Gamma-Ray Bursts with ROSAT

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Abstract

I review the use of ROSAT over the last years for the investigation of well localized gamma-ray burst (GRB) error boxes. In particular, I cover (i) the systematic study of several dozens of IPN locations using the ROSAT All-Sky-Survey data, (ii) results of deep ROSAT pointings of selected small GRB error boxes, (iii) the attempts for and results of quick follow-up observations after GRB events including the three GRBs localized with BeppoSAX, (iv) the correlation of GRB locations with serendipitous ROSAT pointings and (v) the search for X-ray flashes in the database of pointed ROSAT observations.

Key words: Gamma-rays: bursts — X-rays: general — satellite: ROSAT

1. Introduction

The emission of γ-ray bursts (GRB) has been measured over a wide range of photon energies ($\approx$2 keV–2 GeV). While most of the emission is at 0.1–10 MeV the fraction of X-rays to the total power is typically less than a few percent (Higdon & Lingenfelter 1990) during the bursts.

No reliable quiescent counterparts of GRBs have been detected at other wavelengths, and the basic pre-ROSAT results on X-ray counterpart searches can be summarized as follows: (1) *Einstein* observations of 5 GRB error boxes (Pizzichini et al. 1986) have revealed one possible point-like source in the GB 781119 error box, (2) *EXOSAT* observations resulted in upper limit estimates of 5×10^{-13} erg/s/cm^2 for the 3 error boxes of GRB 790305B, 790418 and 791105B (Boër et al. 1988, 1991), (3) *Einstein* HRI images of the SNR N49 show enhanced X-ray emission coincident with the error box of GRB 790305B, the famous Soft Gamma Repeater, but identification is still unclear (Rothschild et al. 1994).

These results have motivated extensive searches with the more sensitive ROSAT satellite. While the above results have been obtained from dedicated pointed observations, ROSAT offers a few additional possibilities with respect to GRB research which will be reviewed here for the first time. References to individual ROSAT results already published in the literature will be given in the corresponding subsections below.

2. ROSAT All-Sky-Survey and GRB error boxes

2.1. ROSAT All-Sky-Survey and Data Analysis

Between 1990 Aug. 1 and 1991 Jan. 25 the ROSAT satellite (Trümper 1983) has performed the first all-sky survey in the soft (0.1–2.4 keV) X-ray energy band (with short additions in 1991 Feb. 16–18 and Aug. 4–12, as well as 1997 Feb.). This dataset offers the unique possibility to investigate the soft X-ray content of a large number of GRB error boxes in a homogeneous approach.

Such an investigation has been performed by selecting the $\approx$50 smallest GRB error boxes, in particular 36 from the 2nd interplanetary network (IPN) 1978–1981 (Atteia et al. 1987), 15 from the 3rd IPN 1991–1993 (Hurley 1993) and 3 COMPTEL/Ulysses error boxes and the three Soft Gamma Repeaters (SGRs). This means, that ROSAT data are taken either about 10 years AFTER the bursts (2nd IPN), or a few months to years BEFORE the bursts. Due to the scanning scheme during the all-sky survey observation the exposure time varies across the sky, i.e. increases towards higher ecliptic latitude. For the GRB error boxes investigated here, the range of exposure times is 70 – 1350 sec.

The data analysis involves several distinct steps and is described in more detail elsewhere (Greiner et al. 1995a). In short, first, a source detection in the three adjacent energy bands 0.1–0.4 keV, 0.5–0.9 keV and 0.9–2.4 keV is performed to find all X-ray sources with a likelihood of existence >8 (corresponding to about 3.5 σ); second, upper limits of the countrate and the likelihood are calculated (again in the three adjacent energy bands) for every spatial resolution element (thus resulting in upper limit countrate maps and likelihood maps in each of the three energy bands) to help assessing the reality of low-significance fluctuations (below 3.5 σ); and third, optical follow-up work (mainly spectroscopic observations) has been performed for the identification of X-ray sources. The analysis has been extended to the nearby surrounding of each box (adding half of the GRB error box widths on each side) which is used as control area.

