A lower occurrence rate of bright X-ray flares in SN-GRBs than $z < 1$ GRBs: evidence of energy partitions?

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ABSTRACT

The occurrence rates of bright X-ray flares in $z < 1$ gamma-ray bursts (GRBs) with or without observed supernovae (SNe) association were compared. Our Sample I: the $z < 1$ long GRBs (LGRBs) with SNe association (SN-GRBs) and with early Swift/X-Ray Telescope (XRT) observations, consists of 18 GRBs, among which only two GRBs have bright X-ray flares. Our Sample II: for comparison, all the $z < 1$ LGRBs without observed SNe association and with early Swift/XRT observations, consists of 45 GRBs, among which 16 GRBs present bright X-ray flares. Thus, the study indicates a lower occurrence rate of bright X-ray flares in Sample I (11.1%) than in Sample II (35.6%). In addition, if dim X-ray fluctuations are included as flares, then 16.7% of Sample I and 55.6% of Sample II are found to have flares, again showing the discrepancy between these two samples. We examined the physical origin of these bright X-ray flares and found that most of them are probably related to the central engine reactivity. To understand the discrepancy, we propose that such a lower occurrence rate of flares in the SN-GRB sample may hint at an energy partition among the GRB, SNe, and X-ray flares under a saturated energy budget of massive star explosion.

Key words: gamma-ray burst: general – stars: supernovae: general

1 INTRODUCTION

Gamma-ray bursts (GRBs) are known as the most luminous electromagnetic explosion in the Universe (see Piran 2004; Mészáros 2006; Kumar & Zhang 2015, for reviews). For example, the total isotropic energy of GRB 160625B can reach $\sim 10^{54}$ erg (Wang et al. 2017). Observations show that long-duration, soft-spectrum GRBs (LGRB) are associated with supernovae (SNe) Ib/c (see van Paradijs 1999; Soderberg 2006; Woosley & Bloom 2006; Della Valle 2007, for reviews), which are generally believed to originate from the collapses of massive stars (Woosley 1993; MacFadyen & Woosley 1999; Woosley, Heger, & Weaver 2002; Heger et al. 2003; Zhang, Woosley, & Heger 2004; Smartt 2009; Woosley & Heger 2012). The direct evidence of the GRBs with SNe association (SN-GRBs) is revealed by Hjorth & Bloom (2012), which classifies the SN-GRBs into five grades as follows. Sample A: spectroscopic SNe; Sample B: a clear light curve bump and some spectroscopic evidence; Sample C: a clear bump consistent with other SN-GRBs put at the spectroscopic redshift; Sample D: a bump, but the inferred SN properties are not fully consistent with other SN-GRBs, or the bump was not well sampled, or there is no spectroscopic redshift for the GRB; Sample E: a bump, either of low significance or inconsistent with other SN-GRBs. Following the spirit of the above classification, Cano et al. (2017b) presented a quite comprehensive database compiled of the observational and physical properties of the GRB prompt emission and SN-GRBs, respectively, which consists of 46 SN-GRBs.

