Confirmation of the $E_{\text{peak}}^{\text{src}} - E_{\text{iso}}$ (Amati) relation from the X-ray flash XRF 050416A observed by Swift/BAT


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Abstract. We report Swift Burst Alert Telescope (BAT) observations of the X-ray Flash (XRF) XRF 050416A. The fluence ratio between the 15-25 and 25-50 keV bands of this event is 1.1, thus making it the softest gamma-ray burst (GRB) observed by BAT so far. The spectrum is well fitted by the Band function with $E_{\text{obs}}^{\text{peak}}$ of $15.6^{+2.3}_{-2.7}$ keV. Assuming the redshift of the host galaxy ($z=0.6535$), the isotropic-equivalent energy $E_{\text{iso}}$ and the $E_{\text{peak}}^{\text{src}}$ energy at the GRB rest frame ($E_{\text{peak}}^{\text{src}}$) of XRF 050416A are not only consistent with the correlation found by Amati et al. and extended to XRFs by Sakamoto et al., but also fill-in the gap of this relation around 30–80 keV range of $E_{\text{peak}}^{\text{src}}$. This result tightens the validity of the $E_{\text{peak}}^{\text{src}} - E_{\text{iso}}$ relation form XRFs to GRBs.

Keywords: Prompt gamma-ray emission, X-ray flash
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INTRODUCTION

The observations of X-ray flashes (XRF) are providing important information for understanding the nature of Gamma-Ray Bursts (GRBs). About 36% of the bright bursts observed by Ginga have $E_{\text{peak}}^{\text{obs}}$ energy, which is the photon energy at which the $\nu F_\nu$ spectrum peaks, around a few keV and also show large X-ray to $\gamma$-ray fluence ratios [1]. The Wide Field Cameras (WFC) on-board the BeppoSAX satellite observed 17 XRFs in five years [2]. Kippen et al. [3] searched for GRBs and XRFs which were observed in both WFC and BATSE. The WFC and BATSE joint spectral analysis of XRFs shows that their $E_{\text{peak}}^{\text{obs}}$ energies are significantly lower than those of the BATSE $E_{\text{peak}}^{\text{obs}}$ distribution [4]. The systematic study of the spectral properties of XRFs observed by HETE-2 also supports this result [5].

The afterglow detection and the redshift measurement from the host galaxy of XRF 020903, which is one of the softest XRF observed by HETE-2, shows the dramatic progress in understanding the nature of XRFs. The prompt emission of XRF 020903 has $E_{\text{peak}}^{\text{obs}} < 5.0$ keV which is two orders of magnitude smaller than that of typical
GRBs. The optical transient and the host galaxy of XRF 020903 were detected. Further spectroscopic observation of the host galaxy suggests that the redshift is $0.25 \pm 0.01$ [6]. Sakamoto et al. [7] calculated the isotropic-equivalent energy $E_{\text{iso}}$ and the peak energy at the source frame $E_{\text{peak}}$ using the redshift of the host galaxy, and found that XRF 020903 follows an extension of the empirical relationship between $E_{\text{iso}}$ and $E_{\text{peak}}$ found by Amati et al. [8] for GRBs (a.k.a. Amati relation). This result provides the observational evidence that XRFs and GRBs form a continuum and are a single phenomenon.

The X-ray flash, XRF 050416A, was detected and localized by the Swift Burst Alert Telescope (BAT) at 11:04:44.5 UTC on 2005 April 16 [9, 10]. Swift autonomously slewed to the BAT on-board position, and both Swift X-Ray Telescope (XRT) and UV-Optical Telescope (UVOT) detected the afterglow [11, 12]. Cenko et al. [13] reported that the host galaxy is faint and blue with large amount of the star formation and its redshift is $z = 0.6535 \pm 0.0002$.

**BAT DATA ANALYSIS**

The left panel of figure 1 shows the energy resolved BAT light curves of XRF 050416A. It is clear that the signal of the burst is only visible below 50 keV. The burst signal is composed of two peaks. The first peak has a triangular shape with the rise time longer than the decay time. The $t_{90}$ and $t_{50}$ in the 15-150 keV band are 2.4 and 0.8 seconds, respectively. This $t_{90}$ belongs to the shortest part of the “long GRB” classification based on the BATSE duration distribution [14]. The fluence ratio between the 15-25 keV band and the 25-50 keV band of 1.1 makes this burst one of the softest GRBs observed by

**FIGURE 1.** Left: The energy resolved light curves of BAT. The hardness ratio between 25-50 and 15-25 keV band is shown in a bottom panel. Right: The time-averaged spectrum with a simple power-law model.

