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X–ray afterglow of gamma–ray bursts with BeppoSAX

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Abstract. BeppoSAX has detected so-far 14 GRB in the field of view of Wide Field Cameras following gamma–ray triggers. We pointed the direction of 12 of them with Narrow Field Instruments. In almost all cases we detected X–ray sources that, in the large majority we associate with the GRB, due to their temporal behaviour. For a large fraction of these GRBs, transient sources in other wavelengths and host galaxies have been detected. The main spectral and temporal features of these afterglow sources, their energetics and the association with other features are reviewed.

Key words: gamma-rays: bursts — instrumentation: detectors

1. BeppoSAX and GRBs

One year and a half ago BeppoSAX discovered the X–ray afterglow source associated to GRB 980228 (Costa et al. 1997). Following this first discovery an impressive collection of new data and a real outburst of interpretation work has rejuvenated all this topic of Astrophysics. These mysterious objects are nowadays less elusive but the amount of problems open probably is not decreased. The expectation is now funded that the Astrophysics Gamma–Ray Burst is taking the place of the "Mystery of Gamma Ray Bursts". GRBs have become the crossroad of a network of knowledge including association with other phenomena, study of parent objects and probe of ancient universe at a scale of distance deeper than that of Supernovae. This discovery was possible with a special use of all the capabilities of BeppoSAX satellite. In the initial configuration that made the first result possible the sequence for the detection of GRB afterglows was:

– a) An onboard trigger from Gamma Ray Burst Monitor;
– b) A detection with Quick Look Analysis of a burst in the X–ray rate meters coincident with a);
– c) Imaging of the burst by processing data of the WFC;
– d) Pointing of the GRB direction with Narrow Field Instruments.

Now the situation has evolved. BeppoSAX is still the main producer of data on GRBs and their afterglow, but not only as an independent instrument. It is now part of a network that is significantly increasing the total amount of data and their significance. The major improvements (and the associated results) with respect to the original procedure are:

– a) Other triggers are used to search for the bursts in the WFC. In particular 2 GRBs have been detected with a trigger from BATSE experiment aboard CGRO;
– b) GRB positions are determined and distributed with increasing precision and decreasing delay, by an independent distribution system and by GCN. One of the transient sources (GRB 980326) has been detected in the optical band without any pointing with NFIs;
– c) Positions originated from other experiments (ASM–XTE, PCA, IPN) have been included in the alert loop and one X-ray transient has been found with BeppoSAX NFIs in a burst direction determined by ASM (GRB 980703);
– d) GRB 980613 has been detected without any onboard gamma–ray trigger but only from the Quick Look inspection of X/Gamma-rays light curves.

2. Detection of gamma–ray bursts with wide field cameras

Wide Field Cameras of BeppoSAX have played the key role in these new developments. Their imaging capability, with a pixel size of 5 minute of arc, and even smaller error boxes for good statistics, has been the key improvement in this new astrophysics, when included in the frame of a more general detection strategy. In particular difficulties arise from the absence of any onboard trigger for the WFC

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Table 1. GRBs detected and localized with BeppoSAX GRBM and WFCs. The peak fluxes are in units of 10^{-7} erg cm^{-2} s^{-1}. The Afterglow Sources are given in units of 10^{-13} erg cm^{-2} s^{-1} around 8 hours after the GRB

GRB	X–ray peak flux	T_x (s)	γ–ray peak flux	T_γ (s)	1st TOO delay	X Afterglow	Counterparts
GRB 960720	0.25	17	10	8			
GRB 970111	1.4	60	56	43	16^h	1.2?	
GRB 970228	1.4	77	37	77	8^h	30	O
GRB 970402	0.16	150	3.2	150	8^h	2.0	
GRB 970508	0.35	25	5.6	15	5.7^h	6.0	O ($Z = 0.835$), R
GRB 971214	0.2	35	6.8	35	6.7^h	8.0	O ($Z = 3.418$)
GRB 971227	0.36	7	3.8	7	14^h	2.8?	
GRB 980109	0.16	20	3.9	20			
GRB 980326	0.84	9	2.7	9			O
GRB 980329	1.3	53	51	35	7^h	8.0	O, R
GRB 980425	0.61	45	2.4	25	9^h	3.0?	O, R?
GRB 980515	0.3	20	3	15	10^h	2.3?	
GRB 980519	0.51	190	13	28	7^h	2.0	O
GRB 980613	0.13	50	1.2	50	9^h	7.0	O ($Z = 1.0964$)