On the other hand, X-ray flares were observed by Swift/X-Ray Telescope (XRT) both in long and short GRBs after the prompt gamma-ray emission (Burrows et al. 2005; Fan & Wei 2005; Zhang et al. 2006; Nousek et al. 2006; Liang et al. 2006; Falcone et al. 2006; O’Brien et al. 2006). A few flares can occur even up to
several days after the GRB trigger (e.g., Chincarini et al. 2007, 2010; Falcone et al. 2007). The physical origins of X-ray flares remain mysterious, which may be related to the late-time activity of the central engine (e.g., Kumar & Panaitescu 2000; Perna, Armitage, & Zhang 2006; Dai et al. 2006; Lazzati & Perna 2007; Falcone et al. 2007; Maxham & Zhang 2009; Chincarini et al. 2010; Margutti et al. 2010), or to the external shock (e.g., Proga & Zhang 2006; Giannios 2006; Curran et al. 2008; Bernardini et al. 2011). The steep decay was observed both in the decay phase of flares and the prompt emission (e.g., Uhm & Zhang 2016; Jia, Uhm, & Zhang 2016; Mu et al. 2016a; Lin et al. 2017a). The physical origins of Lin et al. 2016). A criterion was introduced to http://www.astro.caltech.edu/grbox/grbox.php Lin et al. 2017a Lazzati & Perna 2007), or to the external shock (e.g., Proga & Zhang 2006; Giannios 2006; Curran et al. 2008; Bernardini et al. 2011). The steep decay was observed both in the decay phase of flares and the prompt emission (e.g., Uhm & Zhang 2016; Jia, Uhm, & Zhang 2016; Mu et al. 2016b; Lin et al. 2017a,b). Additionally, the high variabilities in the steep decay phase may originate from the activities of the central engine (e.g., Proga et al. 2003; Lei et al. 2007; Liu et al. 2010; Zhang, Zhang, & Castro-Tirado 2016; Lin et al. 2016). A criterion was introduced to judge the physical origin of X-ray flares, which is based on the relative variability flux and timescale (e.g., Ioka, Kobayashi, & Zhang 2005; Bernardini et al. 2011; Mu et al. 2016b). The external origin of the flares means that the flares are related to afterglow variability. On the contrary, the internal origin corresponds to the late-time activity of the central engine. Two well-known types of central engines are the hyper-accreting stellar-mass black hole (e.g., Paczynski 1991; Narayan, Paczynski, & Piran 1992; MacFadyen & Woosley 1999; Perna, Armitage, & Zhang 2006; Luo et al. 2013; Liu, Gu, & Zhang 2017) and the millisecond magnetar (e.g., Usos 1992; Duncan & Thompson 1992; Rees & Mészáros 2000; Zhang & Mészáros 2002; Dai et al. 2006; Metzger et al. 2015). For a SN-GRB with an X-ray flare from internal origin, the central engine should account for three explosions, i.e., the supernovae, the prompt gamma-ray emission, and the X-ray flare.

The main purpose of this work is to compare the occurrence rates of X-ray flares in the \( z < 1 \) GRBs with or without observed SNe association, and investigate the physics if significant discrepancy exists between these two rates. The remainder of this paper is organized as follows. Sample selection is presented in Section 2. The main fitting procedure used for X-ray flare data is shown in Section 3. Occurrence rate and physical origin of bright X-ray flares are investigated in Section 4. Discussion and conclusions are summarised in Section 5.

2 SAMPLE SELECTION

A recent review paper, Cano et al. (2017b), presented an up-to-date progress report of the connection between LGRBs and their accompanying SNe. Their sample consists of 46 SN-GRBs, which are classified into five grades, as mentioned in Section 1. In this work, the bright X-ray flares in GRBs with or without observed SNe association were studied. Then, the 46 SN-GRBs in Swift/XRT data were examined to investigate the X-ray afterglow of these sources. The following selection criteria were used to derive a sample of targets.

- (1) The starting point is the sample of Swift/XRT-detected GRBs. We picked only events observed by the Swift/XRT. Thus, 19 GRBs without XRT follow-up observations can be removed (the removed sources can be found by referring to Table 1).
- (2) Since most flares occur in the early time (\( t_p \lesssim 100 \text{ s} \), Yi et al. 2016), we chose the GRBs with early Swift/XRT follow-up observations (trigger time \( \lesssim 300 \text{ s} \)), and therefore eight GRBs were removed.
- (3) In addition, by taking into account the Swift orbital constraint, an adequate X-ray afterglow observation in the early time (100 s \( \sim 1000 \text{ s} \)) was necessary. Thus, we removed three GRBs with the poor sampling in the early time.

Among the 46 SN-GRBs in Cano et al. (2017b), there are 16 GRBs matching the aforementioned three criteria. Moreover, two recent SN-GRBs, GRB 161219B/BN 2016jou(Ashall et al. 2017; Cano et al. 2017a) and GRB 171205A/SN 2017iuk (Postigo et al. 2017; Prentice et al. 2017), were added to our Sample I. Thus, Sample I consists of 18 GRBs, among which three sources are X-ray Flashes (XRFs) \(^2\). There are a total of seven XRFs among all the 48 SN-GRBs, which are noted in the first column of Table 1. In addition, the enumerated list pertaining to our sample selection is reported in Table 1, where the related comments are shown in the fourth column.