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2.2. Results

Excluding the SGRs in the following, the basic results can be summarized as follows (preliminary results have been reported already in Greiner et al. 1991, Boer et al. 1994 and Greiner et al. 1995a):

1. We found X-ray sources in only five of the selected GRB error boxes. All five sources have bright active stars (coronal X-ray emission) as optical counterparts.
2. The total area of all selected error boxes is 3.5 □°. With a mean density of ROSAT all-sky survey sources of 1.5/□° one expects 5.3 non-correlated X-ray sources as compared to the 5 sources detected. This statistically supports the conviction that the above mentioned coronal X-ray sources are not related to the GRB sources.
3. The control area is 3× larger than the GRB boxes themselves, i.e. 10.5 □°, thus implying ≈16 non-correlated X-ray sources. In total, 17 X-ray sources are detected, and most of them have "ordinary" optical counterparts.
4. There exists no systematic correlation between GRB error boxes and optically unidentified soft X-ray sources (basically all X-ray sources are optically identified).
5. Even at lower likelihood values of X-ray source detection (i.e. lower source intensity) there is no trend of clustering in/near error boxes.
6. Lasota (1992) has argued that a burst will produce a wind, supersonic expansion of which would lead to a strong shock. Thus, accretion would cease for several years after the burst. Accordingly, the "null" result concerning the 2nd IPN error boxes might be expected. But since we also find no correlation for the 3rd IPN GRB error boxes, the above scenario probably does not apply to GRBs (see more extensive discussion in Greiner et al. 1995b).

3. Deep ROSAT observations of GRB error boxes

Over the last six years nearly a dozen GRB error boxes were observed with the ROSAT satellite for 10–40 ksec exposure time (see Tab. 1 for a complete listing), thus improving considerably the sensitivity limits obtained with earlier X-ray observations at soft energies. For a part of these GRB locations, X-ray sources have been found inside the error boxes. Most notably these include GRB 781119 (the GRB with the earlier Einstein detection) and GRB 920501, the X-ray sources of both of which have been also detected in ASCA observations. In the case of GRB 781119 even a second X-ray source has been found inside the error box.

While originally the discovery of a quiescent X-ray source inside a small GRB error box has been considered as probable evidence for an association of a GRB with a quiescent counterpart, the continuing discovery of further X-ray sources and in particular the detection of more than one X-ray source even in small GRB error boxes (see Tab. 1) makes this association doubtful. Also, the optical identification of these X-ray sources, though not yet completely established in all cases, does not find evidence for unusual objects.

An estimate of the chance probability for the occurrence of a quiescent X-ray source inside a well-localized GRB error box depends on how the question is asked in detail (see Hurley et al. 1996 for various possibilities).

Table 1. Dedicated ROSAT pointings on GRB locations (non-TOO)

GRB[a]	Exposure (sec)	Date	Inst. P/H[d]	$N_X^{b)}$	Ref.[c]
781119	2513	950110	H	2	1
	41164	951221	H	2	1
790313	25111	950209	H	3	2, 11
790325B	14649	910404	P	0	2
	180	910416	P	0	2
790406	19018	911204	P	0	3, 11
790613	13880	910320	H	1	4, 11
881024	10978	910410	P	3	4, 11
910219	14422	931105	P	0	2, 11
910601	20807	921112	P	0	5
910814	25254	920616	P	1	6
920501	30386	931023	P	1	7
	6215	940507	H	1	7
920525	9713	941002	H	0	6
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790305	20999	920317	H	1	8
	9529	951010	H	1	9
	4280	951109	H	1	9
	12472	951209	H	1	9
	7721	960111	H	1	9
	12390	960207	H	1	9
	9578	960308	H	1	9
	10978	960416	H	1	9
	10890	960516	H	1	9
	15313	960615	H	1	9
	11428	960716	H	1	9
	15675	960814	H	1	9
	10794	960913	H	1	9
1806–20	2985	910318	P	0	10
	10078	930402	P	1	10