and from the absence of a robust and fast detector of new sources. This is a consequence of the coded mask technique applied to a large field including several sources, and of the general architecture of the BeppoSAX data handling system, the onboard recording and the downloading once per orbit. The potentiality of the WFC is fully exploited when the Gamma-Ray Burst Monitor provides an onboard generated trigger that steers the search for transient events in the WFC light curve and reduces the search for a GRB to a very small fraction of the total time. Moreover the Narrow Field Instruments of SAX, under the control of the same team, can be pointed to the WFC position as soon as it is derived from the image. During 1996 a series of operations included commissioning, science verification and various adjustment of thresholds and trigger conditions made the number of GRBM triggers reasonable. During this transition a first GRB (960720 Piro et al. 1998a) was detected with WFC and, starting from this point, a procedure was developed that became fully operative at the beginning of December 1996 (described in Costa et al. 1998).

The whole BeppoSAX payload was in stand-by for around two months in summer 1997 because of the premature deterioration of some gyroscopes. With the present pointing system, that makes use of a single gyroscope, the follow up pointing of narrow field instruments may be slower and the burst positioning capability in certain conditions is worse than it was before, but these delays have been off-set by improved procedures, software and skill in various areas.

A gyro-less pointing mode is about to be tested and will be adopted as soon as the last gyroscope becomes obsolete. A further, but not dramatic, slowing of pointing rapidity is expected from this new mode. The BeppoSAX mission, and the associated GRB program, is expected to last at least two more years.

In Table 1, we show the Gamma–Ray Bursts detected with WFCs and GRBM until November 1998, with peak fluxes and duration in the band of the two instruments. All the bursts in the list belong to the class of long burst.

3. Follow up observations with BeppoSAX and other Satellites

Beside GRB 960720 (whose direction was observed after 6 weeks) 12 GRB direction were observed with NFI with delays ranging from 6.0 to 16.0 hours. GRB 980109 was not observed because of a poor aspect and GRB 980326 could not be pointed because of solar angle constraints. The detection of two afterglow sources starting from a BATSE trigger is only a part of the new scenario where BeppoSAX has now become part of a network that has significantly boosted its capability to produce new Gamma-Ray Burst science. In this moment BeppoSAX can be alerted by triggers originated from:

- a) BeppoSAX GRBM,
- b) BeppoSAX GRBM/WFC Quick Look Analysis (possibly helped from a GCN message).

BeppoSAX WFCs positions are distributed by e-mail to more than 200 addresses. These directions have been pointed by ASCA, ROSAT, XTE, ISO, XUV, HST plus numerous, ground based, optical, IR and Radio Telescopes.

BeppoSAX Narrow Field Instruments can also be pointed on directions provided by:

- a) RXTE All Sky Monitor, in one- or two-dimensional mode or PCA,
- b) IPN with Ulysses, BATSE, BeppoSAX, Wind and, more recently, NEAR,
- c) a combinations of these.

Partially stimulated by the BeppoSAX results other satellites have played a role in the game. An important improvement has been the implementation of the new LOCBURST capability. The prompt availability of BATSE coordinates with a precision below 2 degrees, via the GCN network (Barthelmy et al. 1998) made possible other strategies and procedures. RXTE is particularly suitable to make fast TOO pointing. In this short time the afterglow could be strong enough to be detected by PCA and actually a certain number of BATSE positions have been observed. Another important contribution has been the fast distribution of coordinates of GRB detected by ASM. Last but not least IPN-3 has become much faster. As mentioned above SAX itself could benefit of these developments but also ASCA (Murakami et al. 1998). The two major results not started from BeppoSAX WFCs have been, so far, an afterglow source (970828) from RXTE/ASM/PCA plus IPN plus ASCA and an afterglow source (980703) from RXTE/ASM plus SAX.

