OBSERVATION OF GAMMA-RAY BURSTS BY BEPPOSAX

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ABSTRACT

Gamma-ray bursts (GRBs) are among the greatest mysteries of high-energy astrophysics. Since their discovery in 1967, more than 2,000 events have been observed by several experiments; still, no astrophysicist can surely state today what GRBs are and where they come from.

Before the advent of BeppoSAX only a statistical approach to the problem was followed. The first, but still recent, results of such investigations are the isotropy of the GRBs' arrival directions in the sky, and the paucity of weak events with respect to a homogeneous spatial distribution.

The BeppoSAX satellite, not specifically designed for GRB observations, carries the right instrumentation for a novel approach to the GRB problem. It has been able to detect, localize, and follow up a few GRBs on very short time scales. This allowed for the discovery of the first X-ray afterglow of a GRB. The precision and rapidity of the detection, and the wide dissemination of information, has permitted other observatories to pinpoint the event, discovering the first optical/radio afterglow, and the measurement of its distance and size.

*BeppoSAX is a major program of the Italian Space Agency (ASI) with participation of the Netherlands Agency for Aerospace Programs (NIVR).

1 Observed Global Properties of Gamma-Ray Bursts

Gamma-ray bursts are intense, short flashes of gamma rays arriving from any direction in the sky, at unpredictable times. They usually emit most of their energy in the hard-X/gamma-ray range, but they have been detected from a few keV up to tens of GeV.

Bursts were found in 1969 by gamma-ray detectors onboard the military satellites *Vela* 5A, 5B, 6A, and 6B, employed by the USA to monitor against possible Russian and Chinese nuclear tests in the atmosphere in violation of the 1963 Nuclear Test Ban Treaty. After their discovery, they were also found in older data and the first event, it turned out, was recorded on July 2, 1967. Being a result of military investigations they were classified and announced to the scientific community only in 1973.[1]

After their discovery, several gamma-ray experiments were included in the scientific payload of subsequent satellites, and continued to detect GRBs. Today the instrumental sensitivity has reached about 10^{-8} erg cm^{-2} s^{-1}, and they are thus detected at a gross rate of one per day. A crucial contribution to the study of GRBs has been gained by the launch in 1991 of the *Burst And Transient Source Experiment* (BATSE)[2] onboard the *Compton Gamma-Ray Observatory*.

1.1 Morphology and Duration Distribution

It is almost impossible to define a general morphology of GRBs. It changes from one burst to the next, passing from single pulse events to multiple pulses, through a wide variety of shapes and time scales. The single pulse events can last from a few milliseconds to hundreds of seconds. The multiple events are usually longer than a few seconds. Often the multiple structure of an event is found only at very high time resolution (of the order of a few ms). In Fig. 1, some examples from the zoo of GRBs are shown, as detected by the Gamma-Ray Burst Monitor (GRBM)[3,4] onboard BeppoSAX.

Thanks to its high detection efficiency, BATSE has built a duration distribution of GRBs. The duration of a GRB is defined as the time needed to go from 5% to 95% of the total counts detected from a given event. This distribution has a bi-modal shape, with the two broad peaks at about 0.3 and 30 s.

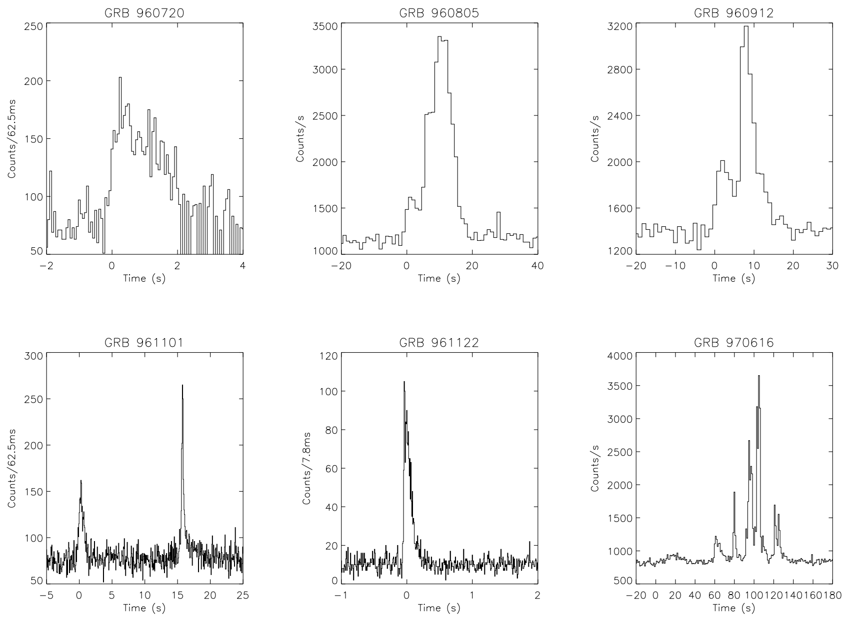

Fig. 1. Sample of GRBs detected by the BeppoSAX/GRBM, illustrating the variety of possible morphologies, durations, and intensities of GRBs.

1.2 Angular Distribution

Again, BATSE has given important information regarding the statistics of the arrival directions of GRBs. Figure 2 shows the distribution of the arrival directions of 1,429 GRBs.[5] Each point in the plot is located at the galactic coordinates of the arrival direction of one GRB, and the graphic representation is given in the Aitoff-Hammer projection (characterized by the preservation of the sky area). As can be seen by eye, and tested through statistical methods, there is no evidence for any kind of anisotropy in the angular distribution.

Since any class of galactic object has a characteristic distribution in this representation (for instance, the youngest stars are mainly distributed in the galactic plane, where the spiral arms are and where star formation is confined), this characteristic of GRBs is a first indication that they are not easily associated to any known class of objects in our galaxy. Moreover, given that our solar system is located about 9 kpc (one parsec is about 3.1×10^{18} cm) away from the center of the galaxy (which has a diameter of about 23 kpc), then the measurement of the isotropy can exclude an origin of GRBs from sources uniformly distributed in the

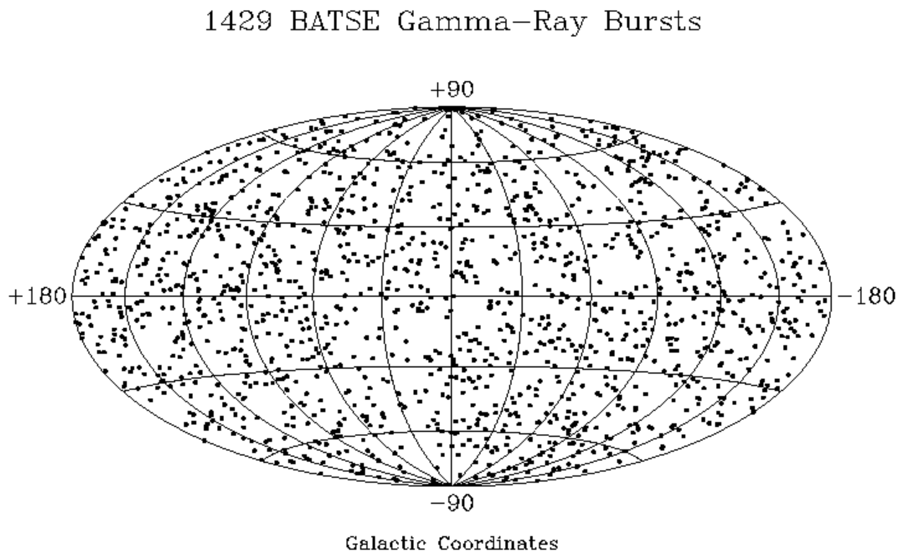

Fig. 2. Sky distribution of the GRB arrival directions, as derived from the detection of 1,429 events by BATSE.[5]

galaxy. In fact, in this case one should observe a dipole moment in the angular distribution (this dipole moment has been used, for example, to measure the distance of the sun from the center of the galaxy by using the space distribution of the globular clusters).

