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Swift/BAT Observations of X-Ray Flashes

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Abstract An analysis of prompt gamma-rays of X-ray flashes (XRFs) observed with the Swift/BAT has been presented. Our sample includes 235 bursts. It is found that the BAT detection ratio of XRFs to typical Gamma-ray bursts (GRBs) is 42:193, for division at $\Gamma = 2$ (roughly corresponding $E_{\rm p} \sim 50\,{\rm keV}$), Γ being the power law index of the BAT spectrum and $E_{\rm p}$, the peak energy ($E_{\rm p}$) of the νf_ν spectrum. This is consistent with the HETE-2 observations. For both XRFs and GRBs Γ are almost normally distributed in the range of 1 to 2.8, similar that observed with HETE-2. The distribution of Γ for the entire set of GRBs/XRFs is not available due to poor statistics on the peak at $\Gamma > 2.3$. This result probably indicates that the BAT spectrum of a typical XRF could have a Γ of roughly 2.3, if they indeed are a distinct soft component of the GRB population. By comparing the fluence and the peak flux in different energy bands, it is found that the XRFs are ordinarily softer than the GRBs, but during the peak time the spectra of both GRBs and XRF are similar, showing that the dominant radiation mechanisms of both GRBs and XRFs are similar.

Key words: gamma-rays: bursts

1 INTRODUCTION

X-ray flashes (XRFs) are a subclass of gamma-ray bursts (GRBs), characterized by a soft spectrum and a low isotropic gamma-ray energy, compared to typical gamma-ray bursts (GRBs) (Heise et al. 2001; Kippen et al. 2003; Sakamoto et al. 2004, 2005, 2006; Lamb et al. 2005; Liang & Dai 2004a). The XRF phenomenon was first discovered with the Beppo-SAX satellite (Heise et al. 2001; Kippen et al. 2003), and was well studied with HETE-2 observations (Sakamoto et al. 2004, 2005; Liang & Dai 2004b; Cui et al. 2005). They expand the energy coverage of prompt gamma-ray emission to the lower energy band, and they may constrain the radiation mechanisms that dominated the prompt emission and the energy budget of the GRB phenomenon. Some models have been proposed, and they can be divided into two classes, intrinsic or extrinsic, which interpret the XRFs as intrinsically different from the GRBs or the same as typical GRBs but with some extrinsic factors (see recent review by Zhang 2007).

The nature of XRFs is still unclear. The GRB mission *Swift* (Gehrels et al. 2004) has achieved many breakthroughs and opened a new era of GRB research (see reviews by Mészáros 2006; Zhang 2007). The peak energy ($E_{\rm p}$) of the νf_ν spectrum of XRFs is lower than $\sim 50\,{\rm keV}$ (Kippen et al. 2003; Liang & Dai 2004a). The energy band of the on-board Burst Alert Telescope (BAT) is 15–150 keV, and is suited to observing XRFs. Using data from the BAT and the X-ray Telescope (XRT, Burrows 2005), Zhang et al. (2007a) found that XRFs are as efficient as GRBs only if the early X-ray data right after the prompt emission are used to estimate the afterglow kinetic energy. If one uses the X-ray data after the shallow-to normal transition break to calculate the kinetic energy, then XRFs are inefficient. The XRT followed some XRFs to very late epochs and revealed that the XRFs seem to be less collimated (e.g., GRB 050416A, Mangano et al. 2007). Gendre, Galli & Piro (2007) studied the observations of XRFs with an XRF sample of known redshifts observed with Swift. The Swift/BAT has accumulated a uniform sample of more than 200 GRBs and its first catalog has been released (Sakamoto et al. 2007). In this paper we present a systematical analysis of the whole sample of XRFs with the data contained in the first BAT catalog (Sakamoto et al. 2007). A description of the data is presented in Section 2, and our results are given in Section 3. A discussion and conclusions are presented in Section 4.