The XRT light curves of all the 18 SN-GRBs in our Sample I \(^3\) are presented in Figure 1. In this figure, a smooth broken power-law or a single power-law (Beuermann et al. 1999) was used to fit the light curve, and the related fitting parameters are reported in Table 2. We examined the 18 GRBs and searched for bright X-ray flares satisfying the condition “\( F_p > 3F \)” (e.g., Yi et al. 2016; Mu et al. 2016a), where \( F_p \) and \( F \) are the peak flux and the underlying continuum flux at the peak time of the flare, respectively. We found that only two sources, GRBs 060904B and 161219B, have bright X-ray flares, as shown by the mark “B” (bright) in the fourth column of Table 1. Then, the occurrence rate of bright X-ray flares in our Sample I (SN-GRB) is only 11.1%, which seems to be lower than that in the general population.

Since the detection of SNe is limited by the distance, secure SNe identification becomes difficult because the SNe appears fainter at a higher redshift (see, e.g., Woosley & Bloom 2006). The SN-GRBs in Table 1 exhibit redshift \( z < 1 \) whereas the median redshift of Swift long GRBs is above 2 (Jakobsson et al. 2006; Salvaterra et al. 2012). Thus, for a comparison, we studied another sample, Sample II, which consists of all the \( z < 1 \) LGRBs between January 2005 and December 2017 that satisfy the aforementioned three criteria, except for the 18 sources in Sample I. In other words, Sample II is composed of the \( z < 1 \) LGRBs with rapid and adequate XRT follow-up observations, and without optically observed SNe association. We should stress that, here the words “without observed SNe association” do not mean “SN-less”. In our opinion, many SN-GRBs may still exist in our Sample II. However, due to observational constraints, accompanying

\[^1\]https://swift.gsfc.nasa.gov/archive/grb_table/  
\[^2\]Hjorth & Bloom (2012) showed that the XRF population is likely associated with massive stellar death. XRFs are included as “low-luminosity” GRBs (Cano et al. 2017b).  
\[^3\]http://www.swift.ac.uk/xrtcurves/ (Evans et al. 2007, 2009) and http://www.astro.caltech.edu/grbox/grbox.php
Table 1. The total 48 SN-GRBs are taken into account in this work, among which the seven XRFs are noted in the first column. The comments in the fourth column: 18 SN-GRBs in Sample I, where the two bright X-ray flares and one dim X-ray fluctuation are denoted as “B” (bright) and “D” (dim), respectively; 8 GRBs without early Swift/XRT follow-up observations; 3 GRBs with the poor sampling in the early time; 19 GRBs without Swift/XRT observations. The definition of the grades of SN-GRBs are from Hjorth & Bloom (2012) and Cano et al. (2017b), which are shown in the fifth column: Sample A: spectroscopic SNe; Sample B: a clear light curve bump and some spectroscopic evidence; Sample C: a clear bump consistent with other SN-GRBs putting at the spectroscopic redshift; Sample D: a bump, but the inferred SN properties are not fully consistent with other SN-GRBs, or the bump was not well sampled, or there is no spectroscopic redshift for the GRB; Sample E: a bump, either of low significance or inconsistent with other SN-GRBs. The SN-GRB references may refer to Table 1 of Kovacevic et al. (2014) and Table 4 of Cano et al. (2017b).

