Statistical Study of the Swift X-Ray Flash and X-Ray Rich Gamma-Ray Bursts

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Supporting material: machine-readable table

Abstract

We build a comprehensive sample to statistically describe the properties of X-ray flashes (XRFs) and X-ray riches (XRRs) from the third Swift Burst Alert Telescope (BAT3) catalog of Gamma-ray bursts (GRBs). We obtain 81 XRFs, 540 XRRs, and 394 classical GRBs (C-GRBs). We statistically explore the different properties of the γ-ray prompt emission, the X-ray emission, the X-ray light-curve type, the association with supernovae (SNe), and the host galaxy properties for these sources. We confirm that most XRFs/XRRs are long GRBs with low values of peak energy $E_{\text{peak}}$ and they are low-luminosity GRBs. XRFs, XRRs, and C-GRBs follow the same $E_{\text{iso}}-E_{\text{peak}}$ correlations. Compared to the classical GRBs, XRFs are favorable to have the association with SN explosions. We do not find any significant differences of redshift distribution and host galaxy properties among XRFs, XRRs, and C-GRBs. We also discuss some observational biases and selection effects that may affect our statistical results. The GRB detectors with wide energy range and low energy threshold are expected for the XRF/XRR research in the future.

Key words: gamma rays: general – radiation mechanisms: non-thermal

Supporting material: machine-readable table

1. Introduction

In addition to the classical long/short dichotomy, gamma-ray bursts (GRBs) have two special subclasses: X-ray flashes (XRFs) and X-ray riches (XRRs). XRFs are the GRBs characterized by the faint signals in the gamma-ray energy band. XRRs, which belong to an intermediate class between XRFs and classical GRBs (C-GRBs), have stronger X-ray emission compared to their gamma-ray emission (e.g., Barraud et al. 2003; Kippen et al. 2003; Amati et al. 2004; Sakamoto et al. 2005, 2006, 2008; D’Alessio et al. 2006). The physical origin of XRFs and XRRs is still under debate.

XRF 050406 was proposed as a GRB with prelonged central engine activity (Romano et al. 2006). This long-term activity was also observed in XRF 011030 (Galli & Piro 2006). GRB jet structure affects the observed GRB energy release, and the off-axis effect may induce the observed XRFs/XRRs (e.g., Yamazaki et al. 2002; Barraud et al. 2005; Granot et al. 2005; Lamb et al. 2005; Xu et al. 2005; Donaghy 2006; Salafia et al. 2016). Observations have provided some evidence for the off-axis jet injection (e.g., Bulmer et al. 2005; Schady et al. 2006; de Ugarte Postigo et al. 2007; Guidorzi et al. 2009). A dynamic transition with a different GRB jet opening angle may also be important to link C-GRBs and XRFs (Mizuta et al. 2006). Alternatively, thermal emission has been thought to be a possible component in the strong X-ray emission of GRBs. Ramirez-Ruiz (2005) proposed a photospheric model that can be used to interpret the dominated X-ray emission of XRFs. Pe’er et al. (2006) calculated the details of the photospheric component of the XRF prompt emission spectrum. XRFs can also be indicators of the orphan GRB afterglows (Urata et al. 2015). These clues naturally lead to one suggestion: that XRFs are low-luminosity GRBs (e.g., Virgili et al. 2009). Moreover, it has been found that supernova (SN) explosions can be associated with XRFs (e.g., XRF 020903, Bersier et al. 2006).

XRF 050215B was the first XRF observed by Swift (Levan et al. 2006), and Swift observational statistics can be well applied to study the physical origins of XRFs and XRRs (Gendre et al. 2007). Sakamoto et al. (2008) built one data set provided by the Swift Burst Alert telescope (BAT) observation from 2004 December to 2006 September. From that sample, they obtained 10 XRFs and 97 XRRs among a total of 158 GRBs. They studied the prompt emission properties and the X-ray afterglow emission characteristics for XRFs, XRRs, and C-GRBs. Some distinct differences between XRFs and C-GRBs in the prompt emission and the X-ray afterglow emission have been illustrated. This exploration encourages us to comprehensively investigate the physical properties of XRFs/XRRs, the relation between XRFs/XRRs and C-GRBs, and the GRB central engine from the statistical point of view. Thus, a large GRB sample is necessary.

We utilize the latest third Swift-BAT3 catalog (Lien et al. 2016), which contains 1104 GRBs detected from 2004 December 17 to 2016 December 2, to systematically investigate the statistical properties of XRFs and XRRs. For each GRB, the catalog provides trigger time, coordinates, redshift, GRB duration time $T_{90}$, spectral models for spectral fitting, spectral photon index, observed peak energy $E_{\text{peak}}$, and fluence in difference energy bands. From this catalog, we classify the possible XRFs/XRRs and build a sample to comprehensively analyze the differences of XRFs/XRRs and C-GRBs. We identify 81 XRFs, 540 XRRs, and 394 C-GRBs included in the sample and statistically analyze their observational characteristics. We examine the possible associations between XRFs/XRRs and SNe. The host galaxy properties of XRFs are also presented. Some observational biases and selection effects are mentioned.
This paper is organized as follows. We classify XRFs, XRRs, and C-GRBs in Table 2. We also specify that 13 sources in our sample have no GRB duration $T_{90}$ numbers. Thus, we cannot classify them as long-duration GRBs (L-GRBs, defined by $T_{90} \geq 2$ s) or short-duration GRBs (S-GRBs, defined by $T_{90} \leq 2$ s). Second, we also select GRBs that have the photon index $\alpha_{\text{PL}} < -2.0$ with a power-law fitting in the BAT3 data set and identify them as XRFs. Third, we note the sources having values of $E_{\text{peak}}^{\text{obs}}$, which can be found in the BAT3 data set. We also check whether these selected sources have $E_{\text{peak}}^{\text{obs}}$ values in other data sets. Finally, we list XRFs and XRRs in Table 2.

