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# Gamma Ray Bursts in the Afterglow Era

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**Abstract** In this review paper I will summarize some of the relevant results obtained with the Italian satellite *BeppoSAX* on the prompt and afterglow emission of Gamma Ray Bursts. I will also discuss the most relevant open issues on these events.

**Key words:** gamma–rays: bursts – gamma–rays: observations

## 1 INTRODUCTION

After about 30 years of mystery, the distance scale issue of Gamma Ray Bursts (GRBs) has been definitely settled thanks to the X-ray astronomy mission *BeppoSAX*, an Italian satellite with Dutch participation (Boella et al. 1997a). *BeppoSAX* not only has permitted this issue to be resolved but has also provided most of the exciting results of the last seven years in GRB astronomy. The satellite (see Fig. 1), launched on 1996 April 30, was switched off on April 29, 2002, after 6 years of operational life. The high performance of *BeppoSAX* for GRB studies was due to a particularly well-matched configuration of its payload, with both wide field instruments (WFIs) and narrow field telescopes (NFTs). The WFIs comprised a $\gamma$–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 NFTs 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).

After the exciting results obtained on GRBs in 1997 (e.g., Costa et al. 1997, Frontera et al. 1998, Metzger et al. 1997, Piro et al. 1998, Feroci et al. 1998, Dal Fiume et al. 2000), many other GRB events were discovered with *BeppoSAX* during its operational life: 1082 events were detected with the GRBM (catalog in preparation), 669 of them (corresponding to 62%) were recognized by the on-board logic and 413 (corresponding to 38%) were identified with the ground software. Light curves with high time resolution (up to 0.5 ms) are available only for the GRBs identified by the on-board logic, while for the other ones, only 1 s ratemeters are available. Of the 1082 events, 168 (corresponding to $\sim 16\%$) are short (<2 s) GRBs, 141 of which recognized by the on-board logic. The most outstanding results were obtained from the 51 GRBs which were simultaneously detected with the GRBM and WFCs, 37 of which were followed-up with the *BeppoSAX* NFTs. Gamma-ray fluence of these GRBs ranges from $1.9\times10^{-4}$ erg cm$^{-2}$ down to $2.5\times10^{-7}$ erg cm$^{-2}$, while their duration is longer than 2 s ('long

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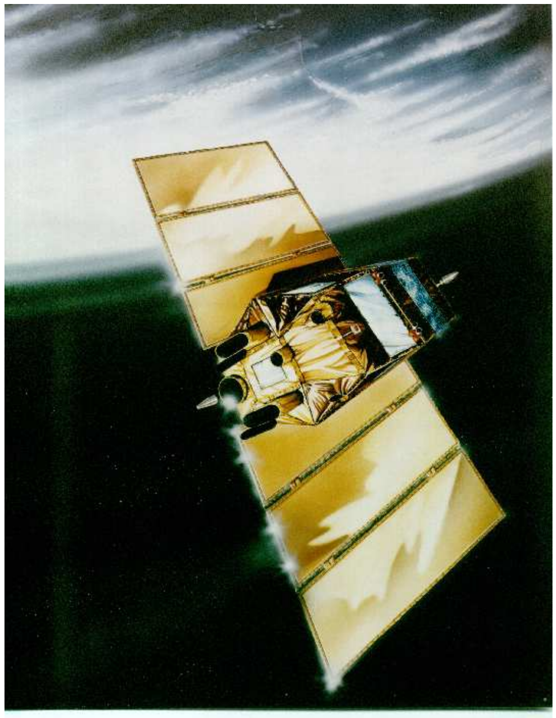

**Fig. 1** Artistic view of the *BeppoSAX* satellite.

GRBs'). X-ray afterglows were discovered in $\sim$ 90% of the followed-on GRBs. However only $\sim$ 50% of the followed-up GRBs are detected in the optical band and $\sim$ 40% in the radio band. This lower rates raise the question about the origin of the so called "dark" GRBs (i.e., GRBs with no optical counterparts). Likely some of them have origin in stellar formation regions with high mass densities, which likely absorb the ultraviolet radiation (in the rest frame of the GRB source). However, many of the dark GRBs could have origin in galaxies at very high redshifts (>5). In these cases the darkness is due to the absorption of the optical radiation by the intergalactic hydrogen.

