A SEARCH FOR X-RAY COUNTERPARTS OF GAMMA-RAY BURSTS WITH THE ROSAT PSPC

ALEXEY VIKHLININ

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138; avikhlinin@cfa.harvard.edu

ApJ Letters, in press

ABSTRACT

We search for faint X-ray bursts with duration 10–300 seconds in the ROSAT PSPC pointed observations with a total exposure of 1.6 × 10⁷ s. We do not detect any events shorter than ~ 100 s, i.e. those that could be related to the classic gamma-ray bursts (GRB). At the same time, we detect a number of long flares with durations of several hundred seconds. Most, but not all, of the long flares are associated with stars. If even a small number of those long flares, that cannot be identified with stars, are X-ray afterglows of GRB, the number of X-ray afterglows greatly exceeds the number of BATSE GRB. This would imply that the beaming factor of gamma-rays from the burst should be > 100. The non-detection of any short bursts in our data constrains the GRB counts at the fluences 1–2.5 orders of magnitude below the BATSE limit. The constrained burst counts are consistent with the extrapolation of the BATSE log N – log S relation. Finally, our results do not confirm a reality of short X-ray flashes found in the Einstein IPC data by Gotthelf, Hamilton and Helfand.

Subject headings: gamma-rays: bursts — surveys — X-rays: bursts

1. INTRODUCTION

Data accumulated over several years of observations by ROSAT and Einstein may contain X-ray counterparts of gamma-ray bursts (GRB). Both instruments have imaging capabilities and can provide precise positions leading to GRB identifications. Soft X-ray data can be used to constrain the log N – log S distribution of gamma-ray bursts at fluxes below those accessible by BATSE. A possibility to find X-ray afterglows of gamma-ray bursts, similar to those recently discovered by BeppoSAX (Costa et al. 1997, Piro et al. 1998), is another motivation for a search for soft X-ray flares.

Gotthelf, Hamilton and Helfand (1996, GHH hereafter) reported a detection of 42 faint X-ray flashes in the Einstein IPC data. Those flashes have typical fluxes of 10⁻¹⁰ – 10⁻⁹ ergs cm⁻² s⁻¹ in the 0.2–3.5 keV energy band and a typical duration of < 10 s. Their detection rate corresponds to about million per year per whole sky. Flashes are not correlated with any known sources, including nearby galaxies.

We have performed a search for faint X-ray bursts in the pointed ROSAT PSPC observations. Using the imaging capabilities of ROSAT, we detect bursts as spatially localized spikes in the count rate with duration less than about 100 seconds. Our dataset covers 2.5 times larger area and has 1.1 times longer exposure than the GHH Einstein IPC dataset.

2. ROSAT DATA AND ANALYSIS

ROSAT mirrors focus soft X-rays in the 0.1–2.4 keV energy band. The prime detector, PSPC, covers a circular region with an area of 2.7 deg². The mirror vignetting is approximately a parabolic function of the off-axis angle; it drops to 50% at the edge of the field of view (FOV). The angular resolution varies from ~ 30'' (FWHM) on-axis to ~ 2'' at the edge of the FOV. The on-axis effective area is 450 cm² at 1 keV. The PSPC background is dominated by cosmic X-rays (Snowden et al. 1992). The PSPC count rate is not saturated for source fluxes up to ~ 1000 photon s⁻¹. These properties of the ROSAT PSPC are relevant for our work; for a detailed description, see Trümper (1983), Aschenbach (1988) and Pfeffermann et al. (1987).

We used ROSAT PSPC pointed observations with exposures > 500 s. Pointings to clusters of galaxies and supernova remnants were excluded because extended emission from the target fills a significant part of the FOV and complicates the analysis. We also excluded all pointings in the direction of high Galactic absorption (N_H > 10³¹ cm⁻²), thus omitting all Galactic plane targets. These selections leave 2256 individual observations with the total exposure of 1.6 × 10⁷ s.

