Comparing Prompt Emission from X-ray Flashes and Gamma-ray Bursts

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Abstract. The final year of the *Beppo*SAX mission provided a much needed clue as to the nature of X-ray flashes. The detection of afterglow counterparts and their underlying hosts provides strong evidence that X-ray flashes and gamma-ray bursts originate from similar sources in cosmologically distant galaxies. These observations support findings that the prompt emission characteristics of X-ray flashes are similar to those of traditional gamma-ray bursts. Using wide-band observations from *Beppo*SAX and BATSE, we present the latest results in our on-going effort to quantify the similarities and differences in prompt emission characteristics.

INTRODUCTION

The revolution in gamma-ray burst (GRB) astronomy prompted by the discovery of multiwavelength afterglow counterparts has brought tremendous progress in understanding the nature of burst progenitors, their surrounding environments, and host galaxies. Understanding of the mechanisms giving rise to the prompt burst emission itself, however, is comparatively confused despite a large amount of observational data. This paper summarizes our ongoing efforts [1, 2, 3, 4] to investigate one revealing characteristic that could help this situation — the lower energy form of the GRB emission process — by comparing prompt GRB properties to those of the so-called X-ray flashes (XRFs). The analysis is based on a sample of XRFs that were selected using *Beppo*SAX Wide Field Camera (WFC; 2–26 keV) X-ray observations, but also detected in 20–300 keV gamma rays through an off-line scan of BATSE data.

OBSERVATIONS

Our test sample is based on the events identified, selected, and classified using the *Beppo*SAX WFC and GRB Monitor (GRBM) instruments. In this scheme, XRFs are differentiated from GRBs based on the lack of GRBM (40–400 keV) detection. Using simultaneous BATSE observations we can reveal wide-band spectral properties and make a more quantitative comparison between XRFs and "traditional" GRBs.

TABLE 1. WFC/BATSE Observation Summary 21-Apr-91 to 26-May-00.

WFC Classification	WFC Detections	Observable with BATSE	BATSE Triggers	BATSE Off-line Detections
GRB	32	21	18	21
XRF	15	9	0	9
Questionable	7	4	0	4
Total	54	34	18	34

Apart from observational outages, the WFC and BATSE instruments operated simultaneously for 3.8 years, ending with the termination of BATSE science operations on 26-May-2000. For all of the GRB-like transient events detected by WFC, we performed an off-line search of the $>$20 keV BATSE data. Results of the search are listed in Table 1. Not all events were observable with BATSE due to data gaps and Earth occultation. The result is that all GRB-like WFC events observable with BATSE were detected with $\geq 5\sigma$ statistical significance in the off-line search. The list of detections includes four questionable events, three of which are likely long-duration ($\sim$1000 s) GRBs [5], and one is likely a Type I X-ray burst. These questionable events are excluded from further analysis. For the remaining 21 GRB and 9 XRF we have a complete set of WFC+BATSE data to use in comparing XRF and GRB properties.

SPECTRAL ANALYSIS

For each of the 30 XRF and GRB events we computed standard parameters (peak flux, fluence, and duration) using the same processes developed for the BATSE GRB catalogs. Furthermore, the WFC and BATSE data were used to jointly estimate the time-averaged, 2 keV to 2 MeV spectrum of each event. Four separate spectral models were used in this process: black body (BB), power law (PL), power law times exponential (COMP), and Band's GRB function.

Based on the chi-squared values for the various models, we make the following conclusions. First, none of the GRB or XRF events are consistent with the BB model, as is expected for non-thermal GRB-like spectra. Second, for most GRB events (19 of 21), and three of the XRF events, a single PL model can be rejected with good confidence. This is typical of GRBs, which usually have strongly curved (i.e., non power-law) broadband spectra. Finally, the change in chi-squared from a power law to a COMP or Band model is statistically significant for most of the GRB and XRF events. This is an important indication that curved spectra are favored for XRFs just as they are for traditional GRBs.

XRFS VS. BRIGHT GRBS

To compare the spectral properties of XRFs to those of well-measured (i.e., bright) GRBs we use the 21 WFC-selected GRBs and the Preece et al. [6] catalog of 156 bright BATSE GRBs (BBGs). Figure 1 compares the distributions of Band-model spectral parameters for the three event samples (similar results were obtained with the COMP model). We use the Kolmogorov-Smirnov (KS) test on unbinned data to compare the different distributions. The statistical significance of the observed deviations between distributions is evaluated through Monte Carlo simulations that account for the sample sizes as well as the measured statistical uncertainties in spectral parameters. The results are that the α and β parameters are reasonably consistent between XRFs and GRBs, but XRFs have significantly lower $E_{\rm peak}$ than GRBs.

