The key role of *BeppoSAX* in the GRB history

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Abstract

Twenty years have already been elapsed from the *BeppoSAX* discovery of the first afterglow of a Gamma-Ray Burst (GRB) in February 28, 1997. Thanks to this discovery, it was possible to unveil the 30 year mystery about GRB origin: GRBs are huge explosions in galaxies at cosmological distances. Starting from the first GRB detection with Vela satellites, I will review the main results obtained before *BeppoSAX*, the story of the *BeppoSAX* discovery of the GRB afterglow with the consequent cosmological distance determination, the main *BeppoSAX* results, and those obtained after the *BeppoSAX* era until nowadays with the still open problems and prospects.

Keyword Gamma rays: bursts

1 Introduction

Gamma-Ray Bursts (GRBs) are among the most intriguing phenomena in the Universe. As it is well known, they are sudden bright flashes of celestial gamma-ray radiation, with variable duration from milliseconds to several hundreds of seconds. In rare cases, their time duration extends up to thousands of seconds. Most of their emission extends from several keV to tens of MeV, but also GeV emission has been discovered in several of them. With the current instrumentation, their observed occurrence rate is 2–3 per day over the entire sky. Their arrival time is unpredictable as it is unpredictable their arrival direction. When they are on, their brightness overcomes any other celestial gamma-ray source.

In this paper, I will briefly review the main steps of the research on GRBs, focusing mainly on the role played by *BeppoSAX* in the understanding of their nature. Extended reviews on the *BeppoSAX* role can be found elsewhere (Costa and Frontera 2011; Frontera 2015).

2 GRB discovery and main efforts before *BeppoSAX*

GRBs were discovered by chance in 1967 with the spy American Vela satellites, devoted to monitor the compliance of the Soviet Union and of other nuclear-capable states with the 1963 “Partial Test Ban Treaty”. The American militaries kept this discovery in their drawers until 1973 when it was published (Klebesadel et al. 1973). The first questions were: which are their progenitors? At which distance are their sites? Which is the power involved?

The solution of these issues implied complex observational problems, like the accurate localization of the events, to test their positional coincidence with the known sources. This was a tough task in the gamma-ray energy band. A possible solution was the search of GRB counterparts at longer wavelengths.

Many satellite missions in the 70s and 80s (e.g., the Russian satellites Venera 11, 12, 13, and 14, Prognoz 6, Prognoz 9, Konus, Granat, the American Pioneer Venus Orbiter and the Solar Maximum Mission) included instrumentation devoted to the detection of GRBs (see Refs. Niel et al. 1976; Barat et al. 1981). The most relevant results about the GRB origin were obtained with the Venera satellites, that found an evidence of an isotropical distribution of the GRB positions.
in the sky (Mazets et al. 1981; Mazets and Golenetskii 1988) as shown in the left panel of Fig. 1.

The isotropy of the GRB distribution in the sky was later definitely confirmed with the BATSE experiment aboard the CGRO American satellite (see right panel of Fig. 1).

In spite of this result, the sites of the GRBs were still matter of debate, as confirmed by the meeting that took place at the Baird Auditorium of the Smithsonian museum of Natural History in Washington DC (USA) on April 22, 1995, where there were two schools of thought: one led by Bodhan Paczynski and the other led by Don Lamb. The viewpoint of Paczynski was the following (Paczynski 1995): “At this time, the cosmological distance scale is strongly favored over the Galactic one, but is not proven. A definite proof (or dis-proof) could be provided with the results of a search for very weak bursts in the Andromeda galaxy (M31) with an instrument ten times more sensitive than BATSE. If the bursters are, indeed, at cosmological distances, then they are the most luminous sources of electromagnetic radiation known in the Universe. At this time, we have no clue as to their nature, even though well over a hundred suggestions were published in the scientific journals.”

Instead, the Don Lamb point of view was very different (Lamb 1995): “We do not know the distance scale to gamma-ray bursts. Here, I discuss several observational results and theoretical calculations which provide evidence about the distance scale. First, I describe the recent discovery that many neutron stars have high enough velocities to escape from the Milky Way. These high-velocity neutron stars form a distant, previously unknown Galactic corona. This distant corona is isotropic when viewed from Earth, and consequently, the population of neutron stars in it can easily explain the angular and brightness distributions of the BATSE bursts.”