| GRB     | SNe   | z     | Comments       | Grade |
|---------|-------|-------|----------------|-------|
| 050416A |       | 0.6528| Sample I D     |       |
| 060218X | 2006aj| 0.0342| Sample I A     |       |
| 060729  | –     | 0.5428| Sample I D     |       |
| 060904B | –     | 0.7029| Sample I(B) C  |       |
| 070419A | –     | 0.9705| Sample I D     |       |
| 080319B | –     | 0.9371| Sample I C     |       |
| 081107  | 2008lw| 0.5295| Sample I B     |       |
| 090618  | –     | 0.5400| Sample I C     |       |
| 100316D | 2010bh| 0.0592| Sample I A     |       |
| 100418A | –     | 0.6239| Sample I D/E   |       |
| 101219B | 2010ma| 0.5518| Sample I A/B   |       |
| 111228A | –     | 0.7163| Sample I E     |       |
| 120424A | 2012dz| 0.2825| Sample I A/     |       |
| 120729A | –     | 0.8090| Sample I D/E   |       |
| 130927A | 2013eq| 0.3399| Sample I B     |       |
| 130831A | 2013fu| 0.4790| Sample I D     |       |
| 161219B | 2016jca| 0.1475| Sample I(B) A  |       |
| 171205A | –     | 0.0386| Sample I A     |       |
| 050824X | –     | 0.8281| no rapid follow-up E |   |
| 091127  | 2009nz| 0.4904| no rapid follow-up B |   |
| 101225A | –     | 0.8470| no rapid follow-up D |   |
| 111209A | –     | 0.6670| no rapid follow-up A/B | |
| 111211A | –     | 0.4780| no rapid follow-up B/C | |
| 130702A | 2013dx| 0.1450| no rapid follow-up A |   |
| 140606B | –     | 0.3840| no rapid follow-up A/B |  |
| 150518A | –     | 0.2560| no rapid follow-up C/D | |
| 050525A | 2005nc| 0.6060| poor sampling B |     |
| 120714B | 2012eb| 0.3984| poor sampling B |     |
| 150818A | –     | 0.2820| poor sampling B |     |
| 970228  | –     | 0.6950| no XRT C       |       |
| 980236  | –     | 0.6950| no XRT D       |       |
| 980125  | 1998bw| 0.0086| no XRT A       |       |
| 990712  | –     | 0.4330| no XRT C       |       |
| 991208  | –     | 0.7063| no XRT E       |       |
| 000911  | –     | 1.0585| no XRT E       |       |
| 011121  | 2001ke| 0.3620| no XRT B       |       |
| 020305  | –     | –     | no XRT E       |       |
| 020405  | –     | 0.6899| no XRT C       |       |
| 020819C | –     | –     | no XRT D       |       |
| 021211  | 2002lt| 1.0040| no XRT B       |       |
| 030529A | 2003dh| 0.1686| no XRT A       |       |
| 030725  | –     | –     | no XRT D       |       |
| 031203X | 2003lw| 0.1053| no XRT A       |       |
| 040924  | –     | 0.8580| no XRT C       |       |
| 041006  | –     | 0.7160| no XRT C       |       |
| 130215A | 2013ex| 0.5970| no XRT B       |       |
Figure 1. The X-ray light curves of 18 SN-GRBs with early Swift/XRT follow-up observations in our Sample I. The best fitting is shown by the red curves. The smooth broken power-law and single power-law are abbreviated to “bpl” and “pl”, respectively. “N05” (Norris et al. 2005) model means function (2) in the fitting of the bright flares from GRBs 060904B and 161219B.
SNe was not observed for those GRBs. The potential influence of such an issue on our results is discussed in the last section. Furthermore, Hjorth & Bloom (2012) showed that SN-less GRBs, such as GRB 060505 (Fynbo et al. 2006), 060614 (Fynbo et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006), and possibly 051109B (Perley et al. 2006) and XRF 040701 (Soderberg et al. 2005), have been observed to deep limits and no accompanying SN is found. Among these sources, only GRBs 051109B and 060614 have XRT rapid follow-up observations, and have adequate observational data in the early time. Since a macronova is likely to be associated with GRB 060614 (Yang et al. 2015), which indicates a merger of two compact objects, 060614 is not included in Sample II. Our Sample II comprises 45 GRBs (44 LGRBs and one XRF), see Table 3 for details. Among all of these 45 GRBs, we found that 16 GRBs have bright X-ray flares, which are denoted as “B” (bright) in the third column of Table 3.

On the other hand, some dim X-ray fluctuations may be regarded as weak X-ray flares. Here we define the dim X-ray fluctuation as the condition “1.5F < F_p < 3F_m” is satisfied. Thus, only one SN-GRB has dim X-ray fluctuation, as denoted by the character “D” (dim) in the fourth column of Table 1. Furthermore, in Sample II, nine GRBs have dim X-ray fluctuations, as reported by “D” in the third column of Table 3. The number of flares, N_{flare}, is also given in the last column of Table 3.