1.3 Peak Intensity Distribution

Given that the distance scale of GRBs is unknown, the typical representation of the GRB intensity is given in "peak intensity," in photons $cm^{-2}\ s^{-1}$ in a given energy range. If one plots the number of events with peak intensity greater than the abscissa value (i.e., the cumulative function) in a log-log scale, in case of homogeneous distribution of GRBs throughout a Euclidean space (that is, a constant number density and luminosity distribution over the space), one would expect a power law distribution with index $-3/2$. This can be easily understood just thinking that the volume increases as the third power of the distance, while the electromagnetic flux decreases as the square power of the distance. What we observe in a typical representation of the available data, like the one shown in Fig. 3, is that the distribution bends for low-peak intensities from the $-3/2$ trend, due

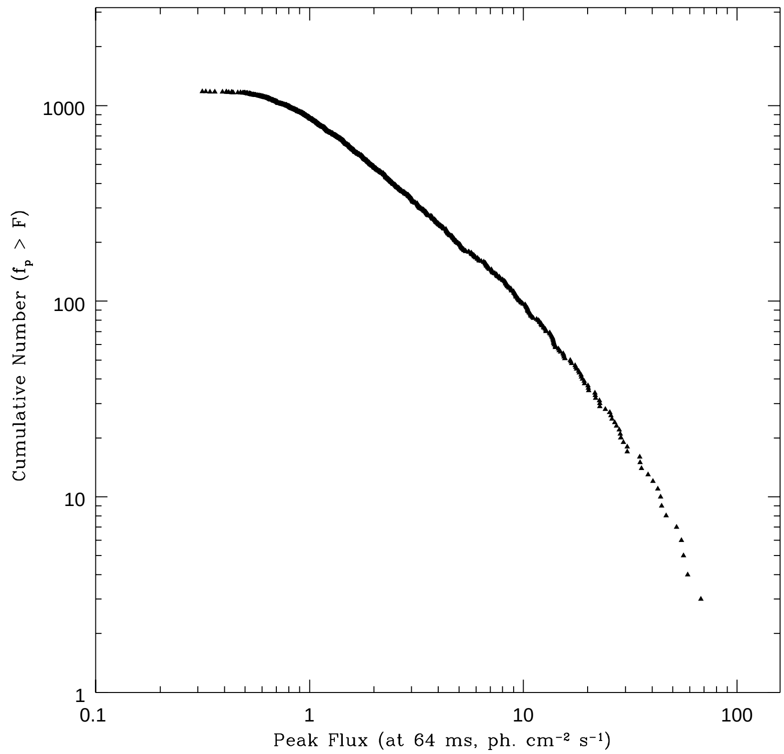

Fig. 3. Peak intensity distribution of the BATSE GRBs.[5]

to a paucity of the weaker events. This is an indication that we may be observing the end of the homogeneous spatial distribution. Of course, any conclusion must deal with the intrinsic emission mechanism of the GRB emitters, which is still unknown, and with its possible evolution in cosmological time. What we can exclude on the basis of this measurement is a homogeneous distribution in our galaxy, with a fixed intrinsic luminosity.

1.4 Spectral Properties

With no realistic information on the emission mechanism, the interpretation of the energy spectra of the recorded events must start with an empirical approach. This was done by several authors who have tried to classify GRBs on the basis of their spectral properties. An interesting result is that there is a general correlation between the hardness (that is, the ratio between a high energy channel and a low energy one) and the duration of the GRB: shorter bursts tend to be harder.[6]

Another general spectral property of GRBs is the characteristic *hard-to-soft* evolution during a single peak.[7–9] This is observed basically in every GRB for which time-resolved spectra, or at least hardness ratios, are available. Possibly connected with this (in case a synchrotron emission mechanism is responsible for the observed radiation) is also the observed property that the duration of single peaks varies like the inverse of the square root of the photon energy.[10]

A very recent analysis on the global spectral properties of GRBs has been performed by Pendleton *et al.*[11] with the very intriguing result of a classification of GRB pulses in High Energy (HE) and Non-High Energy (NHE) types, on the basis of the existence of emission at energies above 300 keV. These two classes seem rather well separated and the NHE type shows an effectively homogeneous intensity distribution, unlike the HE one.

Finally, regarding the time-averaged GRB spectra, Band *et al.*[12] found a good analytical description over the energy range covered by BATSE, that is, 30 keV to 2 MeV. This law basically consists of two power laws smoothly connected through an exponential:

$$N(E) = A \cdot \left(\frac{E}{100keV}\right)^{\alpha} \cdot \exp\left(-E/E_0\right) \,, \qquad (\alpha-\beta)\cdot E_0, \;\geq\; E$$

$$N(E) = A \cdot \left[\frac{(\alpha-\beta)\cdot E_0}{100keV}\right]^{\alpha-\beta} \cdot \exp\left(\beta-\alpha\right) \cdot \left(\frac{E}{100keV}\right)^{\beta} \,, \qquad (\alpha-\beta)\cdot E_0 \;\leq\; E.$$

The physical parameters of this function are the two photon indices α, β and the break energy E_0. The high-energy power law index β is constrained to be smaller than the low-energy one α, but they are otherwise free to vary. What Band *et al.* find, on a sample of 54 GRBs detected by BATSE from 1991 to 1992, is that the parameters vary in a rather limited range. In particular, $-1.5 < \alpha < +1.0$, $-5.0 < \beta < -1.5$, and E_0 ranges from below 100 keV to above 1 MeV, but with a distribution peaked around 200 keV.

It is very interesting that the Band law is able to account for the GRB energy spectra on the basis of only three parameters. The values of these parameters actually can be biased by the restricted energy range of BATSE. Unfortunately, the available sample of energy spectra of GRBs in energy ranges other than the BATSE one is pretty limited. In the past a good sample of GRBs (about 122) were detected by the X-ray and gamma-ray detectors aboard the Japanese-US satellite *GINGA*. An analysis of about one-third of them by Strohmayer *et al.*[13] in the energy range from 2 to 400 keV suggests the possible existence of a further energy break at low energies. A hope for the near future is based on the BeppoSAX satellite that has so far detected five GRBs in the energy range from 2 to 700 keV and will detect more in the next two years. A preliminary analysis of these five events has been performed by Frontera *et al.*,[14] revealing a substantial agreement with the Band law.

2 Current Interpretative Scenarios

The rapid evolution that GRB observational astronomy has undergone in the past year is affecting the theoretical scenario as well. However, in the pre-BeppoSAX era, the observed properties of GRBs were compatible with three basic models for the possible site of the GRB emitters: close to our solar system, an extended halo of our galaxy, and at cosmological distances.

2.1 Local Origin

The closest site compatible with the observed GRB properties is the Oort cloud. The Oort cloud is the supposed birthplace of the comets that are sometimes scattered into our solar system.[15] It is a diffuse cloud extending from the edge of our solar system up to a diameter of the order of 100,000 astronomical units or more (where the farthest planet, Pluto, lies at a mean distance from the sun of 40 a.u.). This site is geometrically compatible with the isotropic distribution of GRBs and is far enough away to account for failure to observe parallax (that is, the absence of a displacement in the apparent position when the event is observed from two or more sites). As for the physical mechanism that could be at the origin of a GRB, it has been suggested that comet-comet collisions[16] could give an appropriate energy release. Reviews of these models, however, conclude that they are unlikely, though still possible.[17]

2.2 Extended Galactic Halo

The other possible galactic solution is given by an extended halo around our galaxy. This structure should be large enough to account for the GRB isotropy, compensating for the off-center position of our solar system with respect to the galaxy. This lower limit is set at about 125 kpc. On the other hand, if this halo would be largely extended we should observe it in the nearby Andromeda galaxy. The absence of this observation places the upper limit at about 400 kpc.[18] The main concern of this geometrical location is that the existence of the extended halo must be postulated *ad-hoc* for GRBs, since no evidence for it is gained for any other class of celestial objects.