## 2 SOME HIGHLIGHT RESULTS

I will summarize here some of the most relevant results on GRBs obtained with *BeppoSAX*. They concern both the prompt GRB phenomenon, the afterglow emission and the GRB environment.

### 2.1 Prompt emission spectra

Thanks to the broad energy band (2–700 keV) covered by WFCs plus GRBM, *BeppoSAX* has allowed un unbiased determination of the prompt emission spectra. We found (Amati et al. 2001) that most of the time averaged spectra are well fit, down to 2 keV, with a smoothly broken power-law proposed by Band et al. (1993) . In the remaining cases a simple power-law fits the data. In many cases ($\sim 70\%$) an optically thin synchrotron shock model (OTSSM) (Tavani 1996) fits the data.

A more constraining test of the emission mechanism is the study of the spectral evolution of the GRB prompt emission. This study has been performed for almost all GRBs detected with the *BeppoSAX* GRBM and WFCs. Results of this analysis can be found in Frontera et al. (2000) for a sample of GRBs occurred until 25 April 1998, and in Frontera et al. (2003c) for the entire population of GRBs detected with both GRBM and WFCs. This investigation shows that there is a general evolution of the spectra, from hard to soft, except for the most intense events, whose hardness either mimics the GRB time profile (e.g., GRB 990123) or does not evolve with time (e.g., GRB 011121, Frontera et al. 2005). An outstanding example of the hard-to-soft spectral evolution is given in Fig. 2, which shows the $EF(E)$ spectra of GRB 970111 in the 10 contiguous time intervals (from A to J) in which we subdivided the GRB time profile. As it can be seen, the fit with an OTSSM is acceptable for the almost the entire duration, except at early times. This property has been found in several GRBs and shows that at early times some other emission mechanism (likely Inverse Compton, as discussed by Frontera et al. 2000) is at work.

### 2.2 Afterglow spectra

In general, the late afterglow spectra, at least in the time interval during which the X-ray observations are possible, are consistent with a power law ($I(E) \propto E^{-\Gamma}$) with a photon index $\Gamma$ distributed according to a Gaussian function with mean value $\Gamma_{\rm m} = 1.93$ and standard deviation $\sigma = 0.35$ (Frontera 2003a). The emission mechanism is likely synchrotron radiation at least in some cases (e.g., GRB 970508, see Galama et al. 1998), but in other cases a synchrotron self Compton mechanism appears to be at work (e.g., GRB 000926, see Fig. 3). In this mechanism X-ray photons are produced by scattering of low energy photons off relativistic electrons, which however produce the low energy photons for synchrotron. This mechanism implies a medium denser than a typical interstellar medium in the X-ray production region. In the case of GRB 000926, the inferred mass density is about 30 cm$^{-3}$. As can be seen from the above figure, multiwavelength spectra, from the radio to X-rays, are crucial to establish the emission mechanisms at work.

Recently also thermal models have been found to better fit the X-ray afterglow spectra of a few GRBs observed with the *XMM–Newton* and *Chandra* X-ray satellites: GRB 001025A (Watson et al. 2002), GRB 011211 (Reeves et al. 2002, Reeves et al. 2003), and GRB 020813 (Butler et al. 2003). In these cases an emitting plasma in collisional ionization equilibrium gives the best description of the data.

### 2.3 Fading law of the afterglow emission and its geometry

In general, in the time intervals in which the X-ray observations have been possible, we find a consistency of the fading law of the X-ray afterglow emission with a single power–law ($F(t) \propto t^{-\delta}$), with distribution of the power-law index $\delta$ consistent with a Gaussian with centroid $\delta_{\rm m} = 1.33$ and standard deviation $\sigma = 0.33$ (Frontera 2003a).