The distributions with the fluence ratio of $S(25–50$ keV)/$S(50–100$ keV) for the total 1015 GRBs in the BAT3 catalog are shown in Figure 1. XRFs, XRRs, and C-GRBs in the sample have the fractions of $(8.0 \pm 0.9)_\%$, $(53.2 \pm 2.2)_\%$, and $(38.8 \pm 1.9)_\%$, respectively. The smaller sample given by Sakamoto et al. (2008) contains 158 GRBs. There are 10 XRFs, 97 XRRs, and 51 C-GRBs. XRFs, XRRs, and C-GRBs in their sample have the fractions of $(6.3 \pm 2.0)_\%$, $(61.4 \pm 6.2)_\%$, and $(32.3 \pm 4.5)_\%$, respectively. It seems that our classified results are roughly consistent with those of Sakamoto et al. (2008). Here, we pay attention to four special cases. (1) GRB 050219B was identified as XRR by Sakamoto et al. (2008), while it is classified as C-GRB in our work. (2) GRB 050815 was identified as XRR by Sakamoto et al. (2008), while it is classified as XRF in our work. (3) There are 10 GRBs (GRB 050824, GRB 060512, GRB 060923B, GRB 060926, GRB070714A, GRB070721A, GRB080218B, GRB080515, GRB080516).
GRB080520, and GRB081007) that have no fluences of $S(25–50 \text{ keV})$ and/or $S(50–100 \text{ keV})$ from the Swift-BAT2 catalog (Sakamoto et al. 2011). (4) There are 11 XRFs (XRF 050406, XRF 050416A, XRF 050819, XRF 060428B, XRF 060805A, XRF 061218, XRF 070126, XRF 080218B, XRF 080315, XRF 080822B, and XRF 160525A) show a fluence ratio of $S(25–50 \text{ keV})/S(50–100 \text{ keV})$ larger than 3.0.\textsuperscript{6}

We plot the fluence ratio $S(25–50 \text{ keV})/S(50–100 \text{ keV})$ versus the BAT-observed GRB duration $T_{90}$ in Figure 2. We calculate the fractions of L-GRBs and S-GRBs for XRFs, XRRs, and C-GRBs in our sample, respectively. Our findings are as follows: (1) For XRFs, there are 70 L-GRBs, 3 S-GRBs, and 8 duration-unclear sources, and the fractions are (86.4 ± 10.3)%, (3.7 ± 2.1)%, and (9.9 ± 3.5)%, respectively. (2) For XRRs, there are 509 L-GRBs, 27 S-GRBs, and 4 duration-unclear sources, and the fractions are (94.3 ± 4.2)%, (5.0 ± 1.0)%, and (0.7 ± 0.4)%, respectively. (3) For C-GRBs, there are 328 L-GRBs, 65 S-GRBs, and 1 duration-unclear source, and the fractions are (83.2 ± 4.6)%, (16.5 ± 2.0)%, and (0.3 ± 0.3)%, respectively. We note that XRFs and XRRs have less S-GRB proportion compared with C-GRBs.\textsuperscript{7} In the meantime, we also report the fraction of XRFs, XRRs, and C-GRBs for L-GRB and S-GRB classes. Three S-GRBs as XRFs have the fraction of (3.2 ± 1.8)%. Twenty-seven S-GRBs as XRRs have the fraction of (28.4 ± 5.5)%. Sixty-five S-GRBs as C-GRBs have the fraction of (68.4 ± 8.5)%. Seventy L-GRBs as XRFs have the fraction of (7.7 ± 0.9)%. Five hundred and nine L-GRBs as XRRs and C-GRBs have the fraction of (56.1 ± 2.5)%. Three hundred and twenty-eight L-GRBs as C-GRBs have the fraction of (36.2 ± 2.0)%.

3. Statistical Analysis

3.1. The Prompt Emission Properties

We collect $E_{\text{peak}}^{\text{obs}}$ values of GRBs from the literature (e.g., Amati et al. 2008, 2009; Sakamoto et al. 2008, 2011; Grupe et al. 2013; D’Avanzo et al. 2014; Liang et al. 2015; Lien et al. 2016; Zaninoni et al. 2016), and we obtain the $E_{\text{peak}}^{\text{obs}}$ values for 77 XRFs, 460 XRRs, and 265 C-GRBs. The fluence ratio $S(25–50 \text{ keV})/S(50–100 \text{ keV})$ versus $E_{\text{peak}}^{\text{obs}}$ is shown in Figure 3. We clearly see the different occupied regions of XRFs, XRRs, and C-GRBs in the figure. It was shown in the fluence ratio–$E_{\text{peak}}^{\text{obs}}$ plot provided by Sakamoto et al. (2008) a gap of $S(25–50 \text{ keV})/S(50–100 \text{ keV})$ fluence ratio from 0.8 to 1.2, and Sakamoto et al. (2008) suggested that this gap is the result of selection effects. However, we do not find this gap in Figure 3, because we take a large sample from the BAT3 catalog. We further show the different $E_{\text{peak}}^{\text{obs}}$ distributions for XRFs, XRRs, and C-GRBs in Figure 4. In order to quantitatively distinguish the different $E_{\text{peak}}^{\text{obs}}$ properties to XRFs, XRRs, and C-GRBs, we use a nonparametric two-sample Kolmogorov–Smirnov (K-S) test to examine the

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\textsuperscript{6} XRF 080315 has the largest fluence ratio of 53.8 ± 143.0 but with large error. This source has no X-ray afterglow from Swift-XRT detection. Due to the lack of X-ray nondetection and the marginal BAT detection (Page & Gehrels 2008), we include this source in Tables 1–3, but we exclude it in all figures of this paper. We also do not find any other notable issues for this burst.

