Six Years of Gamma Ray Burst Observations with "BeppoSAX"

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Abstract. I give a summary of the prompt X–/gamma–ray detections of Gamma Ray Bursts (GRBs) with the "BeppoSAX" satellite and discuss some significant results obtained from the study of the prompt emission of these GRBs obtained with the "BeppoSAX" Gamma Ray Burst Monitor and Wide Field Cameras.

1. The BeppoSAX revolution

All the efforts performed before BeppoSAX, an Italian satellite with Dutch participation (Boella et al. 1997a), of unveiling the mystery of Gamma Ray Bursts (GRBs), had not solved the problem. The most relevant result in this direction was obtained with the BATSE experiment aboard the Compton Gamma Ray Observatory (CGRO): the GRBs were isotropically but not homogeneously distributed in the sky. These facts were very suggestive of an extragalactic origin, but they were not a direct demonstration. Indeed, it was recognized (e.g., Fishman & Meegan 1995) that only the identification of a GRB counterpart at other wavelengths was needed in order to make a breakthrough in setting their distance scale. Moreover the presence of a delayed emission was not considered a necessary consequence the observed GRB phenomenon. Thus, about thirty years after the initial discovery, the GRBs were still a mysterious phenomenon.

Thanks to BeppoSAX, this situation was reversed. The distance scale issue of long (> 1 s) GRBs has been definitely settled, the GRB afterglow emission at multiwavelengths has been discovered, with the GRB phenomenon, which is being unveiled. BeppoSAX has opened a new window in the GRB astronomy, providing most of the exciting results of the last 6 years. The high performance of BeppoSAX for GRB studies is due to a well–matched configuration of its payload, with both wide field instruments (WFIs) and narrow field telescopes (NFIs). The WFIs comprised a γ–ray (40–700 keV) all–sky monitor (Gamma-Ray Burst Monitor, GRBM, Frontera et al. 1997) and two Wide Field Cameras (WFCs, 2–28 keV, Jager et al. 1997). The NFIs included four focusing X-ray (0.1–10 keV) telescopes (one LECS, Parmar et al. 1997; and three MECS, Boella et al. 1997b) and two higher energy direct–viewing detectors (HPGSPC, Manzo et al. 1997, and PDS, Frontera et al. 1997).

The BeppoSAX capability of precisely (arcmin accuracy) localizing GRBs was soon tested, only one month after the first light of the satellite, with the detection of GRB960720 (Piro et al. 1998). Starting from December 1996, at the
BeppoSAX Science Operation Center, an alert procedure for the prompt search of simultaneous GRBM and WFC detections of GRBs was implemented. Thanks to this procedure, the first X-ray afterglow of a GRB which occurred on February 28, 1997 was soon discovered (8 hrs delay) and its fading law determined (Costa et al. 1997). The afterglow light curve, unlike all other transients, decayed according to a power–law. Simultaneously, an optical counterpart of the X-ray afterglow source was detected, which showed the same decay rate (van Paradijs et al. 1997). A ROSAT observation of the NFI error box confirmed the decay law of the fading source and established its positional coincidence with the optical transient (Frontera et al. 1998).

Less than two months later, the first optical redshift (z = 0.835) of a GRB source was determined thanks to the prompt localization (5 hrs delay), provided by BeppoSAX, of GRB970508 (Metzger et al. 1997). The extragalactic distance scale of the first GRB was definitely established. At the same time an exciting result came from the radio observations of the same event: the discovered radio afterglow exhibited, for about one month, rapid variations interpreted as interstellar scintillations. Only a very compact source highly relativistically expanding could be responsible for them (Frail et al. 1997). This result was the first actual confirmation of fireball model for GRBs (see, e.g., review by Piran 1999).

Since that first detection of an X-ray afterglow, many other afterglow detections have been obtained, mainly with BeppoSAX and, less often, with other satellites, i.e., ROSAT, Rossi X–ray Time Explorer (RXTE), ASCA, Chandra X–ray Observatory (CXO), XMM-Newton. In this paper I summarize the GRBs promptly localized with BeppoSAX and discuss some relevant results obtained using GRBM and WFCs.

2. Six Years of BeppoSAX results

Table 1 reports the main information on the 51 GRBs simultaneously detected with GRBM and WFCs. This information includes positioning accuracy obtained with the WFCs, duration of the events in the 2–10 and 40–700 keV energy bands, peak fluxes in these two bands and the time delay between the GRB onset and the first TOO observation with the BeppoSAX NFIs.

