $\Delta \log f_\nu$ and $\Delta \beta$. The late type softening tends to have smaller $\Delta \beta$ and slightly larger $\Delta \log f_\nu$. However, the overlapping is so heavy that we cannot tell the type of a softening merely according to its location in the
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Figure 5. Relation between the variations of the flux density and the spectral index, \( \Delta \log f_{\nu} \) and \( \Delta \beta \), during the softening process observed in the x-ray afterglows of the selected bursts. Filled circles stand for the late type of softening and open circles for the early type.

\( \Delta \log f_{\nu} \) versus \( \Delta \beta \) plane. This difference, if confirmed statistically later, might become a hint in searching for the physical difference between the two softening processes.

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References

[1] Campana S et al, 2006 Nature 442 1008 [SPIRES]
[2] Ghisellini G et al, 2006 Mon. Not. R. Astron. Soc. 372 1699
[3] Gehrels N et al, 2006 Nature 444 1044 [SPIRES]
[4] Zhang B et al, 2007 Astrophys. J. 655 L25 [SPIRES]
[5] Mangano V et al, 2007 Astron. Astrophys. 470 105 [SPIRES]
[6] Zhang B B, Liang E W and Zhang B, 2007 Astrophys. J. 666 1002 [SPIRES]
[7] Tagliaferri G et al, 2005 Nature 436 985 [SPIRES]
[8] Barthelmy S D et al, 2005 Astrophys. J. 635 L133 [SPIRES]
[9] Liang E W et al, 2006 Astrophys. J. 646 351 [SPIRES]
[10] Sakamoto T et al, 2007 Astrophys. J. 669 1115 [SPIRES]
[11] Kumar P and Panaitec A, 2000 Astrophys. J. 541 L51 [SPIRES]
[12] Dermer C D, 2004 Astrophys. J. 614 284 [SPIRES]
[13] Dyks J et al, 2005 arXiv:astro-ph/0511699
[14] Panaitec A et al, 2006 Mon. Not. R. Astron. Soc. 366 1357
[15] Zhang B et al, 2006 Astrophys. J. 642 354 [SPIRES]
[16] Butler N R and Kocevski D, 2007 Astrophys. J. 663 407 [SPIRES]
[17] Qin Y-P, 2008 Astrophys. J. 683 900 [SPIRES]
[18] Starling R L C et al, 2008 Mon. Not. R. Astron. Soc. 384 504
Two types of softening detected in x-ray afterglows of Swift bursts

[19] Qin Y-P, 2002 Astron. Astrophys. 396 705 [SPIRES]
[20] Qin Y-P et al., 2004 Astrophys. J. 617 439 [SPIRES]
[21] Qin Y-P et al., 2006 Phys. Rev. D 74 063005 [SPIRES]
[22] Goodman J, 1986 Astrophys. J. 308 L47 [SPIRES]
[23] Paczynski B, 1986 Astrophys. J. 308 L43 [SPIRES]
[24] Fenimore E E et al., 1996 Astrophys. J. 473 998 [SPIRES]
[25] Sari R and Piran T, 1997 Astrophys. J. 485 270 [SPIRES]
[26] Ryde F and Petrosian V, 2002 Astrophys. J. 578 290 [SPIRES]
[27] Kocevski D, Ryde F and Liang E-W, 2003 Astrophys. J. 596 389 [SPIRES]
[28] Qin Y-P and Lu R-J, 2005 Mon. Not. R. Astron. Soc. 362 1085
[29] Shen R-F et al., 2005 Mon. Not. R. Astron. Soc. 362 59
[30] Lu R-J, Qin Y-P, Zhang Z-B and Yi T-F, 2006 Mon. Not. R. Astron. Soc. 367 275
[31] Lu R-J, Peng Z-Y and Dong W, 2007 Astrophys. J. 663 1110 [SPIRES]
[32] Peng Z-Y et al., 2006 Mon. Not. R. Astron. Soc. 368 1351
[33] Qin Y-P et al., 2005 Astrophys. J. 632 1008 [SPIRES]
[34] Jia L-W, 2008 Chin. J. Astron. Astrophys. 4 451
[35] Qin Y-P, 2008 Astrophys. J. at press [arXiv:0806.3339v1]
[36] Fan Y Z et al., 2006 J. Cosmol. Astropart. Phys. JCAP09(2006)013 [SPIRES]
[37] Dado S, Dar A and Rujula A D, 2008 Astrophys. J. 681 1408 [SPIRES]
[38] Ruffini R et al., 2006 Astrophys. J. 645 L109 [SPIRES]
[39] Bianco C L et al., 2008 AIP Conf. Proc. 966 12 [SPIRES]
[40] Frontera F et al., 2000 Astrophys. Suppl. Ser. 127 59
[41] Band D et al., 1993 Astrophys. J. 413 281 [SPIRES]
[42] Meszaros P and Rees M J, 1997 Astrophys. J. 476 232 [SPIRES]
[43] Sari R, Piran T and Narayan R, 1998 Astrophys. J. 497 L17 [SPIRES]
[44] Chevalier R A and Li Z-Y, 2000 Astrophys. J. 536 195 [SPIRES]