Standard ROSAT data products have a list of good time intervals for each observation. These intervals exclude target occultations by the Earth, the spacecraft passages through the South Atlantic Anomaly and radiation belts, intervals of poor aspect solution, and all detected instrument malfunctions. As is advised in Snowden et al. (1994), we excluded time intervals with the master veto rate > 170 cnt s⁻¹. The soft part of the PSPC bandpass (E < 0.4 keV) is affected by higher background, poorer angular resolution, and the presence of “afterpulse” events (Plucinsky et al. 1993). We, therefore, used only the hard, 0.5–2 keV, energy band.

2.1. Burst Detection

An outline of our burst detection algorithm is as follows. We sort photons detected in the entire FOV according to their arrival time and divide the observation into sequences of n photons, advancing the sequence in steps of n/2 (that is, the sequences are overlapping). In each such sequence, we analyze the photon coordinates searching for spatial concentrations that would correspond to flashes from point-like sources. We use sequence widths, n, of 10, 15, 20, 25, 35, 45, and 60 photons, corresponding to time intervals of 7–40 s for the average ROSAT PSPC background of ~ 1.4 cnt s⁻¹ in the whole FOV (Fig. 4). This matches well the duration of the classic gamma-ray bursts (e.g., Terekhov et al. 1994) and the reported Einstein flashes. To find spatial concentrations of photons within a sequence, we create an image in sky coordinates. For each image pixel, we count photons within the 90% power radius of the PSF, calculated as a function of the off-axis angle (Hasinger et al. 1993). If the number of photons within this radius exceeds the preselected detection threshold, we consider it a burst detection.

The optimal detection threshold depends on the off-axis an-
gle because the size of the detect cell varies. We set detection thresholds such that the probability of a false detection in the analyzed data ($3.6 \times 10^7$ photons detected in the source-free regions) is small, 0.02, and that the distribution of false detections is uniform over the FOV. The false detection probabilities are derived from Monte-Carlo simulations of $5 \times 10^9$ photons randomly distributed inside the FOV. The thresholds vary from 4 photons for the shortest photon sequence and the inner region of the FOV, to 11 photons for the longest photon sequence and the edge of the FOV. If the derived thresholds are lowered by 1 photon, one would expect $\sim 3$ false detections in the whole analyzed data.

The use the photon sequences of a fixed length rather than fixed time intervals greatly reduces a possibility of false detections during the intervals of high background usually caused by scattered solar X-rays. The count rate is not used for burst detection, therefore the high background does not cause false detections as long as it is relatively uniform over the detector. The sensitivity to long bursts is smaller during the high background intervals because the photon sequences span shorter time and hence contain a smaller fraction of the burst flux. Fortunately, high background occurs only in a small fraction of the total exposure (Fig. 1). The loss of sensitivity during these intervals is fully accounted for in our calculations of the detection efficiency.

Our burst detection algorithm requires absence of bright persistent sources. For example, if there is a source with the count rate equal to that of the background, 10 photons in each 20 photon sequence will be detected near the same position. This is above our threshold for burst detection. Even much fainter sources can increase the false detection probability. To avoid this problem, we masked all sources that were detectable in the image accumulated over the entire observation. Sources were detected using a matched filtering algorithm (Vikhlinin et al. 1995). Detection thresholds were 8–50 photons depending on the exposure and off-axis angle. Some of the detectable sources might be bright genuine bursts. To avoid missing such bursts, we analyzed light curves of all excluded sources.

2.2. Detection sensitivity

The probability to detect a burst of a given physical flux is a complex function of the burst flux, duration, off-axis angle, and the background intensity. It is also affected by the Poisson scatter of burst flux. The off-axis angle determines mirror vignetting and detection thresholds. Background rate and burst duration define a fraction of the burst flux within the $n$-photon sequence. To include all these effects into the burst detection probability, we used Monte-Carlo simulations. The burst position was simulated randomly inside the FOV. The burst flux was multiplied by the corresponding vignetting correction. The number of burst photons was simulated from the Poisson distribution. Photon positions were simulated according to the local PSF. Photon arrival times were simulated assuming an exponential light curve, $\exp(-t/t_0)$, with a random start time. The background intensity was simulated from the distribution in Fig 1. Positions of background photons were simulated according to the average PSPC exposure map. The burst detection algorithm was applied to the simulated data. Repeating the described simulations many times, we derived the probability to detect bursts of a given flux and duration.

