Search for X-ray Afterglows from Gamma-Ray Bursts in the RASS

J. Greiner[1], D.H. Hartmann[2], W. Voges[3], T. Boller[3], R. Schwarz[1], S.V. Zharykov[4]

[1] *Astrophysical Institute Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany*
[2] *Clemson Univ., Dept. of Physics and Astronomy, Clemson, SC 29634, USA*
[3] *MPI for Extraterrestrial Physics , 85740 Garching, Germany*
[4] *Special Astrophysical Observatory, 357147 Nizhnij Arkhyz, Russia*

Abstract. We report on a search for X-ray afterglows from gamma-ray bursts using the ROSAT all-sky survey (RASS) data. If the emission in the soft X-ray band is significantly less beamed than in the gamma-ray band, we expect to detect many afterglows in the RASS. Our search procedure generated 23 afterglow candidates, where about 4 detections are predicted. Follow-up spectroscopy of several counterpart candidates strongly suggests a flare star origin of the RASS events in many, if not all, cases. Given the small number of events we conclude that the data are consistent with comparable beaming angles in the X-ray and gamma-ray bands. Models predicting a large amount of energy emerging as a nearly isotropic X-ray component, and a so far undetected class of "dirty fireballs" and re-bursts are constrained.

SURVEY DATA AND EXPECTED AFTERGLOW RATE

If afterglow and burst emission are from separate regions one must seriously consider the possibility that prompt γ-ray and delayed X-ray emission are beamed (if at all) differently. If so, one expects X-ray afterglows to be less beamed than GRBs. We describe here our results to test this possibility with a search for X-ray afterglows that were fortuitously detected during the RASS. All technical details and a more thorough discussion are reported in Greiner et al. (1999).

During the RASS, the ROSAT field of view scans a full 360° circle on the sky, covering a source located inside the scan circle for typically 10–30 sec. A source is covered by consecutive telescope scans between two days (near the ecliptic equator) up to 180 days (at the ecliptic poles). Our study relies on the product of exposure in time and coverage in area so that the large exposure at the poles and low equatorial exposure is compensated by the correspondingly small/large solid angles (according to cos(ecliptic latitude)), thus yielding a rather uniform search pattern. Even with a single exposure of 10–30 s duration the sensitivity of ROSAT is sufficient to detect GRB X-ray afterglows for several hours after the burst (Fig. 1)

The fraction, f, of afterglows detectable during the RASS depends critically on three parameters: (1) the fraction of GRBs that have detectable X-ray afterglows, (2) the possible correlation of X-ray flux to γ-ray peak flux (or fluence, or some other characteristic aspect of the GRB itself), (3) the X-ray intensity decay law. It is currently not clear how one should combine all these factors into a proper statistical distribution from which to derive the overall sampling fraction f. We thus simply use the existing database as a representative set of templates and compare this set to the ROSAT PSPC sensitivity. This implies that the RASS would in fact be sensitive enough to detect all GRB afterglows in 3 subsequent scans, and ~80% in 5 scans (see Fig. 1). We adopt a conservative fraction of $f = 0.8$.

The number of detectable X-ray afterglows from GRBs beamed towards us (based on the BATSE detection rate) during the RASS is $N^{agl} = f \times S_R^{agl} \times R_{GRB}$, where $R_{GRB} = 900$ GRBs/sky/yr $\equiv 1$ GRB/(16628$\square^\circ \times$ days) is the rate density of GRBs and S_R^{agl} is the RASS afterglow coverage function. The temporal completeness of the RASS was 62.5% (Voges et al. 1999), so that $S_R^{agl} = 76435\ \square^\circ \times$ days. Thus, we expect N$^{agl} = 4.6 \times f \sim 3.7$ GRB afterglows to be detected during the RASS.

