THE BEPPOSAX REVOLUTION IN GAMMA–RAY BURST SCIENCE

L. Amati

Istituto di Astrofisica Spaziale e Fisica Cosmica - Sez. Bologna, CNR, via P. Gobetti 101, I-40129 Bologna, Italy

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Abstract. We review the BeppoSAX discoveries and studies in the field of Gamma-Ray Bursts, which allowed a huge step forward in the understanding of these still mysterious and highly interesting astrophysical sources.

Key words: X-rays: general – gamma–rays: observations – gamma–rays: bursts

1. THE BEPPOSAX MISSION AND ITS SCIENTIFIC PAYLOAD

BeppoSAX was a mission of the Italian Space Agency (ASI) with contribution of NIVR (Netherlands) launched in April 1996 and ended in April 2002. It was characterized by a Low Equatorial Orbit with 3.9° inclination and ~600 km altitude, resulting in a low and very stable background (few % variation along a single orbit). The scientific payload covered an unprecedented broad energy band (0.1–300 keV) and was composed by two set of instruments: the Narrow Field Instruments (NFI), pointing along the satellite Z axis, and two wide field instruments pointing in directions perpendicular to it. The NFI included (we report in parenthesis the energy band, the FOV and the angular resolution): the LECS (0.1–10 keV, 0.5°, ~3°), the MECS, composed by three units, (1.3–10 keV, 0.5°, ~1°), the HPGSPC (4–120 keV, 1.1°, collimated) and the PDS (15–300 keV, 1.3°, collimated). The wide field instruments were the Wide Field Cameras (WFC), two units pointing along the ±X axis (2–28 keV, 20° FOV, 3° ang. res.), and the Gamma–Ray Burst Monitor, four units pointing along the ±X and ±Y directions (40–700 keV,
open FOV, burst location capabilities of several degrees). See Boella et al. (1997) and references therein for more details.

2. THE DISCOVERY OF GAMMA-RAY BURSTS AFTERGLOW

The possibility of detecting GRBs simultaneously with the GRBM and the WFC is implicit in the payload design described above and was already considered in the BeppoSAX Observers Handbook, with ∼6 events/year expected. The first of such events was GRB 960720, discovered in the WFC and localized within 3' with off-line analysis. A Target Of Opportunity (TOO) observation with the NFI was performed 45 days after the GRBM detection, but no convincing counterpart was found (Piro et al. 1998). Nevertheless, this result gave great confidence on the BeppoSAX capabilities of accurately localizing GRBs and an on-line procedure was designed and activated at the Satellite Operation Center (SOC) in order to allow for prompt (within 1 orbit duration, 90 minutes) search and localization of GRBs simultaneously detected by the GRBM and WFC. Soon after, this procedure, which exploited at the best the BeppoSAX capabilities, led to the discovery of the first X-ray afterglow source of a GRB (GRB 970228), with the NFI (Costa et al. 1997). The accurate localization of the X-ray afterglow by the NFI allowed the discovery of an optical transient associated to this event, the first optical counterpart to a GRB (Van Paradijs et al. 1997). Subsequently, the accurate localization, fast follow-up and afterglow discovery of another event, GRB 970508, led to the measurement of the first redshift (cosmological !) of a GRB (Metzger et al. 1997) and to the discovery of the first radio afterglow source of a GRB (Frail et al. 1997), allowing the measurement of its compactness and highly relativistic expansion. Of the 51 GRBs simultaneously detected by the BeppoSAX GRBM and WFC and promptly alerted, 37 were followed up with the BeppoSAX NFI. X-ray afterglows were discovered for ∼90% of the followed-on GRBs, vs. ∼50% in the optical and ∼40% in the radio. Redshift estimates were obtained for 14 of these events. All events detected with WFC and GRBM are long (>2 s), but the GRBM detected also short GRBs. These unprecedented discoveries settled the 30 year old question about GRBs distance, allowed first strict testing of GRB models, provided a new phenomenology and opened new observational windows for the study of these sources.
3. PHYSICS OF GAMMA–RAY BURSTS

3.1. Study of the prompt emission from X to gamma–rays

The co–alignment of the WFC units with two of the GRBM detectors allowed not only the accurate localization of those GRBs detected by both instruments but also the study of their prompt emission from $\sim 700$ keV down to 2 keV with unprecedented accuracy and good calibration. The comparison between the X–ray and gamma–ray light curves allowed the study of pulse width $\Delta t$ as a function of photon energy $E$, confirming in several cases the synchrotron predictions of a power–law dependence $\Delta t \propto E^{-0.5}$ (e.g. Piro et al. 1998, Feroci et al. 2001). The extension to low energies of the spectral measurements allowed a more accurate estimate of the low energy spectral index (a crucial observable for prompt emission models), and its evolution, with respect e.g. to BATSE ($>25$ keV). Most ($\sim 70\%$) of the time averaged spectra of GRBs detected with BeppoSAX are well fit down to 2 keV with an optically thin synchrotron shock model (Tavani 1996). The spectral evolution from X to gamma–rays shows in general a hard-to-soft evolution, which may be due to decrease of the magnetic field in the post-shock region due to its expansion or post-shock decrease of the electron energy distribution due to cooling processes. The X–ray spectra accumulated during the first part of the prompt emission are sometimes inconsistent with optically thin synchrotron, indicating that another mechanism, likely Inverse Compton, may be at work at early times. See Frontera et al. (2000a) for details.