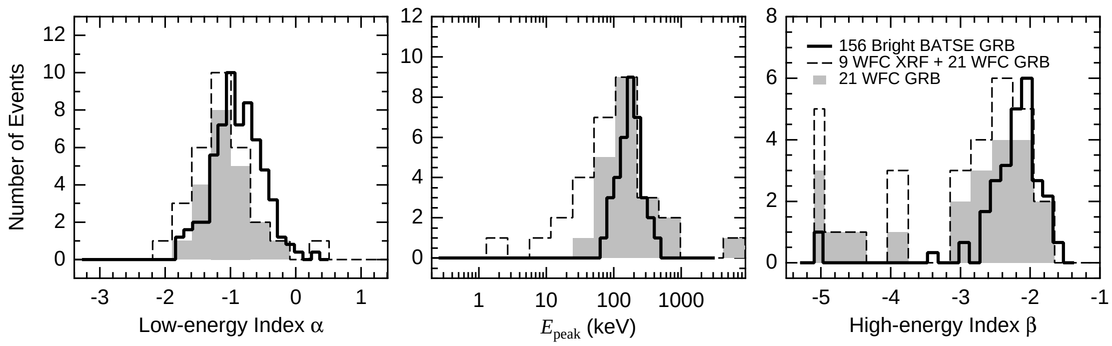

FIGURE 1. Distributions of time-averaged Band model spectral parameters for WFC-selected XRFs and GRBs compared to bright BATSE GRBs (normalized to peak of dashed curves).

XRFS VS. DIM GRBS

The above bright burst comparison ignores the known GRB hardness–intensity correlation. It is therefore important to compare XRFs to weak GRBs that have similar (gamma-ray) brightness. To do this we use the Mallozzi et al. [7, MAL] burst sample, which includes 523 long-duration ($T_{50} > 1$ s) BATSE bursts that were fit using the Band spectral model. Figure 2 compares these bursts with the WFC-selected events. The hardness–intensity correlation is evident in WFC GRBs and MAL GRBs.

To compare XRFs and dim GRBs we first modeled the hardness-intensity ($E_{\rm peak}$ vs. peak flux) correlation using a power-law fit to binned GRB data (including statistical uncertainties). The power-law was then extrapolated into the intensity regime of the XRFs, assuming different models for the GRB intensity (LogN–LogP) distribution. Finally, the KS test was used to compare the unbinned XRF data to the extrapolated GRB $E_{\rm peak}$ distribution. This analysis indicates that (within sizable uncertainties) XRFs and extrapolated dim WFC GRBs are statistically consistent, with chance KS probability $P_{\rm KS} \approx 0.2$–0.4 (depending on the choice of LogN–LogP). The extrapolated BATSE GRBs, however, have significantly larger $E_{\rm peak}$ than XRFs.

The above comparison ignores differences in selection biases between the WFC and BATSE samples. Starting with the BATSE power-law fit, we simulated the effect of the WFC selection bias assuming (1) α and β are independent of burst intensity and described by the BBG distributions of Figure 1, (2) random burst directions over the WFC field of view, and (3) the approximate WFC trigger criteria. The effect of this simulated bias on the power-law hardness–intensity correlation is indicated on the rightmost plot in Figure 2. Including this bias, the $E_{\rm peak}$ distribution of XRFs and extrapolated

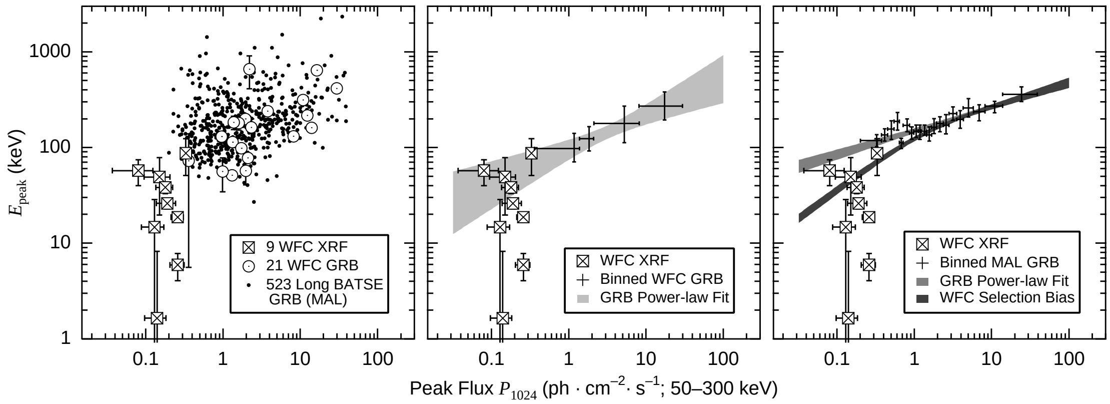

FIGURE 2. Long-duration GRB hardness–intensity data (left) binned and fit to a power law (center). The rightmost plot shows BATSE GRB data with a power-law fit. The lower most curve indicates the effect of a simulated WFC selection bias on the power-law correlation.

BATSE-selected dim GRBs are statistically consistent, with $P_{\rm KS} \sim 0.1$ (depending on the choice of LogN–LogP).

CONCLUSION

While XRF-like events have been detected by *Ginga* in the past and HETE-II at present, the WFC+BATSE sample probably offers the greatest broad-band sensitivity. The nine jointly observed XRFs therefore represent a unique resource for comparing prompt XRF and GRB behavior.

Our results indicate that the prompt, broad-band emission from XRFs is quantitatively consistent with that expected from weak, long-duration, traditional GRBs. Combined with their similar temporal properties, this strongly suggests that XRFs and long GRBs are produced by a continuous variation of the same phenomenon. The detailed hardness–intensity correlation over the full range spanned by XRFs and GRBs presumably provides a valuable clue as to the nature of this phenomenon.

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