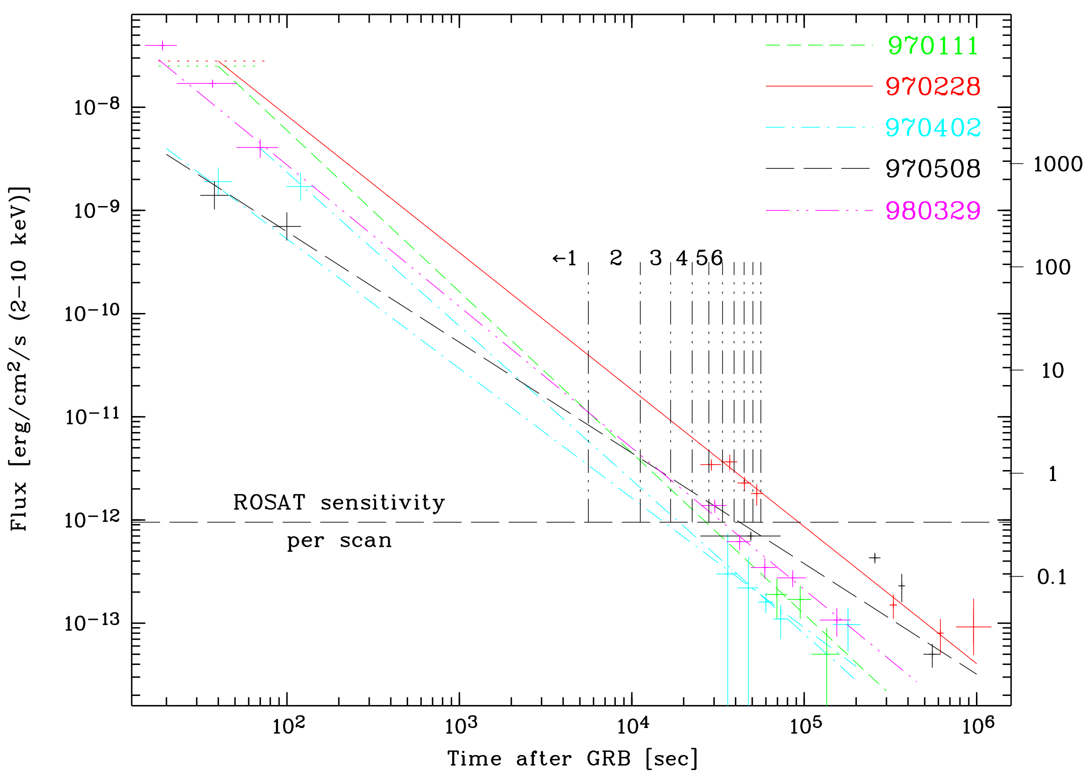

FIGURE 1. Afterglow light curves of some observed GRB X-ray afterglows in the 2–10 keV range (GRB 970111: Feroci et al. 1998; GRB 970228: Costa et al. 1997; GRB 970402: Nicastro et al. 1998; GRB 970508: Piro et al. 1998; GRB 980329: in 't Zand et al. 1998) extrapolated into the ROSAT band (scale on the right). The vertical lines mark the time windows for the possible coverage of a GRB location by ROSAT during its scanning mode.

THE SEARCH FOR AFTERGLOW CANDIDATES

We produced scan-to-scan light curves for all RASS sources with either a count rate larger than 0.05 cts/s or a detection likelihood exceeding 10, resulting in a total of 25,176 light curves. Each of these light curves consists of about 20 to 450 bins spaced at 96 min., with each bin corresponding to 10–30 sec. exposure time. We apply three selection criteria to these light curves: (1) The maximum bin should have a signal-to-noise ratio of S/N>3 above the mean count rate around the maximum. (2) The mean count rate derived from observations obtained until one bin prior to the maximum count rate should be consistent with zero. (3) The mean count rate at times later than those covered by 5 bins past maximum should also be consistent with zero. This suppresses transient sources that have quiescent emission at detectable levels, such as flare stars.

Application of the above listed criteria yields a total of 32 GRB afterglow candidates. We then proceed with additional conditions that proper afterglows should display: (i) Sources with double and multi-peak structures are excluded, because this pattern does not fit "standard" X-ray afterglow behavior (4 sources). (ii) Sources with a rise extending over several bins and zero flux immediately after the peak are removed (2 sources). (iii) Sources with low-level (below the RASS threshold) persistent X-ray emission during serendipituous pointed ROSAT observations were excluded (3 sources). (iv) We correlate the candidate list with optical, infrared, and radio catalogs, and exclude sources with known counterparts (1 source).

The application of these selection steps yields a total of 23 transients as viable X-ray afterglow candidates. About 50% of the light curves display single peaks, i.e. outbursts with just one bin satisfying S/N>3 and otherwise zero count rate. The remainder shows decays that more closely resemble GRB afterglow behavior.

To estimate the flare star fraction of the events we obtained optical spectra for six randomly selected sources. All 6 objects are Me flare stars. Three further objects of our sample were optically identified by other groups, and also are flare stars. Based on the optical brightness of these flare stars and the well-known $L_{\rm X}/L_{\rm opt}$ ratio of 1/50...1/100 the expected X-ray intensity during quiescence is 1×10^{-14}...2×10^{-13} erg/cm^2/s. This corresponds to ROSAT PSPC count rates of 0.0015...0.03 cts/s and is below the RASS sensitivity, thus consistent with the non-detection outside the X-ray flare (which caused detection during the RASS).