Figure 2 shows the on-axis burst flux corresponding to an 80% detection probability as a function of burst duration $T_{90}$ — time interval over which 90% of the burst flux is emitted. The limiting sensitivity varies slowly between 11 and 18 photons for $2 < T_{90} < 30$ s. For longer bursts, a significant fraction of flux is outside the longest photon sequence, and the limiting sensitivity correspondingly increases.

3. RESULTS

![Diagram 1](image1.png)

**Fig. 1.** — The distribution of the inverse ROSAT PSPC background rate in the whole FOV. The background rate was measured in sequences of 200 photons consecutively detected in source-free regions. The distribution represents the probability to measure a given count rate at a random moment in time.

![Diagram 2](image2.png)

**Fig. 2.** — The on-axis burst flux corresponding to a 80% detection probability as a function of burst duration (solid line). The dashed line shows flux at which 37% of bursts are detected.
No bursts were found in the source-free regions. All bursts detected in the light curves of detected sources were longer than several hundred seconds (see below). Therefore, short, 10 s, flares similar to those detected by GHH in the *Einstein* data, were not found in any place of the ROSAT FOV. Our results clearly contradict those of GHH and so a detailed comparison of the two searches must be made.

The total exposure of our ROSAT dataset, 1.6 × 10^8 s, is slightly longer than the *Einstein* exposure 1.5 × 10^8 s. The geometric area of the ROSAT PSPC FOV is 2.5 deg^2, while the *Einstein* IPC covers only 1 deg^2. In both instruments, the mirror vignetting is approximately parabolic and equals ~50% at the FOV edge; if anything, vignetting is more severe for the *Einstein* IPC. Therefore, our ROSAT data has an effective coverage (the product of exposure and the FOV area) 2.7 times larger than that of *Einstein*, which means that 2.7 more flares should be found in the ROSAT data, if the two searches have a similar sensitivity. GHH flares have T90 < 10 s. Our sensitivity limit for this duration is 14 photons. The average flux of GHH flares is 11 and 7 photons for “soft” and “hard” events, respectively. Since 37 out of 42 GHH flares were detected in the region where sensitivity is < 60% of that on-axis, the average on-axis flux is conservatively larger than 18.3 and 11.7 photons for “soft” and “hard” events, respectively. Our 0.5–2 keV energy band only partially overlaps with the *Einstein* energy band 0.16–3.5 keV used in GHH, and so conversion of count rates depends on the source spectrum. For sources with normal spectra, the ROSAT PSPC is more sensitive. For example, for N_H = 10^{21} cm\(^{-2}\) and a typical AGN spectrum with a photon index 1.5–2, the PIMMS software predicts the ROSAT count rate 1.3–1.5 times that of *Einstein*. GHH derive a photon index of ~2 for their hard flares, so we can conservatively assume that ROSAT count rates should be at least 30% higher for these events. For “soft” events, ROSAT sensitivity should be even higher. Therefore, we expect ROSAT on-axis fluxes of at least 23.8 and 15.2 photons for soft and hard flares, respectively. This is above our 80% sensitivity limit (Fig. 2), and so at least ~40 hard and ~50 soft flares are expected in the ROSAT data. To conclude, the discrepancy between ROSAT and *Einstein* cannot be explained by a difference in sensitivity.