2 DATA DESCRIPTION

The first BAT catalog contains 237 bursts observed between 2004 December 19 and 2007 June 16. There are no data for GRBs 041219A and 041219B, so we do not include these two bursts in our sample. The spectral index (Γ), peak flux (P), and the gamma-ray fluences (S) in 15–25 keV, 25–50 keV, 50–100 keV, and 100–150 keV of these bursts are taken from this catalog. It is well-known that the GRB spectrum is fitted with the Band function (Band et al. 1993). The peak energy ($E_{\rm p}$) of the νf_ν spectrum is $\sim 250\,\rm keV$ for a typical GRB, which is out of the BAT band. In order to constrain the parameters of the Band function $E_{\rm p}$ should be in the middle of the energy band of BAT. The spectrum accumulated by BAT is generally fitted with a simple power law, $f_\nu \propto \nu^{-\Gamma}$ (Zhang et al. 2007a). As shown in table 5 of Sakamoto et al. (2007), the BAT spectra of some GRBS are also roughly fitted by a cutoff power law, but the fitting χ^2 are not significantly improved and the spectral parameters are not sufficiently constrained, except for GRB 050219, 050525A, 050820B and 060117 (see also Zhang et al. 2007a). The peak energy of the four exceptions are 92^{+12}_{-8}, 82^{+4}_{-3}, 111^{+21}_{-13}, 70^{+5}_{-7} keV, approximately in the middle of the BAT energy band. Therefore, we adopt the single power law fitting results in our analysis.

3 RATIO OF XRFS TO GRBS

An empirical relation between the the photon index Γ of the BAT spectrum and the peak energy of the Band function was discovered by Zhang et al. (2007b) and Sakamoto et al. (2007), namely,

$$\log E_{\rm p} = (2.76 \pm 0.07) - (3.61 \pm 0.26) \log \Gamma. \tag{1}$$

We use this relation to estimate $E_{\rm p}$ of the *Swift* GRBs. We show the distributions of Γ and $E_{\rm p}$ in Figure 1. We also show the peak energy distributions of the BATSE GRBs and HETE-2 GRBs for comparison. The BATSE data are for a bright GRB sample (Preece et al. 2000). The HETE-2 data are taken from Liang & Dai (2004). It is found that the observations of Swift and HETE-2 are consistent. The peak energy of the BATSE sample is statistically larger than that of the BAT and HETE-2 samples, but this should be due a sample selection effect. The BATSE sample we used is bright, which is selected with the observed fluence and peak flux (Preece et al. 2000). According to the relation between $E_{\rm p}$ and flux, a brighter GRB will have a larger $E_{\rm p}$ (Liang et al. 2004b): this is known as the "Amati-relation" (Amati et al. 2002). Therefore, the peak energy of BATSE sample are larger than that of the Swift and HETE-2 samples.

We adopt the criterion $E_{\rm p} \sim 50\,\rm keV$ to separate XRFs and GRBs (Kippen et al. 2003; Liang et al. 2004). From Equation (1), a peak energy of 50 keV corresponds to $\Gamma \sim 2$. With this division, the ratio of XRFs to GRBs in our sample is 42:193, roughly consistent with the HETE-2 observations (Lamb et al. 2005; Liang & Dai 2004b). Zhang et al. (2007a) suggested that the Γ value of a typical XRF is > 2.3, which corresponds to a peak energy of ~ 28 keV, being consistent with the typical $E_{\rm p}$ of the XRFs as argued by Liang & Dai (2004b) with the HETE-2 data. With this division, the ratio of XRFs to GRBs in our sample is 18:217. In the analysis below we use the division by $E_{\rm p} \sim 50\,\rm keV$.

4 FLUENCES AND PEAK FLUXES IN DIFFERENT ENERGY BANDS

Figure 2 shows relations between fluences in different energy bands for the XRFs and GRBs. From Figure 2(a), we find that S_{15-25}, S_{25-50} and S_{50-100} are comparable to one another in strength, while the $S_{100-150}$ are below the line of $\log S_{100-150} = \log S_{15-25}$, indicating that S_{15-25} is significantly larger than $S_{100-150}$ for the XRFs. The GRBs do not show such a feature. See Figure 2(b). Their S_{25-50} and S_{50-100} are larger than S_{15-25}. These results indicate that the division at $\Gamma > 2$ is roughly consistent with $S_{15-25} > S_{100-150}$. The peak energy of XRFs thus is in the range $25 \sim 100$ keV. The fact that the fluences of GRBs in the four energy bands are almost a constant shows that their $E_{\rm p}$ are beyond the BAT band. The relation of P_{15-25} to P_{25-50}, P_{50-100} and $P_{100-150}$ are shown in Figure 3 for both the XRFs and GRBs. It