Thus, in 1995, the distance scale of the GRB sites was still a mystery, with the following premonitory conclusion of the debate by Martin Rees (1995): “I’m enough an optimist to believe that it will only be a few years before we know where (and perhaps even what) the gamma-ray bursts are.”

3 The BeppoSAX revolution

The great step forward was done with the Italian BeppoSAX satellite with Dutch participation (Boella et al. 1997): in 6 months from the beginning of its operational life (September 1996), BeppoSAX allowed to establish that GRBs are huge explosive events in galaxies at cosmological distances.

Why BeppoSAX? Actually the initial main goals of BeppoSAX did not include GRBs. Only in 1984, 2 years after the BeppoSAX approval, during the phase A study, as Principal Investigator of the high-energy instrument PDS (Frontera et al. 1997), I proposed to use the four CsI(Na) scintillator detectors, foreseen as active anti-coincidence shields of the four phoswich detection units, as Gamma-Ray Burst Monitor (GRBM) (Internal Report of CNR-TESRE, No. 99, 1984). The fact that the axis of two of these shields was parallel to that of the two Wide Field Cameras (WFCs) (Jager et al. 1997) was, indeed, very suggestive. The expectation was that about 3 GRBs per year (see BeppoSAX Observers’ Handbook, Issue 1.0, 1995) could enter into the common field of view of WFC and GRBM, and thus, they could be identified

Fig. 1 Left: distribution of GRBs in the sky in Galactic coordinates as obtained with the Konus experiment aboard the Venera 11–14 missions. Reprinted from Mazets and Golenetskii (1988). Right: sky distribution in Galactic coordinates of 2704 GRBs detected with BATSE. Reprinted from Paciesas et al. (1999)
as true events by GRBM and accurately positioned (within 3–5 arcmin) by WFCs. Indeed, transient events detected with WFCs could be originated by other phenomena (e.g., star flaring and X-ray bursts), while their detection in the GRBM energy band was an almost certain signature of GRBs. Obviously, it was required to develop, among other things, an in-flight trigger system and a proper electronic chain. The GRBM proposal had also an international echo (Hurley 1986).

In 1990, a less expensive formulation of the GRBM proposal was approved by the Italian Space Agency (ASI) and identified as a further instrument of BeppoSAX. The final BeppoSAX configuration is shown in Fig. 2 and several descriptions of GRBM were reported (Pamini et al. 1990; Frontera et al. 1997; Costa et al. 1998).

The different orientations of the GRBM units implied a different exposed area to the same GRB. By means of a Monte Carlo code, we found that this feature could be exploited to obtain a crude GRB direction as later demonstrated with the catalog of GRBs detected with GRBM (Frontera et al. 2009). In any case, the localization accuracy was sufficient for deriving photon spectra (Pamini et al. 1990). In addition, given that the GRBM units were located in the center of the satellite, the implementation of the GRBM required a very detailed description of the whole BeppoSAX satellite based on both simulations and calibrations. The simulations were done by developing a very detailed Monte Carlo code (Rapisarda et al. 1997), while the last calibration campaign was performed at ESTEC (Noordwijk, NL) after the integration of the instrument in the satellite (Amati et al. 1997).

Before the BeppoSAX launch, in response to the first international call for the observation of celestial X-ray sources with BeppoSAX, the PDS/GRBM team submitted a proposal to get WFC data in the case of GRBs identified with the GRBM. A similar proposal was submitted by the BATSE team for GRBs identified with the BATSE experiment. Both proposals were approved.

BeppoSAX was launched on 30 April 1996 from Cape Canaveral with an Atlas-Centaur rocket. After a commissioning phase up to June 1996, and a 3 month duration Science Verification Phase (SVP) (July–September 1996), the satellite entered in its operational phase in October 1996. The first GRB in the field of view of WFC was detected during SVP, on July 20, 1996, but it could be accurately localized only 20 days after the event, and, about 1 month from the burst, the BeppoSAX Narrow Field Instruments (NFIs) were pointed to the GRB direction: no X-ray counterpart was found (Piro et al. 1998a).