As can be seen, all the GRB events detected with both WFCs and GRBM are long (≥2 s), even if a sizable fraction (22GRBM are short (Guidorzi et al. 2003a). In addition, most of the detected events are classical GRBs, except two, which are X-ray rich events (981226, 990704). Four of the detected GRBs (960720, 010213, 010304, 010501) were discovered with the off-line analysis, three (010518, 020321, 020322) were alerted by the ground trigger software, 36 were followed up with the NFIs.

X-ray afterglows, whose measurements were performed starting from ≤ 5.7 hrs after the main event, are discovered in about 90% of the followed-on GRBs, against about 50% in the optical and about 40% in the radio. Thus an open problem is the origin of GRBs with no optical emission (dark). Are they very weak? Do not they emit optical radiation? Is this radiation strongly absorbed by the circumburst medium? Are they at very large distances? Do they fade very rapidly? Likely some or more than one of the above reasons could
Table 1. GRBs detected with the BeppoSAX GRBM and WFCs

| GRB   | Positionerr radius| 2–10 keV T<sub>2–10keV</sub> (s) | 40–700 keV T<sub>40–700keV</sub> peak flux (a) | 1<sup>st</sup> TOO delay (hrs) |
|-------|-------------------|----------------------------------|-----------------------------------------------|-------------------------------|
| GRB960720 | 3 0.25             | 17                               | 10                                            | 8                             |
| GRB970111 | 3 1.4              | 60                               | 56                                            | 43                            |
| GRB970228 | 3 1.4              | 80                               | 37                                            | 8                             |
| GRB970402 | 3 0.16             | 150                              | 3.2                                           | 150                           |
| GRB970508 | 1.9 0.35           | 29                               | 5.6                                           | 15                            |
| GRB971214 | 3.3 0.2            | 35                               | 6.8                                           | 35                            |
| GRB971227 | 8 0.36             | 7                                | 3.8                                           | 7                             |
| GRB980109 | 10 0.16            | 20                               | 3.9                                           | 20                            |
| GRB980326 | 8 0.84             | 9                                | 2.7                                           | 9                             |
| GRB980329 | 3 1.3              | 68                               | 51                                            | 7                             |
| GRB980425 | 8 0.61             | 40                               | 2.4                                           | 31                            |
| GRB980515 | 4 0.3              | 20                               | 3                                             | 15                            |
| GRB980519 | 3 0.51             | 190                              | 13                                            | 28                            |
| GRB980613 | 4 0.13             | 50                               | 1.6                                           | 50                            |
| GRB981226 | 6 0.085            | 260                              | 0.56                                          | 20                            |
| GRB990123 | 2 0.5              | 100                              | 170                                           | 100                           |
| GRB990217 | 3 0.11             | 25                               | 1.1                                           | 25                            |
| GRB990510 | 3 1.4              | 80                               | 24                                            | 75                            |
| GRB990625 | 60 0.065           | 11                               | 0.11                                          | 11                            |
| GRB990627 | 3 0.065            | 60                               | 1.6                                           | 28                            |
| GRB990704 | 7 1.3              | 40                               | 1.8                                           | 23                            |
| GRB990705 | 3 0.85             | 45                               | 37                                            | 42                            |
| GRB990712 | 2 3.1              | 30                               | 6.3                                           | 30                            |
| GRB990806 | 3 0.35             | 30                               | 5.5                                           | 30                            |
| GRB990907 | 6 0.39             | 220                              | 9.5                                           | 1                             |
| GRB990908 | 8 0.35             | 130                              | 1.0                                           | 50                            |
| GRB991014 | 6 0.54             | 10                               | 4.2                                           | 3                             |
| GRB991105 | 5 0.24             | 40                               | 6.4                                           | 13                            |
| GRB990210 | 2 1.6              | 20                               | 180                                           | 20                            |
| GRB990214 | 6.5 0.63           | 115                              | 40                                            | 10                            |
| GRB990528 | 2 0.62             | 120                              | 14                                            | 80                            |
| GRB990529 | 4 0.2              | 30                               | 7                                             | 14                            |
| GRB990615 | 2 0.8              | 120                              | 1                                             | 12                            |
| GRB990620 | 3.6 0.9            | 20                               | 7                                             | 15                            |
| GRB991011 | 2 0.07             | 60                               | 25                                            | 31                            |
| GRB991109 | 2.5 0.6            | 65                               | 4.2                                           | 60                            |
| GRB990213 | 6 0.65             | 25                               | 14                                            | 23                            |
| GRB990214 | 3 1.7              | 30                               | 5.5                                           | 20                            |
| GRB990220 | 4 1.5              | 150                              | 5.6                                           | 40                            |
| GRB990222 | 2.5 2.1            | 280                              | 86                                            | 170                           |
| GRB990304 | 2.5 0.59           | 24                               | 11                                            | 15                            |
| GRB990412 | 1.6 0.64           | 90                               | 17                                            | 74                            |
| GRB990501 | 6 0.09             | 41                               | 1.5                                           | 37                            |
| GRB990518 | 5 0.15             | 30                               | 1.3                                           | 25                            |
| GRB990518 | 5 0.15             | 30                               | 1.3                                           | 25                            |
| GRB9901121 | 2 3.65             | 100                              | 73                                            | 105                           |
| GRB991211 | 2 0.09             | 400                              | 0.5                                           | 400                           |
| GRB990321 | 5 0.06             | 90                               | 1.1                                           | 70                            |
| GRB990322 | 3 0.17             | 50                               | 3.0                                           | 15                            |
| GRB990409 | 3 0.36             | 60                               | 1.8                                           | 40                            |
| GRB990410 | 2 0.19             | > 1290                           | 1.3 (b)                                       | 1800 (b)                      |
| GRB990427 | 3 0.19             | 60                               | < 0.66 (3σ)                                   | -                             |