[a] Below the dotted lines are SGRs.
[b] Number of X-ray sources inside the GRB error box
[c] (1) Boër et al. (1997), (2) PI: Boër, (3) Boër et al. (1994), (4) PI: Ricker, (5) McNamara et al. (1995), (6) Harrison et al. (1996), (7) Hurley et al. (1996), (8) Marsden et al. (1996), (9) PI: Danner, (10) Cooke 1993, (11) Greiner (unpubl.)
[d] ROSAT detector: P(SPC) or H(RI)

However, one has to bear in mind that at the low sensitivity limits reached already, the number density of X-ray sources is already remarkably high. From the results of many deep pointed observations and combined with the very deep Lockman hole observations of ROSAT an improved log N–log S distribution of X-ray sources has been derived (Hasinger 1997) which gives 100 (700) X-ray sources per 1 □° at the level of 10^{-14} (10^{-15}) erg/cm^2/s. Thus, the probability for a chance coincidence of a quiescent, soft X-ray source with a GRB location is 25%–100% for a 10 arcmin^2 size error box.

For the case of GRB error boxes without a detected quiescent X-ray source, the flux limits of 10^{-14}...10^{-15} erg/cm^2/s can be used to constrain particular GRB scenarios (Boër et al. 1994). For instance, a neutron star accreting matter from the interstellar material would have to be at more than ≈several kpc distance.

4. Quick ROSAT follow-up observations of GRBs

4.1. Overview

Motivated by the occurrence of a few very long lasting GRBs and by the detection of distinct spectral softening over the burst duration a number of attempts have been made to observe well-localized GRB locations with ROSAT as quick as possible after the GRB event in the hope to find the "smoking gun". To this end, the GRB had to be localized quickly, a target-of-opportunity observation had to be proposed, and the GRB location had to be within the ROSAT observing window (≈30% of the sky at any moment). In several cases, even a second follow-up observation has been performed to allow a variability check of the detected X-ray sources. Tab. 2 lists the GRBs which have been observed as target-of-opportunity (TOO) together with the time delay between the GRB and the ROSAT observation.

The fastest response with ROSAT so far is 5 days which is near the minimum possible time achievable due to the various scheduling constraints (a curious exception is the TOO towards SGR 1806–20 which was triggered by one of the repeating bursts, and turned out to happen just one hour after another repeating burst).

An X-ray source has been found in each of the two GRBs 920501 and 960720. In both cases there is no strong evidence that these X-ray sources may be related to the GRB event.

4.2. ROSAT pointings towards the BeppoSAX GRBs

The localization of GRBs to an accuracy of several arcmin within less than a day as achieved for GRB 960720, 970111 and 970228 by the BeppoSAX wide-field camera (WFC) has renewed the interest for really quick follow-up X-ray observations. While the GRB 960720 location was reported only four weeks after the event, the ROSAT delay time for TOO pointings has been brought down to 5 days (see Tab. 2). The initial results are shortly summarized below and more detailed and updated information is accessible over the URL http://www.aip.de:8080/~jcg/:

Table 2. ROSAT TOOs towards GRB locations

GRB	Exposure (sec)	Delay	N_X	Ref.[a)]
920501	2748	18 days	1	1
920711	2432	28 weeks	0	2, 7
930704/940301	3156	4 weeks	25	3, 4
960720	6960	6 weeks	1	5
960720	2791	24 weeks		8
970111	1198	5 days	0	6
970111		4 weeks		8
970228		11 days		8
SGR 1806–20	1416	1hr (12 days)	0	7

[a)] (1) Hurley et al. (1996), (2) PI: Hurley, (3) Greiner et al. (1996a), (4) Greiner et al. (1997) (5) Greiner et al. (1996b), (6) Frontera et al. (1997), (7) Greiner (unpubl.), (8) data not yet available during writing

