CONFIRMATION OF THE $E_{\text{peak}}^{\text{iso}}$, $E_{\text{iso}}$ (AMATI) RELATION FROM THE X-RAY FLASH XRF 050416A OBSERVED BY THE SWIFT BURST ALERT TELESCOPE

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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 energy 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 a Band function with $E_{\text{peak}}^{\text{iso}}$ of 15.0$^{\pm}$2.3 keV. Assuming the redshift of the host galaxy ($z = 0.6535$), the isotropic equivalent radiated energy $E_{\text{iso}}$ and the peak energy at the GRB rest frame ($E_{\text{peak}}^{\text{iso}}$) 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 the 30–80 keV range of $E_{\text{peak}}^{\text{iso}}$. This result tightens the validity of the $E_{\text{peak}}^{\text{iso}}$, $E_{\text{iso}}$ relation from XRFs to GRBs. We also find that the jet break time estimated using the empirical relation between $E_{\text{peak}}^{\text{iso}}$ and the collimation corrected energy $E_{\text{c}}$ is inconsistent with the afterglow observation by the Swift X-Ray Telescope. This could be due to the extra external shock emission overlaid around the jet break time or to the nonexistence of a jet break feature for XRFs, which might be a further challenge for GRB jet emission models and XRF/GRB unification scenarios.

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1.INTRODUCTION

Observations of X-ray flashes (XRF) are providing important information for understanding the nature of gamma-ray bursts (GRBs). Detailed studies of XRFs started a few years ago based on BeppoSAX observations (Heise et al. 2001; Kippen et al. 2003), but X-ray–rich events had already been detected by the Ginga satellite. Yoshida et al. (1989) reported that soft X-ray emission below 10 keV coexists with gamma-ray emission of GRBs. About 36% of the bright bursts observed by Ginga have a value of $E_{\text{peak}}^{\text{iso}}$, the photon energy at which the $pF_{\gamma}$, spectrum peaks, of around a few keV and also show large X-ray to gamma-ray fluence ratios (Strohmayer et al. 1998).

The Wide-Field Camera (WFC) on board the BeppoSAX satellite observed 17 XRFs in 5 years (Heise et al. 2001). Kippen et al. (2003) searched for GRBs and XRFs that were observed in both WFC and BATSE. The WFC and BATSE joint spectral analysis of XRFs shows that their energies are significantly lower than those 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 $0.25 \pm 0.01$ (Soderberg et al. 2004). Sakamoto et al. (2004) calculated the isotropic equivalent energy $E_{\text{iso}}$ and the peak energy at the source frame $E_{\text{peak}}^{\text{iso}}$, using the redshift of the host galaxy and found that XRF 020903 follows an extension of the empirical relation between $E_{\text{iso}}$ and $E_{\text{peak}}^{\text{iso}}$ found by Amati et al. (2002) for GRBs (also known as the Amati relation). This result provides observational evidence that XRFs and GRBs form a continuum and are a single phenomenon.

In this paper, we report on the prompt emission properties of XRF 050416A as observed by the Burst Alert Telescope (BAT) on board the Swift satellite. The X-ray flash, XRF 050416A, was detected and localized by the Swift (Gehrels et al. 2004) BAT (Barthelmy et al. 2006) at 11:04:44.5 UTC on 2005 April 16 (Sakamoto et al. 2005b, 2005c). Swift autonomously slewed to the BAT on-board position, and both the Swift X-Ray Telescope (XRT; Burrows et al. 2006) and the UV-Optical Telescope (UVOT; Roming et al. 2006) detected the afterglow (G. Cusumano et al. 2006 and S. Holland et al. 2006, both in preparation). The afterglow emission of XRF 050416A was also observed by ground observatories at various wavelengths (Cenko et al. 2005a, 2005b; Anderson et al. 2005; Li et al. 2005; Kahharov et al. 2005; Price et al. 2005; Soderberg et al. 2005). Cenko et al. (2005c) reported that the host galaxy is faint and blue with a large amount of the star formation and that its redshift is $z = 0.6535 \pm 0.0002$. Through-out this paper, the quoted errors are at the 90% confidence level and the sky coordinates are in J2000.0 unless we state otherwise.