\textsuperscript{7} There are only three XRFs (XRF 090417A, XRF 110112A, and XRF 140622A) that are S-GRBs. GRB 110112A has no host galaxy evidence (Fong et al. 2013; Tunnicliffe et al. 2014). We do not find any other notable information for the short-duration XRFs.

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Figure 1. Distributions of the fluence ratio $S(25–50 \text{ keV})/S(50–100 \text{ keV})$ of GRBs in Swift-BAT3 sample. The dashed lines show the distribution borders between C-GRBs and XRFs, and between XRRs and XRFs, respectively. Here, we list the sources with the fluence ratio larger than 3.0: XRF 050819 (the ratio is 3.08 ± 0.99), XRF 050406 (the ratio is 3.15 ± 1.22), XRF 060805A (the ratio is 3.29 ± 2.20), XRF 080218B (the ratio is 4.24 ± 3.08), XRF 060428B (the ratio is 4.44 ± 1.80), XRF 080822B (the ratio is 4.74 ± 2.86), XRF 050416A (the ratio is 5.83 ± 2.39), XRF 160525A (the ratio is 6.50 ± 5.47), XRF 061218 (the ratio is 8.25 ± 10.66), and XRF 070126 (the ratio is 8.82 ± 9.46).
different $E_{\text{peak}}^\text{obs}$ distributions for the XRF/XRR samples, the XRR/C-GRB samples, and the XRF/C-GRB samples, respectively. Because the K-S probability numbers are very small (the $P$-values are far less than 0.0001), we confirm that the $E_{\text{peak}}^\text{obs}$ distributions among XRFs, XRRs, and C-GRBs have significant differences.

The $E_{\text{peak}}^\text{obs}$ distribution of XRFs ranges from 0.9 keV to 80.0 keV, with a mean value of $24.3 \pm 1.6$ keV. The $E_{\text{peak}}^\text{obs}$
distribution of XRRs ranges from 1.2 keV to 1780.0 keV, with a mean value of 105.6 ± 5.3 keV. The $E_{\text{peak}}^{\text{obs}}$ distribution of C-GRBs ranges from 64.6 keV to 2602.8 keV, with a mean value of 257.7 ± 14.1 keV. It is clear that XRFs and XRRs have smaller $E_{\text{peak}}^{\text{obs}}$ values compared with C-GRBs. Our results are consistent with those of Sakamoto et al. (2005, 2008). We confirm that XRFs and XRRs release their prompt energies mostly in the X-ray band.

We also investigate the correlation between peak energy $E_{\text{peak}}^{\text{obs}}$ and the fluence $S(15–150\text{ keV})$ for all GRBs in our sample. The data are plotted in Figure 5. In principle, the effect of the data errors should be taken into account when we perform the correlation fitting. In this paper, we adopt the maximum likelihood method that has been well applied for the $E_{\text{peak},z}$-$E_{\gamma,\text{iso}}$ correlation fitting given by Amati et al. (2008). We use the maximum likelihood method and obtain the correlation fitting as $\log(E_{\text{peak}}^{\text{obs}})\text{(keV)} = (2.96 ± 0.13) + (0.16 ± 0.02)\log(S(15–150))\text{keV}$ with the extrinsic scatter $\sigma = 0.39 ± 0.01$. We also plot the correlation of $\log(E_{\text{peak}}^{\text{obs}})\text{(keV)} = (5.46 ± 0.25) + (0.62 ± 0.14)\log(S(15–150\text{ keV})]$ that was given by Sakamoto et al. (2008). We see that our fitting result is different from that of Sakamoto et al. (2008). In order to clarify the difference of this correlation among XRFs, XRRs, and C-GRBs, we separate C-GRBs as one group and put XRRs and XRFs as the other group. We obtain the fitting for C-GRBs as $\log(E_{\text{peak}}^{\text{obs}})\text{(keV)} = (3.01 ± 0.13) + (0.12 ± 0.02)\log(S(15–150))\text{keV}$ with the extrinsic scatter $\sigma = 0.26 ± 0.01$, and the fitting for XRRS and C-GRBs as $\log(E_{\text{peak}}^{\text{obs}})\text{(keV)} = (2.67 ± 0.16) + (0.13 ± 0.03)\log(S(15–150))\text{keV}$ with the extrinsic scatter $\sigma = 0.36 ± 0.01$. Therefore, although the difference between XRFs and XRRs/C-GRBs is clear, it seems no significant difference between XRFs/XRRs and C-GRBs because XRRs and C-GRBs has large overlap region seen in Figure 5.

3.2. The Observed Properties with Redshift

The redshift distributions of the XRFs, XRRs, and C-GRBs are shown in Figure 6. Using the K-S test to the redshift distributions for the XRFs and XRRs samples, the XRRs and C-GRBs samples, and the XRFs and C-GRBs samples, we find that K-S test probabilities are $P = 0.13$, $P = 0.36$, and $P = 0.13$, respectively. The K-S test results confirm that there are not significant differences among XRFs, XRRs, and C-GRBs for the redshift distribution.

