ELSEVIER

Nuclear Physics B (Proc. Suppl.) 69/1-3 (1998) 640-645

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

RXTE Observations of GRB Afterglows

Francis E. Marshall, Jean Swank, and Azita Valinia, [a] Robin Corbet, Toshiaki Takeshima, and Scott Barthelmy, [b] Craig Robinson, Chryssa Kouveliotou, Valerie Connaughton, Marc Kippen, and Robert Preece, [c] Hale Bradt, Alan Levine, Ron Remillard, and Don Smith, [d] and Kevin Hurley [e]

[a]Laboratory for High Energy Astrophysics, Goddard Space Flight Center,
Code 662, Greenbelt, MD, 20771 USA

[b]Universities Space Research Association and
Laboratory for High Energy Astrophysics, Goddard Space Flight Center,
Code 662, Greenbelt, MD, 20771 USA

[c]Marshall Space Flight Center,
ES-84, Huntsville, AL 35812 USA

[d]Center for Space Research, MIT, Cambridge, MA, 02138 USA

[e]Space Sciences Lab., Univ. of California, Berkeley, CA 94720 USA

Variable X-ray sources that appear to be the afterglows of the strong gamma-ray bursts GRB 970616 and GRB 970828 have been discovered with the RXTE PCA. First seen less than 4 hours after the burst, the flux from the sources decreased with time. Although near the sensitivity limit of the PCA, the sources are the brightest afterglows yet seen in X-rays. Similar observations of two other bursts did not detect any afterglows. These results are part of a continuing collaboration between RXTE, BATSE, and IPN scientists to rapidly detect X-ray afterglows of bright gamma-ray bursts.

1. Introduction

The spectacular detection of long-lived afterglows with BeppoSAX [1] has opened the study of gamma-ray bursts (GRBs) to the broad range of instrumentation currently available in astronomy. This quickly led to the discovery of afterglows at other wavelengths [2] and to the first determination of a distance to a GRB [3]. In general the observations support the relativistic fireball model for GRBs [4]. Many questions about the nature of GRBs remain. What is the original source of energy for the burst? What is the distribution of distances to the bursts? What causes the wide range in the ratio of X-ray afterglow flux to GRB peak flux? Why are some optical afterglows so weak? Is the strength of the afterglow related to some property of the GRB?

A thorough understanding of the nature of GRB afterglows is likely to require a substantial sample of events. We have established a collaborative effort to use RXTE and CGRO to search for afterglows as soon as possible after the detection of GRBs. Our primary goal is to discover additional afterglows and provide their locations to the community using the Gamma-ray burst Coordinates Network (GCN) for followup observations. We will also use the large area and rapid-response capability of RXTE to make detailed measurements of the light curve and spectra of afterglows.

2. RXTE Capabilities and Strategies

The RXTE mission has several features that are quite useful for observing the afterglows of GRBs. Rapid response is one of the main goals of the mission. The Science Operations Center is staffed continuously, and real-time data are received from the satellite $\sim$ 80% of the time. Typically commands can be sent to the spacecraft once per 96-minute orbit. While the pre-

0920-5632/98/$19.00
PII S0920-5632(98)00314-4

launch goal was to be able to respond to Targets of Opportunities (TOOs) in seven hours or less, special procedures for GRBs have reduced this time by about a factor of two. Although there are no imaging capabilities, source positions can be determined to a few tenths of a degree for bursts brighter than a few mCrab by making multiple scans across the source. The large area ($\sim 7000 cm^2$) and broad energy range (2-60 keV) of the Proportional Counter Array (PCA) provides a sensitive search for variability for sources brighter than a few mCrab. In general, the lack of imaging limits the sensitivity of the PCA to a few tenths of a mCrab because of spatial variations in the brightness of the X-ray sky. However, observations after the GRB afterglow has disappeared can be used to reduce the effect of these fluctuations.