### 3 FITTING PROCEDURE

The X-ray flare properties were investigated by fitting the 0.3 – 10 keV(Swift/XRT) light curve with an empirical function proposed by Norris et al. (2005), for t > t_t, 

\[
F_t = A e^{-(t - t_t) / \tau}.
\]

where \(F_t\) is the X-ray flux at time \(t\), \(A\) is the amplitude, \(\tau\) is the characteristic time, and \(t_t\) is the break time of the flare. The fitting procedure is detailed in Norris et al. (2005), and the results are shown in Table 3.

Table 2. Fitting parameters of the 18 SN-GRBs in our Sample I. From left to right: GRB, the power-law function parameters \((F_t\) and power-index \(\alpha\)); the smooth broken power-law function parameters \((F_1\) and \(\alpha_1\), \(F_2\) and \(\alpha_2\), \(t_b\), \(\omega\), and \(\text{red } - \chi^2\)). The fitting re-

### Lower occurrence of X-ray flares in SN-GRBs

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The fitting results of the X-ray flares are reported in Table 4. In Sample I, each of GRBs 060904B and 161219B has a single bright flare. In Sample II, 26 bright flares exist in 16 GRBs, among which five GRBs have multiple flares and 11 GRBs have a single flare, as shown in the last column of Table 3. In this work, our concerns focus on whether or not, the central engine exhibits reactivity behaviour. As investigated by Bernardini et al. (2011), a sizable fraction of late-time flares (i.e., those with peak time \(t_p < 10^3 s\)) are compatible with afterglow variability. On the contrary, the early flares are more likely to be related to central engine reactivity. If a GRB has multiple X-ray flares, it is reasonable to judge whether the central engine becomes reactive after the prompt emission by studying the physical origin of the first flare. Thus, for a GRB with multiple flares, only the first flare was fitted. The fitting procedure of GRBs 060904B and 161219B is shown in Figure 2.

In addition, to estimate the relative variability flux \(\Delta F_t / F_t\), where \(\Delta F_t\) and \(F_t\) are the increase of the flux and the flux at time \(t\), respectively, then, the underlying continuum was fitted by 

\[
F_t = A e^{-(t - t_t) / \tau}.
\]

The peak time of the flare is \(t_p = t_t + t_\omega = (\tau_{1/2})^{1/2} + t_\omega\). The time of flare onset \(t_0\) is adopted in Equation (1). Then, the above equation is simplified as 

\[
F_t = A e^{2(\tau_{1/2})^{1/2}} - \frac{t - t_t}{\tau}.
\]

Thus, the peak flux of flare is \(A = F_{\text{max}} = F_{t_p}\), and \(t_p = (\tau_{1/2})^{1/2}\). The flare width is measured between the two 1/e intensity points, 

\[
\omega = \Delta t_{1/e} = \tau_{1/2}(1 + \mu)^{1/2}.
\]

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In addition, to estimate the relative variability flux \(\Delta F_t / F_t\), where \(\Delta F_t\) and \(F_t\) are the increase of the flux and the underlying continuum flux at the peak time of the flare, respectively, then, the underlying continuum was fitted by using a simple power-law (black solid line, Fig. 2) (e.g., Bernardini et al. 2011; Margutti et al. 2011). The fitting results of the underlying continuum are reported in Table 4. The quantities \(t_p^{\text{int}}\) and \(\omega^{\text{int}}\) are also shown in Table 4.
Table 3. Sample II of 45 $z < 1$ GRBs. From left to right: 44 LGRBs and one XRF (091018); redshift $z$; bright X-ray flares and dim X-ray fluctuations denoted by “B” (bright) and “D” (dim), respectively; number of flares.