We also plot the BAT-observed duration $T_{90}$ and the fluence $S(15–150\text{ keV})$ as a function of redshift in Figures 7 and 8, respectively. We do not find significant differences of $T_{90}$ and $S(15–150\text{ keV})$ distributions among XRFs, XRRs, and C-GRBs, and we do not see significant redshift evolutions of $T_{90}$ and $S(15–150\text{ keV})$ for XRFs, XRRs, and C-GRBs.
3.3. The Correlations among $E_{\gamma,iso}$, $E_{peak,z}$, and $E_{X,iso}$

There is a universal correlation among the isotropic prompt energy $E_{\gamma,iso}$ emitted in the rest frame $1-10^4$ keV energy band, the rest frame energy peak of the prompt emission energy spectrum $E_{peak,z}$, and the X-ray energy emitted in the rest frame $0.3-10$ keV energy band $E_{X,iso}$ for GRBs (e.g., Bernardini et al. 2012; Margutti et al. 2013; Figure 5). The correlation can be described by the following function:

$$\log(E_{\gamma,iso}^{obs} \text{ keV}) = (2.96 \pm 0.13) + (0.16 \pm 0.02) \log[S(15-150) \text{ keV}]$$

The XRFs, XRRs, and C-GRBs are marked as black squares, red dots, and blue triangles, respectively.

Figure 5. Relationship of the 15–150 keV fluence and the $E_{\gamma,iso}^{obs}$ for XRFs, XRRs, and C-GRBs. The green solid line is the best fit to the data with the function $\log(E_{\gamma,iso}^{obs} \text{ keV}) = (2.96 \pm 0.13) + (0.16 \pm 0.02) \log[S(15-150) \text{ keV}]$, and the green dashed lines are marked for the 1σ regions. The extrinsic scatter $\sigma = 0.39 \pm 0.01$. The pink dashed–dotted line is the best fit to the data without taking into account the errors reported by Sakamoto et al. (2008), and the function is $\log(E_{\gamma,iso}^{obs} \text{ keV}) = (5.46 \pm 0.25) + (0.62 \pm 0.14) \log[S(15-150) \text{ keV}]$. The XRFs, XRRs, and C-GRBs are marked as black squares, red dots, and blue triangles, respectively.

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Figure 6. Redshift distribution of GRBs in the Swift-BAT3 sample. XRFs, XRRs, and C-GRBs are marked as the pink solid line, the red dashed line, and the blue dashed–dotted line, respectively.
In order to check whether XRFs, XRRs, and C-GRBs in our sample follow this correlation, respectively, we collect the $E_{\gamma,\text{iso}}$ and $E_{X,\text{iso}}$ data of the GRBs in our sample from Amati et al. (2008), Margutti et al. (2013), and Liang et al. (2015). First, the relation between $E_{X,\text{iso}}$ and $E_{\gamma,\text{iso}}$ is shown in Figure 9. We perform the maximum likelihood method and obtain the fitting of $(E_{X,\text{iso}}) = (13.31 \pm 2.73) + (0.73 \pm 0.05) \log(E_{\gamma,\text{iso}})$ with the extrinsic scatter of $\sigma = 0.57 \pm 0.04$. The $E_{X,\text{iso}}-E_{\gamma,\text{iso}}$ relation is consistent with that derived by Margutti et al. (2013). Second, we also investigate the correlation between $E_{\text{peak},z}$ and $E_{\gamma,\text{iso}}$. The result is shown in Figure 10. The correlation fitted by the maximum likelihood method is $\log(E_{\text{peak},z}) \text{ (keV)} = (2.17 \pm 0.04) + (0.46 \pm 0.03)$
with the extrinsic scatter of $\sigma = 0.26 \pm 0.02$. Our result is consistent with the correlation reported by Amati (2006).

Third, in Figure 11, we present the relation between $E_{X,\text{iso}}$ and $E_{\gamma,\text{iso}}$ by the maximum likelihood method with the fitting of $\log(E_{X,\text{iso}}) = (49.69 \pm 0.27) + (0.75 \pm 0.11) \log(E_{\gamma,\text{iso}})$, and the extrinsic scatter is $\sigma = 0.73 \pm 0.04$.

log[$E_{X,\text{iso}}/(10^{52} \text{ erg})$] with the extrinsic scatter of $\sigma = 0.26 \pm 0.02$. Our result is consistent with the correlation reported by Amati (2006).
Our result is consistent with that of Margutti et al. (2013). Finally, the \( E_{\text{iso}} = \text{E}_\gamma + \text{E}_{\text{peak}} \) relation is shown in Figure 12. The result with the fitting of \( \log(E_{\text{iso}}) = (4.78 \pm 2.79) + (0.92 \pm 0.06) \log(E_{\text{peak}}) \) and the extrinsic scatter of \( \sigma = 0.44 \pm 0.04 \) produced by the maximum likelihood method is consistent with that of Margutti et al. (2013) as well.