(a) Peak fluxes in units of 10<sup>-7</sup> erg cm<sup>-2</sup> s<sup>-1</sup>
(b) 15–1000 keV KONUS data. GRBM was switched off.
be at the origin of the dark GRBs. With the future missions (e.g., SWIFT), the origin of the dark GRBs will be certainly unveiled.

3. Some significant results

I review below few of the most relevant results obtained with the GRBM plus WFC instruments aboard BeppoSAX, in particular the discovery of X–ray rich GRBs, the test of synchrotron shock model from the shape of the X–/gamma–ray prompt emission spectra and their evolution, the discovered relation between peak energy of the $\nu F(\nu)$ spectrum and the isotropic electromagnetic energy released in the GRB prompt emission, the discovery of a transient absorption feature during the rise time of the burst profile of GRB990705 (evidence of a transient absorption feature from GRB011211 is under investigation, Frontera et al. 2003).

3.1. X–ray rich GRBs: the link between classical GRBs and XRFs

A new class of GRBs has been discovered with BeppoSAX. It includes GRBs which, unlike classical GRBs, emit most of their energy in the X–ray band (2–28 keV). Two outstanding examples of X–ray rich GRBs were detected with BeppoSAX: GRB981226 (Frontera et al. 2000a), and GRB990704 (Feroci et al. 2001). Their light curves are shown in Fig. 1. As can be seen, both GRBs are well visible in the 2–26 keV band, but they are barely visible in the 40–700 keV interval. Also a percursor with onset 180 s before the main event, is only observed in the X–ray band, but not in gamma–rays. Gamma–ray emission is only visible for a short time in correspondence of the GRB onset in the case of GRB981226, and in correspondence of the main peak in the case of GRB990504.

A useful parameter which characterize the X–ray richness is the ratio between the fluences in the 2–10 keV and 40–700 keV energy band, respectively (softness ratio). Figure 2, from the paper by Feroci et al. (2001), shows the behaviour of the softness ratio for the two X–ray rich GRBs compared with that of some classical GRBs. Their separation from the classical GRBs is apparent. The softness ratio of X–ray flashes (XRF, Heise et al. 2001, not plotted in the figure) is still more separated, making X–ray rich events GRBs as the link between classical GRBs and XRFs.

Both two X–ray rich GRBs were followed-on with the BeppoSAX NFIs. The afterglow spectra are consistent with power–laws (photon indices $\Gamma$ of $1.92\pm0.47$ for GRB981226 and $1.69^{+0.60}_{-0.34}$ forGRB990704), as those of many classical GRBs. Also the afterglow light curves shows decay rates typical of classical GRBs. However an unexpected dip of at least two hours in the afterglow decay rate is observed at the beginning of the GRB981226 afterglow observation, which was started 11 hrs after the main event. This feature was interpreted as due to a temporary cessation (or strong reduction) of the X–ray afterglow due to the absence (or very reduced density) of ambient gas, like a cavity surrounding the explosion (Frontera et al. 2000a).
Figure 1. Light curves of two X–ray rich GRBs. Left: GRB981226, reprinted from Frontera et al. (2000a). Right: GRB990704, reprinted from Feroci et al. (2001).