2. BAT DATA ANALYSIS

The BAT data analysis was performed using the Swift software package (HEAsoft 6.0). The background was subtracted using the modulations of the coded aperture (mask-weighting technique). In this technique, photons with energies higher than 150 keV become transparent to the coded mask and these photons are treated as a background. Thus, in this mask-weighted technique the effective BAT energy range is from 14 to 150 keV.
were derived directly from fitting the time-averaged and 1 s peak spectra, respectively, assuming a Band function with $\alpha = -1$. Table 2 summarizes the spectral parameters of the BAT time-averaged spectrum. Figure 2 shows the time-averaged spectrum, accumulated over the time interval from $-0.5$ to $3$ s since the BAT trigger time, 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 (Band et al. 1993). Motivated by this result, and also by the fact that almost all GRB and XRF spectra are well described by the Band function (Preece et al. 2000; Kippen et al. 2003), we tried to fit the spectrum with a Band function assuming the low-energy photon index $\alpha$ to be fixed at $-1$, which is the typical value for both GRBs (Preece et al. 2000) and XRFs (Kippen et al. 2003; Sakamoto et al. 2005a). The fitting shows a significant improvement from a simple power-law model to the Band function of $\Delta \chi^2 = 7.75$ for 1 degree of freedom. To quantify the significance of this improvement, we performed 10,000 spectral simulations assuming our best-fit spectral parameters in a simple power-law model and determined in how many cases the Band function fit gives $\chi^2$ improvements of equal or greater than 7.75 over the simple power-law model. We found equal or higher improvements in $\chi^2$ in 62 simulated spectra out of 10,000. Thus, the chance probability of having an equal or greater improvements in $\chi^2$ is $0.6\%$. The observed $E_{\text{peak}}$ energy, $E_{\text{peak}}$, is well constrained at 15.6$^{+2.7}_{-2.7}$ keV, and it confirms the soft nature of this burst. We also applied a constrained Band function fit (Sakamoto et al. 2004) to the BAT spectrum.

![Fig. 1.—Light curve of XRF 050416A in five energy bands: 15–25, 25–50, 50–100, 100–150, and 15–150 keV. The bottom panel shows the hardness ratio between the 25–50 and 15–25 keV bands.](image)

![Fig. 2.—BAT spectrum of XRF 050416A with a simple power-law model. The spectral bins in the figure are at least 3 $\sigma$ or are grouped into sets of 13 bins.](image)

**TABLE 2**

**The Time-averaged Spectral Parameters of XRF 050416A**

| Model       | $\alpha$ | $\beta$ | $E_{\text{peak}}$  | $K_{90}$  | $\chi^2$/dof |
|-------------|-----------|---------|---------------------|-----------|--------------|
| PL$^a$      | $-3.1 \pm 0.2$ | $4.3 \pm 0.3$ | $10^{-2}$       | 50.74/57  |
| PL$^b$      | $-3.4 \pm 0.4$ | $4.7 \pm 0.5$ | $10^{-2}$       | 43.88/53  |
| Band        | $-1^{b}$  | $15.6^{+2.7}_{-2.7}$ | $3.5^{+0.4}_{-0.4}$ | $10^{-1}$ | 42.99/56    |

Note. — $E_{\text{peak}}$ is in units of keV; $K_{90}$ is in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$.

$^a$ Fitting result using only spectral bins above 20 keV.

$^b$ Fixed.

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. When we calculate the spectral lag (Norris et al. 2000) between the 25–50 and 15–25 keV bands, the cross-correlation function lag is $-0.066^{+0.014}_{-0.018}$ s (1 $\sigma$ error). These temporal characteristics are very unusual for typical GRBs (e.g., Mitrofanov et al. 1996; Norris et al. 2000); thus, it is difficult to understand them in the framework of the standard internal shock models in which the rise time is always shorter than the decay time and the hard emission always exceeds the soft emission (e.g., Piran 1999; Kobayashi et al. 1997). The $t_{90}$ and $t_{50}$ in the 15–150 keV band are 2.4 and 0.8 s, respectively. This $t_{90}$ belongs to the shortest part of the “long GRB” classification based on the BATSE duration distribution (Paciesas et al. 1999). The fluence ratio between the 15–25 and the 25–50 keV bands of 1.1 makes this burst one of the softest GRBs observed by BAT so far. The bottom panel of Figure 1 shows the count ratio between the 25–50 and 15–25 keV bands. The spectral softening is clearly visible during the first and the second peak.

As reported by the BAT team, we applied the energy-dependent systematic error vector in the spectral files before doing any fitting procedure. The background-subtracted (mask-weighted) spectral data were used in the analysis. The XSPEC version 11.3.1 software package was used for fitting the data from 14 to 150 keV to the model spectrum.

Table 1 shows the fluences and peak photon fluxes in the various energy bands. These fluences and peak photon fluxes were derived directly from fitting the time-averaged and 1 s peak spectra, respectively, assuming a Band function with $\alpha = -1$.