We also examine the difference between XRFs/XRRs and C-GRBs from the above correlations. We separate XRFs/XRRs and C-GRBs as two groups. From Figure 9, we obtain \( \langle E_{\text{iso}} \rangle = (9.85 \pm 2.77) + (0.79 \pm 0.05) \log(E_{\text{iso}}) \) with the extrinsic scatter of \( \sigma = 0.68 \pm 0.07 \) for C-GRBs and \( \langle E_{\text{iso}} \rangle = (13.45 \pm 2.53) + (0.73 \pm 0.05) \log(E_{\text{iso}}) \) with the extrinsic scatter of \( \sigma = 0.39 \pm 0.04 \) for XRFs/XRRs. Thus, we do not find significant difference in this correlation. We analyze the data in Figure 10 that the relation of \( \log(E_{\text{peak,2}}) \) (keV) = \((2.83 \pm 0.06) + (0.11 \pm 0.05) \log(E_{\text{iso}}/(10^{52} \text{erg})) \) with the extrinsic scatter of \( \sigma = 0.31 \pm 0.04 \) is for C-GRBs and the relation of \( \log(E_{\text{peak,2}}) \) (keV) = \((2.11 \pm 0.03) + (0.41 \pm 0.04) \log(E_{\text{iso}}/(10^{52} \text{erg})) \) with the extrinsic scatter of \( \sigma = 0.23 \pm 0.03 \) is for XRFs/XRFs. Thus, we clearly see the difference between XRFs/XRRs and C-GRBs in this correlation. From Figure 11, we obtain the relation of \( \log(E_{\text{iso}}) = (48.07 \pm 1.03) + (1.24 \pm 0.35) \log(E_{\text{peak,2}}) \) with the extrinsic scatter of \( \sigma = 0.86 \pm 0.09 \) for C-GRBs and the relation of \( \log(E_{\text{iso}}) = (49.46 \pm 0.28) + (0.90 \pm 0.12) \log(E_{\text{peak,2}}) \) with the extrinsic scatter of \( \sigma = 0.62 \pm 0.05 \) for XRFs/XRFs. Thus, it seems that XRFs/XRRs and C-GRBs have no significant difference in this correlation. Finally, from Figure 12, we obtain the relation of \( \log(E_{\text{iso}}) = (5.67 \pm 3.36) + (0.90 \pm 0.07) \log(E_{\text{iso}}) - 0.6 \log(E_{\text{peak}}) \) with the extrinsic scatter of \( \sigma = 0.54 \pm 0.08 \) for C-GRBs and the relation of \( \log(E_{\text{iso}}) = (4.10 \pm 2.88) + (0.93 \pm 0.06) \log(E_{\text{iso}}) - 0.6 \log(E_{\text{peak}}) \) with the extrinsic scatter of \( \sigma = 0.36 \pm 0.05 \). Therefore, we do not find any significant difference between XRFs/XRRs and C-GRBs in this correlation.

In order to investigate the \( \gamma \)-ray isotropic-equivalent luminosity \( (L_{\gamma,\text{iso}}) \) distributions for XRFs, XRRs, and C-GRBs, we collect the \( L_{\gamma,\text{iso}} \) values of the GRBs in our sample from D’Avanzo et al. (2014), Liang et al. (2015), and Cano et al. (2017). We obtained 55 sources with \( L_{\gamma,\text{iso}} \) values, including 5 XRFs, 26 XRRs, and 24 C-GRBs. The \( L_{\gamma,\text{iso}} \) distributions are shown in Figure 13. Our results are as follows: the \( L_{\gamma,\text{iso}} \) values have the range from \( 2.60 \times 10^{46} \) to \( 6.89 \times 10^{50} \text{erg s}^{-1} \) for XRFs; the \( L_{\gamma,\text{iso}} \) values are from \( 1.03 \times 10^{49} \) to \( 3.51 \times 10^{52} \text{erg s}^{-1} \) for XRFs; and the \( L_{\gamma,\text{iso}} \) values are from \( 1.20 \times 10^{49} \) to \( 1.78 \times 10^{53} \text{erg s}^{-1} \) for C-GRBs. We find that XRFs and XRRs have lower \( L_{\gamma,\text{iso}} \) values than C-GRBs. This indicates that XRF sources are low-luminosity GRBs.

3.4. The X-Ray Light-curve Shapes

In order to investigate the X-ray afterglow properties of XRFs, XRRs, and C-GRBs, we simply examine the types of X-ray afterglow light curves for XRFs, XRRs, and C-GRBs from Swift/XRT GRB light-curve repository.\(^8\) The definitions of X-ray afterglow light curves given by Margutti et al. (2013) are as follows: type 0 (simple power law), type I (broken power law), type II (broken power law plus power-law decay), and Type III (double broken power laws). We further check the X-ray light-curve types of XRFs, XRRs, and C-GRBs in our sample. Our results are as follows: (1) There are 33 XRFs having the XRT light curves. For these XRFs, the proportions

\(^8\) http://www.swift.ac.uk/xrt_curves/
of Type 0, Type I, Type II, and Type III are $(14.7 \pm 6.6)\%$, $(44.1 \pm 11.4)\%$, $(32.4 \pm 9.8)\%$, and $(8.8 \pm 5.1)\%$, respectively. (2) There are 198 XRRs having the XRT light curves. For these XRRs, the proportions of Type 0, Type I, Type II, and Type III are $(17.4 \pm 2.9)\%$, $(30.8 \pm 3.9)\%$, $(45.3 \pm 4.7)\%$, and $(6.5 \pm 1.8)\%$, respectively. (3) There are 135 C-GRBs having the XRT light curves. For these C-GRBs, the proportions of Type 0, Type I, Type II, and Type III are $(25.2 \pm 4.3)\%$, $(47.6 \pm 5.0)\%$, $(23.4 \pm 3.3)\%$, and $(3.8 \pm 1.7)\%$, respectively.
Although we focus on low-luminosity GRBs and XRFs in this paper, we note that high-luminosity GRBs may also have SN association. For example, bright GRB 130427A is associated with SN 2013cu (Maselli et al. 2014; Melandri et al. 2014; Vestrand et al. 2014).

Note. Grades are classified by Hjorth & Bloom (2012): (A) Strong spectroscopic evidence; (B) A clear light-curve bump as well as some spectroscopic evidence resembling a GRB-SN; (C) A clear bump consistent with other GRB-SNe at the spectroscopic redshift of the GRB; (D) A bump, but the inferred SN properties are not fully consistent with other GRB-SNe or the bump was not well sampled or there is no spectroscopic redshift of the GRB; (E) A bump, either of low significance or inconsistent with other GRB-SNe. Type refers to the supernova explosion type. $E_K$ is the supernova ejecta kinetic energy, in the unit of $10^{52}$ erg. $M^*$ is the stellar mass of the GRB host galaxy. Z is the metallicity of the GRB host galaxy. SFR is the star formation rate of the GRB host galaxy, in the unit of $M_\odot$ yr$^{-1}$.