From this experience, it was clear that a possible residual X-ray radiation, if any, could have been found only in the case it was possible to promptly point the NFIs along the direction of well-localized events. To this end, by analyzing the needed operations and short-cutting all the interfaces, we set up a procedure that would minimize the time needed to take a decision about the real detection of a GRB by GRBM, its localization with WFCs, and, in the case a source image was found, request of a BeppoSAX Target of Opportunity (TOO) to re-point the NFIs toward the localized GRB.

The first time that the above procedure was entirely applied was on January 11, 1997. A bright burst, GRB 970111, was detected by the GRBM and found in the FOV of one of the two WFCs (see left panel of Fig. 3). The earliest position of the event was determined with 10 arcmin error radius (see right panel of Fig. 3). This position was adopted for the X-ray follow-up after 16 h. In this WFC error box, a unusual radio source (VLA1528.7 + 1945), variable on time scales of days, was observed by Dale Frail with the Very Large Array in Socorro (NM, USA). A similar variability was never observed before in a radio source. The source was thus considered as the possible radio counterpart of the GRB event. A paper was rapidly submitted to Nature. However, after about 20 days, a revised WFC error box was produced with centroid about 4 arcmin far from the previous one and with only 3 arcmin error radius (see right panel of Fig. 3). This new error box excluded the radio source and the paper was withdrawn. The paper was later published in ApJ (Frail et al. 1997a). One of the two bright X-ray sources found with the BeppoSAX NFI was in the same position of the radio source and identified with a non peculiar ROSAT source (Feroci et al. 1998).

Fig. 2 The BeppoSAX payload, with the GRBM shown in red. Note that two opposite GRBM units are oriented as the two WFCs (color figure online)
The experience acquired with GRB 970111 is an important warning for the today multi-messenger astronomy. It shows the need of a very accurate positional coincidence, in addition to the temporal coincidence, to have the maximum probability of associating an electromagnetic counterpart to a gravitational wave (GW) or neutrino event, or an optical/IR counterpart to a GRB event. A mission like THESEUS (Amati et al. 2018), now accepted by ESA for a phase A study, thanks to its accurate position capability in X-rays and to its prompt follow-up with the IR telescope onboard, is the best solution to optimize the likelihood of the association of a GRB to a GW event and/or an optical/IR counterpart to a GRB.

The solution of the mystery about the GRB sites started with the discovery of the X-ray and optical counterpart of the GRB event occurred on 28 February 1997 (GRB 970228). It consisted of one bright peak, trailed by a train of three more peaks of decreasing intensity (see left panel of Fig. 4). The NFI follow-up was performed in 8 h after the burst time and lasted about 9 h. In the MECS FOV, a previously unknown source (SAX J0501.7 + 1146) was found with a flux of \((2.8 \pm 0.4) \times 10^{-12}\) erg/cm\(^2\)/s in 2–10 keV. The field of the refined WFC error box and in the intersection of the WFC error box with the IPN annulus, no source was observed. Adapted from the figure of the paper later published in ApJ (Frail et al. 1997b).

Fig. 3 Left: light curve of GRB 970111. Reprinted from Feroci et al. (1998). Right: earliest and latest WFC error boxes, along with the annulus obtained with the Interplanetary Network. As can be seen, in the refined WFC error box and in the intersection of the WFC error box with the IPN annulus, no source was observed. Adapted from the figure of the paper later published in ApJ (Frail et al. 1997b).

Fig. 4 Left light curve of GRB 970228. Right: X-ray images of GRB 970228 detected with MECS at two different epochs. The image on the left includes data from 8 to 16 h after the burst. The image on the right includes 9 h of data starting 3 days and half after the burst. The source was found to be faded by a factor 20. Reprinted from Costa et al. (1997b)
was pointed again 3 days after and the source had faded by a factor 20 (see right panel of Fig. 4).

By subdividing the first observation into three subsets, a light curve was produced. It resulted that the source was decaying according to a power law: \( N(t) \propto t^{-1.33} \). Quite surprisingly, the flux in the same band detected by the WFC was consistent with the same power-law index, showing that the fading X-ray source was the delayed emission (afterglow) of the GRB (Costa et al. 1997a).