However, if GRBs are emitted at a distance of the order of 100 kpc, then the observed intensities imply an intrinsic luminosity of the order of 10^{42} erg s^{-1}. This amount of energy can be easily obtained from compact galactic objects (i.e., neutron stars) undergoing nondestructive phenomena, like internal readjustment or surface explosions. The most common scenario in this case would be a thermal cooling of the star surface after the GRB explosion.

2.3 Cosmological Origin

From a geometrical point of view, to place the GRB emitters at cosmological distances is the most suitable way to match the observed properties of isotropy and apparent inhomogeneity. The former would be an automatic result of the large distance to the emitters, while the latter could come from redshift effects and/or intrinsic source evolution. The main argument against this model is the lack of unambiguous observational evidences, like time dilation effects[19] or gravitational lensing.

If the mean emission distance were at redshift $z \sim 1$ (that is, about 10^{12} times the radius of our solar system) then the implied intrinsic luminosity would be of the order of 10^{51} erg s^{-1}. This can only be obtained through a catastrophic event, like the merging of two compact components of a binary system such as a neutron star-neutron star or a neutron star-black hole binary.[20] The necessary rate, taking into account the observed distribution of GRBs, is about 10^{-6} per galaxy per year.[21]

Given the destructive nature of the emission process, an experimental proof against the cosmological model would be the detection of a repeating source of GRBs. This has actually been detected in three cases so far, but they have shown peculiar spectral characteristics compared to the GRBs and have therefore been reclassified as *Soft Gamma-Ray Repeaters*. Such objects seem to be hosted in supernova remnants.

In the case of a catastrophic event such as the merging of two compact stars taking place, it is hard to think of an evolution other than that described by the *fireball* model.[22,23] In its basic version this is a relativistic expanding shell of electron-positron pairs deriving from the annihilation of neutrinos and antineutrinos carrying out most of the energy of the initial explosion. The expanding shell, possibly enriched with a few highly energetic protons, collides with the interstellar medium, provoking a shock front that accelerates the electrons, causing them to emit (for example, synchrotron radiation). The Lorentz factor of the expanding shell can account for the blue-shift of the X-rays into the gamma-ray band typical of GRBs. The morphological/temporal diversity can be accounted for by the possible diversity in the environmental conditions and/or by the existence of more than one shell, and therefore, from the interaction of one with the other.[24]

3 BeppoSAX and GRBs

3.1 Pre-SAX Experimental Scenario

After the accidental discovery by the *Vela* satellites, the search for GRBs continued with small experiments onboard the later ongoing space missions. GRB experiments flew onboard: *Orbiting Geophysical Observatory 3* and *5; Orbiting Solar Observatory 6, 7,* and *8*; *Apollo 16; Solrad 11A* and *11B; Helios 2; Prognoz 6* and *7; Pioneer Venus Orbiter; International Sun Earth Explorer 3*; the *KONUS* and *SIGNE* experiments onboard *Venera 11*, *12*, and *Wind; SIGNE 3; Solar Maximum Mission; HEAO-1*; the *MIR* space station; *GINGA; WATCH* and *SIGMA* onboard *GRANAT* and *EURECA; Ulysses;* and *TGRS* on *Wind*. The output of these experiments were limited catalogues of events, with some of them localized at the arcmin precision.[25]

The first experiment dedicated to the systematic study of GRBs was BATSE onboard the *Compton Gamma-Ray Observatory*. BATSE was conceived to study the angular distribution of the arrival directions in order to determine whether it could be associated with the distribution of known objects in our galaxy. The main result obtained by this experiment is that the GRB angular distribution is actually not related to the mass distribution within our galaxy, and shows a high degree of isotropy. The strategy chosen by BATSE was to detect a large number of GRBs, localizing them with a precision from a few to tens of degrees. In fact, BATSE has already detected about 2,000 GRBs and continues to detect them at a rate of about six per week.

Given the excellent but not conclusive results achieved by the previous experiments, a new mission was conceived, dedicated to the study of and prompt reaction to GRBs. This mission, *High Energy Transients Explorer* (HETE),[26] was launched at the end of 1996, but the deployment of the payload failed. The results achieved by BeppoSAX indicate that the HETE concept was correct, and therefore, the satellite is scheduled to be launched again in 1999 as *HETE-2*.

3.2 BeppoSAX: Generalities and Instrumentation

BeppoSAX[27] (*Satellite Italiano per Astronomia X*, renamed Beppo after the nickname of the Italian physicist Giuseppe Occhialini) is a major mission of the Italian Space Agency (ASI) with participation of the Dutch space agency (NIVR). The prime industrial contractors (Alenia Spazio for the space segment and Nuova Telespazio for the ground segment) carried out the project under the scientific responsibility of a consortium of Italian research institutions (CNR institutes of Palermo, Rome, Bologna, and Milan and GIFCO units of Milan, Ferrara, Rome, and Palermo), the SRON Institute (Utrecht, Holland), and the Space Science Department of ESA (Noordwijk, Holland).

The BeppoSAX satellite was launched on April 30, 1996, from Cape Canaveral, Florida. A two-stage Atlas-Centaur rocket put the spacecraft on an almost equatorial orbit (3.9° inclination with respect to the Earth's equator) at an altitude of about 600 km above the Earth's surface. The chosen orbit is particularly well-suited for exploiting the shield of the geomagnetic field against the cosmic rays that are one of the primary sources of background in X-ray astronomy.

The spacecraft performs a complete orbit around Earth in about 97 minutes. Once per orbit it passes over the ground station in Malindi (Kenya) and downloads all the data recorded onboard during the current orbit, and uplinks all the telecommands needed for the operations in the next orbit. The entire radio contact of the satellite with the ground station lasts about ten minutes each orbit. After the data have been recorded on the ground in Malindi they are relayed through the Intelsat satellite to the Science Operation Center in Rome, where they are archived and analyzed by the Duty Scientists 24 hours a day.

A schematic of the scientific payload of the satellite is shown in Fig. 4, where the single instruments are visible. They are basically divided into Narrow Field Instruments (NFI, with a field of view of about 1.5°, always looking at the same direction in the sky):

- One Low-Energy Concentrator Spectrometer (LECS, 0.1–10 keV);[28]
- Three Medium-Energy Concentrator Spectrometers (MECS, 2–10 keV);[29]
- One High-Pressure Gas Scintillation Proportional Counter (HPGSPC, 4–100 keV);[30]
- One Phoswich Detection System (PDS, 15–300 keV);[3]

and Wide Field Instruments, looking at directions 90° from the NFI field of view:

- Two Wide Field Cameras (WFC, 2–30 keV, field of view at zero response of $40° \times 40°$) pointed at two opposite directions;[31]
- One Gamma-Ray Burst Monitor (GRBM, 40–700 keV, open field of view, including the WFC field of view).[3,4]

The BeppoSAX instrumentation is, therefore, well-matched both for wide band (more than three decades of energy, from 0.1 to 300 keV) pointed observations of celestial sources with good spatial and energy resolution, and for wide field monitoring of transient X/gamma events with the WFC and GRBM.