Observations with the PCA are triggered either by bright GRBs detected with the Burst And Transient Source Experiment (BATSE) or by GRBs that are imaged with the All-Sky Monitor (ASM) experiment on RXTE. The observing strategy of RXTE depends on the trigger. The error regions for most GRBs detected with BATSE are far too large to be scanned quickly with the PCA. For the bright bursts, positions can be determined in $\sim$ 20 minutes by a member of the BATSE science team with a systematic uncertainty of about 1.6°. Observations with RXTE are only attempted for those bursts for which the total positional uncertainty due to both systematic and statistical errors is less than 2°. These bursts provide a complementary sample to the typically much weaker bursts seen with the WFC on Beppo-SAX. The burst positions must also be more than $\sim$ 40° from the Sun to avoid violating spacecraft constraints. The RXTE operation center is alerted by the Locburst notice distributed through the GCN. The possible TOO is evaluated for observing efficiency, possible confusing X-ray sources, and whether it is scientifically desirable to interrupt the current RXTE observation. About 50% of the time, RXTE can do a rapid replanning to scan over the error region to search for a new X-ray source within about 3 hours of the burst. Because the PCA field-of-view is significantly smaller than the error region,

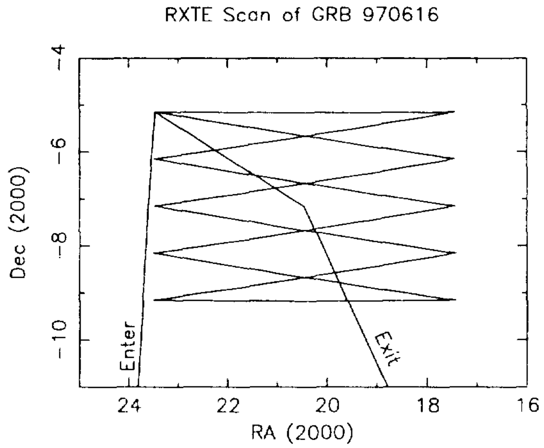

Figure 1. Typical PCA scan pattern.

RXTE performs multiple maneuvers to scan the error region. Fig. 1 shows the scanning pattern used for GRB 970616; patterns for other bursts are similar. The goal is to cover the entire error box at least twice in the observing time available in a single RXTE orbit (typically $\sim$ 60 minutes). Once the operations team is certain that an observation will occur, an announcement is sent to the astronomical community via the GCN. Initial results are also distributed using the GCN after the observation is complete.

A few per cent of bursts will happen to be in the fields-of-view of one of the three ASM cameras on RXTE. Approximately a dozen such bursts have been found in the first 21 months of the mission, but only one such burst was localized quickly enough for the PCA to search for an afterglow. About half the time an error region a few arc minutes by a few degrees long is produced. For some bursts, an error region a few arc minutes on a side is made. The MIT ASM team is improving their procedures for rapidly identifying and localizing such bursts. GRB 970828 was localized in about 1 hour, and an afterglow was detected with the PCA 3.2 hours after the burst. These bursts are typically much weaker, but they are also much easier for the PCA to observe because their positions are better known. For these

Table 1
RXTE PCA GRB afterglow observing log

	Trigger	BATSE Intensity	Response	Result
970603	6249	1566	none	
970603	6251	5581	3.25 hours	
970612	6266	5649	none	
970616	6274	13628	3.22 hours	0.5 mCrab source
970704	6293	19440	3.11 hours	weak ROSAT source
970807	6329	9524	3.22 hours	poor coverage
970815	6336	20161	none	
970828	6350	11232	3.54 hours	1.0 mCrab source
970831	6353	3633	none	
970925	6397	8293	4.46 hours	wrong position scanned
970929	6404	22873	none	
971009	6422	10452	none	

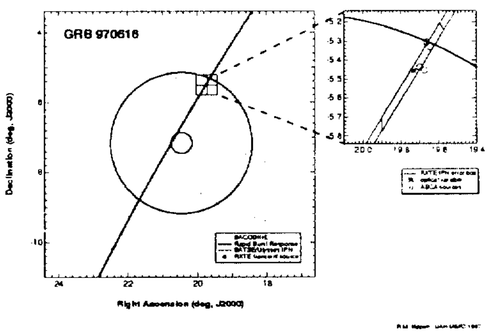

Figure 3. GRB 970616 Error Boxes.

was looking directly at the source. The reduction in counting rate shown in the middle of the figure is caused by the source being occulted by the Earth. Monitoring of the source with the PCA continued until about 7.5 hours after the trigger. The source was not seen during a second RXTE observation that began 5.4 days after the trigger.