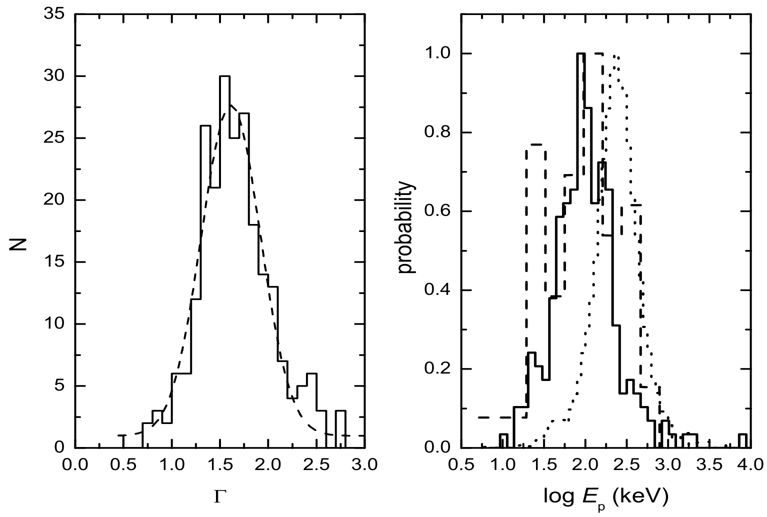

Fig. 1 Distributions of Γ and E_p for the Swift GRBs in our sample. The dashed and dotted lines in the right panel are for the HETE-2 GRBs and for a bright sample of BATSE GRBs, respectively.

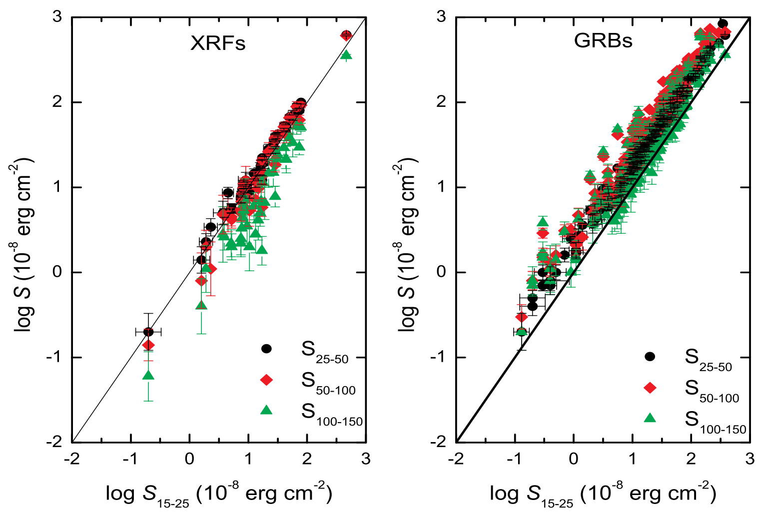

Fig. 2 Gamma-ray fluences in 25–50 keV and 50–100 keV bands versus fluences in 15–25 kev band for XRFs (left) and GRBs (right).

is found that $P_{100-150}$ of some XRFs are comparable to P_{25-50} and P_{50-100}, suggesting that their $E_{\rm p}$ during the peak time are above the BAT band, similar to GRBs. These facts reveal that the XRFs are ordinarily soft, but during the peak time they are similar to the GRBs.

The distributions of the observed fluence and peak flux for both the XRFs and GRBs are shown in Figure 4. A K-S test for the differences in the peak flux and fluence distributions between the GRBs and XRFs gives $D_{\rm K-S} = 0.38$ with a probability $p_{\rm K-S} = 1.37 \times 10^{-4}$ and $D_{\rm K-S} = 0.35$ with $p_{\rm K-S} = 2.62 \times 10^{-4}$, respectively. These results show that the differences in the observed fluence and the peak flux in the BAT band between XRFs and GRBs are marginally significant.