3.3 The GRBM and WFC Instruments

Given the unpredictability of the GRB arrival directions, the two key instruments in the BeppoSAX research on GRBs are the two wide field detectors, the GRBM for the gamma-ray range, and the WFCs for the X-ray range.

3.3.1 Gamma-Ray Burst Monitor

The GRBM is a secondary function of the anticoincidence shields of the PDS experiment, performed through dedicated onboard electronics. The instrument is composed of four identical CsI(Na) scintillator slabs, about 1000 cm^2 each, surrounding the PDS detectors in a box-like configuration. Each slab is viewed by

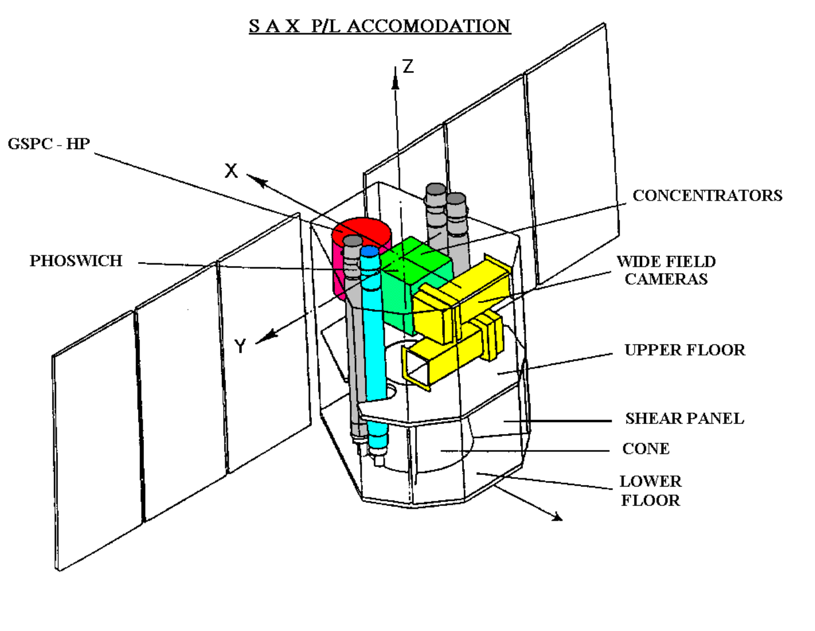

Fig. 4. Schematics of the BeppoSAX satellite with the scientific instruments indicated. The GRBM is a part of the Phoswich Detection System, located in the core of the satellite.

two independent photomultipliers. The instrument characteristics are reported in Table 1, with particular reference to the trigger criteria for GRB selection.

3.3.2 Wide Field Cameras

The two Wide Field Cameras onboard BeppoSAX are two position-sensitive proportional counters, with a coded mask in front of their collimated field of view. The basic operational principle is that the X-ray photons collected from each direction of the sky within the field of view are uniquely codified through the code of void/filled elements of the mask. A reconstructed image of the sky can then be obtained through a deconvolution algorithm operated on ground. Further details can be found in Table 2 and in Jager *et al.*[31]

3.4 Why BeppoSAX Is Well-Suited for GRBs

The presence of such a complete instrumentation on the same satellite has turned out to be the real breakthrough in the astronomy of GRBs. In fact, the GRBM is able to trigger on GRBs in their traditional energy range, but it is only able to

Table 1. Instrumental characteristics of the GRBM onboard BeppoSAX.

Energy Range	40–700 keV
Detector Geometry	4 orthogonal shields; 4,400 cm^2 total area
Detector Type	CsI(Na) — 10 mm thick
Field of View	open
Energy Resolution	16% @ 511 keV
Energy Thresholds	Programmable from ground
GRB Trigger Criteria	Simultaneously on two shields: Counts in n_1 seconds must exceed by $n_2\sigma$ the moving average of the background computed on n_3 seconds. Programmable parameters: $0.008 \leq n_1 \leq 4$ $4 \leq n_2 \leq 16$ $8 \leq n_3 \leq 128$
Transmitted Data (separately for each of the four shields in the case a GRB is detected)	Trigger time T_0 (16 μs resolution) Light curve: from $T_0 - 8$ s to T_0: 7.8 ms bin from T_0 to $T_0 + 10$ s: 0.5 ms bin from $T_0 + 10$ s to $T_0 + 98$ s: 7.8 ms bin
Housekeeping Data (separately for each of the four shields, regardless of the trigger presence)	Counts/s above 100 keV Counts/s in the energy range 40–700 keV Energy spectra (256 channels) integrated over 128 s fixed intervals

Table 2. Instrumental characteristics of the WFC onboard BeppoSAX.

Energy Range	2–26 keV
Detector Type	Multiwire proportional counter
Gas Filling	94%Xe+5%CO_2+1%He, 2.2 bar
Effective Area	140 cm^2
Field of View	40°x40° at zero response
Energy Resolution	20% (spatial average, @ 6 keV)
Source Location Accuracy	1 arcmin
Sensitivity in 10^5s	a few mCrabs

give a very rough estimation of their location in the sky. On the other hand, the WFCs work in an energy range not proper for the GRBs' recognition, but where it is easier to estimate the position of a transient event in the sky, through the coded mask technique. Therefore, whenever a GRB occurs within the field of view of one of the two WFCs, each covering about 3% of the sky, it can be promptly recognized through a proper trigger by the GRBM and localized by the WFC to a level of accuracy (about 3 arcmin) good enough to be an appropriate target for the NFI. All of this can happen in about one to two hours after the detection of the GRB onboard. Soon after, the operations to point the NFI can start and the new orientation can be acquired within three to five hours. While the operations for pointing the BeppoSAX/NFI to the region of the sky in which the GRB was observed are in progress, the BeppoSAX team also alerts the largest number of ground- and space-based telescopes working at other wavelengths in order to have them also on-source as soon as possible.

The above can only be performed thanks to the joint special effort of all the BeppoSAX team components: the BeppoSAX Science Operation Center, the Mission Scientist, the Mission Director, the GRBM and WFC hardware team scientists, the Operation Control Center, and the Science Data Center. In fact, at any time of the day the BeppoSAX team can be alerted of the occurrence of such an important detection and it reacts in the shortest possible time. During the first five months of 1997, the rate of occurrence has been roughly once every 1.5 months. Then, after a three-month interruption of the scientific operations due to maintenance activities, no new GRB has been detected through November 1997, though the satellite is in a standard performance condition.

4 BeppoSAX Discoveries on GRBs

Before the advent of BeppoSAX, GRB astronomy had proceeded on a statistical approach. Since no GRB counterpart had been found during the searches done a long time after the GRB explosions, and there was no idea of how to get precise GRB positions shortly after the event, the only thing left to do was to detect as many GRBs as possible and study their global properties on large numbers of events. This approach has led to an important global characterization of the GRB class, mainly thanks to BATSE. The revolution introduced by BeppoSAX is the capability to study the GRBs on a single-event basis, therefore fixing some fundamental parameters. Before BeppoSAX no one had an idea of what could happen to a GRB emitter soon after the event: whether or not it is visible, at what wavelength, and for how long.

The operations for a prompt reaction to GRBs started in December 1996. The first detection was on January 11, 1997: GRB970111. Even though an important observational effort had been spent on this event, no immediate result was obtained either from BeppoSAX or from any ground-based observatory. The second chance was on February 28, 1997: GRB970228.