However, specially in the optical band, breaks in the afterglow light curves of several GRBs have been observed (Frail et al. 2001). These breaks, in some cases, are also visible in the X-ray data, if the tail of the prompt X-ray emission is assumed to already be X-ray afterglow emission (e.g., GRB 010222, Fig. 4). In fact this assumption has been demonstrated to be true by Frontera et al. (2000), who found a correlation between X-ray fluence of the tail of the prompt emission and that of the late afterglow. The fading breaks and their time of occurrence, within the statistical uncertainties, appear to be independent of the photon energies.

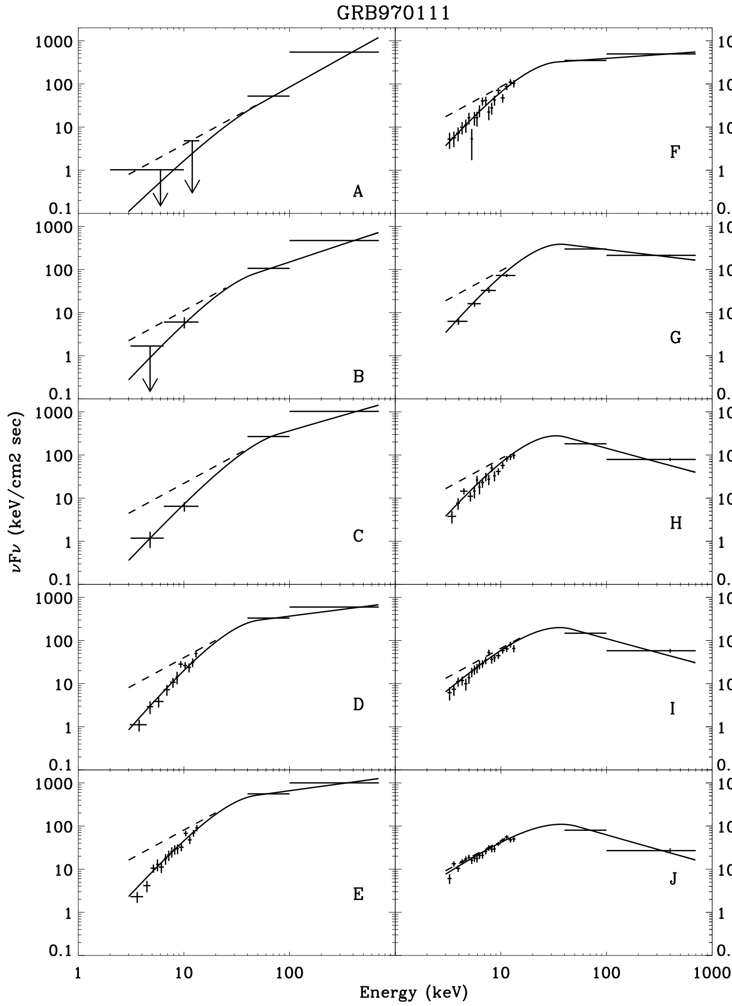


**Fig. 2** $EF(E)$ spectrum of the GRB 970111 prompt emission in the 10 contiguous time intervals (from A to J) in which the GRB time profile was subdivided. The GRB time duration in gamma–rays is 47 s. The time intervals have durations of 3 s for A, B, C, E, and G intervals, 4 s for H and I, 5 s for F, 6 s for D, and 13 s for the last (J). The dashed line shows the maximum spectral slope which can be expected, below the energy peak, in the case of the OTSSM (see text). The continuous line shows the best fit with a Band function. Reprinted from Frontera et al. (2000).

The interpretation of these achromatic breaks has been discussed by various authors. In the framework of the fireball model, a break is expected to occur if the relativistically expanding material is concentrated within a cone with angular width $\theta_c$. As long as the Lorentz factor $\gamma$ of the ouflowing material is larger than $1/\theta_c$, due to relativistic beaming, the radiation is emitted within an angle $\theta_{\rm b} = 1/\gamma$ from the cone axis, with $\theta_{\rm b} < \theta_c$. When $\gamma$ drops below $1/\theta_c$, the observer begins to see the edge of the cone and then the effect of the collimated outflow: a light curve steepening. At the same time, the jet begins to expand sideways, the ejecta encounter

