Optical and X-ray Observations of the Afterglow to XRF 030723

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Abstract. The X-ray-flash XRF 030723 was detected by the HETE satellite and rapidly disseminated, allowing for an optical transient to be detected ~ 1 day after the burst. We discuss observations in the optical with Magellan, which confirmed the fade of the optical transient. In a 2-epoch ToO observation with Chandra, we discovered a fading X-ray source spatially coincident with the optical transient. We present spectral fits to the X-ray data. We also discuss the possibility that the source underwent a rebrightening in the X-rays, as was observed in the optical. We find that the significance of a possible rebrightening is very low (~ 1σ).

OBSERVATIONS

The X-ray-flash (i.e. for the fluence $S$, log[S$_X$(2 – 30 kev)/S$_Y$(30 – 400 kev)] > 0.0) XRF 030723 was detected by the HETE satellite [10] with a 2' radius (90% confidence) SXC localization. An optical transient (OT) was reported approximately three days after the burst by Fox et al. [7]. These authors observed a fade from $R$ ~ 21.3 by 1.1 mag between 1.23 and 2.23 days after the burst.

On 25 July 2003, the Chandra Observatory targeted the field of XRF 030723 for a 25 ksec (E1) observation spanning the interval 09:52-17:05 UT on 25 July, 51.4 - 59.0 hours after the burst. The SXC error circle from Prigozhin et al. [10] was completely contained within the field-of-view of the Chandra ACIS-I array. On 4 August 2003, Chandra re-targeted the field of XRF 030723 for an 85 ksec followup (E2) observation, spanning the interval 4 August 22:22 UT to 5 August 22:27 UT, 12.69 to 13.67 days after the burst. For this observation, the SXC error circle from Prigozhin et al. [10] was completely contained within the field-of-view of the Chandra ACIS-S3 chip.

From 24.8 hours to 25.2 hours after the burst (centered on July 24.31 UT), we observed the SXC error circle with the LDSS2 instrument on the 6.5m Magellan Clay telescope at Las Campanas Observatory in Chile. Four 6-minute Harris R-band exposures were taken in ~ 0.6" seeing. Coaddition of the images gives a limiting magnitude of $R$ = 24.5. On July 28.385 UT, 5.13 days after the burst, we again observed the the SXC error circle with Magellan. We obtained two 200-second exposures with the MagIC instrument in ~ 0.8" seeing, reaching a limiting magnitude of $R$ = 24.3.
TABLE 1. Source ("Cts") and background ("bg") counts and positions for the three Chandra sources detected within the SXC error region. We estimate a position uncertainty of 1.4″. Astrometry was performed using six stars from the USNO-A2 catalog.

| # | Chandra Name       | E1 Cts (bg) | E2 Cts (bg) |
|---|--------------------|------------|------------|
| 1 | CXOU J214924.4-274248 | 78.5 (1.5) | 75.6 (2.4) |
| 3 | CXOU J214926.9-274146 | 19.9 (3.1) | 121.8 (4.2) |
| 4 | CXOU J214928.7-274211 | 16.2 (3.8) | 98.1 (4.9) |

CHANDRA DETECTION AND FITS

As reported in Butler et al. [2], 3 candidate sources were detected within the revised SXC error region in our E1 observation. Positions and other data for these sources are shown in Table 1. None of the sources were anomalously bright relative to objects in Chandra deep field observations [see, e.g., 11]. The brightest object within the SXC error circle (source #1), lies 62″ from the center of the SXC error circle, and is within 0.7″ of the optical transient reported by Fox et al. [7].

Table 1 shows the number of counts detected in E1 and in E2. The E2 observations were reported in Butler et al. [3]. Accounting for the difference in exposure times and sensitivity, the number of counts detected for a steady source in E2 should be ~ 6 times the number of counts detected in E1. Thus, sources 3 and 4 appear to have remained constant, while source 1 has faded. The number of counts detected in E2 corresponds to a ~ 7σ significance decrease (i.e. factor of ~6) in flux since the E1 observation.