4.1 Discovery of the First GRB Afterglow: GRB970228

4.1.1 BeppoSAX Detection and X-Ray Follow-up Observation

February 28, 1997 is the date that changed the 30-year-old history of GRB astronomy. At 02:58:00.8 Universal Time (UT) a moderately intense, multipeak GRB triggered the GRBM onboard BeppoSAX.[32] The same GRB was also detected in one of the two WFCs, and therefore, localized at about 10 arcmin precision, later reduced to 3 arcmin. The peak intensity of the GRB in the GRBM band (40–700 keV) was 3×10^{-6} erg cm^{-2} s^{-1}, while it was 1.4×10^{-7} erg cm^{-2} s^{-1} in the WFC band (2–26 keV). Figure 5 shows the light curve of this GRB as seen from the GRBM and WFC instruments.

The NFI were pointed to the GRB location in the sky in a time as short as eight hours after the trigger detection. The previously unknown X-ray source

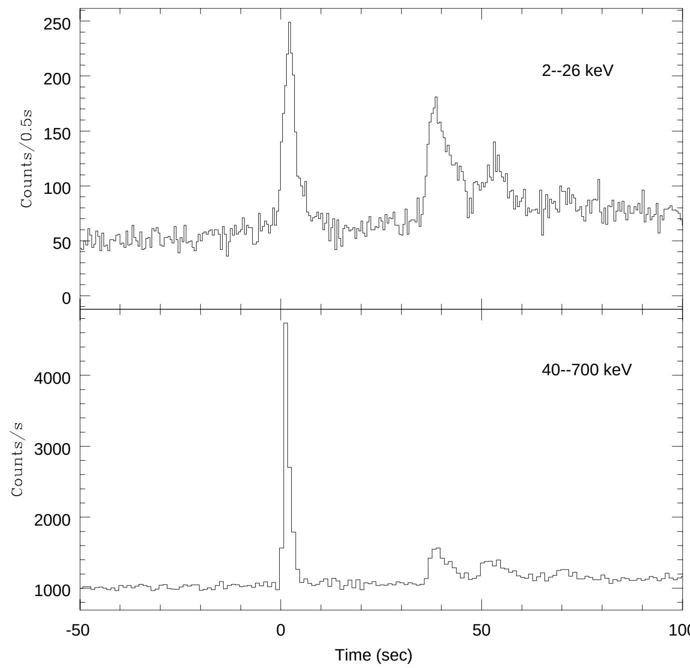

Fig. 5. BeppoSAX GRBM and WFC light curves of GRB970228.

1SAXJ0501.7 + 1146 was detected in the field of view of the LECS and MECS instruments at the celestial coordinates: Right Ascension (R.A.) = $05^h01^m44^s$ and Declination (Decl.) $= +11°46'.4$ (equinox 2000.0). This first observation lasted about 14,000 s of net observing time, and the source mean flux in the 2–10 keV energy range was 3×10^{-12} erg cm^{-2} s^{-1} (that is about 10,000 times weaker than the reference celestial source for X-ray astronomy, the Crab Nebula, in the same band).

What was particularly intriguing in this detection is that the new source appeared to be fading away during the observation. So, we found in a small region of the sky that a few hours earlier hosted a GRB a previously undetected source with a time behavior indicating it was disappearing. We therefore decided to again point the NFI to the source, and this happened on March 3, 17:37 UT, for an exposure time of 16,000 s. Figure 6 shows the comparison between the results of the two observations. Looking at this figure one can imagine our astonishment: We had discovered the first "afterglow" of a GRB!

The evaluation of the temporal decay law of the X-ray flux detected from the counterpart of GRB970228 was initially performed by using the two NFI

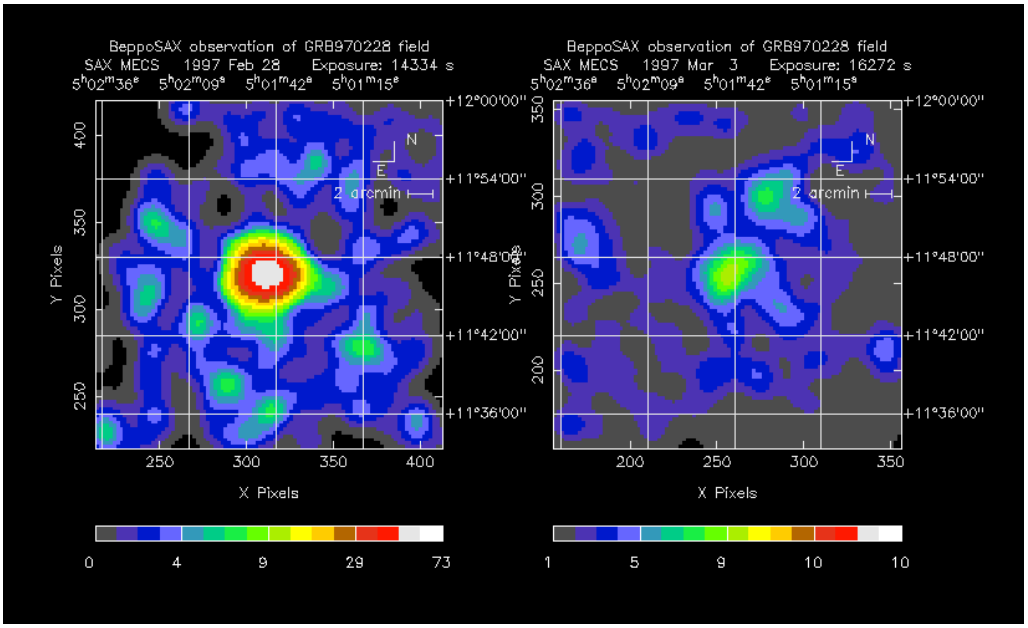

Fig. 6. BeppoSAX MECS images of the GRB970228 afterglow, eight hours after the GRB (left) and three days after the GRB (right).

observations only. The mean flux of the source appeared to decrease following a power law dependence on time ($\sim t^{-\alpha}$) with index $\alpha = (1.3 \pm 0.1)$. A further X-ray observation with the Japanese X-ray satellite ASCA detected again the source about one week later with a flux consistent with the same law.[33] This kind of temporal behavior agrees with the general predictions of the fireball models for GRBs.[34]

If one observes the GRBM and WFC light curves of the GRB970228 in Fig. 5, it appears rather clearly that the second train of pulses of the GRB are much more soft than the first pulse, that is, the ratio between X rays and gamma rays is higher. We therefore decided to compare this second part of the GRB flux with its afterglow. In Fig. 7 the result is shown: The mean X-ray flux of the second part of the GRB [indicated as WFC (35–70 s) in the figure] is perfectly consistent with the backward extrapolation of the power law decay derived from a fit to the NFI data only. The same figure also shows the average X-ray flux of the entire GRB [indicated as WFC (0–100 s) in the figure] and it appears less clearly correlated to the above law. Our guess from this analysis is, therefore, that the afterglow to GRB970228 actually started soon after the GRB. A further confirmation of