Fig. 5 shows the declining flux measured with the PCA as well as the preliminary fluxes reported for the ASM and ASCA observations. The afterglow decayed by a factor of ~ 4 during the time interval of 3.5 to 7.5 hours after the burst. The PCA data are consistent with a power-law decay in the flux ($\propto t^{-s}$) with a best-fit decay index s of 1.58. Decay indices from 1.38 to 1.86 provide statistically acceptable fits. The lines in the figure show the range of acceptable fits. The decay seen during the PCA observation appears to continue at least until the ASCA observation which began about 100 ks after the GRB, while an extrapolation to early times predicts more flux than seen with the ASM. This decay rate is slightly steeper than the index of 1.32 seen for GRB 970228 starting 8 hours after that burst [1].

The spectrum of the afterglow 5.0 hours after the burst is consistent with a power-law shape with a photon index Γ of 2.10 ± 0.25 assuming no absorption beyond that expected from our galaxy. This is consistent with the spectral shape seen for GRB 970228 [1]. Relativistic blast wave models [15] predict a relationship between the spectral in-bursts, the PCA is used to detect afterglows, confirm the small error boxes and improve the long error boxes, and produce light curves and spectra of the afterglow.

In a little over 4 months, RXTE has discovered afterglows in 2 of 6 observations in responding to 6 of 12 triggers. In two of these observations the error region was not covered very well because of procedural mistakes. Table 1 lists the BATSE trigger number, the peak BATSE counting rate, and the response time for RXTE to begin scanning the error box. The response is given as "none" if no observations were made. For GRB 970704 a weak source was seen, but because its position is consistent with that of a ROSAT source and inconsistent with the IPN annulus for the burst, it is unlikely to be related the GRB. The other two GRBs for which a source was detected are discussed in more detail below.

3. GRB 970616

The PCA observations of GRB 970616 was triggered by BATSE Trigger No. 6274 [5] at RXTE Mission Elapse Time (MET) of 109102192 seconds, and the scanning pattern shown in Fig. 1 was used to search for an afterglow. The scan rate was about 3 degrees per minute, and a source would remain in the PCA field-of-view for about 40 seconds. A weak source with celestial coordinates (19.72, -5.50) was detected on three of the scans [6]. Fig. 2 shows the count rate after subtracting the estimated internal background as a function of RXTE MET for two of the scans. The predicted count rate for the best-fit model for the source position and intensity is shown with "*". The best-fit intensity of 4.7 counts per second corresponds to a flux of $\sim 1.0 \times 10^{-11}$ ergs/s-cm^2 in the 2 to 10 keV band. As shown in Fig. 3, the source position is consistent with the IPN annulus determined from the relative arrival times of the gamma rays at CGRO and Ulysses [7]. A second observation with RXTE 27 hours later did not detect this source. Four weak X-ray sources were found near the RXTE/IPN error box in a subsequent observation with ASCA [8], but there is no compelling reason to associate any of them with the GRB [9]. Optical and radio observations of

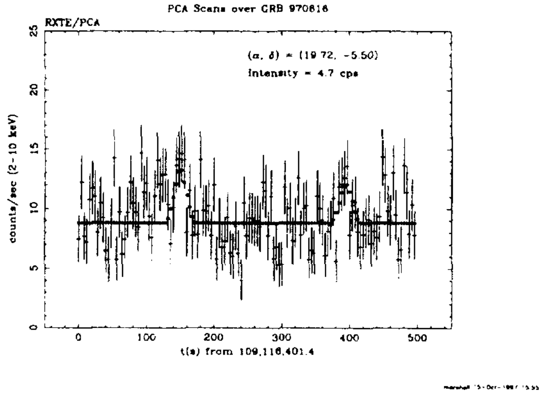

Figure 2. PCA scans of GRB 970616.

the error region did not find compelling afterglow candidates either.

4. GRB 970828

GRB 970828 was a bright burst detected with BATSE and localized with the ASM [10]. The BATSE trigger time corresponds to an RXTE MET of 115407879 seconds. An X-ray afterglow was detected 3.5 hours later with the PCA [11] at a position consistent with that determined with the ASM. Further X-ray observations with ASCA [12] and the PCA demonstrate that the afterglow faded in X-rays. No counterpart has been seen at other wavelengths. For example, optical observations [13] found no counterpart down to an R-magnitude of 24.5. Frail and Kulkarni [14] found no radio counterpart down to ~ 0.3 mJy.