To properly determine the fade factor we fit the E1 and E2 spectral data jointly. We reduce the spectral data using the standard CIAO1 processing tools. We use "contamaf"2 to correct for the quantum efficiency degradation due to contamination in the ACIS chips, important for energies below ~ 1 keV. We bin the data into 12 bins, each containing 12 or more counts, and we fit an absorbed power-law model by minimizing $\chi^2$. The model has three parameters: two normalizations, and one photon index $\Gamma$. The absorbing column has been fixed at the Galactic value in the source direction, $N_H = 2.4 \times 10^{20}$ cm$^{-2}$. The model fits the data well ($\chi^2_v = 8.9/9$, Figure 1). The best fit photon number index is $\Gamma = 1.9 \pm 0.3$, which is a typical value for the X-ray afterglows of long duration GRBs [4]. Using this model, we find that the E1 flux is $(2.2 \pm 0.3) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (0.5-8.0 keV band), while the E2 flux is $(3.5 \pm 0.5) \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (0.5-8.0 keV band). The decrease in flux between the two epochs can be described by a power-law with a decay index of $\alpha = -1.0 \pm 0.1$. This value of $\alpha$ is consistent with the power-law decline reported in the optical by Dullighan et al. [6] for $t \lesssim 1.5$ day after the GRB; however, the index is considerably flatter than the index at $t > 1.5$ days reported by Dullighan et al. [6]. This flatter X-ray decay may possibly be related to the rebrightening of the optical afterglow reported by Fynbo et al. [8].

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1 http://cxc.harvard.edu/ciao/
2 http://space.mit.edu/CXC/analysis/ACIS_Contam/script.html
FIGURE 1. The counts in Epoch 1 (ACIS-I, left plot) and Epoch 2 (ACIS-S, right plot) are fitted simultaneously using an absorbed power-law model ($\chi^2_v = 8.9/9$).

OPTICAL FADE, BREAK

We detected the OT of Fox et al. [7] in 2-epochs with Magellan, confirming those authors claims. Including the other detections reported over the GCN (Figure 2 (a)), we estimate a late time power law decay index of $\alpha \sim -2$, and an early power law decay of $\alpha \sim -0.9$. The break in the light curve occurs between 30-50 hours after the burst. Our measurements have been calibrated against the USNO photometry data reported Henden [9].

FIGURE 2. Left Plot: Optical light-curve in R-band taken from reports to the GCN [7, 5, 6, 1, 12, 8]. Our data are marked with stars. A temporal break may be present in the spectrum at $t \sim 1$ day [6]. The rightmost points have been argued to imply a rebrightening [8]. Right Plot: The Count rate during the Chandra E2 observation may be rising as was the optical flux during the same period. The significance of any rise is, however, $\lesssim 1\sigma$.

X-RAY REBRIGHTENING?

The afterglow emission in the optical was apparently rebrightening during our E2 Chandra observation [8]. We speculated above that the flat decay law we measure between E1 and E2 with Chandra may have been in part due to a rebrightening. To test whether this is or is not true, we test the E2 data against two hypotheses: (1) the count rate versus time is described by the power-law model which fits the overall
E1,E2 decay $r(t) = 8.56 \times 10^{-4} \times \frac{12.69\text{days}}{t} \text{cts/s}$, (2) the count rate versus time is described by the power-law model which fits the optical rise during the E2 observation $r(t) = a \times \left(\frac{t}{12.69\text{days}}\right)^{3.7} \text{cts/s}$, where $a$ is a free parameter. Using the arrival times $t_i$ for 75 photons, we choose the model which maximizes the likelihood:

$$\mathcal{L}(t_1,t_2,\ldots,t_n) = r(t_1) \cdot r(t_2) \cdot \ldots \cdot r(t_n) \cdot \exp\left\{ - \int_{t_0}^{t_n} r(\tau) d\tau \right\},$$

where the integral in the exponential is carried out for the good time intervals of *Chandra* data acquisition. We find a best fit value for $a$ of $7.67 \times 10^{-4}$ cts/s. (Figure 2 (b) shows the E2 counts in 10 ksec bins, with models (1) and (2) overplotted.) The corresponding difference in log($\mathcal{L}$) is 0.379. Simulating arrival times for 75 photons using model (1), a more extreme value of $\delta \log(\mathcal{L})$ found from fitting both models is observed to occur for approximately 1/3 of the trials. Thus, a rebrightening is preferred by the data, but at only 1$\sigma$ significance.

**CONCLUSIONS**

We have derived power-law spectral parameters to X-ray data taken in two epochs with *Chandra* for XRF 030723. The photon index $\Gamma$ we derive is a typical value for long-duration GRBs, possibly indicating a similarity between these objects an XRFs. The decrease in model normalization between the two epochs ($\Delta \chi^2 = 43.6$, for 1 additional degree of freedom; i.e. 6.6$\sigma$) confirms that source #1 is the X-ray counterpart to XRF 030723 and to the OT discovered by Fox et al. [7]. Our optical observations, along with the other observations reported over the GCN (Figure 2 (a)), imply a break in the R-band light curve at $t \sim 1$ day after the burst. We have tested for an X-ray rebrightening, but we find only very weak evidence for a rebrightening similar to that observed in the optical by Fynbo et al. [8].

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