Meanwhile, the coordinates of WFC and those improved of NFIs were distributed by the GRBM team directly and through IAU circulars (see Costa et al. 1997a). Various observers performed optical observations. The group led by Jan Van Paradijs was the first to perform two observations of the same field with the same filter. From the comparison of two images taken with the William Herschel Telescope on February 28 and other two taken with the same telescope and with the Isaac Newton Telescope on March 8, it resulted that a previously unknown optical point-like source was fading (see Fig. 5) from \( V = 21.3 \) to \( V > 23.6 \) (van Paradijs et al. 1997).

To confirm the association of the X-ray afterglow source with the GRB event, we proposed a pointing of the event with the High-Resolution Imager (HRI) aboard the X-ray satellite \textit{ROSAT}. This instrument, in the 0.1–2.4 keV pass-band, could provide the best position and the smallest error box of the event direction, thanks to its high angular resolution (10 arcsec radius) and sensitivity. The observation was performed on March 10 and lasted 3 days. HRI detected eight sources in its 20 arcmin FOV, but only one (RXJ050146 + 1146.9) was within the error box of the afterglow source found with \textit{BeppoSAX} (Frontera et al. 1998b) and found (see right panel of Fig. 6) coincident, within 2 arcsec, with the discovered optical transient. The intensity of the \textit{ROSAT} source was found to be fully consistent (see left panel of Fig. 6) with the power law derived from the \textit{BeppoSAX} LECS afterglow spectrum estimated in the 0.1–2.4 keV band (Frontera et al. 1998b). With these results, the association of the \textit{ROSAT} and \textit{BeppoSAX} sources with the 970228 afterglow became conclusive.

In addition, the spectral analysis of the event and its afterglow was performed (Frontera et al. 1998a). While the spectrum of the prompt event was consistent with a Band function and showed, within each peak, the already known hard-to-soft evolution, the spectrum of the afterglow was a power law, \( N(E) \propto E^{-2.04} \), constant with time.

In conclusion, both temporal and spectral trends of the afterglow advocated in favor of a nonthermal process and would be, in the following, the basic building blocks for all the GRB theories.

An observation of the Hubble Space Telescope, performed 39 days after the burst, showed that the point-like source had faded down to \( V \) magnitude 26.4 and was embedded in a faint nebular source (see right panel of Fig. 5) with \( V \approx 25 \) extended \( \sim 1 \) arcsec, likely but yet not necessarily, a host galaxy (Sahu et al. 1997).

The further turning point of the \textit{BeppoSAX} discovery was on May 8, 1997, when the event GRB 970508 was identified by GRBM and localized with WFC (see left panel of Fig. 7). The X-ray follow-up with \textit{BeppoSAX} NFIs was the fastest up to then: 5.4 h after the burst. The X-ray afterglow was detected. The NFI position was soon distributed and an optical counterpart was detected. The new object, contrary to the GRB 970228 optical counterpart, had a flux that increased for around 2 days, arriving to \( R = 20.14 \) and then started to fade with the usual power law. On May 11, when

![Fig. 5](image-url)
the optical afterglow was still relatively bright, the CalTech/NRAO group observed it with the Keck Low-Resolution Imaging Spectrograph. Various absorption lines were identified: some at redshift \( z = 0.835 \) and some other at redshift \( z = 0.767 \) (Metzger et al. 1997). The first of these two \( z \) values was found, weeks later when the point–like object had almost completely faded, in the emission lines from the galaxy that had hosted the fading object. The mystery of the GRB sites was solved. Remote galaxies harbor GRBs.

The immediate consequence was to fix the energy scale. From the derived luminosity distance, we derived the energetics of GRB 970508: \( E_{\text{iso}} = (0.61 \pm 0.13) \times 10^{52} \) ergs, assuming isotropic emission.

GRB 970508 was also relevant for the discovery of the first radio afterglow with the VLA radio telescope (Frail et al. 1997). The radio emission showed the phenomenon known as scintillation that derives from the effects of interstellar clouds on sources of very small angular size. In GRB 970508, the scintillation disappeared after around 2 months. From the angular size and from the distance, Frail et al. (1997) derived the expansion velocity of the fireball that came out to be around \( 2c \), an apparent superluminal effect typical of sources expanding at relativistic velocity.