We can offer only one astrophysical explanation of this discrepancy — a possibility of an unusual flare spectrum causing low ROSAT fluxes. One can estimate how unusual this spectrum should be. The 37% sensitivity limit, at which the sky coverage of our search becomes equal to that in GHH, corresponds to 10 photons for T90 < 10 s. To make the ROSAT flux below this limit, the *Einstein* count rate must be at least 1.2 times higher than that of ROSAT. This is only possible if the photon index is very small (< 0.5) or the spectrum is strongly self-absorbed (N_H > 10^{22} cm\(^{-2}\)). We cannot exclude either flat spectrum or absorption, but they seem incompatible with the flare photon index of 2 derived by GHH.

### 3.1. Light curves of detectable sources

We also analyzed light curves of 93850 sources which were detected and excluded from our main burst search. The light curves were extracted within the 90% power radius around the source position. Source photons were binned into 10, 20, 40, ..., and 320 s time intervals. For a burst detection, we required that the peak flux exceeded 5 photons in a time bin, that the peak flux was at least three times higher than the average over the observation, and that the Poisson probability of this deviation was less than 5 × 10^-3 (i.e., a 5σ detection). These criteria correspond to a sensitivity approximately equal to the sensitivity of the burst detection in the source-free regions. ROSAT is routinely wobbled by ±2–3′ during the observation. The wobbling causes a spurious variability in a small fraction of the FOV attenuated by the window support structure of the PSPC. We excluded these regions from the source variability analysis. We also excluded 20% of the total exposure affected by high background.

We detected 141 bursts in the source light curves. The integral flux in these events was in the range 10–1000 photons. The quiescent flux was consistent with zero in approximately half of the bursting sources. All but one burst have T90 > 200 s. Examination of the Digitized Sky Survey (DSS) plates has shown that 112 bursting sources were Galactic stars. One burst comes from the X-ray binary LMC X-4. Dates and positions of the remaining 28 bursts are listed in Table 1. Many of these non-identified events still have star-like optical counterparts in the DSS, but the faintness of the counterpart (fainter than ~10^8) makes a reliable identification with Galactic stars impossible. Some bursting sources are probably extragalactic. Five of 28 flares are detected in the general direction of M31. The only short burst (8 photons in ~20 s) is located within the optical boundaries of M81. The peak luminosity in this event was ~7 × 10^{38} erg s\(^{-1}\), assuming that it was located in M81 at D = 3.5 Mpc. This was 40 times above the source quiescent luminosity, but only a small fraction, 4.5%, of the flux was emitted during the burst. These properties resemble Galactic X-ray bursters.

### Table 1 Long bursts without a stellar identification

| Date (dd/mm/yy) | R.A. (J2000) | Decl. (J2000) | ID |
|----------------|-------------|--------------|----|
| 05/07/91       | 00 31 26.5  | +26 41 38    | star-like |
| 25/07/92       | 00 38 25.3  | +31 23 50    | uncertain |
| 27/07/91       | 00 41 23.0  | +41 49 08    | uncertain |
| 26/07/91       | 00 44 57.4  | +41 59 25    | star-like |
| 10/01/93       | 00 45 31.4  | +41 54 24    | (a) |
| 31/01/93       | 00 47 32.8  | +42 50 03    | star-like |
| 25/07/92       | 00 49 47.9  | +42 20 36    | star-like |
| 19/07/90       | 03 34 45.3  | −25 37 27    | star-like |
| 27/03/92       | 05 28 11.8  | −12 39 15    | star-like |
| 29/09/93       | 06 00 35.4  | −38 50 25    | uncertain |
| 25/08/93       | 06 45 18.8  | +82 48 23    | star-like |
| 22/08/93       | 07 14 36.3  | +85 47 46    | star-like |
| 03/04/93       | 07 33 26.6  | +31 44 08    | star-like |
| 29/09/93       | 09 55 26.5  | +69 09 48    | in M81 |
| 18/05/92       | 09 56 01.7  | −05 12 41    | star-like |
| 11/05/93       | 10 34 09.4  | +22 58 45    | star-like |
| 20/12/91       | 11 19 03.2  | +07 49 27    | star-like |
| 30/12/91       | 12 35 30.0  | +00 30 51    | star-like |
| 21/12/91       | 12 49 00.3  | −06 28 09    | star-like |
| 03/02/93       | 13 38 15.1  | −19 54 29    | star-like |
| 26/11/91       | 13 39 09.1  | +48 21 10    | star-like |
| 02/07/94       | 13 41 21.6  | +29 02 02    | star-like |
| 23/07/90       | 14 17 22.5  | +25 05 16    | star-like |
| 23/01/92       | 15 04 18.8  | +10 37 24    | nothing |
| 16/03/93       | 16 40 56.3  | +70 42 38    | star-like |
| 07/08/93       | 16 39 51.1  | +70 51 34    | star-like |
| 31/05/93       | 22 14 21.5  | −16 53 56    | uncertain |
| 01/06/92       | 23 20 38.8  | +08 21 09    | star-like |