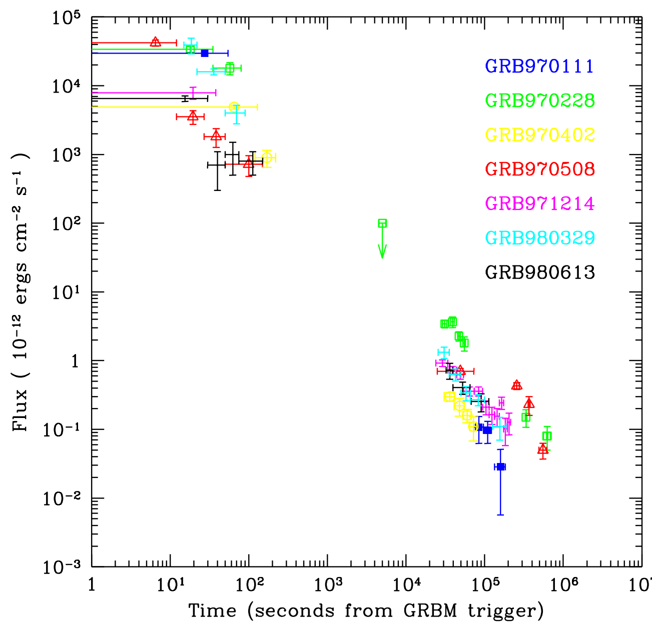

Fig. 1. X–ray afterglows

4. Afterglow sources

Some of the TOO pointings gave the detection of a fading source, clearly associated with the burst, while some did not. In the Table 1. we show the presence of a clear or ambiguous afterglow source in the X, Optical and Radio Bands. Remembering that three of the 14 positions were not followed up, we have 7 unambiguous detections and four doubtful results. This can derive from the absence of afterglow, e.g. for an high absorption, proving the evidence of a high density environment, as suggested to explain the absence of optical transient associated to the GRB. But this could come as well from the quick decay, too fast for the pointing capability of BeppoSAX NFI. Which of the two is real is of high importance and these GRBs without afterglow deserve a short discussion.

4.1. Unambiguous detection

We consider unambiguous a detection when during the first part of the NFI observation a source is present, in the error box of WFC, with an average luminosity that makes unlikely a random occurrence of such a source in solid angle included in the error box. Moreover we require that the source has a well established fading behaviour. In the Fig. 1 we show the decay of the most luminous afterglow sources. On the left side we have indicated, as a reference, the average flux in the $2-10$ keV band during the main burst itself.

4.2. Ambiguous detection

Here we report the ambiguous afterglow detection (one or more) found in the WFCs positions and the associated probability of a random occurrence based on the cumulative distribution of ASCA-GIS (Cagnoni et al. 1998).

- GRB 970111: WFC error box = 8 square arcminutes. TOO delay 16h, J21528.1+1937 flux = 1.2 10^{-13} erg cm^{-2} s^{-1}, probability of random occurrence in such a field = 2.5%; suspect fading,
- GRB 971227: WFC error box = 6 arcmin radius (the Window Back skeleton covers a part of the error box), TOO delay 16h, J1257.5+5915 flux = 1.2 10^{-13} erg cm^{-2} s^{-1}, probability of random occurrence in such a field = 40%, J1257.3+5924, flux = 3 10^{-13} erg cm^{-2} s^{-1}, possible fading, probability of random occurrence in such a field = 6.5%;
- GRB 980425: WFC error box 8 arcmin radius, TOO delay 10h, $J1935.0+5248$ flux = 3 10^{-13} erg cm^{-2} s^{-1}, likely associated with SN1998bw (or its host), probability of random occurrence in such a field = 13%, $J1935.3-5252$ flux = 1.6 10^{-13} erg cm^{-2} s^{-1}, fading, probability of random occurrence in such a field = 40%;
- GRB 980515: WFC error box = 8 arcmin radius, TOO delay 10h, $J2116.8-6712$, flux = 2.3 10^{-13} erg cm^{-2} s^{-1}, fading, probability of random occurrence in such a field = 20%.

We conclude that 1 or 2 of these sources may be field sources. The statement that there are GRBs without an X–ray afterglow is not excluded, but is not supported at

all by BeppoSAX data. On the other side the possibility that all the poor detections derive from fast decay afterglow should be seriously considered. It is a matter of fact that fast afterglows do exist and all the previous cases of ambiguity belong to:
1) Late TOOs.
2) Bad attitude reconstruction.
It is very likely that the sources detected in the error boxes of GRB 970111 (Feroci et al. 1998) and GRB 971227 (Antonelli et al. 1999), are really associated to the GRB afterglow, because of the small error box and of the clear fading respectively. The situation of GRB 980425 is much more intriguing and is discussed in detail in Pian et al. (1999).

5. Spectra

We can derive information on spectra of well established afterglow sources. The paucity of photons makes difficult fitting data with laws including many parameters. The main feature of the analysed spectra is a power law with an index ranging from 1.5 to 2.3. Within the errors they are consistent with a unique power law index of 1.9 ± 0.3 (with a reduced χ^2 of 0.9). In no case did we find evidence of a cut-off. By jointly fitting power law and photoelectric absorption we derive confidence intervals of the absorption column. Most of these intervals include the galactic value (Owens et al. 1998). A few slightly exceed this value but none with a compelling significance.