Figure 2. Ratio $S(2–10 \text{ keV})/S(40–700 \text{ keV})$ between X–ray and gamma–ray fluences for various GRBs detected with the BeppoSAX WFC and GRBM. The position in the diagram of the X–ray rich GRBs 981226 and 990704 is marked. Reprinted from Feroci et al. (2001).
3.2. Test of the 2–700 keV prompt emission mechanism

As discussed in various papers (e.g., Amati et al. 2002), most of the time averaged spectra of the GRBs observed with BeppoSAX WFCs and GRBM are well fit down to 2 keV with a smoothly broken power-law (‘Band function’, Band et al. 1993) (in the other cases, a single power–law describes the data). The Band function, as discussed by Tavani (1996), has a spectral shape similar to that of the synchrotron radiation if the energy spectrum of the emitting electrons is hybrid, i.e., it is distributed partially according to a Maxwellian function and partially according to a power–law. The synchrotron spectrum derived by Tavani (1996) also assumes a negligible self absorption (Optically Thin Synchrotron Shock Model, OTSSM). We fit the time averaged spectra of 19 GRBs with this model (Amati et al. 2001). The result is that in about 70% of the cases the OTSSM fit well the data. Two examples of these fit results are shown in Fig. 3. A property of the OTSS model is that, below the peak energy of the $EF(E)$ spectrum, the photon index is $-2/3$, independently of the electron energy distribution and uniformity of the associated magnetic field, if no electron cooling takes place during the GRB. We find that this does not occur in 30% of our data. In these cases, the spectral index is consistent with that expected in the case of an electron cooling: photon index between $-2/3$ and $-1.5$.

A more constraining test of the prompt emission mechanism is the spectral evolution of the GRB emission. This study has been performed for almost all GRBs detected with the BeppoSAX GRBM and WFCs (see Frontera et al. (2000b) for a sample of GRBs, and Frontera et al. 2003a for the entire population of BeppoSAX GRBM and WFCs events). The analysis, in addition to a general hard to soft evolution, shows that in most cases the spectra soon after the GRB onset cannot be fit with an OTSSM, which however becomes acceptable as the time elapses. This feature shows that likely some other emission mechanism (e.g. Inverse Compton, as discussed by Frontera et al. 2000b) is at work at the early times.

Figure 3. Time averaged $EF(E)$ spectrum of GRB970111 (left) and GRB980329 (right), with superposed the fit with the optically thin synchrotron shock model (Tavani 1996). Reprinted from Amati et al. 2001.
3.3. Peak energy vs. isotropic released energy correlation

An investigation devoted to search out correlations between parameters derived from the redshift–corrected energy spectra of GRBs with known redshift has permitted us to discover (Amati et al. 2002) a power–law relation (see Fig. 4) between peak energy $E_p$ of the $E\Phi(E)$ redshift–corrected time averaged spectra and isotropic electromagnetic energy $E_{\text{rad}}$ released in the GRB event:

$$E_p \propto E_{\text{rad}}^{0.52\pm0.06}$$ (1)

The relation is now confirmed (D. Lamb, private communication) by HETE results. It puts strong constraints to the GRB emission models: independently of the beaming, eq. (1) must be satisfied. A discussion on possible interpretations of the above relation is given by Zhang and Mészáros (2002) in the context of the internal and external shock models.

3.4. Test of the GRB environment

With the WFC and GRBM spectral data, it has also been possible to gain information on the GRB environment from the study of the hydrogen-equivalent column density behaviour with time, and the search of X–ray lines in the prompt emission. Both these investigations have given positive results, with the discovery of variable hydrogen column density from some GRBs and the discovery of a transient absorption line from at least one GRB. We discuss both.

Variable column density A decreasing $N_H$ has been detected in the X–ray spectra of at least events three GRB events: GRB980329 (Frontera et al. 2000),
GRB010222 (in t Zand et al. 2001), GRB010214 (Guidorzi et al. 2003). The $N_H$ time behaviour observed from GRB980329 is explained (Lazzati & Perna 2001) if the GRB event occurs in an overdense region within a molecular cloud, with properties similar to those of star formation globules (Bok globules).

**Transient absorption feature from GRB990705** A clear evidence of a transient absorption feature was found in the X-ray spectrum collected during the rise (first 13 s) of GRB990705 (event total duration of about 40 s).