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1Earlier versions of the ROSAT data processing contained an error which resulted in assigning the same 0.5″ detector pixel to 5–30 consecutively detected photons. The ROSAT data do not contain this error any longer. We, however, were able to detect such “events” in some previously processed datasets.
of all other bursts indicate that the detected events are not related to X-ray flares detected by Einstein.

4. DISCUSSION

Ginga and BeppoSAX observations show that classic gamma-ray bursts are accompanied by a powerful, rapidly varying emission in the X-ray band (Yoshida et al. 1989, Frontera et al. 1998). We would detect this emission if the GRB had fallen inside the ROSAT FOV. Therefore, the non-detection of any short events in our ROSAT can be used to constrain the burst counts at a flux limit below that accessible by BATSE. A non-detection of any events in our search translates to a 90% upper limit of 7.2 × 10^4 bursts per year in the whole sky. Our limiting fluence is ~ 20 photons for T_{90} ~ 10−100 s. This corresponds to 2.6 × 10^{-10} erg cm^{-2} in the 0.5–2 keV band, conservatively assuming the maximum absorption N_H = 10^{21} cm^{-2} in all pointings, and a 0.5–2 keV photon index Γ = 1, consistent with the average X-ray spectrum of Ginga bursts and the BeppoSAX spectrum of GRB 970508. The average ratio of 50–300 keV and 0.5–2 keV fluxes of Ginga gamma-ray bursts is ~ 60 (Yoshida et al. 1989). BeppoSAX spectrum of GRB 970508 (Frontera et al. 1998) yields a 50–300/0.5–2 keV flux ratio of ~ 15 for a primary, hard pulse, and ~ 1 for a secondary, soft pulse. This range of observed GRB spectra corresponds to a limiting 50–300 keV fluence of 2.6 × 10^{-10}–1.5 × 10^{-8} erg cm^{-2} for our search. This is a 2.5–1 orders of magnitude improvement in sensitivity over BATSE (Fig. 3).

With the present data, we cannot exclude a possibility that some of the detected long flares are X-ray afterglows of gamma-ray bursts, similar to those detected by BeppoSAX. We consider this possibility unlikely, mainly because 112 out of 141 of these events are confidently identified with Galactic stars. Of the remaining 28 events, 27 have optical counterparts in the Digitized Sky Survey plates obtained years before the X-ray event. This is quite different from the properties of the optical transients associated with BeppoSAX GRB. For example, the 970508 transient was R = 19.8 in the maximum, that is, below or just at the limit of the DSS sensitivity. Therefore, flaring stars or perhaps AGN is a likely nature of the detected long flares. If, however, just several of them are indeed GRB afterglows, an immediate implication is that gamma-ray bursts are highly collimated, because the long X-ray flares occur at a rate ~ 10^3 per year compared to the BATSE rate of ~ 700 GRB per year and because in X-rays, we do not see main bursts in the long flares.

This work was supported by the Smithsonian Institution postdoctoral fellowship and the RBRF grant 95-02-05933. The author thanks R. A. Sunyaev for the encouragement of this work, and M. Markevitch, W. Forman, P. Gorenstein, and H. Tananbaum for interesting discussions.

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