We thus argue that the bulk of the "afterglows" are probably due to X-ray flares from nearby late-type stars, and that the existing data support the notion that the RASS contains at most a few X-ray afterglows from GRBs. This interpretation is consistent with the expected number of afterglows (N^{agl} = 3.7). 1RXS J120328.8+024912 is the best candidate for a GRB X-ray afterglow simply due to the fact that the ROSAT error box does not contain a bright ($m < 22$ mag) stellar object though the light curve is single-peaked. While it is difficult to determine the likelihood that a flare of this large amplitude from a position with no optical counterpart could be due to a statistical fluctuation, we note that this event is among the largest amplitude events of our whole sample.

If we argue that the RASS data contain a few afterglows, then data are obviously consistent with the expected theoretical rate (especially considering the significant uncertainties affecting our estimate of the afterglow expectation value). This implies that GRB afterglows do not have a significantly wider beaming angle in the X-ray band relative to the gamma-ray band. This is to some extent in agreement with predictions of the "standard" fireball model (Meszaros & Rees 1997; Piran 1999), given the fact that we are only sampling a few hours of emission following the GRB. As the fireball slows due to interaction with a surrounding medium the bulk Lorentz factors of the flow decrease and the beaming angle increases. However, the RASS data cover a time interval of ∼1–8 hrs after the GRB event. During this time the fireball is expected to decelerate from $\Gamma \gtrsim 100$ to $\Gamma \sim 10$. Thus, the flow is still highly relativistic and the afterglow emission is still far from isotropic.

On the other hand, if we argue that those of the events which are not optically identified are in fact GRB afterglows, then the rate apparently exceeds expectations. However, the enhancement factor is less than a few. Furthermore, the uncertainties are large and the sample is still small. Again we would conclude that the RASS results support consistency between observations and theoretical expectations, with only marginal evidence for less beaming in the X-ray band.

Both points of view basically conclude the same; beaming of GRBs and of their afterglows is, if it exists, comparable. This conclusion supports a similar result (Grindlay 1999) obtained from an analysis of fast X-ray transients observed with *Ariel V* (Pye & McHardy 1983) and earlier instruments. We also emphasize that our results and those discussed by Grindlay (1999) can be used to place constraints on presently undetected GRB populations that preferentially emit in the X-ray band. Dermer & Mitman (1999) pointed out that the initial fireball Lorentz factor, Γ_0, is crucial for determining the appearance of the GRB. Since Γ_0 is related to the ratio of total burst energy to rest mass energy of the baryon load a "clean" (low baryon load and/or large energy) fireball is characterized by Γ_0 in excess of 300 (according to Dermer's definition), while a "dirty" fireball (heavy load) is characterized by a very small Lorentz factor. Dermer & Mitman argue that clean fireballs produce GRBs of very short duration with emission predominantly in the high-energy regime, while dirty fireballs produce GRBs of long duration that preferentially radiate in the X-ray band. These bursts are in fact predicted to be X-ray bright, but have probably not yet been detected by BATSE and similar instruments, because these detectors are "tuned" to events for which Γ_0 falls in the range 200–400 (Dermer & Mitman 1999). The absence of a significant number of X-ray transients in the RASS and the *Ariel* survey thus suggests that the frequencies of "dirty" GRBs relative to bursts with a "normal" baryon load is comparable.

Vietri et al. (1999) drew attention to the "anomalous" X-ray afterglows from GRB 970508 and GRB 970828, which exhibit a resurgence of soft X-ray emission and evidence for Fe-line emission. These authors interpret the delayed "rebursts" in the framework of the SupraNova model (Vietri & Stella 1998) in which the GRB progenitor system creates a torus of iron-rich material. The GRB fireball heats the torus, which cools via Bremsstrahlung, leading to a "reburst" in the X-ray band. The emission pattern of this heated torus should be nearly isotropic, so that one expects many X-ray afterglows that are not accompanied by GRBs. The RASS data place severe constraints on this type of reburst scenario, because these delayed components are predicted (Vietri *et al.* 1999) to be bright (10^{-4} erg cm^{-2}) and of long duration ($\sim 10^3$ s). The rarity of afterglows in the RASS data suggests that GRBs from "SupraNovae" do not constitute the bulk of the observed GRB population, unless the GRBs are also roughly isotropic emitters (which is in conflict with the correspondingly large energy requirements).

Another constraint can be placed on GRBs related to supernovae (SN). If the association of GRB 980425 with SN1998bw is real (e.g. Galama et al. 1998, Woosley et al. 1999) then such SN-related GRBs would dominate the total GRB rate by a factor of $\sim$1000 due to their low luminosities implied by the small redshift (z = 0.0085) of the host galaxy. It can be argued that GRB 980425 was beamed away from us, and we merely saw the less beamed afterglow emission. If this is true, we expect many X-ray afterglows in the RASS data. Again, our results constrain these possibilities, but more quantitative results require detailed simulations.

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