| GRB        | z     | Flare | $N_{\text{flare}}$ |
|------------|-------|-------|--------------------|
| 050219A    | 0.2115| –     | –                  |
| 050826     | 0.297 | –     | –                  |
| 051016B    | 0.9364| –     | –                  |
| 051109B    | 0.08  | –     | –                  |
| 060202     | 0.785 | D     | 1                  |
| 060512     | 0.4428| B     | 1                  |
| 060814     | 0.84  | D     | 1                  |
| 060912A    | 0.937 | –     | –                  |
| 061021     | 0.3463| –     | –                  |
| 061110A    | 0.758 | –     | –                  |
| 070318     | 0.84  | B     | 1                  |
| 070508     | 0.82  | –     | –                  |
| 070521     | 0.553 | –     | –                  |
| 071112C    | 0.8227| B     | 1                  |
| 080430     | 0.767 | –     | –                  |
| 080916A    | 0.689 | –     | –                  |
| 081109     | 0.9787| –     | –                  |
| 090424     | 0.544 | –     | –                  |
| 090814A    | 0.696 | –     | –                  |
| 091018XRF  | 0.971 | –     | –                  |
| 100508A    | 0.5201| D     | 1                  |
| 100621A    | 0.542 | –     | –                  |
| 100816A    | 0.804 | B     | 1                  |
| 110715A    | 0.82  | D     | 1                  |
| 111225A    | 0.297 | D     | 1                  |
| 120722A    | 0.9586| B     | 1                  |
| 120907A    | 0.97  | D     | 1                  |
| 130925A    | 0.347 | B     | 5                  |
| 131113A    | 0.599 | B     | 3                  |
| 140506A    | 0.889 | B     | 3                  |
| 140512A    | 0.725 | B     | 1                  |
| 140710A    | 0.558 | B     | 1                  |
| 141004A    | 0.57  | –     | –                  |
| 150323A    | 0.593 | D     | 1                  |
| 150727A    | 0.313 | –     | –                  |
| 150821A    | 0.755 | B     | 1                  |
| 151027A    | 0.81  | B     | 1                  |
| 160117B    | 0.86  | B     | 2                  |
| 160131A    | 0.97  | –     | –                  |
| 163014A    | 0.726 | B     | 1                  |
| 160425A    | 0.555 | B     | 2                  |
| 160804A    | 0.736 | D     | 1                  |
| 161129A    | 0.645 | –     | –                  |
| 170519A    | 0.818 | B     | 1                  |
| 170607A    | 0.557 | D     | 1                  |

where $t_{\text{peak}} = t_p/(1 + z)$ and $\omega_{\text{peak}} = \omega/(1 + z)$ are the peak time and width of flares in the rest frame, respectively.

4 OCCURRENCE RATES AND PHYSICAL ORIGIN OF BRIGHT X-RAY FLARES

This work focuses on the occurrence rates of bright X-ray flares in the SN-GRB sample (Sample I) and the general $z < 1$ GRBs without observed SNe association (Sample II). As shown in Section 2, for Sample I, among the 18 SN-GRBs (15 LGRBs and three XRFs), only two SN-GRBs have bright X-ray flares, and the occurrence rate is 11.1%. For a comparison, for Sample II, among the 45 GRBs (44 LGRBs and one XRF), 16 sources present bright X-ray flares, and the occurrence rate is 35.6%. Thus, the occurrence rate of X-ray flares in the SN-GRB systems is lower than that in Sample II. In addition, such a discrepancy between these two samples can be examined by the Fisher’s exact test 4, which shows the one-tailed $P = 0.0466$ ($< 0.05$). On the other hand, if the dim X-ray fluctuation is included as the weak flare, then 16.7% (3/18) of Sample I and 55.6% (25/45) of Sample II have X-ray flares, again showing the discrepancy between these two samples. Moreover, the Fisher’s exact test shows the one-tailed $P = 0.0048$ ($< 0.05$). Thus, the discrepancy may indicate that the SN-GRB systems have a lower occurrence rate of X-ray flares than the general $z < 1$ GRB

4 http://www.langerud.com/stat/fisher.htm
systems without observed SNe association. In other words, a lower occurrence rate of X-ray flares may exist in the SN-GRB sample than in the general $z < 1$ GRB population.