### Table 3

| Class | Total Number | Type 0 [fraction] | Type I [fraction] | Type II [fraction] | Type III [fraction] |
|-------|--------------|-------------------|-------------------|-------------------|-------------------|
| XRF   | 34           | 5 $([14.7 \pm 6.6\%])$ | 15 $([44.1 \pm 11.4\%])$ | 11 $([32.4 \pm 9.8\%])$ | 3 $([8.8 \pm 5.1\%])$ |
| XRR   | 201          | 35 $([17.4 \pm 2.9\%])$ | 62 $([30.8 \pm 3.9\%])$ | 91 $([45.3 \pm 4.7\%])$ | 13 $([6.5 \pm 1.8\%])$ |
| C-GRB | 135          | 34 $([25.2 \pm 4.3\%])$ | 60 $([44.4 \pm 5.7\%])$ | 37 $([27.4 \pm 4.5\%])$ | 4 $([3.0 \pm 1.5\%])$ |

### Table 4

| Source         | $z$ | $E_{\text{peak}}$ (keV) | Supernova Grade | Type | $E_K$ | log ($M^*/M_\odot$) | log ($Z/Z_\odot$) | SFR |
|----------------|-----|--------------------------|-----------------|------|------|----------------------|-------------------|-----|
| XRF 050416A    | 0.6528 | 14.8$^{+13.8}_{-13.3}$ | ...              | D    | ...  | 9.19                 | ...               | ... |
| XRF 050252A    | 0.606  | 80.4$^{+17}_{-15}$       | 2005nc          | B    | 1.89$^{+0.07}_{-0.05}$ | ...               | ...               | ... |
| XRF 050824     | 0.8278 | 80.0                    | ...             | E    | 0.57$^{±0.03}$ | -0.3                | ...               | ... |
| XRF 060218     | 0.03342 | 4.7$^{±0.3}$            | 2006aj          | A    | 1.02$^{±0.23}$ | 7.78                | -0.53             | 0.05 |
| XRF 060729     | 0.5428 | 201.2$^{±68.9}$         | ...             | D    | 2.44$^{±0.09}$ | ...                 | ...               | ... |
| XRF 060904B    | 0.7029 | 84.1$^{±13.3}$          | ...             | C    | 0.99$^{±0.51}$ | ...                 | ...               | ... |
| XRF 070419A    | 0.9705 | 26.5$^{+18}_{-18.9}$    | ...             | D    | ...               | ...                 | ...               | ... |
| GRB 080319B    | 0.9382 | 650.6$^{±33.5}$         | ...             | C    | 2.27$^{±0.19}$ | ...                 | ...               | ... |
| XRF 081007     | 0.5295 | 39.9$^{±9.8}$           | 2008hw          | B    | 1.90$^{±1.50}$ | ...                 | ...               | ... |
| XRF 090618     | 0.54   | 162.0$^{±3.0}$          | ...             | C    | 3.65$^{±0.20}$ | ...                 | ...               | ... |
| XRF 091127     | 0.49044 | 34.0$^{±1.0}$           | 2009nz          | B    | 1.35$^{±0.04}$ | 8.6                 | -0.29             | 0.22 |
| XRF 100316D    | 0.0591 | 9.6$^{+4.3}_{-4.3}$     | 2010bh          | A    | 1.54$^{±0.14}$ | 8.93                | -0.39             | 0.14 |
| XRF 101219B    | 0.55185 | 54.8$^{±7.8}$           | 2010ma          | A/B  | 1.0$^{±0.6}$  | ...                 | ...               | ... |
| XRF 101225A    | 0.847  | 57.0$^{±24.9}$          | ...             | D    | 3.2$^{±1.6}$  | ...                 | ...               | ... |
| GRB 111209A    | 0.677  | 768.8                   | 2011k           | A/B  | ...               | ...                 | -0.39             | ... |
| XRF 111228A    | 0.71627 | 33.8$^{±4.1}$           | ...             | E    | ...               | ...                 | ...               | ... |
| XRF 120422A    | 0.28253 | 97.1                    | 2012bw          | A    | 2.55$^{±0.21}$ | 8.95                | -0.4              | 0.4  |
| XRF 120714B    | 0.3984 | 71.2$^{±5.9}$           | 2012eb          | C    | ...               | ...                 | ...               | ... |
| XRF 120729A    | 0.8    | 175.9$^{±17.6}$         | ...             | D/E  | ...               | 8.3                 | ...               | 6    |
| XRF 130215A    | 0.597  | 101.6$^{±16.9}$         | 2013ez          | B    | ...               | ...                 | ...               | ... |
| GRB 130427A    | 0.3399 | 932.9$^{±111.9}$        | 2013cu          | B    | 6.4$^{±0.7}$  | 9.32                | -0.2              | 0.9  |
| XRF 130831A    | 0.4791 | 67.0$^{±4.0}$           | 2013fu          | A/B  | 1.9$^{±0.9}$  | ...                 | ...               | ... |
| XRF 150818A    | 0.282  | 99.8$^{±10.1}$          | ...             | B    | ...               | ...                 | ...               | ... |

### 3.5. Investigation of the Association of XRF/XRR with Supernova

If we propose that XRFs and XRRs are low-luminosity GRBs, it is reasonable to consider the possible association between XRFs/XRRs and SNe (Soderberg et al. 2005; Woosley & Bloom 2006). An example is XRF 060218 that is associated with SN 2006aj (Pian et al. 2006). We take the statistical results from Hjorth & Bloom (2012), Cano (2013), and Cano et al. (2017). Twenty-three GRBs in our sample are associated with the SN explosion. These GRBs include 6 XRFs (XRF 050416A, XRF 050824, XRF 060218/2006aj, XRF 070419A, XRF 081007/SN 2008hw, and XRF 100316D/SN 2010bh), 14 XRRs (XRF 050525A/SN 2005nc, XRF 060729, XRF 060904B, XRF 090618, XRF 091127/SN 2009nz, XRF 101219B/SN 2010ma, XRF 101225A, XRF 111228A, XRF 120422A/SN 2012bz, XRF 120714B/SN 2012eb, XRF 120729A, XRF 130215A/SN 2013ez, XRF 130831A/SN 2013fu, and XRF 150818A), and 3 C-GRBs (GRB 080319B, GRB 111209A/SN 2011kl, and GRB 130427A/SN 2013cu). Our statistical results are shown in Table 4. It seems that XRFs and XRRs are more favorable to link with SN events than C-GRBs.