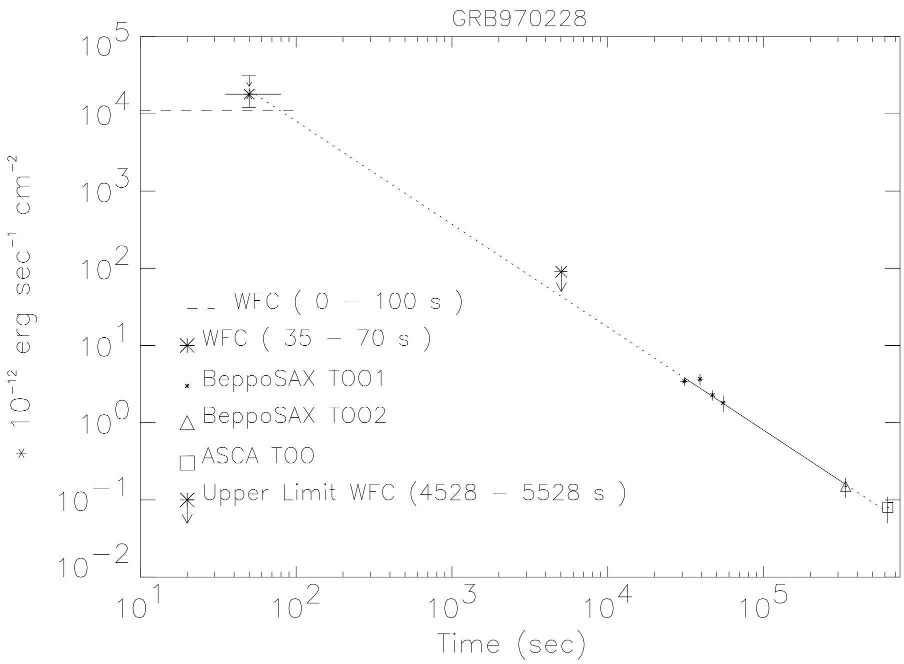

Fig. 7. BeppoSAX decay curve of the GRB970228 afterglow in the 2–10 keV energy range, obtained with the WFC and the NFI. The result of the ASCA observation is also shown at the bottom right.[32]

this comes from the spectral analysis[35] that shows a spectral continuity of the GRBM/WFC spectra with the NFI only for the second set of pulses.

Another important result of the spectral analysis of the GRB970228 afterglow is that it seems to exclude a thermal origin of the emission, therefore suggesting that a model in which the radiation comes from the cooling of the surface of a neutron star cannot work in this case.

4.1.2 Optical Follow-Up Observation

While the X-ray monitoring of GRB970228 was going on, an observational campaign of the same object was simultaneously started with the most important optical telescopes. This campaign led to the discovery[36] of an optical transient associated with the X-ray afterglow. This new optical source was discovered in the images taken the same night of the GRB and about one week later with the Isaac Newton Telescope (INT) and the William Herschel Telescope (WHT) at the Canary Islands. The source showed a brightness decline from the first to the second observation of about 2.5 magnitudes (V band), corresponding to a flux decrease of about a factor of 300. This was the first discovery of an optical afterglow of a GRB.

The source was continuously monitored up to September 1997 from the most important world-wide telescopes.[37] As in the X-ray domain, the optical flux of the source showed a decrease well-described by a power law with index –1.12 (Ref. 38), again in agreement with the general predictions of the fireball model. But there was still other information to gather from the optical observations. Very important in this respect are the two pointings of the Hubble Space Telescope (HST),[39,40] the optical telescope orbiting around Earth, and therefore, not suffering from the disturbances due to Earth's atmosphere. In the images taken with HST, the presence of a nebulosity emerges around the point source located by the ground-based telescopes. An indication of this was also derived from the first images taken at the WHT and INT and other on-ground telescopes. Since both the source and the nebulosity were very weak, there is still today no clear agreement among scientists whether or not the intensity of this fuzziness is constant with time and what its interpretation is. Many people think that the nebulosity was actually constant, and in this case, the easiest interpretation would be that it is the host galaxy of the object. If this interpretation is someday confirmed, this would be the first experimental evidence for an extragalactic origin of GRB970228.

Confirmation of the positional consistency between GRB970228, the X-ray afterglow, and the optical counterpart also comes from other measurements. In fact, the German satellite ROSAT, capable of locating an X-ray source with an accuracy of about 10 arcsec, pointed the GRB970228 field on March 10, 1997.[41] It detected the X-ray source 1SAX J0501.7 + 1146 at a flux level consistent with the extrapolation of the decay law derived from the BeppoSAX measurements and refined its position at a few arcsec accuracy, still coincident with the location of the optical transient.

Furthermore, using the GRB arrival times at the BeppoSAX GRBM and at the Ulysses (an interplanetary mission at that time about 2,000 light seconds away from Earth) GRB detector, Hurley *et al.*[42] were able to derive an annulus in the sky of the possible arrival directions of GRB970228. This annulus crosses the WFC and NFI error boxes. The X-ray/optical afterglow lies just within the sky area derived from the overlap of all of these error boxes. In Fig. 8, the final location of the source is shown together with all the error boxes.

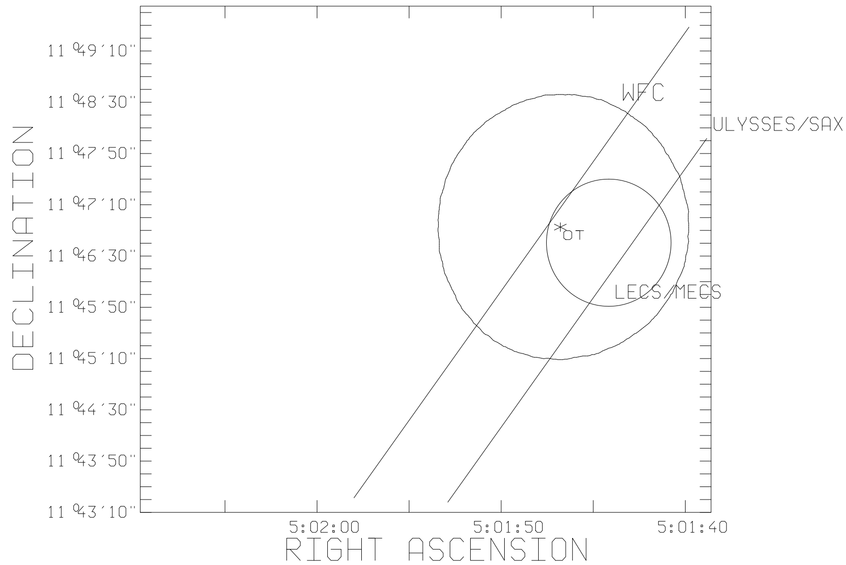

Fig. 8. Error boxes for GRB970228, obtained with the BeppoSAX WFC and the NFI (larger and smaller circles) and with the Ulysses/BeppoSAX triangulation (strip).

4.1.3 Other Wavelengths

The field of GRB970228 was also observed at wavelengths other than X-ray and optical. Radio follow-up observations were carried out at the *Very Large Array* (VLA, Socorro, New Mexico) at a frequency of 1.43 and 8.46 GHz (Ref. 43) starting less than one day after the GRB and continuing up to August 1997. No positive detection has been obtained for the X/optical source, at a level of tens of microJansky (1 Jy is the typical unit of radio astronomy and corresponds to 10^{-26} watt m^{-2} Hz^{-1}). Searches at the wavelength of 3.5 mm (Ref. 44) gave null detections as well, at a level of a few mJy.

4.2 The First Measurement of a GRB Distance: GRB970508

If GRB970228 was the first GRB event for which an X-ray and optical counterpart were found, the event that triggered the BeppoSAX/GRBM on May 8, 1997, had to carry even more striking results.