It should be noted that the physics of X-ray flares may be based on the internal origin or the external one. Ioka, Kobayashi, & Zhang (2005) showed that simple kinetic arguments can give limits on the timescale $\omega$ and amplitude $\Delta F$ of variabilities in GRB afterglows. They proposed that four kinds of afterglow variability are kinematically forbidden under some standard assumptions, and derived the limits for dips (bumps) that deviate below (above) the baseline with a timescale and amplitude (see their Figure 1 for details). These limits are helpful to identify whether or not, the physical origin is afterglow variability or the late-time activity of the central engine. Similar to Ioka, Kobayashi, & Zhang (2005), Bernardini et al. (2011), and Mu et al. (2016a), we plot a figure based on the relative variability flux $\Delta F/F$ and the relative variability timescale $\omega/t_p$ to judge the physical origin of the X-ray flares. As shown in Figure 3, most flares are located in the upper left region, which indicates that they are likely to be of internal origin.

In another way, by setting the zero time at the GRB trigger time, the flares formed in the external shock process may have a maximum decay slope of $\alpha = 2 + \beta$, where $\beta$ is the spectral index. Consequently, a decay with slope steeper than $2 + \beta$, i.e., $\alpha > 2 + \beta$, may indicate the internal origin (e.g., Kumar & Panaitescu 2000; Liang et al. 2006). Such a simple criterion can also be simplified as an even simpler one, $\alpha > 3$, since $\beta$ is usually around 1. The light curve index $\alpha$ in the decay phase (from $t_p$ to $t_p + \tau_{\text{dec}}$) can be roughly estimated as

$$\alpha = \frac{\log(c)}{\log[(t_p + \tau_{\text{dec}})/t_p]},$$

(4)
The four theoretical solid lines are identical with those in Figure 6 of Bernardini et al. (2011), i.e., density fluctuations on axis (blue line) and off-axis (red line), off-axis multiple regions density fluctuations (green line), patchy shell model (black line), see Ioka, Kobayashi, & Zhang (2005) for details.

where \( \tau_{\text{dec}} = \tau_0[(1 + 4\mu)^{1/2} + 1]/2 \) is the decay time of the flare. The temporal decay index is listed in Table 5. The spectral analyses for the steep decay segments are performed by using a power-law spectral model\(^5\). The spectral analyses results, i.e., the values of the spectral index in the decay phase \( \beta \), are reported in Table 5. It is seen from Figure 4 that, most flares are located above the red solid line and the black dashed line, which implies that most flares are likely to be of internal origin. Such a result is in good agreement with the data shown in Figure 3. We therefore argue that most X-ray flares studied in this work are related to the reactivity of the central engine (Romano et al. 2006; Bernardini et al. 2011; Wu, Hou, & Lei 2013; Yi et al. 2015).

5 DISCUSSION AND CONCLUSIONS

This work focuses on the different occurrence rates of bright X-ray flares in the \( z < 1 \) GRBs with (Sample I) or without (Sample II) observed SNe association. Our Sample I consists of 18 SN-GRBs, among which only two GRBs have bright X-ray flares. Sample II consists of 45 GRBs, among which 16 GRBs have bright X-ray flares. Our study has shown a lower occurrence rate of bright X-ray flares in the SN-GRB sample \( (2/18, 11.1\%) \) than in Sample II \((16/45, 35.6\%)\). In addition, if the dim X-ray fluctuation is included as a dim flare, then 16.7% \((3/18)\) of the SN-GRB systems and 55.6% \((25/45)\) of Sample II have flares, again showing the discrepancy between these two samples. Thus, the discrepancy may indicate that a lower occurrence rate of X-ray flares may exist in the SN-GRB sample than in the general \( z < 1 \) GRB population.

It is known that there exists a strong selection effect of distance on the luminosity and the total energy of GRBs. In the present work, however, we focus on those close GRBs with \( z < 1 \), so the selection effect of distance may not be essential. To our knowledge, none of the known selection effects seems to play a role that could account for the apparent deficit of flares in the SN-GRB sample.

