The very long X-ray afterglow of XRF 050416A

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Abstract.
XRF 050416A was discovered by the Swift Burst Alert Telescope and re-pointed with the Swift narrow field instruments only 64.5 s after the burst onset. The $15-150$ keV BAT average spectrum has a photon index of $\Gamma \sim 3.0$ which classifies the bursts as an X-ray flash. The afterglow X-ray emission was monitored by the Swift X-Ray Telescope up to 74 days after the burst. The X-ray light curve shows a decay with three different phases: an initial steep decay with a decay slope of $\sim$ 2.4 (phase A), then, starting at $\sim$172 s from the burst onset, a second phase with a flat decay slope of ~ 0.44 (phase B), and finally, after $\sim$1450 s from the burst onset, a third long-lasting phase with a decay slope of ~ 0.88 (phase C). We find evidence of spectral evolution from a softer emission in the phase A of the afterglow decay, with $\Gamma \sim 3.0$, to a harder emission with $\Gamma \sim 2.0$ in the phases B and C. A redshift of 0.6535 was measured for the source. The spectra show intrinsic absorption in the host galaxy of $\sim 6.8 \times 10^{21}$ cm^{-2}.

The consistency of the phase A photon index with the BAT photon index suggests that the initial fast decaying phase of the XRT afterglow might be the low energy tail of the prompt emission. The lack of jet break signatures in the X-ray afterglow light curve suggests very low collimation of the expanding fireball.

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INTRODUCTION

The Swift Burst Alert Telescope (BAT) detected and located a gamma-ray burst on 2005 April 16, 11:04:44.5 UT [1, 2]. The light curve showed a single peak followed by a small bump with T_{90}=2.4±0.2 s, with most of the energy emitted in the $15-50$ keV band. The time-averaged energy distribution was modeled with a power law ($N(E) \propto E^{-\Gamma}$) with photon index $\Gamma = 3.1 \pm 0.2$ (90% confidence level) and gave a fluence of $(3.2 \pm 0.3) \times 10^{-7}$ erg cm^{-2} in the $15-50$ keV band and $(3.6 \pm 0.4) \times 10^{-7}$ erg cm^{-2} in the $15-350$ keV band [3]. The soft spectrum and the fact that the fluence in the X-ray energy band ($15-30$ keV) is larger than the fluence in the gamma-ray band

($30-400$ keV) classifies this event as an X-ray flash (XRF; 4). The exhaustive ground analysis of the BAT data is presented in [3]. The satellite executed an immediate slew and began collecting data at 11:05:49 UT (64.5 s after the trigger) with the Ultraviolet and Optical Telescope (UVOT) and at 11:06:00.6 UT (i.e. 76.1 s after the trigger) with the X-Ray Telescope (XRT).

In the first 100 s of observation UVOT revealed a new source in the V filter at $\mathrm{RA_{J2000}}= 12^{\mathrm{h}}33^{\mathrm{m}}54^{\mathrm{s}}.56$, $\mathrm{Dec_{J2000}}=+21^{\circ}\ 03'\ 27''3$, with magnitude V=19.38 *mag* [5]. On ground analysis of XRT data revealed that at the same location a fading X-ray source was present [6].

Ground based follow-up optical, NIR and radio observations were performed with several instruments. In particular, a spectroscopic redshift of 0.6535 was measured with the Keck telescope [7].

Here we present first results on the long lasting and very well sampled X-ray afterglow of XRF 050416A.

XRT LIGHT CURVE AND SPECTRA

XRT was on target 76.1 s after the BAT trigger. It was operating in AUTO state and went through the standard sequence of observing modes. After the slew, operated in Low Rate PhotoDiode (LR) mode, XRT took a 2.5 s frame in Image (IM), 8 initial frames in Windowed Timing (WT) mode, and then correctly switched to Photon Counting (PC) mode for the rest of the orbit. XRF 050416A was then observed for 29 consecutive orbits for a total exposure time of 57454 s. XRF 050416A was further observed several times up to 74 days later in PC mode. This extraordinary observational campaign has allowed us to extract one of the longest and best sampled Swift X-ray light curves. Details on XRT data reduction and extraction of the light curve are given in [8]. Here we just want to stress that during on-ground analysis the source appeared to have been detected already during the slew and in the image frame (though the the on-board centroiding algorithm failed to converge). It was then possible to add to the light curve both an IM point and a LR point, where the latter had enough statistics for spectral analysis too.

The XRT light curve can be modeled by a doubly broken power law, with an initial slope $\alpha_{\mathrm{A}} = 2.4 \pm 0.5$, a first break at the time $T_{\mathrm{break,1}} = 172 \pm 36$, a second flat slope $\alpha_{\mathrm{B}} = 0.44 \pm 0.13$, a second break at the time $T_{\mathrm{break,2}} = 1.450 \pm 0.013$, and a final uninterrupted decay with slope $\alpha_{\mathrm{C}} = 0.88 \pm 0.02$. Hereafter, with phase A, B and C we will refer to the time period before the first break at 172 s, the period between the two breaks and the period after the second break at 1450 s, respectively.