Because the source position was quickly determined with an accuracy of a few arc minutes, it was possible for the PCA to observe the source repeatedly. Fig. 4 shows the counting rate seen during 6 scans across the source. Times when the PCA was pointing at the source are labeled in the figure with an "s", and they clearly are local peaks in the counting rate. The highest count rate was seen during the first scan across the source, and it corresponds to a 2-10 keV flux of $\sim 2 \times 10^{-11}$ ergs/s-cm^2. The final "s" shows when the scanning had stopped, and the PCA

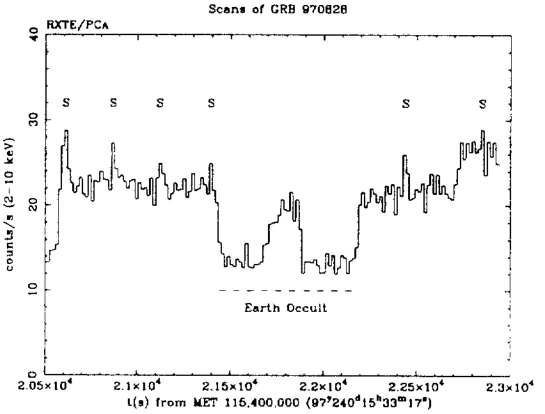

Figure 4. GRB 970828 Scans.

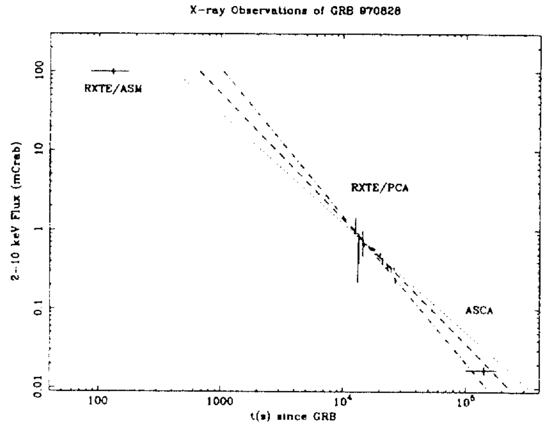

Figure 5. GRB 970828 Light Curve.

dex and the decay rate that is consistent with the observations. However, this simple model cannot explain all of the data. The spectrum of the GRB itself is complicated and varies during the burst, and the average spectrum at high energies is steeper than that of the afterglow. Further the optical emission is at least 800 times weaker than the extrapolation of the flatest possible X-ray spectrum which may indicate extinction in the optical band.

5. Future Enhancements

RXTE will continue to study X-ray afterglows from GRBs. As experience has been gained, the planning procedures have become more reliable and more rapid. The RXTE control center will soon test procedures to maneuver quickly to the GRB target with no re-planning required. Once the GRB position is known, the command to maneuver the spacecraft can be given as soon as there is a command contact, which typically occurs once every 96 minutes. In ideal circumstances, RXTE could be observing the GRB a few minutes after its position is determined, but the typical delay will be approximately an hour. It is hoped that the afterglows will be substantially brighter than that of the two afterglows reported here so that the large area of the PCA can be used effectively.

The algorithms for detecting GRBs with the ASM are also being made more rapid and more reliable. Although the detection of a GRB with BATSE is now used as a trigger to search for bursts in the ASM, it should be possible to detect bursts using only data from the ASM. Because of the accuracy of ASM positions, ASM-detected GRBs are well suited for the rapid maneuvering described above.

We thank the organizing committee and all participants for a stimulating meeting.

REFERENCES

1. E. Costa et al. 1997, Nature, 387, 783.
2. J. van Paradijs et al. 1997, Nature, 386, 686.
3. M. R. Metzger et al. 1997, Nature, 387, 878.
4. P. Meszaros and M. J. Rees 1997, Ap.J. 476, 232.
5. V. Connaughton et al. 1997, IAU Circular No. 6683.
6. F. E. Marshall et al. 1997, IAU Circular No. 6683.
7. K. Hurley, C Kouveliotou and F. Marshall 1997, IAU Circular 6687.
8. T. Murakami et al. 1997, IAU Circular No. 6687.

9. J. Greiner et al. 1997, IAU Circular No. 6722.
10. R. Remillard et al. 1997, IAU Circular No. 6726.
11. F. E. Marshall, J. K. Cannizzo and R. H. D. Corbet 1997, IAU Circular No. 6727.
12. T. Murakami et al. 1997, IAU Circular No. 6732.
13. S. C. Odewahn et al. 1997, IAU Circular No. 6735.
14. D. A. Frail and S. R. Kulkarni 1997, IAU Circular No. 6730.
15. R. A. M. J. Wijers, M. J. Rees, and P. Meszaros 1997, MNRAS 288, L51.