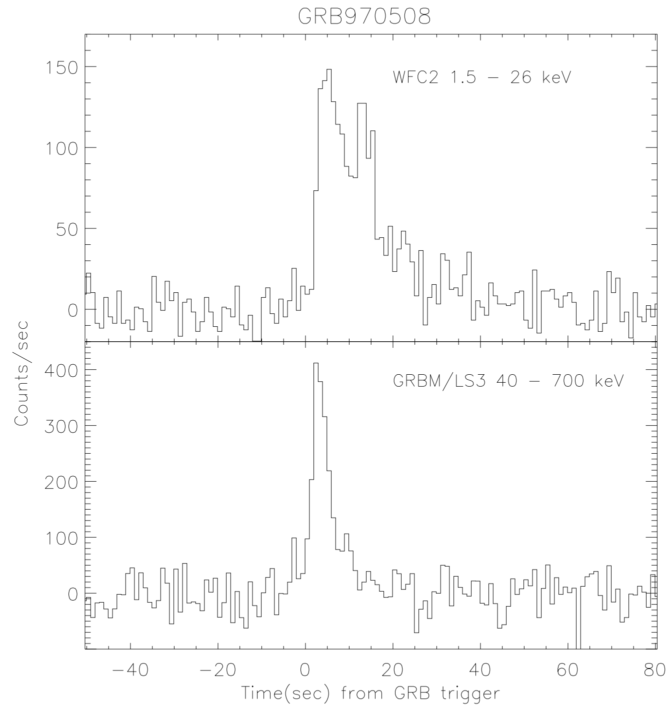

Fig. 9. WFC and GRBM light curves of GRB970508 (Ref. 45).

4.2.1 GRBM and WFC Detection

The GRBM detected the trigger for GRB970508 at 21:41:50 UT, just a few minutes before the satellite was passing over the ground station in Malindi.[45] The event was simultaneously detected in one WFC, thus providing a prompt localization of the event at the coordinates R.A. = $06^h53^m28^s$ and Decl. = 79°17'.4 (equinox 2000.0), with a 99% error radius of 3'. In Fig. 9, the light curve of the event is shown in the energy ranges of GRBM and WFC, showing a single-peak structure in the GRBM and a double-peak structure in the WFC. This event was much weaker than the February event. The peak flux was 3.4×10^{-7} erg cm^{-2} s^{-1} in the 40–700 keV energy range, and 6×10^{-8} erg cm^{-2} s^{-1} in the 2–26 keV band.

4.2.2 BeppoSAX X-Ray Follow-up Observation

Given the favorable detection condition (i.e., just before the data download in Malindi) and the experience gained from the BeppoSAX team, the NFI were pointed to the GRB location just 5.7 hours after the event was triggered, and stayed on source for an exposure time of 28,000 s. This was again a world record at that time. As in the GRB970228 case (and in the GRB970402 case, see Sec. 4.3.2) a previously unknown X-ray source was detected at the position R.A. $= 06^h 53^m 46.7^s$ and Decl. $= +79°16'02''$ (equinox 2000.0), consistent with the GRB error box, 1SAXJ0653.8 + 7916. The BeppoSAX NFI pointed at the source again three more times, after 2.7 days (24,000 s exposure), 4.1 days (12,000 s exposure), and 5.7 days (73,000 s exposure). The source was detected in each of the four NFI pointings. Also, an analysis of the WFC data has revealed that the X-ray counterpart of the GRB was detected in the WFC up to 4,000 s after the GRB.

As in the case of GRB970228, we have plotted the mean source flux on a log-log plot, and the result is shown in the upper panel of Fig. 10. In this case the time history of the GRB in the 2–10 keV band is plotted. Unlike GRB970228, the source power law decay is far from being smooth and uniform, but shows the presence of new activity after a first decay. The ability of the BeppoSAX team to point the source very quickly and the peculiar decay law have also allowed, for the first time, the study of the spectral evolution of the afterglow of a GRB over the four NFI pointings.[46] The four spectra are reported in Fig. 11, and a clear spectral evolution can be seen, with the hard-to-soft trend typical of the GRBs, which therefore seems to apply to their afterglows as well.

4.2.3 Optical Follow-Up Observation

The optical follow-up of this event benefited from the experience and better organization of the BeppoSAX team. The first observations started as early as four hours after the event.[47] The optical counterpart was identified independently by several observers[47–51] at a position R.A. $= 06^h 53^m 49.43^s$ and Decl. $= +79°16'19''.6$ (equinox 2000.0). This world-wide effort allowed us to follow the temporal behavior of the optical transient from the very beginning to the present. In Fig. 12 we show the collection of observations from many telescopes. The time history of the source appears very complicated, and qualitatively different from what was detected in the case of the February event, or better, it looks like in that case we missed the first brightening of the optical transient.

The most important thing, however, is that the optical counterpart was detected so quickly that it was still bright enough to allow for an optical spectrum to be taken. This was actually done at the Keck telescope (Hawaii) by Metzger *et al.*[52] and revealed the presence of some absorption line features. These were identified to be FeII and MgII absorption lines cosmologically redshifted, by an

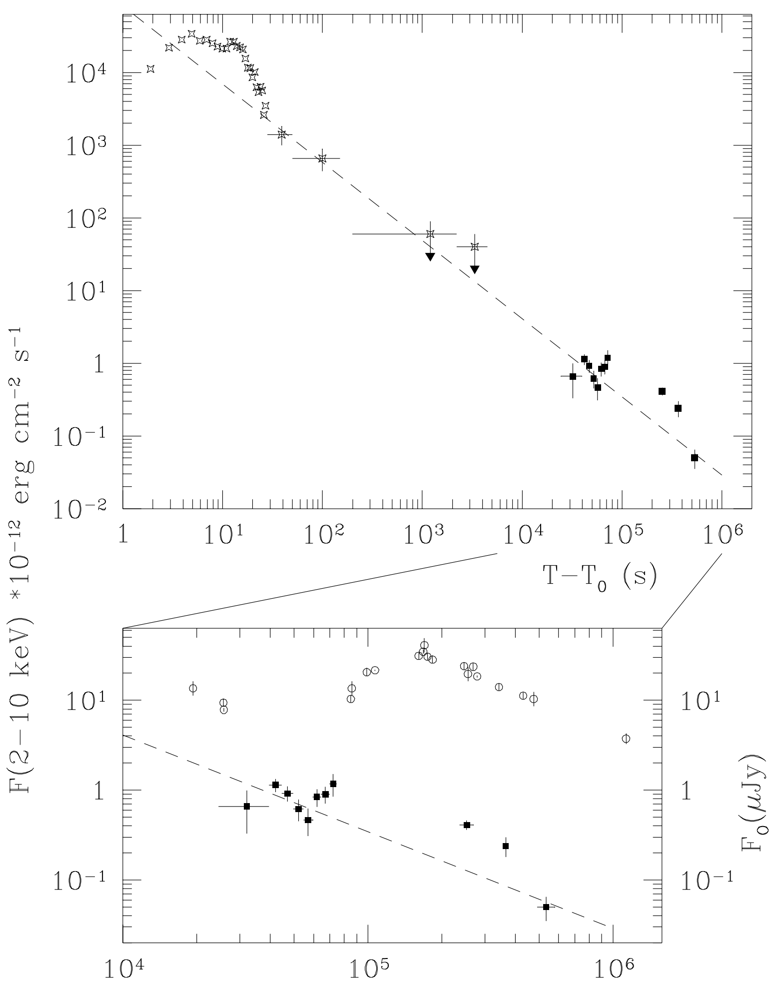

Fig. 10. Top panel: decay law of the GRB970508 afterglow as detected by the BeppoSAX WFC and NFI. The WFC provided the data up to 5,000 seconds after the burst. Bottom panel: enlargement of the X-ray decay law and comparison with the simultaneous time history of the optical transient (open circles; see also Fig. 12).