**TABLE 1.** The time-averaged spectral parameters of XRF 050416A

<table>
<thead>
<tr>
<th>Model</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$E_{\text{peak}}$</th>
<th>$K_{30}$</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL</td>
<td>$-3.1 \pm 0.2$</td>
<td></td>
<td>$(4.3 \pm 0.3) \times 10^{-2}$</td>
<td>50.74 / 57</td>
<td></td>
</tr>
<tr>
<td>Band</td>
<td>$&lt;-3.4$</td>
<td>$15.6^{+2.3}_{-2.7}$</td>
<td>$3.5^{+1.7}_{-0.8} \times 10^{-4}$</td>
<td>42.99 / 56</td>
<td></td>
</tr>
</tbody>
</table>

GRBs. The optical transient and the host galaxy of XRF 020903 were detected. Further spectroscopic observation of the host galaxy suggests that the redshift is $0.25 \pm 0.01$ [6]. Sakamoto et al. [7] calculated the isotropic-equivalent energy $E_{\text{iso}}$ and the peak energy at the source frame $E_{\text{peak}}$ using the redshift of the host galaxy, and found that XRF 020903 follows an extension of the empirical relationship between $E_{\text{iso}}$ and $E_{\text{peak}}$ found by Amati et al. [8] for GRBs (a.k.a. Amati relation). This result provides the observational evidence that XRFs and GRBs form a continuum and are a single phenomenon.

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FIGURE 2. The isotropic-equivalent energy, $E_{\text{iso}}$, versus the peak energy at the GRB rest frame, $E_{\text{peak}}^{\text{src}}$, for XRF 050416A (square) and the known redshift GRBs from BeppoSAX (circle) and HETE-2 (triangle)

BAT so far. The bottom panel of figure 1 left shows the count ratio between the 25-50 keV and 15-25 keV bands. The spectral softening is clearly visible during the first and the second peak.

The right panel of figure 1 shows the time-averaged spectrum, accumulated over the time interval from $-0.5$ seconds to 3 seconds since the BAT trigger time, was fitted with a simple power-law model. The photon index $\beta$ which is much steeper than $-2$ strongly indicates that the BAT observed the higher energy part of the Band function [15]. Motivated by this result, we tried to fit the spectrum with the Band function assuming the low energy photon index $\alpha$ to be fixed at $-1$, which is the typical value for both GRBs [4] and XRFs [3, 5]. The fitting shows a significant improvement from a simple power-law model to the Band function of $\Delta \chi^2$ of 7.75 for 1 degree of freedom.

The observed $E_{\text{peak}}$ energy, $E_{\text{peak}}^{\text{obs}}$, is well constrained at $15.6^{+2.3}_{-2.7}$ keV, and it confirms the soft nature of this burst.

One of the most important discoveries related to XRF 050416A is the confirmation of the $E_{\text{peak}}^{\text{src}} - E_{\text{iso}}$ relation [8]. We calculate the $E_{\text{peak}}$ energy at the GRB rest frame, $E_{\text{peak}}^{\text{src}}$, and the isotropic-equivalent energy ($1 - 10^4$ keV at the rest frame), $E_{\text{iso}}$, using the redshift of the host galaxy ($z=0.6535$). Assuming $\alpha = -1$, $E_{\text{peak}}^{\text{src}}$ and $E_{\text{iso}}$ of XRF 050416A are $25.1^{+4.4}_{-3.7}$ keV and $(1.2 \pm 0.2) \times 10^{51}$ erg, respectively. Figure 2 shows the data point of XRF 050416A with the known redshift GRBs of BeppoSAX and HETE-2 sample [16, 17, 7]. XRF 050416A not only follows the $E_{\text{peak}}^{\text{src}} \propto E_{\text{iso}}^{0.5}$ relation, but also fills in the gap of the relation around $E_{\text{peak}}^{\text{src}}$ of $30 - 80$ keV. This result tightens
the validity of this relation at five orders of magnitude in \( E_{iso} \) and at three orders of magnitude in \( E^{src}_{peak} \). XRF 050416A bridges the gap between XRFs which have \( E^{src}_{peak} \) of less than 10 keV and GRBs in the \( E^{src}_{peak} - E_{iso} \) relation.

**DISCUSSION**

According to the XRT afterglow observation of XRF 050416A, the decay slope of the afterglow emission is \( \sim -0.9 \) from 0.015 days to \( \sim 34.7 \) days after the GRB trigger without any signature of a jet break [18].

Using \( E^{src}_{peak} \) and \( E_{iso} \) of XRF 050416A measured by BAT, we can estimate the jet break time using the relation between \( E^{src}_{peak} \) and the jet collimation-corrected energy \( E_{\gamma} \) found by Ghirlanda et al. [19] (Ghirlanda relation). When we use the empirical relation between \( E_{iso}, E^{src}_{peak} \), and the jet break time at the rest frame, \( t^{src}_{jet} \), derived by Liang & Zhang [20] which is purely based on observational properties, the jet break time in the observer's frame is estimated to be \( \sim 1.5 \) days after the GRB on-set time. Thus, the estimated jet break time using the empirical \( E^{src}_{peak} - E_{iso} - t^{src}_{jet} \) relation is inconsistent with the null detection of a jet break until more than 34.3 days after the trigger by XRT. This non-jet break feature in the XRT afterglow light curve might be a further challenging for GRB jet emission, models and XRF/GRB unification scenarios.

**REFERENCES**

17. Lamb, D.Q. et al., NewAR, 48, 423