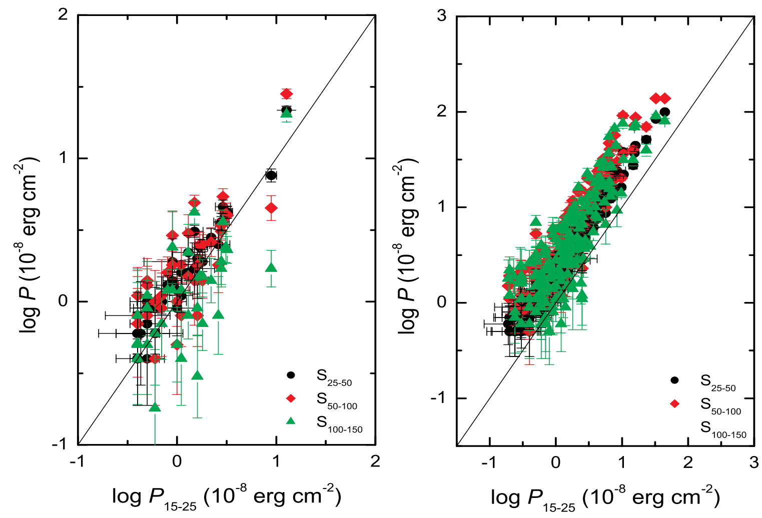

Fig. 3 Peak fluxes in 25–50 keV, 50–100 keV and 100–150 keV bands versus that in 15–25 keV band for XRFs (left) and GRBs (right).

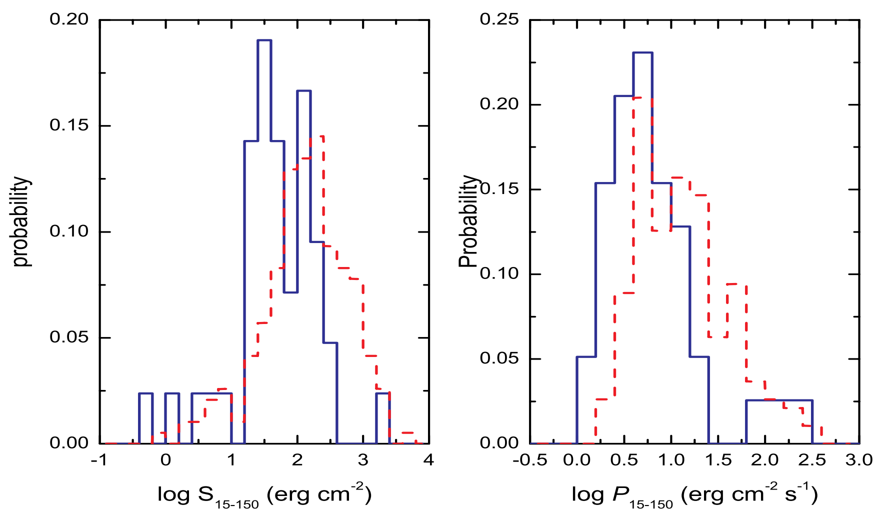

Fig. 4 Comparison of the distributions of total fluences (left) and peak fluxes (right) in the 15–150 keV band between the GRBs and XRFs in our sample. Solid line for GRBs and dashed line for XRFs.

5 DISCUSSION AND CONCLUSIONS

We have systematically analyzed the prompt gamma-rays of XRFs observed with BAT, and compared them with typical GRBs. With the division at $\Gamma = 2$ (corresponding to $E_{\rm p} \sim 50\,$keV) we found that the BAT detection ratio of XRFs to GRBs is 42:193, roughly consistent with the HETE-2 observations. The distribution of Γ is almost normal in the range from 1 to 2.8, a small peak of XRFs at $\Gamma = 2.3$ may be a statistical fluctuation, similar to that observed with HETE-2 (Liang & Dai 2004b). Although a bimodal distribution of the Γ for the entire set of GRBs/XRFs cannot be claimed due to poor statistics for the peak at $\Gamma > 2.3$, a likely indication of our results is that the BAT spectrum of typical XRFs could have values of Γ roughly around 2.3, as suggested by Zhang et al. (2007a).

The fluences of the XRFs in the energy band 15–100 keV are comparable to that of the GRBs, but they are located at significantly lower band of the range, indicating that the XRFs are ordinarily soft (Gendre, Galli & Piro 2007). However, during the peak time the spectra of some XRFs become similar to GRBs. This fact implies that the observed flux is correlated with $E_{\rm p}$, as shown in typical GRBs (Liang, Dai & Wu 2004b). The distributions of observed fluence and peak flux for both XRFs and GRBs indicate that the observed fluence and the peak flux in the BAT band for XRFs and GRBs are marginally significantly different. These results reveal that the dominating radiation mechanisms of both GRBs and XRFs are similar.

As shown in Figure 1, a small peak of XRFs at $\Gamma = 2.3$ is observed for the bursts in our sample. The poor statistics cannot claim the peak at $\Gamma \sim 2.3$, and we deem that it a statistical fluctuation. However, if XRFs are indeed a unique population from typical GRBs, they should have a $\Gamma > 2.3$, which is much softer than the current Swift GRB sample. In fact, the current Swift GRB trigger criterion cannot examine whether or not XRFs are a distinct GRB population.

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