4 International resonance of the BeppoSAX discoveries

The resonance of the BeppoSAX discoveries in the scientific community was enormous. In the first 2 years (1997–1998), the number of papers citing BeppoSAX was equivalent to that citing HST (about 200/year). For 2 years, the GRB discoveries were classified by the Science journal among the top ten over the world and over all the science fields.

ESA modified the data flow of the INTEGRAL satellite to allow a prompt localization of GRBs with the on-ground analysis of the gamma-ray imager IBIS data. NASA issued an Announcement of Opportunity for a new medium-sized scientific satellite: many missions dedicated to GRBs were submitted and one (Swift, now Neil Gehrels Swift) selected. The Swift satellite has the same BeppoSAX configuration, but the GRB localization and X-ray telescope re-pointing are automatically performed in a very short time (\( \sim 100 \) s) (Gehrels et al. 2004).

The largest radio and optical telescopes devoted observing time to follow-up GRBs localized with BeppoSAX. Some of them modified their procedures or their equipment to make these observations faster.
Several optical or NIR telescopes were built with robotic pointing of the coordinates distributed by BeppoSAX through the already existing GCN network set up by NASA, which got an impressive boost by the BeppoSAX findings.

In addition, the Fermi satellite was designed taking into account the BeppoSAX payload configuration: a GBM instrument to identify GRBs, LAT telescope to localize them (Atwood et al. 2009; Meegan et al. 2009). A similar design was adopted for AGILE, with a gamma-ray imager sensitive in the range 30 MeV–50 GeV, and a hard X-ray imager (SuperAGILE) sensitive in the range 18–60 keV with a Field of View (FOV) of about 1 sr (Tavani et al. 2008).

5 Immediate consequences of the BeppoSAX discoveries on the GRB theoretical models

The cosmological distance scale of GRBs swept away all the Galactic models. The observed properties, like an energy release in gamma rays up to \( \sim 10^{54} \) erg (assuming isotropy) in a short time (tens of second), the nonthermal spectra, the short time variability (down to ms time scale), and the photon energies \( > 1 \) MeV, were generally interpreted as a result of the formation of a fireball in relativistic expansion (see Fig. 8). This model, already developed before the BeppoSAX discovery of the X–ray afterglow (e.g., Guilbert et al. 1983; Goodman 1986; Paczynski 1986), had an immediate success for its capability to explain the spectral and temporal GRB properties (e.g., Wijers et al. 1997; Sari et al. 1998), through the conversion of the fireball kinetic energy into electromagnetic radiation. This conversion was assumed to occur through shocks between contiguous shells within the fireball for the prompt emission, or with the external medium for the afterglow emission (see, e.g., Meszaros et al. 1994; Paczynski and Xu 1994).
In spite that the fireball model was considered the GRB standard model, some drawbacks were noticed. Among them, the small conversion efficiency of the internal shocks (e.g., Daigne and Mochkovitch 1998), while external shocks should be more efficient. This was found inconsistent with the observation results: more energy released during the prompt emission, at least on the basis of the afterglow measurements available up to 10 keV.

Concerning progenitors, several models were proposed. For short GRBs, the merging of a white dwarf-neutron star system, or that of a binary neutron star system or that of a neutron star-black hole system were considered the most likely mechanisms (Narayan et al. 1992). For long GRBs, instead, failed supernovae (Woosley 1993) or the collapse of a rapidly rotating star to a Kerr black hole (collapsar) (Paczynski 1998) with the formation of hypernovae, were the most favorite models. But also, other models were proposed, like the supranova model (Vietri and Stella 1998), the transition, by accretion, of a neutron star to a deconfined quark star (Berezhiani et al. 2003), and the ElectroMagnetic Black Hole (EMBH) model (Ruffini et al. 2001).

### 6 Some major further BeppoSAX discoveries on GRBs

Other relevant results were obtained with BeppoSAX. They include:

(a) the discovery of a transient absorption edge at 3.8 keV in the prompt emission of the BeppoSAX GRB 990705 (Amati et al. 2000). The feature was found to be consistent with a redshifted K-edge of an iron environment. The derived redshift ($z = 0.86$) was later found to be consistent with that measured from the GRB host galaxy (Le Floc’h et al. 2002).