As mentioned in the second section, owing to observational constraints, many SN-GRBs may still exist in our Sample II. In addition, we should point out that our work is based on the assumption that there may exist a group of bona fide SN-less LGRBs. Otherwise, our arguments as well as the division of Samples I and II will make less sense. If Sample II does consist of two groups, i.e., SN-GRBs (Sample Ia) and bona fide SN-less GRBs (Sample Ib), we would argue that our main results, i.e., the discrepancy on the occurrence of X-ray flares, can still work. The arguments are as follows. We assume that Samples I, Ia, and Ib have \( N_1 \), \( N_2 \), and \( N_3 \) sources, respectively. If there indeed exists a discrepancy on the occurrence rate of X-ray flares between the SN-GRBs and the bona fide SN-less LGRBs, we assume that the occurrence rate is \( f_1 \) for the former and \( f_2 \) for the latter, with \( f_1 < f_2 \). Obviously, the real difference in the rates is \( f_2 - f_1 \). In such case, according to our analyses based on Samples I and II, the apparent difference will be \( [(f_1 + N_2 + f_2 + N_3)/(N_1 + N_2)] - f_1 = [N_1/(N_2 + N_3)] \times (f_2 - f_1) \), which is even lower than the real one, i.e., \( f_2 - f_1 \). In other words, if there exists an apparent discrepancy between Samples I and II, such a discrepancy is likely to be even more significant in the real case (between Sample Ib and Sample I plus Ia). We therefore argue that even though it is not clear how many SN-GRBs exist in our Sample II, the discrepancy suggested in this work may still have potential significance.

In our opinion, the physical understanding of the lower rate of occurrence in the SN-GRB systems may be the following. From the view of the energy source, both the radiation of an SNe and the prompt gamma-ray emission together with the X-ray flare, originate from the total energy of col-\(^5\) http://www.swift.ac.uk/xrtspectra/addspec.php/
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Table 5. Parameters for the physical origin of Sample I and Sample II. From left to right: GRB; ω/tp is the relative time-scale, where ω is the width evaluated between 1/e intensity points, and tp is the peak time of the flare; ∆F/F is the relative flux at tp, and F is calculated from the best fitting of the underlying continuum; α is the temporal decay index; β is the average spectral index in the decay phase.

| GRB     | ω/tp ± | ∆F/F ± | α ± | β ± |
|---------|--------|--------|-----|-----|
| Sample I|        |        |     |     |
| 060904B | 0.39 ± 0.01 | 527 ± 176 | 5.10 | 1.19 |
| 161219B | 0.45 ± 0.03 | 5.67 ± 0.56 | 4.50 | 1.11 |
| Sample II|      |        |     |     |
| 060512  | 0.37 ± 0.08 | 3.38 ± 0.38 | 5.37 | 2.63 |
| 070318  | 0.58 ± 0.04 | 2.33 ± 0.38 | 3.51 | 1.08 |
| 071112C | 0.34 ± 0.05 | 3.01 ± 0.24 | 5.87 | 0.81 |
| 100816A | 0.42 ± 0.09 | 1.74 ± 1.45 | 4.74 | 0.88 |
| 120722A | 0.66 ± 0.24 | 210 ± 143  | 3.07 | 1.55 |
| 130925A | 0.33 ± 0.01 | 10.50 ± 2.57 | 6.11 | 0.88 |
| 131103A | 0.37 ± 0.04 | 9.86 ± 22.13 | 5.37 | 1.47 |
| 140506A | 0.41 ± 0.01 | 32.54 ± 3.91 | 4.93 | 1.27 |
| 140512A | 0.41 ± 0.02 | 8.93 ± 8.25  | 4.96 | 0.66 |
| 140710A | 0.46 ± 0.08 | 21.77 ± 4.14 | 4.37 | 1.04 |
| 150821A | 0.22 ± 0.05 | 2.89 ± 1.12  | 9.19 | 1.32 |
| 151027A | 0.28 ± 0.01 | 9.74 ± 0.31  | 7.05 | 0.88 |
| 160117B | 0.38 ± 0.04 | 14.00 ± 6.08 | 5.36 | 1.15 |
| 160314A | 1.05 ± 0.28 | 7.99 ± 2.84  | 2.92 | 1.10 |
| 160425A | 0.26 ± 0.01 | 8.73 ± 5.66  | 7.58 | 1.10 |
| 170519A | 0.33 ± 0.05 | 9.36 ± 8.81  | 6.16 | 2.04 |

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