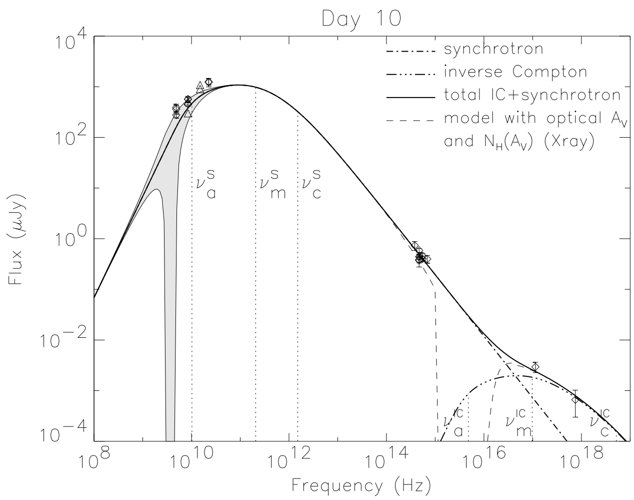


**Fig. 3** Afterglow spectrum of GRB 000926. The fit with synchrotron plus Inverse Compton model is shown. Reprinted from Harrison et al. (2001).

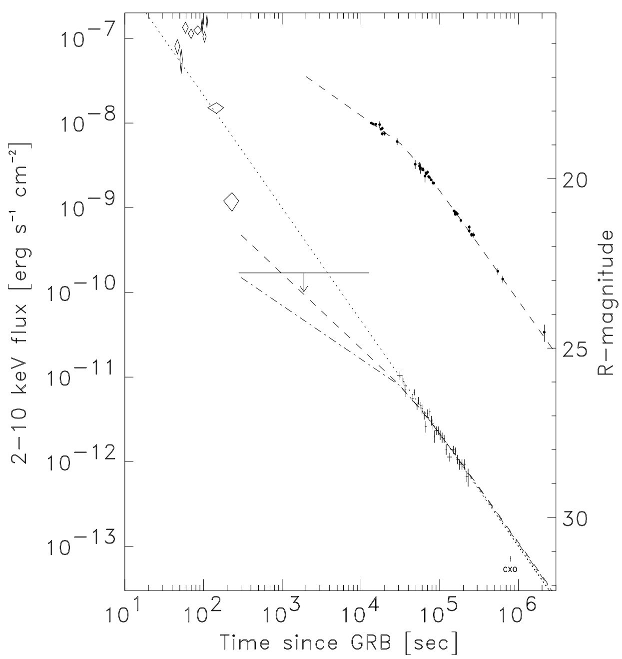


**Fig. 4** X-ray light curve of the GRB 010222 afterglow, compared with that observed in the optical band. Diamonds and upper limit denote the fluxes of the prompt X-ray emission. Reprinted from in't Zand et al. (2001).

more surrounding material and then decelerate faster than in the spherical case. That increases even more the rate of decrease of the emitted radiation. This model has been discussed and detailed in various external conditions by several authors (e.g., Rhoads 1997, Sari et al. 1999 ).

Assuming a jet geometry, the break time distribution corresponds to the distribution in the jet opening angles. This would help in reducing the dramatic GRB energetic problem. Indeed, while the released gamma–ray energy $E_{\rm iso}(\gamma)$ obtained assuming isotropy, ranges from $5 \times 10^{51}$ to $3 \times 10^{54}$ erg (e.g., Amati et al. 2002 ), the released energy $E_\gamma$ in the case of a jet with opening angle $\theta_c$ would be a factor $2/\theta_c^2$ lower. Assuming a jet geometry and a uniform distribution of the energy within the jet, from the available data, Frail et al. (2001) found that the distribution of the released energy per GRB is centered at $5 \times 10^{50}$ erg, a value almost compatible with the energy released in a supernova explosion.

From the time behaviour of the X-ray afterglow light curves, we can infer only a lower limit to the jet angle. This is a few degrees, which is consistent with the lowest opening angles derived by Frail et al. (2001).