(b) the discovery of a decreasing column density in the prompt emission from the BeppoSAX GRB 000528 (Frontera et al. 2004).

(c) Discovery of the GRB/Supernova connection. The location of the BeppoSAX GRB 980425 was found to be consistent with that of the type Ic supernova SN1998bw explosion (Galama et al. 1998). Beside the positional coincidence, the SN explosion was simultaneous, within one day, with GRB 980425, and, thence, the latter was the likely starting event. The SN was unusually bright (hypernova) and characterized by a high expansion velocity (Patat et al. 2001). The uncertainty about the chance coincidence of SN1998bw with GRB 980425 was definitively removed in 2003, when the type Ic SN2003dh was found to be associated with GRB 030329 (Stanek et al. 2003). Indeed, while the early spectra of the optical emission from SN2003dh consisted of a power-law continuum, after a week, these spectra, corrected for the afterglow emission, became remarkably similar to that of SN1998bw. Nowadays, it has been definitely confirmed that several long GRBs originate in supernova explosions (see Table 1). In general, these SNe are type Ic with high expansion velocities and much larger energy release than in normal SNe. However, there are GRBs not associated with SNe (see Della Valle et al. 2006), demonstrating that there are GRBs originating in very faint supernovae or they are due to different phenomena (see Table 1). For a recent review on GRB-SN connection, see Hjorth (2013).

(d) Discovery of the “Amati relation”. This relation concerns the correlation between the redshift-corrected photon energy $E_{\text{peak}}$, at which the $\nu F_{\nu}$ spectrum peaks, and the total released energy during the burst $E_{\text{iso}}$ in the hypothesis of isotropic emission (see Fig. 9). It was found with a set of BeppoSAX GRBs, whose redshift was determined with optical spectrometers.

### Table 1 List of the SNe associated with GRBs. Most of them have a known redshift with values $< 1$. As can be seen, there are also cases in which, in spite of a low redshift, there is no evidence of an associated SN

| GRB     | Redshift, $z$ | Type$^a$ | SN search          |
|---------|--------------|----------|--------------------|
| 980425  | 0.0085       | long-UL  | SN 1998bw          |
| 020903  | 0.251        | XRF-UL   | LC bump & spectrum |
| 021211  | 1.006        | long-UL  | SN 2002lt          |
| 031203  | 0.105        | long-UL  | SN 20031w          |
| 030329  | 0.168        | long     | SN 2003dh          |
| 050525A | 0.606        | long-UL  | SN 2005nc          |
| 060218  | 0.033        | XRF-UL   | SN 2006aj          |
| 091127  | 0.49         | long-UL  | SN 2009nz          |
| 100316D | 0.059        | long-UL  | SN 2008bh          |
| 101219B | 0.55         | long-UL  | SN 2008ma          |
| 120422A | 0.283        | long-UL  | NS 2012bz          |
| 011121  | 0.36         | long-UL  | LC bump & spectrum |
| 050826  | 0.297        | long-UL  | LC bump             |
| 060729  | 0.54         | long-UL  | LC bump             |
| 090618  | 0.54         | long     | LC bump             |
| 080120  | long         | LC bump GROND |
| 081007  | long         | LC bump GROND |
| 090424  | long         | LC bump GROND |
| 100902A | long         | LC bump GROND |
| 110402A | long         | LC bump GROND |
| 040701  | 0.215        | XRF-UL   | no SN (<0.1 SN98bw) |
| 060505  | 0.089        | “long”-UL| no SN (<0.004 SN98bw) |
| 060614  | 0.125        | “long”   | no SN (<0.01 SN98bw) |
| 101225A | 0.40         | long     | no SN (GCN 11522)  |