**TABLE 1**

**Energy Fluences and Peak Photon Fluxes of XRF 050416A Assuming a Band Function with $\alpha = -1$**

| Energy Band (keV) | Energy Fluence (ergs cm$^{-2}$) | Peak Photon Flux (photons cm$^{-2}$ s$^{-1}$) |
|------------------|---------------------------------|-----------------------------------------------|
| 15–25            | $(1.7 \pm 0.2) \times 10^{-7}$  | $(9 \pm 0.4) \times 10^{-6}$                  |
| 25–50            | $(1.5 \pm 0.2) \times 10^{-7}$  | $1.7 \pm 0.2$                                 |
| 50–100           | $3.4^{+0.4}_{-0.4} \times 10^{-8}$ | $3.2^{+0.4}_{-0.4} \times 10^{-8}$            |
| 100–150          | $4.2^{+0.5}_{-0.5} \times 10^{-9}$ | $2.5^{+0.3}_{-0.3} \times 10^{-9}$            |
| 15–150           | $(3.5 \pm 0.3) \times 10^{-7}$  | $5.0 \pm 0.5$                                 |

$^7$ See http://legacy.gsfc.nasa.gov/docs/swift/analysis/bat_digest.html.
The spectral parameters of an XRF, and also, as reported by the BAT team,9 there is a known problem of ∼15% smaller effective area in the Crab spectrum below 20 keV when fitting with a prelaunch response matrix. Since the postlaunch response matrix that we used in the analysis was applying a correction similar to that of XRF 050416A. The result is shown in Figure 3. The flattening trend of the photon index below 25 keV is also clear in this figure. Thus, we conclude that the deviation from a simple power-law model below 25 keV is a real feature of the spectrum of XRF 050416A.

3. DISCUSSION

One of the most important discoveries related to XRF 050416A is the confirmation of the $E_{\text{peak}}^\text{iso}$ relation (Amati et al. 2002). We calculate the $E_{\text{peak}}$ energy at the GRB rest frame, $E_{\text{peak}}$, and the isotropic equivalent energy (1–10 keV) at the 99% confidence level, $E_{\text{peak}}^\text{iso}$. Using $E_{\text{peak}}$ and $E_{\text{peak}}^\text{iso}$, we can estimate the jet break time using the relation between $E_{\text{peak}}$ and the jet collimation corrected energy $E_{\text{coll}}$ found by Ghirlanda et al. (2004; the Ghirlanda relation). However, there is a debate about the assumption of the jet model used by Ghirlanda et al. (2004) to derive the relationship between $E_{\text{peak}}$ and $E_{\text{jet}}$ (Xu 2005; Liang & Zhang 2005). Based on this argument, we use the empirical relation between $E_{\text{peak}}$ and $E_{\text{jet}}$ at the rest frame, $E_{\text{jet}}$, derived by Liang & Zhang (2005). Note that there is no assumption of a jet model in the formula found by Liang & Zhang (2005), and thus their relation

XRF 050416A not only follows the $E_{\text{peak}}^\text{iso}$ relation but also fills in the gap of the relation around $E_{\text{peak}}^\text{iso} = 30–80$ keV. This result tightens the validity of this relation by 5 orders of magnitude in $E_{\text{peak}}^\text{iso}$ and 3 orders of magnitude in $E_{\text{peak}}$.

The confirmation of the $E_{\text{peak}}^\text{iso}$ relation from XRFs to GRBs gives us a clear indication that XRFs and GRBs form a continuum and are a single phenomenon. There are several jet models to explain a unified picture of XRFs and GRBs. The off-axis jet model (Yamazaki et al. 2004; Toma et al. 2005), the structured jet model (Rossi et al. 2002; Zhang & Mészáros 2002; Zhang et al. 2004), and the variable jet opening angle model (Lamb et al. 2005) are the most popular models in this aspect. On the other hand, there are theoretical models to explain XRFs in the framework of the internal shock model (Mészáros et al. 2002; Mochkovitch et al. 2004) and of the external shock model (Dermer et al. 1999; Huang et al. 2002; Zhang et al. 2004), and the variable jet opening angle model (Lamb et al. 2005) are the most popular models in this aspect. On the other hand, there are theoretical models to explain XRFs in the framework of the internal shock model (Mészáros et al. 2002; Mochkovitch et al. 2004) and of the external shock model (Dermer et al. 1999; Huang et al. 2002; Dermer & Mitman 2004). The cited jet models and internal/external shock models not only explain the existence of XRFs and the jet collimation corrected energy $E_{\text{coll}}$, XRF 050416A bridges the gap in the $E_{\text{peak}}^\text{iso}$ relation between XRFs, which have $E_{\text{peak}}^\text{iso}$ of less than 10 keV, and GRBs.