GRB 960720 was originally localized with an error circle of 10′ and observed with ROSAT on August 31, 1996, about 10 days after the notification by the BeppoSAX team (Heise, priv. comm.). Nine quiescent X-ray sources were detected during the ROSAT HRI pointing, eight of which were within the GRB error circle (Greiner et al. 1996b). At the same time, pointings with ASCA and the narrow-field instruments on BeppoSAX detected one quiescent X-ray source (Piro et al. 1996, Murakami et al. 1996) which turned out to be the superposition of 3 X-ray sources as seen with the HRI (sources #4, #5 and #6 in Fig. 1). An improvement of the WFC location algorithm has reduced the error circle of GRB 960720 to 3′, and shifted the error circle in a way that it contains only one HRI X-ray source (which previously was outside the error box). This X-ray source RX J1730.7+4906 (#3 in Fig. 1) has been identified with the radio-loud quasar QSO 1729+491 (= 4C 49.29), and though the probability of having one X-ray source inside the 3′ GRB error box is not too small, the probability of having a strong radio source in the GRB error circle is as small as $2{\times}10^{-4}$ (Greiner & Heise 1997).

GRB 970111 also was originally localized to 10′ (Costa et al. 1997a). Again, a BeppoSAX pointing about 16 hours after the GRB (Butler et al. 1997) and a ROSAT HRI observation 5 days after the GRB (Frontera et al. 1997) revealed several X-ray sources (some of which were also detected during the ROSAT all-sky survey; see Voges & Boller 1997) which later turned out to not be within the revised 3′ GRB error box.

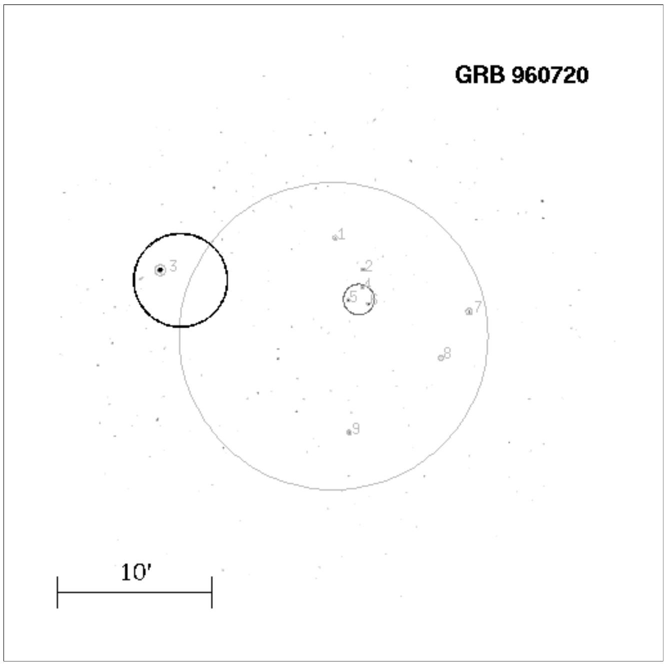

Fig. 1. Image of the ROSAT HRI observation of GRB 960720. The numbered circles are the detected X-ray sources with the size of the circles representing the FWHM of the point spread function. The bold, $3'$ radius circle to the left is the revised GRB error box (Zand et al. 1997), while the large circle is the first reported error box on which the pointing was centered. The small circle encompassing the HRI sources #4, #5 and #6 is the steady X-ray source as seen by BeppoSAX and ASCA.

GRB 970228 was localized within a few hours with $3'$ accuracy (Costa et al. 1997b), and for the first time a fading X-ray source was detected in BeppoSAX pointings performed 8 hours and 3 days after the GRB (Costa et al. 1997c). Also a fading radio and optical object have been identified within the $50''$ error circle of the fading X-ray source. The ROSAT follow-up observation was possible only 11 days after the GRB, and the data are not yet available during the writing of these lines.