Possible evidence of a shock breakout (Campana +2017)

| 171205  | 0.0368       | long     | SN bump             |
(Amati et al. 2002). After we published this result, other relationships were reported: the “Yonetoku relation” between $E_{\text{peak}}$ and the bolometric peak luminosity $L_{\text{p,iso}}$ (Yonetoku et al. 2004), the “Ghirlanda relation” between $E_{\text{peak}}$ and the released energy $E_{\text{r}}$ corrected for the beaming factor ($E_{\text{r}} = (1 - \cos\theta)E_{\text{iso}}$), given that a jet-like structure for the GRB emission was assumed (Ghirlanda et al. 2004). A discussion of the weaknesses of the Ghirlanda relation can be found in Frontera et al. (2012a). Other relations were later reported between prompt and afterglow emission or concerning only the afterglow. For a review, see Dainotti and Del Vecchio (2017). In spite of the more recent relations, the Amati relation remains the most robust and it is now confirmed by all long GRBs for which it has been possible to derive, along with $z$, their bolometric fluence and peak energy $E_{\text{p}}$. The only exception is the nearby GRB 980425. Some authors suspected that this relation could be influenced by selection effects (see Butler et al. 2009). However, the time resolved spectra, obtained by slicing the GRB time profile in several time intervals and deriving the spectra in each of them, show a correlation between the time resolved $E_{\text{p}}$ and the corresponding flux (see Ghirlanda et al. 2010; Frontera et al. 2012a, b). Thus, it is now generally accepted. A possible interpretation of the correlation has also been recently proposed by us (Frontera et al. 2016). Thanks to this relation, GRBs appear to be a promising tool to describe the expansion rate history of the universe and an independent estimate of the cosmological parameters (see Amati and Della Valle 2013).

(e) Discovery of X-ray flashes. These events were detected with the WFCs aboard BeppoSAX in the 2–25 keV energy band as bright X-ray sources lasting of the order of minutes, but remaining undetected in the BeppoSAX GRBM (Heise et al. 2001). Their temporal and spectral properties were found very similar to those of the X-ray counterparts of GRBs.

7 The post-BeppoSAX era

In spite of the huge advances obtained thanks to the BeppoSAX discoveries, many questions about GRBs were left unanswered, like the early afterglow properties, the late breaks in the X-ray light curves, the afterglow of short bursts, the origin of dark GRBs, the GRB environment, the origin of X-ray flashes.

One of the missions that is giving a very high contribution to the GRB astrophysics is Swift, launched on November 20, 2004. Several results have been obtained and reviews of the most important ones have been reported (see Gehrels et al. 2009; Kumar and Zhang 2015; Gehrels and Cannizzo 2017). I wish to mention here some of these results, like the different decay modes (Margutti et al. 2013) of the early X-ray afterglow light curves (see Fig. 10), and the great contribution to the determination of the redshift distribution of GRBs (see Fig. 11).

Also the HETE 2 mission (e.g., Lamb et al. 2004), launched in October 2000, had an important role in the post-BeppoSAX era, in particular for the understanding of the X-ray flashes (see Pelangeon et al. 2008). Thanks to HETE 2, it was possible to establish that X-ray flashes show properties similar to those of GRBs, apart from their...
lower peak energy (see left panel of Fig. 12) and a lower $z$ distribution (see right panel of Fig. 12).

Also the Fermi mission launched on June 11, 2008 and the AGILE mission launched on April 23, 2007 are providing a great contribution to the understanding of the GRB phenomenon at high energies (see Zhang et al. 2011). One of the most intriguing results is the delay of the onset of the high gamma-ray energy light curves with respect to that at low energies (see left panel of Fig. 13), and the hardening of the spectrum with time from the GRB onset with the appearance of a high-energy spectral component in the tail of the gamma-ray light curve (see right panel of Fig. 13).

Concerning progenitors, there is a general consensus that long GRBs are the result of core collapse of very massive stars. This conclusion comes from the following facts: (a) the well-established GRB–SN connection; (b) long GRBs are located in the brightest regions of the galaxies with high star formation rate (SFR) and where the most massive stars occur.

Concerning short GRBs, from the absence of evidence of simultaneous SN explosions and from the association with galaxies with a wide range of star formation properties (inclusive of low SFR), it can be concluded that, very likely, they are the result of compact binary (e.g., NS–NS) merging, as it was initially supposed. The recent association of a gravitational wave signal (GW 170817) with a short GRB (170817), has confirmed this scenario (Abbott et al. 2017).