3.2. X–ray afterglow

The X–ray afterglow of GRBs are characterized by a power-law decay and a power-law spectrum. The distribution of the decay indices $\delta$ is a Gaussian with $<\delta>=1.33$ and $\sigma=0.33$. The distribution of the spectral photon indices $\Gamma$ is a Gaussian too, with $<\Gamma>=1.93$ and $\sigma=0.35$. These findings are in agreement with the predictions of external shocks synchrotron models (e.g. Sari et al. 1999), also if in some cases (e.g. GRB 970508, see Piro et al. 1999) deviations from the monotonic decay have been observed. Also multi-wavelength spectra, combining the X–ray data with those at lower wavelengths, are crucial to establish the true mechanism(s) at work. Consistency with synchrotron predictions was found e.g. for
GRB 970508 (Galama et al. 1997), but deviations from the predicted spectral shape in the X-ray band were found for GRB 000926 (Harrison et al. 2001) and GRB 010222 (in ’t Zand et al. 2001). These deviations are consistent with relevant Inverse Compton on the low energy photons.

3.3. Connection between prompt and afterglow emission

Evidence that the X-ray afterglow starts during the tail of the prompt emission emerged from the BeppoSAX data. In several cases (e.g., GRB 970228) this evidence is direct, because the extrapolation of the power–law best fitting the 2–10 keV afterglow light curve is consistent with the 2–10 keV flux measured by the WFC during the last part of the prompt emission. A study of a sample of GRBs simultaneously detected by the WFC and GRBM (Frontera et al. 2000a) showed that: a) prompt emission spectra evolve toward the spectra of the late afterglow; b) the 2-10 keV fluence of the late prompt emission and its evolution are consistent with that of the afterglow emission. The afterglow onset time inferred from the later analysis was found to occur at ∼60% of the GRB duration, on average. This allowed the estimate of the initial Lorentz factor of the shocked fluid, with a mean value found of 150.

3.4. Breaks in the afterglow light curves: indications of jet

In case of a jet-like geometry of the GRB emission, an achromatic break in the afterglow light curve is expected at the time when the beaming angle starts to exceed the jet angle. Breaks in the light curve may also be due to transition to non–relativistic (NRE) phase of the expanding fireball. Several detections of breaks in the optical and radio bands have been reported. Indication of a break in the GRB 990510 X-ray afterglow, consistent with that observed in the optical band and with a theoretical model, was found by Pian et al. (2001) by comparing the afterglow data with those of the prompt emission. In the same way, a break in the GRB 010222 X-ray afterglow fading law was found by in’t Zand et al. (2001), but in this case the break is consistent with a transition to a NRE phase. Our systematic analysis of all the BeppoSAX GRBs for which there was detection of X–ray afterglow confirms these results. The post-break temporal indices derived from X-ray light curves, when plotted vs. their spectral photon indices, show that two GRBs 990510 and
010214) are consistent (basing on the relationships predicted by Sari et al. 1999) with the emission from a spreading jet, while the third (GRB 010222) cannot be distinguished by a an isotropic expansion. The fact that at least some GRBs seem to be collimated and the study of the distribution of the jet angles have a strong impact on the understanding of the energetics and the progenitors of these phenomena.

4. ABSORPTION AND EMISSION FEATURES

4.1. Transient absorption features in the early prompt emission

A transient absorption edge at \( \sim 3.8 \) keV in the first 13 s of the prompt X–ray emission of GRB 990705, associated with a variable column density \( N_H \), was discovered by Amati et al. (2000). This feature was interpreted as a redshifted K absorption edge of neutral Fe within a shell of material around the GRB site, photo-ionized by the GRB photons. The consequences of this interpretation were: estimate of the X–ray redshift (0.86±0.17) of the burst source, which was later confirmed by the optical redshift of the GRB host galaxy (LeFloch et al. 2002); an iron abundance relative to solar of \( \sim 75 \), typical of supernova explosions; a large mass of Fe, unless Fe is clumped and a clump is along the line of sight. An alternative interpretation, allowing to reduce the implied iron relative abundance and mass, is that the absorption line is due to resonant scattering of GRB photons off H–like Fe (transition 1s-2p, \( E_{\text{rest}} = 6.927 \) keV) (Lazzati et al. 2001). Variable intrinsic absorption was also found in the prompt emission of GRB 980329. The \( N_H \) time behavior of this source can be explained e.g. if the GRB event occurs in over-dense regions within molecular clouds (Bok globules). A very recent spectral analysis performed on the whole sample of GRBs simultaneously detected by the WFC and GRBM put in evidence the presence of a transient absorption feature in the X–ray spectrum of GRB 011211 and of a variable column density in the X–ray spectrum of GRB 000528 (papers in preparation).