4.3. X-ray variability time-scale

For the pointings prior to February 1997 (for which the ROSAT data have been processed and results are available) the detected X-ray sources have (and could only) been checked for possible variability on timescales of months to years by comparison to both, the ROSAT all-sky survey data (taken 1990/91) and later follow-up pointings. Variability on shorter timescales will be checked very soon with further pointings on GRB 970111 and 970228.

No fading X-ray source has been identified so far on the timescale of more than 5 days and the sensitivity level as reachable in a few thousend second ROSAT observation. The recent discovery of a fading X-ray source observed 8 hours and 3 days after the GRB event by BeppoSAX (Costa et al. 1997c) demands to reduce the ROSAT response time down to 3 days in the future to achieve $10''$ size error boxes for any upcoming GRB with a fading X-ray source.

5. Correlating GRBs with ROSAT pointings

Given the $\approx 3\,\square^\circ$ field of view of the ROSAT PSPC, and an approximate duty cycle of $\approx$40% over its 4 yrs livetime, the chance probability for a serendipitous GRB observation with the ROSAT PSPC is $\approx$25%. It is therefore tempting to check whether a GRB occurred accidentally during a ROSAT observation inside its field of view.

I have correlated the trigger times of the GRBs between April 21, 1991 until Sep. 16, 1994 as listed in the 3B catalog (Meegan et al. 1996) with the actual ROSAT observation intervals (OBI) of all pointings during the given time interval. If the GRB trigger time is within a ROSAT OBI, then the angular distance is calculated between the BATSE centroid position of the GRB and the ROSAT pointing direction. In total, 11(5) cases have been found with a time coincidence and an angular distance of $<20^\circ (10^\circ)$.

The smallest ever distance is 5°.6 for the gamma-ray burst 3B 930724B. Fortunately, 3B 930724B is quite well localized: it has a 2°.0 BATSE error radius, and an IPN triangulation ring is also available based on the Ulysses timing (Hurley 1995). Though the IPN arc does not cross the BATSE error circle, it is clear that the PSPC pointing 900495 is well off the GRB position (see right panel of Fig. 2). Just to be sure, a timing analysis has been performed on all sources detected in this pointing, and no transient source is detected.

Among the other cases with less than 20° angular distance there exist two hits for which the ROSAT pointing location falls into GRB error circle: these are the gamma-ray bursts 3B 930219C and 3B 930228. Of course, these GRB locations are only crudely known, and the ROSAT field ov view covers only a tiny fraction of the GRB error box. The detailed numbers for these two GRBs are as follows:

- 3B 930219C has a 9°.2 BATSE error radius, and was not detected by any other satellite instrument. The ROSAT HRI pointing is 6°.2 off the BATSE centroid position, and the HRI field of view covers 0.15% of the GRB error box (see left panel of Fig. 2). An analysis of the HRI pointing reveals no transient of fading X-ray source, thus excluding the occurrence of the GRB within the location of the HRI pointing.
- 3B 930228 has a 18°.6 BATSE error radius, and also no detection by any other instrument. The ROSAT PSPC pointing is 8°.9 off the BATSE centroid position, and the PSPC field of view covers 0.30% of the GRB error box. Again, no transient X-ray source is found in the ROSAT data.