Ruffini et al. (2016) have proposed a binary nature also for the progenitors of long XRFs/GRBs which exhibit two distinct episodes in their light curves. According to their model, in these cases, a CO core undergoes an SN explosion which triggers an hypercritical accretion onto an NS companion in a tight or more separated binary system. Depending on the tightness level, the formation or not of a BH is driven, and a GRB or an XRF event, respectively, is produced. An outstanding candidate which they consider for their model in the case of formation of a black hole is the very luminous GRB 090618 ($E_{iso} = 3 \times 10^{53}$ erg) for which there is an evidence of an SN bump 10 days after the event (Izzo et al. 2012), while an example of the second class of candidate events is the underluminous GRB 060218 ($E_{iso} = 5 \times 10^{49}$ erg), also with an associated SN and the evidence of an SN shock breakout (see Waxman et al. 2007 and Table 1).

![Redshift distribution of GRBs. Most of them have been discovered and localized with Swift. Reprinted from the review by Gom-](image)

Fig. 11  Redshift distribution of GRBs. Most of them have been discovered and localized with Swift. Reprinted from the review by Gomboc (2012)

![Distribution of the peak energy $E_p$ with fluence separated for different classes of events (X-ray Flashes, X-ray Rich, and GRBs).](image)

Fig. 12  Left: Distribution of the peak energy $E_p$ with fluence separated for different classes of events (X-ray Flashes, X-ray Rich, and GRBs). Adapted from Sakamoto et al. (2005). Right: $z$ distribution of GRBs and X-ray Flashes. Figure adapted from that of Péllangeon et al. (2008).
Some still open issues and opportunities offered by GRBs

Several questions are still open on GRB physics and properties, like the central engine that powers the GRB events (black hole plus torus? a magnetar? a quark star?), the ejecta composition (matter dominated? magnetically dominated jet?), the radiation mechanism (synchrotron radiation? synchrotron self Compton? thermal upscattering of a thermal photon source?), the still not measured hard X-ray afterglow spectrum (is it the tail of that measured at low energies?), cosmological issues (are GRBs good tracers of the star formation history of the Universe? Can high-z GRBs probe the reionization history of the Universe? Are GRBs sources of ultra-high-energy gamma rays? If yes, which is the emission physics?). For a review of the open issues, see Zhang (2011).

GRBs also offer the opportunity to settle questions of fundamental physics, like the test of the Lorentz invariance violation that is expected in some theories of quantum gravity. As above mentioned, GRBs can also be used as beacons to derive the cosmological parameters, and they are crucial for the multi-messenger astronomy (Abbott et al. 2017).

It is expected that many other exciting discoveries will be done in the near future with space and ground facilities, some of which already operational, like Swift, Fermi, AGILE, and INTEGRAL, the large optical and radio telescopes, like VLT, Keck, EVLA, and the LIGO and VIRGO gravitational interferometers.

In addition, other missions are being studied, or are under development, or are just operational. They include space X-/gamma-ray missions, like the Chinese–French mission SVOM (4 keV–5 MeV) expected to be launched in 2021, the Chinese–UK mission Einstein Probe (0.5–4 keV), aimed for a launch by the end of 2022, the THESEUS mission just approved by ESA for a phase A study (see Fig. 14), with a launch in 2032 if approved; extremely large optical facilities like EELT, TMT and GMT; new radio facilities like LOFAR and SKA; gravitational wave missions like the large ESA mission eLISA foreseen to be launched in the early 2030s; very high-energy gamma-ray facilities like MAGIC, HESS, VERITAS, and CTA; large neutrino facilities like ANTARES, ICECUBE, and KM3NET.

I would like to conclude with an X-/gamma-ray mission concept, ASTENA (Advanced Surveyor of Transient Events and Nuclear Astrophysics) under study by an international collaboration led by the University of Ferrara in the framework of the European programme AHEAD. The mission includes an array of 18 Wide Field Monitors–Imager Spectrometers (WFM–IS) with a total useful area of about 2 m² and an energy band from 2 keV to 20 MeV, and a focusing Narrow Field Telescope (NFT) with a collection area of about 7 m² and an energy band from 50 to 700 keV. Its sensitivity is expected to improve that of the best gamma-ray instruments, inclusive of NuSTAR, by two orders of magnitude. The NFT will be the ideal instrument to study.
among others, the high-energy GRB afterglow spectra still unknown.

In conclusion, the discovery of the GRB sites and afterglow with BeppoSAX will continue to push up the frontiers of our knowledge of the Universe for many years.

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