Average spectra extracted for the time intervals corresponding to the three phases were fitted with an absorbed power law model. The best fit results show an evidence for spectral variation among phases: the emission in phase A (with a photon index of $3.0^{+0.3}_{-0.4}$) is significantly softer than in the phases B and C, both consistent with a photon index of $2.04^{+0.11}_{-0.05}$ obtained by the joint fit of phase B and C spectra. The fit gave a value of $6.8^{+1.0}_{-1.2} \times 10^{21}$ cm^{-2} for the column density in excess with respect to the Galactic absorption (equal to 0.21×10^{21} cm^{-2}).

The complete light curve of the X-ray afterglow of XRF 060123A in flux units (0.2-10

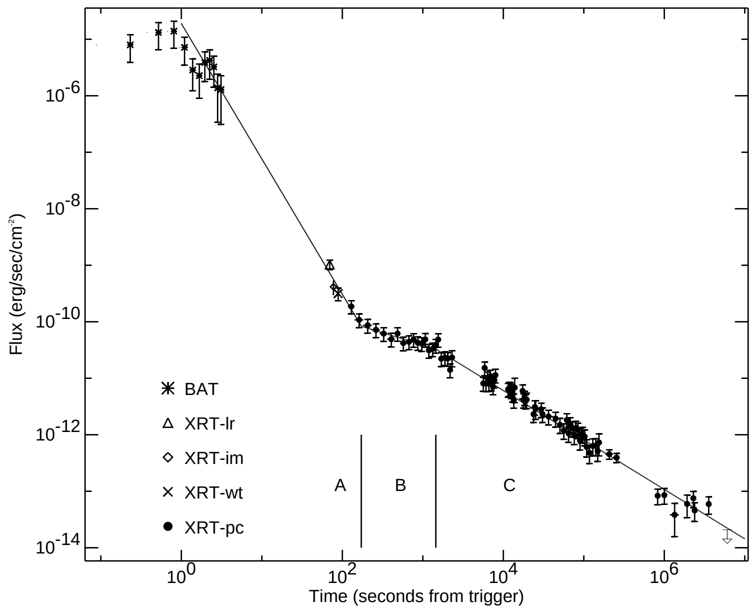

FIGURE 1. XRT light curve of XRF 050416A in flux units together with the BAT light curve extrapolated to the same 0.2-10 keV energy range used for the the XRT light curve. Phases A, B and C discussed in the text are marked. Note that the late extrapolation of the phase C decay is consistent with the flux upper limit measured 65 – 74 days after the prompt emission.

keV energy range) is shown in figure 1, together with the extrapolation of the BAT light curve to the XRT energy band. The XRT count rate light curve was converted into flux units by applying a conversion factor derived from the spectral analysis. The BAT light curve was extrapolated into the XRT energy band by converting the BAT count rate with the factor derived from the BAT spectral parameters obtained by a power law fit.

DISCUSSION

We have presented results of the analysis of the X-ray afterglow of XRF 050416A. XRT monitored the XRF 050416A X-ray emission from $\sim$64.5 s after the BAT trigger up to 74 days and observed its afterglow light curve evolving through three distinct phases corresponding to distinct decay slopes. The interpretation of these phases can be summarized as follow.

Phase A: The early steep and soft X-ray afterglows observed by Swift are generally interpreted as the tail of the gamma-ray burst emission due to high latitude emission (e.g. 9). For XRF 050416A we found that the best fit photon index determined for the phase A spectrum is consistent within the errors with the value obtained in the prompt burst emission fitting the BAT spectrum with a single power-law model. This suggests that the prompt burst emission and the phase A X-ray emission represent the time evolution of the same phenomenon observed in different energy ranges. In this scenario the first break in the X-ray light curve should be due to the emergence of the afterglow after fading of the GRB. To be consistent with the high latitude effect phase A decay slope should be $\alpha = 2 + \beta$ where β is the energy index measured during the decay. The decay slope of phase A ($\alpha_{\mathrm{A}} = 2.4 \pm 0.5$) is definitely lower than the $\sim 4.0 \pm 0.4$ slope predicted by the high latitude effect for the observed $\beta \sim 2 \pm 0.4$ but can be reconciled with the model if we assume the shell emission does not stop instantaneously.

Phases B: The standard interpretation of the flat decay slope during phase B and the second temporal break in the afterglow is based on refreshed shocks (10). In the initial stages of the fireball evolution the forward shock, whose emission produces the X-ray afterglow, may be continuously refreshed with the injection of additional energy. Within this scenario, a flat decay of the afterglow is expected as the refreshed forward shock decelerates less rapidly than in the standard case. A transition to the standard afterglow evolution (i.e. a break) with no remarkable spectral changes is also expected when the additional energy supply ends. This is consistent with our findings.

Phase C: The phase C decay slope and spectral index are roughly consistent with $\alpha_C = (3p-2)/4$ and $\beta_C = p/2$ for $p \sim 2$. This is what is expected for fireball expansion in a uniform ISM when $\nu_c < \nu_X$ (here ν_X represents the typical X–ray frequency and ν_c is the synchrotron cooling frequency) and before the jet break. No other closure relation is satisfied by the phase C spectral and temporal indices. Since phase C remarkably continues uninterrupted to the end of the XRT observation 74 days after the burst, this interpretation would imply the absence of jet breaks in the X-ray afterglow.

Spherical expansion then becomes a distinct possibility for this afterglow. We note that up to now the detection of jet breaks in XRF afterglows is null, suggesting that XRFs in general may be less collimated than GRBs, in agreement with this result.

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