### 2.4 The $E_{\rm p}$ vs. $E_{\rm rad}$ relationship

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 between intrinsic peak energy $E_{\rm p}$ of the $\nu F(\nu)$ spectra and isotropic electromagnetic energy $E_{\rm rad}$ released in the GRB event:

$$E_{\rm p} \propto E_{\rm rad}^{0.52\pm0.06} \,. \tag{1}$$

The relation is now confirmed (Amati 2004) by more *BeppoSAX* and HETE-2 results. It puts strong constraints to the GRB emission models: independently of the radiation pattern geometry, the $E_{\rm p}$ vs. $E_{\rm rad}$ relation has to be satisfied. The optically thin synchrotron shock model expects a similar relation, but only with too simplified assumptions, like the same duration of all GRBs (Lloyd et al. 2000). A discussion on the possible interpretations of the above relation is given by Zhang and Mészáros (2002) within the internal and external shock scenario.

### 2.5 The GRB environment

Two main probes of the GRB environment are offered by the X-ray data: detection of low energy cutoffs in the GRB continuum spectra of the prompt and/or afterglow emission, detection of emission and/or absorption spectral features. Both these probes not only give information on the circumburst environment, but are an important tool to unveil the nature of the GRB progenitors. Indeed we expect to find a dense, star-forming medium in the case of collapse of a massive star (hypernova model, Woosley 1993), and a low density interstellar medium in the case of coalescence of a binary system such as two neutron stars or a neutron star and a black hole (Eichler et al. 1989, Narayan et al. 1992). I summarize here the status of the observations.

#### *2.5.1 Absorption cutoff in the continuum spectra*

Significantly high hydrogen column densities $N_{\rm H}$ with starting values up to $\sim 10^{23}$ cm$^{-2}$ and decreasing behaviour with time, have been discovered in the prompt emission of two GRBs: GRB 980329 (Frontera et al. 2000) and GRB 000508 (Frontera et al. 2004a). Variable $N_{\rm H}$ has also been found from GRB 010214 (Guidorzi et al. 2003) and in the case of GRB 990705 (Amati et al. 2000), from which also a transient absorption feature has been discovered (see below). The time behaviour of $N_{\rm H}$ in the case of GRB 030329 has been investigated by Lazzati

**Table 1** Emission lines detected in the GRB X-ray afterglows

| GRB | Measured line energies (keV) | Identification | Rest frame energies[b] (keV) | Ref. |
|---|---|---|---|---|
| 970508 | $3.4 \pm 0.3$ | Fe I –XX K$\alpha$ | $6.24 \pm 0.55$ | Piro et al. 1999 |
| 970828 | $5.04^{+0.23}_{-0.31}$ | Fe XXVI re[a] | $9.86^{+0.45}_{-0.41}$ | Yoshida et al. 1999 |
| 991216 | $3.49 \pm 0.06$ | Fe XXVI | $3.49 \pm 0.06$ | Piro et al. 2000 |
| | $4.4 \pm 0.5$ | Fe XXVI re[a] | $8.9 \pm 1.0$ | |
| 000214 | $4.7 \pm 0.2$ | Fe I–XXVI | 6.4–6.97 | Antonelli et al. 2000 |
| 001025A | $0.80^{+0.04}_{-0.05}$ | Mg XII | [1.46] | Watson et al. 2002 |
| | $1.16^{+0.05}_{-0.05}$ | Si XIV | [2.01] | |
| | $1.64^{+0.07}_{-0.07}$ | S XVI | [2.62] | |
| | $2.2^{+0.1}_{-0.1}$ | Ar XVIII | [3.32] | |
| | $4.7^{+0.8}_{-0.4}$ | Ni XXVIII | [8.10] | |
| 011211 | $0.44 \pm 0.04$ | Mg xi K$\alpha$ | $1.38 \pm 0.10$ | Reeves et al. 2003 |
| | $0.71 \pm 0.02$ | Si xiv K$\alpha$ | $2.22 \pm 0.06$ | |
| | $0.88 \pm 0.02$ | S xvi K$\alpha$ | $2.78 \pm 0.05$ | |
| | $1.22 \pm 0.03$ | Ar xviii K$\alpha$ | $3.83 \pm 0.08$ | |
| | $1.46 \pm 0.07$ | Ca xx K$\alpha$ | $4.6 \pm 0.2$ | |
| 020813 | $1.31 \pm 0.01$ | S XV | [2.45] | Butler et al. 2003 |
| 030227 | $0.62^{+0.03}_{-0.02}$ | Mg XII | [1.46] | Watson et al. 2003 |
| | $0.86^{+0.02}_{-0.03}$ | Si XIV | [1.99] | |
| | $1.11^{+0.02}_{-0.02}$ | S XVI | [2.60] | |
| | $1.35^{+0.04}_{-0.03}$ | Ar XVIII | [3.30] | |
| | $1.66^{+0.04}_{-0.04}$ | Ca XX | [4.07] | |