In one case only (GRB 970508, Piro et al. 1998) did we find evidence of a spectral variation during the afterglow, correlated with the intensity. The source associated with this GRB rebursted with a hardening of the spectrum, and subsequently decayed with more rapid law and soft spectrum than that of all other afterglow sources. In the very beginning (Piro et al. 1999) we found evidence of an Fe line. This seems much more than a coincidence since the other burst which showed a reburting behaviour (GRB 970828, Yoshida et al. 1998) shows as well evidence of an Fe line. In the frame of Synchrotron Shock models the re–acceleration of particles is possibly associated with the encounter of a relatively dense cloud of materials, which is also needed to interpret the Fe feature as fluorescence reprocessing of the primary X-rays from a circumburst environment.

6. Decay law

In Fig. 1 we show the fluxes of the well established afterglow sources. Since the limit of detectability is of $\approx 5\ 10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ most of the detected afterglow sources span in one decade of flux. GRB 970508 shows the above mentioned complexities but the majority of the bursts detected with a reasonable statistics, decay with a plain power law and the statistics does not allow for any detail in the light curve. We can state that the slope of the decay law is more differentiated than the energy spectrum. The situation is complicated by intrinsic limitations of BeppoSAX that cannot be overcome. For the majority of bursts, we can determine the slope of the decay with a reasonable sensitivity only by using the values of the flux measured by Wide Field Cameras soon before the flux sinks below the threshold of detectability (around $10^{-9}\,\mathrm{ergs\,cm^{-2}\,s^{-1}}$) and making an assumption on the start of the afterglow. WFC cannot detect any more the GRB after a few $\approx 10^2\,\mathrm{s}$ and the Narrow Field Instruments cannot be on source in less than 5 hours. In a few cases this assumption is supported by the spectral evolution (Frontera et al. 1998) but in most cases the assumption on the start of the afterglow and, thence, the slope derived by this way, may include a large amount of discretion.

From a preliminary analysis some bursts (e.g. 970228, 980613) seem to have a gap between the prompt burst and the afterglow. In some others (e.g. 970508, 971214 or 980329) we find hints of a continuous evolution from the GRB to the afterglow. This is relevant not only to understand details of models but even to determine the total energy in the afterglow. Luckily our ignorance is not complete thanks to a few serendipitous detections by other satellites. Few data from SIGMA and HEAO1 enlighten this point. One case confirms that a GRB can continuously evolve to the afterglow (Burenin et al. 1999) while another (Connors & Hueter 1999) confirms that a gap may exist after the GRB vanishes and before the afterglow epiphany, and this is consistent with SAX results.

7. Open questions and possible improvements

We can therefore state that BeppoSAX has discovered a phenomenology that is not common to all sources but shows at least less variance than the major features of GRBs in the classical band. Most GRBs have associated an afterglow source with a hard, non thermal, spectrum, and low absorption and most of them fade according to a smooth power law. How much this sample is representative of all GRBs depends how much we are conditioned from selection effects and this study is still in a very preliminary stage (Feroci et al. 1999). Some features common to most of the objects, such as the association with a host (4 with a measured high red-shift) fix the distance scale for a large subset. This is a dramatic improvement of the scenario. But still we doubt that other important features may escape us due to instrumental limits and other selection effects.

- 1) Do Gamma–Ray Burst without afterglow sources exist?
- 2) Are some Gamma–Ray Burst associated with SN?
- 3) Are short bursts generating afterglows as the long ones?

- 4) Do Gamma–Ray Burst without Gamma–Rays exist?

Question 1) will not be answered by SAX that cannot distinguish between fast afterglow and no afterglow. Question 2) requires more GRBs from BeppoSAX and a more careful search for afterglows. Question 3) should in principle be answered by BeppoSAX. As shown before all GRBs detected in the WFCs have a long duration. A lower sensitivity to short bursts may be due to the present trigger criteria of GRBM (a short integration time of 1 s). But we have a rich sample of short bursts detected with GRBM and, in any case, we recall that the BATSE triggers and positions are systematically monitored: no short burst has apparently occurred, so far, in the field of view of a WFC. In another paper (Smith et al. 1999) we describe the efforts to improve the detection of short bursts at quick look level. The actions to answer question 4) (GRBs with a low Gamma-Ray content and no Gamma-Ray trigger) are already operative. Due to the improved skill and procedures at the Science Operation Center, ad after the detection of GRB 980613, we expect some results in this direction.

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