Two possible interpretations have been proposed. Amati et al. (2000) interpreted the feature as a K absorption edge of neutral Fe (rest frame energy $E_K = 7.1$ keV) within a shell of material around the GRB location, which is photo-ionized by the GRB photons. With this assumption, the GRB redshift derived is $z_{\text{X-rays}} = 0.86 \pm 0.17$, and the iron relative abundance is $A/A_\odot \sim 75$, which is typical of a young supernova explosion environment. A successful test of this model is the later measurement of the redshift ($z_{\text{opt}} = 0.8420 \pm 0.0002$ of the GRB host galaxy (Le Floc’h et al. 2002), which is nicely consistent with the X-ray redshift value. The drawback of this model is the large mass of Fe implied (several solar masses), unless the Fe material is clumped and a clump was along the line of sight (Boettcher et al. 2001). In order to overcome this problem, Lazzati et al. (2001) interpreted the absorption feature as an absorption line due resonant scattering of GRB photons off H–like Fe (transition 1s–2p, $E_{\text{rest}} = 6.927$ keV). With this assumption, the X–ray redshift is still consistent with that of the GRB host galaxy, the line broadening is interpreted as dispersion in the outflow velocity (up to 0.1c), the required relative Fe abundance ($A/A_\odot \sim 10$) is still consistent with the site of a young supernova explosion, but the Fe mass required is only $\sim 0.2 M_\odot$.

Thus, independently of the specific model, the observed feature points to an iron-rich circumburst environment, in which a supernova explodes first, and the GRB occurs later on. These results are consistent with the expectations of the 'supranova' model for GRB progenitors (Vietri & Stella 1998).

Evidence of another X-ray transient absorption line from GRB011211 is under evaluation (Frontera et al. 2003b).

4. Conclusions

*BeppoSAX* has given a key contribution to the study of the GRB prompt emission properties in an unprecedented broad energy band (2-700 keV). Certainly many questions are left unsolved by *BeppoSAX*, which hopefully will be answered by the future missions (e.g., SWIFT), but I am certain that the six years of BeppoSAX will be unlikely left down.

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References

Amati, L. et al. 2000, Science, 290, 953
Amati, L. et al. 2001, in: Gamma–Ray Bursts in the Afterglow Era, eds. E. Costa, F. Frontera & J. Hjorth (Springer, Berlin), p. 34
Amati, L. et al. 2002, A&A, 390, 81
Band, D. et al. 1993, ApJ, 413, 281
Boella, G. et al. 1997a, A&AS, 122, 299
Boella, G. et al. 1997b, A&AS, 122, 327
Boettcher, M. et al. 2001, Gamma–Ray Bursts in the Afterglow Era, eds. E. Costa, F. Frontera & J. Hjorth (Springer, Berlin), p. 160
Costa, E. et al. 1997, Nature, 387, 783
Feroci, M. et al. 2001, A&A, 378, 441
Fishman, G.A. & Meegan, C.A. 1995, ARA&A, 33, 415 (1995)
Frail, D.A. et al. 1997, Nature, 389, 261
Frontera, F. et al. 1997, A&AS, 122, 357
Frontera, F. et al. 1998, A&A, 334, L69
Frontera, F. et al. 2000a, ApJ, 540, 697
Frontera, F. et al. 2000b, ApJS, 127, 59
Frontera, F. et al. 2003a, in preparation
Frontera, F. et al. 2003b, in preparation
Guidorzi, C. et al. 2003a, these Proc.s
Guidorzi, C. et al. 2003b, A&A, 401, 491
Heise, J. et al. 2001, in: Gamma–Ray Bursts in the Afterglow Era, eds. E. Costa, F. Frontera & J. Hjorth (Springer, Berlin), p. 16
Jager, R. et al. 1997, A&AS, 125, 557
Lazzati, D. & Perna, R. 2001, MNRAS, 330, 383
Lazzati et al. 2001, ApJ, 556, 471
Le Floc’h, E. et al. 2002, ApJ, 581, L81
Manzo, G. et al. 1997, A&AS, 122, 341
Metzger, M.R. et al. 1997, Nature, 387, 878
Parmar, A.N. et al. 1997, A&AS, 122, 309
Piran, T. 1999, Phys. Rep., 314, 575
Piro, L. et al. 1998, A&A, 329, 906
Tavani, M. 1996, ApJ, 466, 768
Vietri, M. & Stella, L. 1998, ApJ, 507, L45
van Paradijs, J. et al. 1997, Nature, 386, 686
in ’t Zand, J.J.M. et al. 2001, ApJ, 559, 710
Zhang, B. & Mészáros, P. 2002, ApJ, 581, 1236