[a] Recombination edge.
[b] Values in [ ] are the fluorescence energies in the rest frame of the element.

& Perna (2002). According to their model, the $N_{\rm H}$ time profile can be explained if the GRB occurs in overdense regions similar to the cocoon of star formation within molecular clouds.

Also in the case of the X-ray afterglow emission, evidence of a hydrogen column density higher than that Galactic one, has been found from GRB 980329 (in't Zand et al. 1998), GRB 980707 (Vreeswijk et al. 1999), and GRB 011222 (in't Zand et al. 2001). For GRB 980329, the result found by in't Zand et al. (1998) is however not confirmed by De Pasquale et al. (2003).

### *2.5.2 X-ray emission lines*

Evidence of X-ray emission features has been found in the afterglow spectra of 8 GRBs (see Table 2.5.1). The lines found with *BeppoSAX* concern 2 GRBs (970508, 000214), those found with *Chandra* concern GRB 991216 and GRB 020813, while those found with *XMM–Newton* concern GRB 001025A, GRB 011211 and GRB 030227. A line from GRB 970828 was detected with the Japanese X-ray satellite *ASCA*. It is important to point out that the significance of all these lines is only at the level of $3\sigma$ or a bit more, that their significance has been questioned (Sako et al. 2004) and that in half of the cases the lines are visible only for a limited time interval. In particular the feature at 3.5 keV from GRB 970508 is visible only during the first part (10 hrs) of the follow–up observation of this burst (Piro et al. 1998), that from GRB 970828 is observed for $\sim$ 5.5 hrs during a flare activity of the GRB afterglow (Yoshida et al. 1999), those from GRB 011211 are visible only during the first 5000 s of the GRB afterglow observation which started 11 hrs after the main event (Reeves et al. 2003), while the lines from GRB 030227 are visible only since 20 hrs after the GRB (Watson et al. 2003).

Taking into account that four of the GRBs with emission lines have host galaxies with known redshifts (0.835 for GRB 970508, 0.9578 for GRB 970828, 1.02 for GRB 991216 and 2.14 for GRB 011211), the line features of the first 3 events, as shown in Table 2.5.1, are consistent with Fe fluorescence lines or recombination edges, while those from GRB 011211 are consistent with blue-shifted (by $\sim 0.1c$) fluorescence lines of light metals. Similar blue-shifts have also been inferred for the outflowing material associated with GRB 020813 (Butler et al. 2003) and GRB 001025A (Watson et al. 2002). Also in the case of GRB 991216, outflowing velocities of $\sim 0.1c$ have been inferred from the Fe line width (Piro et al. 2000). These velocities are those expected for the material ejected by a supernova exploded a few months before the GRB event. Independently of the specific identification, all the detected lines point to the presence of ionized metals at the time of the afterglow measurements, with the ionizing radiation likely being due to the GRB power output. The amount of Iron needed to justify the observed lines mainly depends on the density of the scattering cloud and on its distance from the GRB site. It could range from a sizable fraction of a solar mass according to Vietri et al. (2001) to a much smaller amount ($\sim 10^{-5}$ $M_\odot$) in the scenario proposed by Mèszàros and Rees (2001). The relative metal abundance (with respect to the solar) inferred for the lines is very large: about 10 in the case of the light metals (e.g. Butler et al. 2003), even higher than 60 in the case of Iron (e.g., Piro et al. 2000). Thus X-ray lines rule out the NS merger models and strongly point to an environment typical of a young supernova explosion.