According to the XRT afterglow observations of XRF 050416A, the decay slope of the afterglow emission is $\sim -0.9$ from 0.015 to 34.7 days after the GRB trigger without any signature of a jet break (G. Cusumano et al. 2006, in preparation; Nousek et al. 2005).

Using $E_{\text{peak}}$ and $E_{\text{peak}}^\text{iso}$ of XRF 050416A measured by BAT, we can estimate the jet break time using the relation between $E_{\text{peak}}$ and the jet collimation corrected energy $E_{\text{coll}}$ found by Ghirlanda et al. (2004; the Ghirlanda relation). However, there is a debate about the assumption of the jet model used by Ghirlanda et al. (2004) to derive the relationship between $E_{\text{peak}}$, and $E_{\text{jet}}$ (Xu 2005; Liang & Zhang 2005). Based on this argument, we use the empirical relation between $E_{\text{peak}}$, and $E_{\text{jet}}$, the jet break time at the rest frame, $t_{\text{jet}}^\text{iso}$, derived by Liang & Zhang (2005). Note that there is no assumption of a jet model in the formula found by Liang & Zhang (2005), and thus their relation

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Footnotes:

9 See the “Corrections to Response” section of the BAT Digest (http://legacy.gsfc.nasa.gov/docs/swift/analysis/bat_digest.html).
is purely based on observational properties. When we use equation (5) of Liang & Zhang (2005), \( E / 10^{55} \) ergs = 0.85 \( \times \left( E_{\text{peak}}^{\text{GRB}} / 100 \text{ keV} \right)^{2.5} \left( t_{\text{jet}} / 1 \text{ day} \right)^{-1.4} \), the jet break time in the observer’s frame is estimated to be 1.5 days after the GRB onset time. Note that this estimated jet break time is consistent with the estimation using the Ghirlanda relation assuming a circumburst density of 3 cm\(^{-3}\). Thus, the estimated jet break time using the empirical \( E_{\text{break}}^{\text{GRB}} = \gamma_{\text{jet}} \), in the variable opening angle model and recalculate the jet break time, the break time is 0.7 days assuming a circumburst density of 10 cm\(^{-3}\). In the variable jet opening angle model, there is no way to explain both the Ghirlanda relation and the null detection of the jet break by XRT simultaneously.

One natural way to explain the nondetection of the jet break feature is that extra components are overlaid around a jet break feature. According to the afterglow calculations in the X-ray band by Zhang et al. (2006), there are several possibilities for hiding a jet break feature due to some kind of emission by the external shock. These are external shock emission from (1) the dense clouds surrounding a GRB progenitor (e.g. Lazzati et al. 2002), (2) a moderately relativistic cocoon component of a two-component jet (e.g., Granot 2005), and (3) a jet with large fluctuations in angular direction (patchy jets; Kumar & Piran 2000). On the other hand, it might be the case that XRFs indeed do not show the signature of a jet break in the afterglow. Indeed, although the numbers in the sample are limited, there is no clear observational indication of a jet break in any XRF afterglow light curve so far. If the later case is true, we need to change our view of XRFs completely. Thus, the multiwavelength observations of XRF afterglows will be crucial to investigate whether a jet break feature exists in XRFs or not.