4.2. X-ray lines in the afterglow spectra

BeppoSAX discovered X-ray emission features in the afterglow spectra of GRB 970508, first case ever (\( E_l =3.4\pm0.3 \) keV, Piro et
al. 1999), and GRB 000214 ($E_l = 4.7 \pm 0.2$ keV) (Antonelli et al. 2000). This lines were interpreted as redshifted neutral or ionized Fe lines. X-ray emission features were discovered also by other missions (ASCA, Chandra, XMM-Newton), e.g. in the afterglow spectra of GRB 970828, GRB 991216 and GRB 011211. Very important information on the circum–burst material and the nature of the progenitor were inferred from the observed X-ray lines: high density medium surrounding the GRB; overabundance of metals (up to $\sim 60$ times the solar abundance); high velocity outflow of the X-ray emitting plasma (up to $\sim 0.1c$). X-ray lines rule out the NS merger models and strongly point to an environment typical of a young supernova explosion.

5. OTHER TOPICS AND MORE RECENT RESULTS

5.1. The GRB/SN connection

One of the two candidate sources (S1, Pian et al. 2000) of the afterglow emission from GRB 980425 was coincident with SN1998bw in ESO 184-G82 ($z=0.0085$). Likely S2 was a source field and S1 was the afterglow source, but it showed a fading with unusual power-law index ($\delta = 0.2$). The unusual behavior was confirmed by the 6 month later BeppoSAX observation. The association of GRB 980425 with Type Ic SN 1998bw is now established. Likely the detected X-ray light curve is the superposition of two components: a) the GRB afterglow continuum emission; b) the SN emission from a peculiar type Ic SN. These results were the first observational support to the GRB/SN connection hypothesis, reinforced by subsequent indications of bumps in the light curves of some GRBs and very recently by the evidence of a connection between GRB 030329 and SN2003 (Stanek et al. 2003, Hjorth et al. 2003).

5.2. Dark and X–ray rich GRBs

About 50% of the BeppoSAX accurately localized and promptly followed-up GRBs do not have an optical counterpart, and are therefore classified as dark GRBs. Statistical studies show that the optical searches of these events have been carried out to magnitude limits fainter on average than the known sample of optical afterglow. Some of the dark GRBs could be intrinsically faint events, but this fraction
cannot be high because the majority of them show X-ray afterglow emission comparable to that observed in GRBs with optical afterglows. The possible explanations of dark GRBs include: very high $z$ (>5, with optical flux absorbed by intervening $\text{Ly}_\alpha$ forest clouds), very dense circum–burst material, obscuration by scattering with dust in their host galaxy. In addition to dark GRBs, there are 3 GRBs (981226, 990704 and 000615) belonging to the WFC/GRBM sample that show a ratio between the X-ray and gamma-ray fluence (or peak flux) much higher than the average. These X-ray rich GRBs are dark and their X–ray afterglows do not show peculiar characteristics, even if the decay index of GRB 990704 (Feroci et al. 2001) is quiet flat and the afterglow of GRB 981226 show indication of a rise during the beginning of the first BeppoSAX TOO (Frontera et al. 2000b). Among possible explanations of X-ray rich GRBs there are a low Lorentz factor, due e.g. to high barion loading of the fireball, or a very high $z$.

5.3. X–Ray Flashes

Among the FXTs detected by the BeppoSAX WFC there are $\sim$30 events showing the same properties of the X-ray counterparts of GRBs (light curve shape, duration, non thermal spectrum, isotropic distribution) but with no corresponding signal in the GRBM: new events called X-Ray Flashes (XRFs). In principle, XRFs could be a different class of sources, but there is evidence that they are a sub-class of GRBs: a) for most events the extrapolation of WFC spectra to high energies are consistent with GRBM upper limits; b) an off–line inspection of BATSE light curves in 25-100 keV shows that 9 out of 10 XRFs observable by this instrument were actually detected (Kippen et al. 2003); c) very recently, X-ray afterglow emission was detected for three XRFs (011030, 020427, 030723), see e.g. Amati et al. (in preparation). XRFs extend to very low energies the distribution of the spectral peak energies of GRBs, which is thus much broader than inferred from CGRO/BATSE (narrow distribution around 200 keV). Possible interpretations of the nature of these sources include: events with very low Lorentz factor (due e.g. to high barion loading of the fireball), events at very high $z$, collimated events seen very off-axis.
5.4. The $E^\text{rest}_p$ vs. $E_{\text{rad}}$ relationship

Basing on a sample of BeppoSAX GRBs with known redshift, Amati et al. (2002) found that the peak energy of the intrinsic EF(E) spectrum, $E^\text{rest}_p$, is correlated, with a power–law dependence with index $\sim 0.5$, to the isotropic equivalent radiated energy $E_{\text{rad}}$. Such dependence, confirmed by HETE–2 measurements and possibly holding also for XRFs (Lamb et al. 2004), could be explained if the radiation is due to synchrotron and it is isotropically emitted or it is emitted with the same beam angle. In any case, it can put strong constraint to the models for the prompt emission of GRBs (see e.g. Zhang & Meszaros 2002).

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