### *2.5.3 Transient absorption features in the prompt emission*

Evidence of transient absorption features in the prompt emission has been found for two events: GRB 990705 (Amati et al. 2000) and GRB 011211 (Frontera et al. 2004b). In the case of GRB 990705, an absorption line feature at 3.8 keV is apparent during the rise time of the burst, but it fades thereafter (see Frontera et al. 2001). Also in the case of GRB 011211 an absorption feature at 6.9 keV is visible during the rise of the burst, but not later.

The absorption feature from GRB 990705, interpreted by Amati et al. (2000) as a cosmologically redshifted K edge due to neutral Fe around the GRB location implies a GRB redshift of $0.86 \pm 0.17$. This value was later confirmed by the optical redshift ($z_{\rm opt} = 0.84$) of the associated host galaxy (Le Floc'h et al. 2002). With this assumption, the Iron relative abundance with respect to the solar one is $\mathrm{Fe/Fe}_\odot = 75 \pm 19$, which is typical of a supernova explosion environment. An alternative explanation of the feature was given by Lazzati et al. (2001), who assume that the feature is an absorption line due to resonant scattering of GRB photons off H-like Iron (transition 1s-2p, $E_{\rm rest} = 6.927$ keV). Also in this case the redshift derived is still consistent with that of the host galaxy and the line width is interpreted as due to the outflow velocity dispersion (up to $\sim 0.1c$) of the material. The Fe relative abundance inferred is of $\sim 10$ with respect to the solar one. Thus, in both scenarios, the observed feature points to the presence of an iron-rich environment.

In the case of the transient line feature from GRB 011211, the scenario is much more complex. Given that the redshift of the GRB optical counterpart is known ($z = 2.14$), even if the line feature is interpreted as due to resonant scattering of GRB photons off H–like Ni XXVIII (rest frame energy of 8.1 keV), the measured line energy implies a very high blue-shift (by $0.75c$) of the absorbing material. A possible intepretation of the feature is discussed by Frontera et al. (2004b).

What can be inferred from the observed X-ray lines? They imply a high density medium surrounding the GRB, an overabundance of metals, a high velocity outflow of the X-ray absorption plasma (up to $0.7c$). In order to produce the observed synthesized nuclei, likely the SN explodes first, with variable time delay between SN and GRB, depending on the specific event.

### 2.6 GRB-SN connection

The conclusions of the last two sections strongly point to a connection between supernovae and GRBs. The most direct evidence of this connection has been recently obtained in the case of GRB 030329/SN 2003dh (Stanek et al. 2003, Hjorth et al. 2003). Nine days after the burst the optical afterglow spectrum of GRB 030329 appears to be the superposition of a power-law continuum plus a spectrum consistent with that observed from Type Ic supernova SN1998bw, which was associated with GRB 980425 (Patat et al. 2001) on the basis of a positional and temporal coincidence. Thus the GRB 030329/SN 2003dh connection has shed light also on the GRB 980425/SN 1998bw connection issue (see, e.g., Pian et al. 2000 and references therein). On the basis of the results on GRB 030329, the connection of GRB 980425 with SN 1998bw appears strongly enforced. Also the recent *XMM–Newton* observation of SN 1998bw enforces such connection. Indeed, combining the *XMM–Newton* data with the *BeppoSAX* data, the X-ray light curve of GRB 980425/SN 1998bw appears to be the superposition of two components, the GRB power–law fading emission plus the emission from a peculiar type Ic supernova (Pian et al. 2004).

## 3 CONCLUSIONS

In spite of the big step forward accomplished in the last 7 years after the discovery of the first X-ray afterglow, many questions about the GRB phenomenon are still open, which can only be answered with further X-ray observations. A thorough discussion of the open issues can be found elsewhere (Frontera 2003a). Many of these issues are expected to be settled in the coming years, mainly with the launch of the SWIFT satellite. But a relevant contribution is expected also to be given by INTEGRAL, AGILE, and GLAST satellites, and later by the LOBSTER experiment aboard the International Space Station.

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