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REFERENCES

Amati, L. 2003, Chinese J. Astron. Astrophys., 3 (Suppl.), 455
Amati, L., et al. 2002, A&A, 390, 81
Anderson, G., et al. 2005, GCN Circ. 3266, http://gcn.gsfc.nasa.gov/gcn3/3266.gcn3
Band, D. L., et al. 1993, ApJ, 413, 281
Barthelmy, S. D., et al. 2006, Space Sci. Rev., in press
Burrows, D., et al. 2006, Space Sci. Rev., in press
Cenko, S. B., et al. 2005a, GCN Circ. 3256, http://gcn.gsfc.nasa.gov/gcn3/3256.gcn3
———. 2005b, GCN Circ. 3269, http://gcn.gsfc.nasa.gov/gcn3/3269.gcn3
———. 2005c, GCN Circ. 3542, http://gcn.gsfc.nasa.gov/gcn3/3542.gcn3
Dermer, C. D., Chiang, J., & Böttcher, M. 1999, ApJ, 515, 636
Dermer, C. D., & Mitman, K. E. 2004, in ASP Conf. Ser. 312, Third Rome Workshop on Gamma-Ray Bursts in the Afterglow Era, ed. M. Feroci et al. (San Francisco: ASP), 301
Gehrels, N., et al. 2004, ApJ, 611, 1005
Ghirlanda, G., Ghisellini, G., & Lazzati, D. 2004, ApJ, 616, 331
Granot, J. 2005, ApJ, 631, 1022
Granot, J., Panaitecu, A., Kumar, P., & Woosley, S. E. 2002, ApJ, 570, L61
Heise, J., in ‘t Zand, Z., Kippen, R. M., & Woods, P. M. 2001, in Gamma-Ray Bursts in the Afterglow Era, ed. E. Costa, F. Frontera, & J. Hjorth (Berlin: Springer), 16
Huang, Y. F., Dai, Z. G., & Lu, T. 2002, MNRAS, 332, 735
Kaharakov, B., et al. 2005, GCN Circ. 3274, http://gcn.gsfc.nasa.gov/gcn3/3274.gcn3
Kippen, R. M., Woods, P. M., Heise, J., in ‘t Zand, J., Briggs, M. S., & Preece, R. D. 2003, in AIP Conf. Proc. 662, Gamma-Ray Burst and Afterglow Astronomy 2001, ed. G. R. Ricker & R. Vanderspek (Melville: AIP), 244
Kobayashi, S., Piran, T., & Sari, R. 1997, ApJ, 490, 92
Kumar, P., & Piran, T. 2000, ApJ, 532, 286
Lamb, D. Q., Donaghy, T. Q., & Graziani, C. 2005, ApJ, 620, 355
Lamb, D. Q., et al. 2004, NewA Rev., 48, 423
Lazzati, D., et al. 2002, A&A, 396, L5

Li, W., et al. 2005, GCN Circ. 3270, http://gcn.gsfc.nasa.gov/gcn3/3270.gcn3
Liang, E., & Zhang, B. 2005, ApJ, 633, 611
Mészáros, P., Ramírez-Ruiz, E., Rees, M. J., & Zhang, B. 2002, ApJ, 578, 812
Mizokanov, I. G., et al. 1996, ApJ, 459, 570
Mochkovitch, R., Duigne, F., Barrand, C., & Atteia, J. L. 2004, in ASP Conf. Ser. 312, Third Rome Workshop on Gamma-Ray Bursts in the Afterglow Era, ed. M. Feroci et al. (San Francisco: ASP), 381
Norris, J. P., Marini, G. F., & Bonnel, J. T. 2000, ApJ, 534, 248
Nousek, J. A., et al. 2005, ApJ, submitted (astro-ph/0508332)
Paciesas, W. S., et al. 1999, ApJS, 122, 465
Piran, T. 1999, Phys. Rep., 314, 575
Preece, R. D., et al. 2000, ApJS, 126, 19
Price, P. A., et al. 2005, GCN Circ. 3312, http://gcn.gsfc.nasa.gov/gcn3/3312.gcn3
Roming, P., et al. 2006, Space Sci. Rev., in press
Rossi, E., Lazzati, D., & Rees, M. J. 2002, MNRAS, 332, 945
Sakamoto, T., et al. 2004, ApJ, 602, 875
———. 2005a, ApJ, 629, 311
———. 2005b, GCN Circ. 3264, http://gcn.gsfc.nasa.gov/gcn3/3264.gcn3
———. 2005c, GCN Circ. 3273, http://gcn.gsfc.nasa.gov/gcn3/3273.gcn3
Sari, R., Piran, T., & Halpern, J. P. 1999, ApJ, 519, 117
Soderberg, A. M., et al. 2004, ApJ, 606, 994
———. 2005, GCN Circ. 3318, http://gcn.gsfc.nasa.gov/gcn3/3318.gcn3
Strohmayer, T. E., Fenimore, E. E., Murakami, T., & Yoshida, A. 1998, ApJ, 500, 873
Toma, K., Yamazaki, R., & Nakamura, T. 2005, ApJ, 635, 481
Xu, D. 2005, ApJ, submitted (astro-ph/0504052)
Yamazaki, R., Ioka, K., & Nakamura, T. 2004, ApJ, 607, L103
Yoshida, A., et al. 1989, PASJ, 41, 509
Zhang, B., Dai, X., Lloyd-Ronning, N. M., & Mészáros, P. 2004, ApJ, 601, L119
Zhang, B., & Mészáros, P. 2002, ApJ, 571, 876
Zhang, B., et al. 2006, ApJ, in press (astro-ph/0508321)