### 3.6. Host Galaxy Properties

The host galaxies of XRFs were investigated in the work of Bloom et al. (2003). Here, we investigate the host galaxy properties for the XRFs, XRRs, and C-GRBs in the BAT3 catalog. We pay attention to several parameters of GRB host galaxies from the GRB Host Studies (GHostS) database. The physical quantities of GRB host galaxy are stellar mass ($M^*$), metallicity ($Z$), and star formation rate (SFR). We list these
parameters of XRFs and XRRs in Table 5. The distributions of $M^*$ for XRFs, XRRs, and C-GRBs are shown in Figure 14. This figure includes 6 XRFs, 17 XRRs, and 28 C-GRBs. We cannot find the significant differences among XRFs, XRRs, and C-GRBs, as we estimate the K-S test probabilities between XRFs and XRRs ($P = 0.67$), XRRs and C-GRBs ($P = 0.30$), and XRFs and C-GRBs ($P = 0.28$). The distributions of metallicity $Z$ for XRFs, XRRs, and C-GRBs are shown in Figure 15. We obtain metallicity values of 5 XRFs, 6 XRRs, and 13 C-GRBs. It is hard to distinguish the differences among XRFs, XRRs, and C-GRBs. The K-S test probabilities between XRFs and XRRs, between XRRs and C-GRBs, between XRFs and C-GRBs are $P = 0.97$, $P = 0.44$, and $P = 0.90$, respectively. The distributions of SFR are shown in Figure 16. Four XRFs, 11 XRRs, and 22 C-GRBs are included. The K-S test probabilities are $P = 0.27$ (between XRFs and XRRs), $P = 0.09$ (between XRRs and C-GRBs), and $P = 0.03$ (between XRFs and C-GRBs). Therefore, it seems that there is an SFR difference between XRFs and C-GRBs. Here, we also note that only four XRFs have SFR values. This limitation prevents us for the further investigation.

GRB host galaxies are usually considered to be low-mass, low-metallicity, and star-forming galaxies (Christensen et al. 2004; Fynbo et al. 2009; Savaglio et al. 2009). However, we see that some GRBs are hosted in massive and/or high-metallicity galaxies (e.g., Hashimoto et al. 2015). Mao (2010) proposed a possible redshift evolution of GRB host galaxies from the theoretical point of view. From the observational point of view, one survey of the Swift-GRB host galaxy has recently been performed (Perley et al. 2016). We hope that more GRB host properties of XRFs, XRRs, and C-GRBs can be explored for further statistical analysis in the future.

### 3.7. Observational Biases and Selection Effects

We should mention some selection effects and observational biases that may affect our statistical results. First, the GRB prompt emission spectrum is usually fitted by the Band function (Band et al. 1993). However, the detection energy range of Swift-BAT is 15–350 keV, such that the spectral fitting is performed in the narrow energy range. The $E^\text{obs}_{\text{peak}}$ determination is from the cutoff power-law spectral model. Thus, the $E^\text{obs}_{\text{peak}}$ values in this sample might be different from those obtained from other space telescope detections with a wide energy range. Because GRB detections in a large energy range with a low energy threshold are required to accurately measure the $E^\text{obs}_{\text{peak}}$ numbers, some future sensitive telescopes, such as the Space Variable Objects Monitor (SVOM) and the Einstein Probe (EP), are expected (Yuan et al. 2017). Second, GRB redshift values are determined by the spectral observations in the optical band. Thus, we cannot ignore the fact that many XRFs/XRRs have no redshift determinations. Hence, the XRF/XRR quantities related to the redshift cannot be determined. One incomplete sample may have bias on the redshift distribution (e.g., Fiore et al. 2007). Third, the