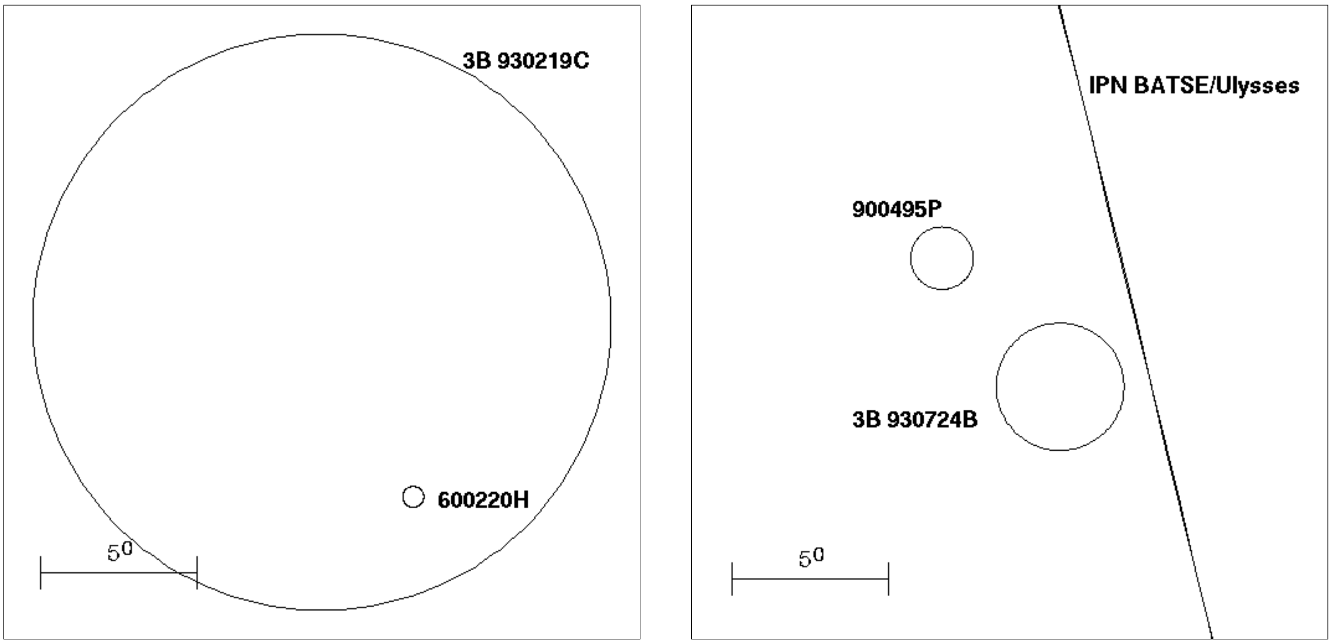

Fig. 2. Scetch of the locations of 2 ROSAT pointings simultaneously to GRBs: **Left panel:** simultaneous ROSAT HRI observation of 3B 930219C covering ≈0.15% of its error box. **Right panel:** simultaneous almost-hit of a ROSAT PSPC observation and 3B 930724B.

6. Search for X-ray flashes in ROSAT data

Gotthelf et al. (1996) found 42 soft X-ray flashes in a search of 1.5×10^7 s Einstein IPC data. These flashes were argued to be of astrophysical origin, and are distributed isotropically on the sky. They do not correlate with any known sources, in particular not with the nearby galaxy distribution. Based on this result, Hamilton et al. (1996) conclude that GRBs cannot originate in a galactic halo with limiting radii between 150–400 kpc.

Vikhlinin (1997) has searched 2.1×10^7 s ROSAT PSPC data for the occurrence of similar X-ray flashes. Despite greater sensitivity, larger field of view and longer exposure as compared to the Einstein data, he does not find any flash! This is surprising, because the Einstein X-ray flashes were reported to have soft spectra, so ROSAT should have seen such flashes. While this leaves the nature of the X-ray flashes detected with Einstein open for re-evaluation, it invalidates the conclusion regarding the distance scale of GRBs.

7. Conclusion

The search for quiescent X-ray counterparts in small GRB error boxes with ROSAT is tedious and, in the end, unfortunately, not conclusive so far. This strengthens the need for X-ray coverage of future GRB missions. The very recent discovery of an X-ray source within the error box of GRB 970228 fading in intensity over a couple of days (Costa et al. 1997c) has opened a new avenue for X-ray follow-up observations in particular and towards the understanding of GRBs in general.

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