### Table 5: Host Galaxy Properties of XRFs and XRRs

| Source         | $z$     | $E^\text{obs}_{\text{peak}}$ (keV) | SFR     | log($M^*/M_\odot$) | log($Z/Z_\odot$) |
|----------------|---------|-----------------------------------|---------|---------------------|------------------|
| XRF 050416A    | 0.6528  | $14.8^{+5.8}_{-3.0}$             | 2.32    | 9.19                | …                |
| XRF 050824     | 0.8278  | 80.0                             | …       | …                   | 0.3              |
| XRF 060218     | 0.03532 | $4.7 \pm 0.3$                    | 0.05    | 7.78                | 0.53             |
| XRF 061210     | 0.4095  | …                                | 9.52    | …                   | …                |
| XRF 071031     | 2.692   | $2.1_{-10.7}^{+107.8}$           | …       | …                   | 1.85             |
| XRF 071227     | 0.381   | $35.5 \pm 5.3$                   | 0.6     | 10.65               | 0.2              |
| XRF 090205     | 4.6497  | $38.4_{-3.8}^{+9.0}$             | …       | 10.83               | …                |
| XRF 100316D    | 0.0591  | $9.6_{-1.1}^{+0.3}$              | 0.14    | 8.93                | 0.39             |
| XRF 050223     | 0.584   | 68.1                             | 1.44    | 9.73                | …                |
| XRF 050724     | 0.257   | 11.5                             | …       | 10.64               | …                |
| XRF 060614     | 0.125   | $98.5_{-17.8}^{+29.9}$           | 0.01    | 7.95                | …                |
| XRF 061006     | 0.4377  | …                                | 0.17    | 8.86                | …                |
| XRF 070306     | 1.4959  | …                                | 13      | 10.36               | -0.29            |
| XRF 070429B    | 0.9023  | $72.9 \pm 13.0$                  | …       | 10.42               | …                |
| XRF 070612     | 0.671   | 137.7                            | 81      | …                   | -0.4             |
| XRF 070724     | 0.4571  | $45.9 \pm 8.6$                   | 15.3    | 9.92                | …                |
| XRF 070802     | 2.4541  | 58.3                             | …       | 9.85                | …                |
| XRF 080123     | 0.495   | 8.2                              | …       | 10.02               | …                |
| XRF 080525     | 1.78    | …                                | 9       | 10.8                 | …                |
| XRF 081109     | 0.979   | $169.7 \pm 42.3$                 | 9.9     | 9.82                | …                |
| XRF 090417B    | 0.345   | 112.9                            | …       | 10.14               | …                |
| XRF 090426     | 2.609   | $55.1 \pm 8.1$                   | …       | 10.81               | …                |
| XRF 091127     | 0.49044 | $34.0 \pm 1.0$                   | 0.22    | 8.6                 | -0.29            |
| XRF 100621A    | 0.542   | $83.0 \pm 9.0$                   | …       | 8.98                | …                |
| XRF 111008A    | 4.9907  | $122.6 \pm 29.7$                 | …       | …                   | -1.7             |
| XRF 120422A    | 0.28253 | 97.0                             | 0.4     | 8.95                | -0.4             |
| XRF 120729A    | 0.8     | $175.9 \pm 17.6$                 | 6       | 8.3                 | …                |
| XRF 130060A    | 5.9134  | 150.3                             | 36.2    | …                   | -1.1             |

Note. SFR is star formation rate of GRB host galaxy, in the unit of $M_\odot$ yr$^{-1}$. $M^*$ is stellar mass of GRB host galaxy. $Z$ is metallicity of GRB host galaxy. All data are taken from GRB Host Studies (GHostS) database.
observations for GRB host galaxies are also complicated. The detection of the high-redshift GRB host galaxies is one challenge. For example, Basa et al. (2012) performed the host galaxy search for three GRBs with $z > 5$ using the Hubble Space Telescope, and they did not find any evidence of high-redshift GRB hosts. Although Mao (2010) presented the
possible redshift evolution of GRB host properties, the GRB redshift distribution with the cosmic star formation has some biased effects (e.g., Dainotti et al. 2015).

4. Summary

We present a comprehensively statistical analysis to study the XRF/XRR properties in the Swift-BAT3 catalog. We have obtained 81 XRFs and 540 XRRs in our sample. We have analyzed the properties of γ-ray prompt emission, X-ray emission, X-ray light-curve type, association with SNe, and host galaxy properties for XRFs, XRRs, and C-GRBs. We list the major findings as follows: (1) Most XRFs/XRRs have low values of $E_{\text{peak}}$. We confirm that XRFs/XRRs mainly release their energy in the X-ray band, and they are low-luminosity GRBs. (2) Most XRFs/XRRs are long-duration GRBs. (3) XRFs, XRRs, and C-GRBs follow the same $E_{\text{iso}}-E_{\gamma,\text{iso}}-E_{\text{peak},\gamma}$ correlations. (4) We do not find any differences of redshift distributions among XRFs, XRRs, and C-GRBs in our sample. (5) XRFs seem to favor the association with SN explosions. (6) We find marginal but interesting evidence that different SFRs are shown between XRRs/XRFs and C-GRBs.

Although we see some differences between XRFs/XRRs and C-GRBs in some correlation studies and statistic results, we notice that the properties of XRFs, XRRs, and C-GRBs do not show a sharp difference. We confirm that XRFs and XRRs belong to GRBs. However, the physical origin of XRF/XRR is still unclear. The jet off-axis effect is traditionally applied to explain the observational phenomena of XRFs/XRRs. The constraints of the jet beaming and the opening angle were already proposed (Rhoads 1999; Frail et al. 2001). However, it is not the case that each GRB with the jet off-axis is XRF/XRR. For example, GRB 080710 with the observational evidence of the jet off-axis (Krühler et al. 2009) is classified as C-GRB in this paper. On the other hand, the direct measurements to identify the jet off-axis evidence cannot be performed for each GRB. The jet beaming angle statistics related to the study of XRF/XRR is expected (Gao & Dai 2010). It is suggested that the GRB thermal component in the X-ray band can be one possible reason to explain XRF/XRR energy release. As an example, GRB 090618, identified as XRR in this paper, had a detection of thermal X-ray emission by Swift X-ray telescope, and this XRR is associated with SN explosion (Can et al. 2011; Page et al. 2011). Starling et al. (2012) presented 11 Swift-detected GRBs with optical SN explosions, and the thermal X-ray signatures were clearly identified. However, compared to the XRFs/XRRs listed in this paper, the observed GRBs with the thermal emission that have optical SN explosion evidence are still very rare. From some recent theoretical modeling analysis, thermal emission may regulate the GRB spectral peak energy (Beloborodov 2013). Photospheric models can reproduce the GRB thermal emission in the γ-ray band (Vurm et al. 2013). We expect further observational cases of the GRB thermal emissions, although most of XRR and XRF spectra are still nonthermal. Finally, the GRB detectors with wide energy range and low energy threshold are expected especially for the study of XRFs and XRRs in the future.

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