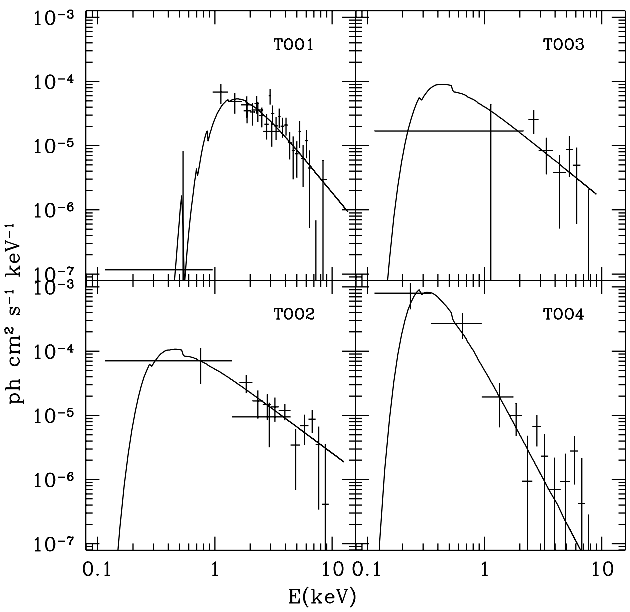

Fig. 11. Spectra of the GRB970508 afterglow as detected in the four BeppoSAX NFI pointings. A hard-to-soft evolution appears evident.

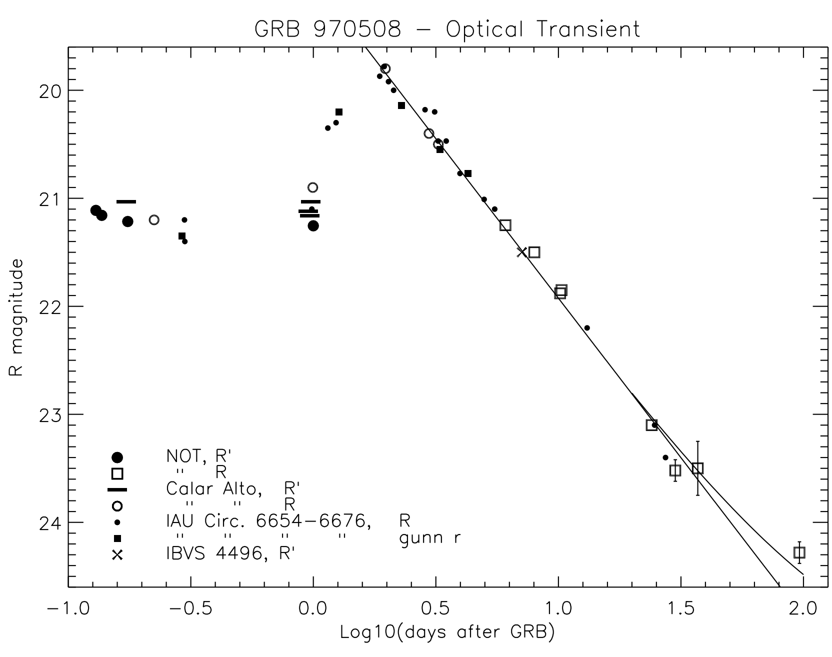

Fig. 12. Light curve of the optical transient associated with GRB970508 (Ref. 51).

amount $z = 0.835$. This is the first direct measurement of the distance of a GRB, and it definitely shows that GRB970508 came from outside our own galaxy.

This GRB was also observed with the *Hubble Space Telescope* in order to find evidence for a host galaxy, like the one supposed to be detected in the GRB970228 case. The results[53] of the observation show a perfectly point-like source, with definitely no evidence for any host galaxy.

4.2.4 Radio Follow-Up Observation

GRB970508 has entered the astronomy books not only because of its X-ray and optical counterpart, but also because it is the first GRB with a radio afterglow. In fact, the radio observations of the GRB970508 field started at the VLA just 3.7 hours after the GRB trigger.[54] A new radio source, VLA J065349.4 + 791619, was seen in a position consistent with the optical transient associated with the GRB. The source flux was monitored at the frequencies of 1.43, 4.86, and 8.46 GHz. Soon after the GRB, the source was not detectable, but after about one week it started brightening, reaching a mean flux of about 0.6 mJy at 4.86 GHz. The source exhibited short-term variations with amplitude of a factor of two or more. These variations can be interpreted as due to *diffractive scintillation* because of scattering of the radio wave with the interstellar matter. If this interpretation is correct, and if the source distance is taken to be $z = 0.835$ (this would correspond to a distance of 10^{28} cm), then the short-term variations allow for the estimation of the source size: After a few weeks the linear dimension of the source should have been of the order of 10^{17} cm.

Furthermore, a monitoring of the same source with the *Very Large Baseline Interferometer* (VLBI)[55] has allowed for the derivation of a positioning as accurate as 0.2 milliarcseconds. The measurement of a null proper motion at the level of 50 milliarcseconds per year is fully consistent with a cosmological distance to the object.

4.3 Life is Never Easy: GRB970111 and GRB970402

From above it would seem that the problem of knowing what GRBs are and from where they come is now solved. This is actually not true since BeppoSAX localized two more GRBs (actually before the May event), and very different results were obtained from them.

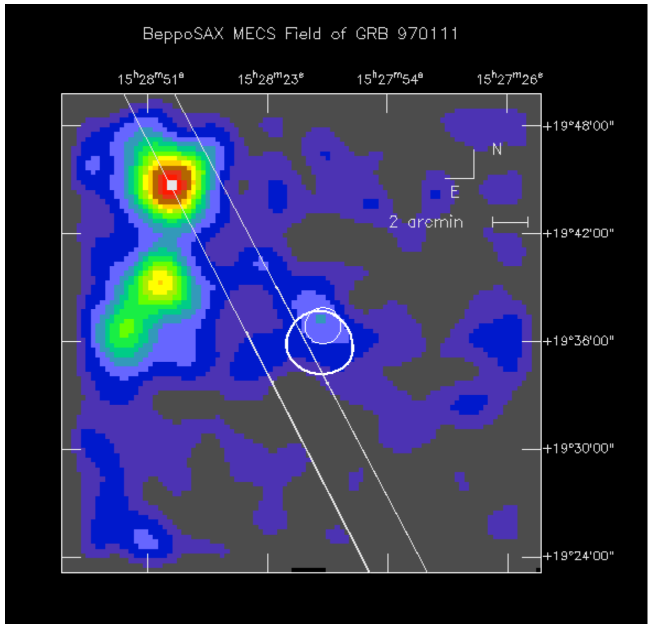

Fig. 13. Image of the GRB970111 field[56] taken by BeppoSAX with the candidate afterglow inside the WFC error box (small and large circle, respectively), and the annulus obtained by the triangulation between Ulysses and BATSE and GRBM.

4.3.1 GRB970111

The first GRB to which BeppoSAX was able to promptly react occurred on January 11, 1997, 09:43:59.9 UT from the location in the sky at the coordinates R.A. $= 15^h 28^m 11^s$ and Decl. $= +19°35'.9$ (error radius 1.8', equinox 2000.0) (Ref. 56). The field was imaged by the BeppoSAX NFI just 16 hours after the GRB trigger, for an exposure time of about 52,000 s. The only result of such an observation is the detection of a very weak source (flux $\sim 5 \times 10^{-14}$erg cm^{-2} s^{-1}), 1SAX J1528.1 + 1937, at a position consistent with the WFC error box, but not consistent with the triangulation with the Ulysses satellite.[57] In Fig. 13 we show the image taken by BeppoSAX with the X-ray source error circle indicated, superimposed on the triangulation annulus. Also, no optical or radio counterpart was detected for this GRB.[57–59]

What is puzzling in these results is that GRB970111 is the brightest GRB detected by BeppoSAX/WFC and among the brightest GRBs ever detected by BATSE. In particular, the 40–700 peak flux was about 4×10^{-6} erg cm^{-2} s^{-1} and the 2–10 keV peak flux was 4×10^{-8} erg cm^{-2} s^{-1}. On the contrary, the candidate X-ray afterglow is definitely below the flux level expected, if one considers the cases

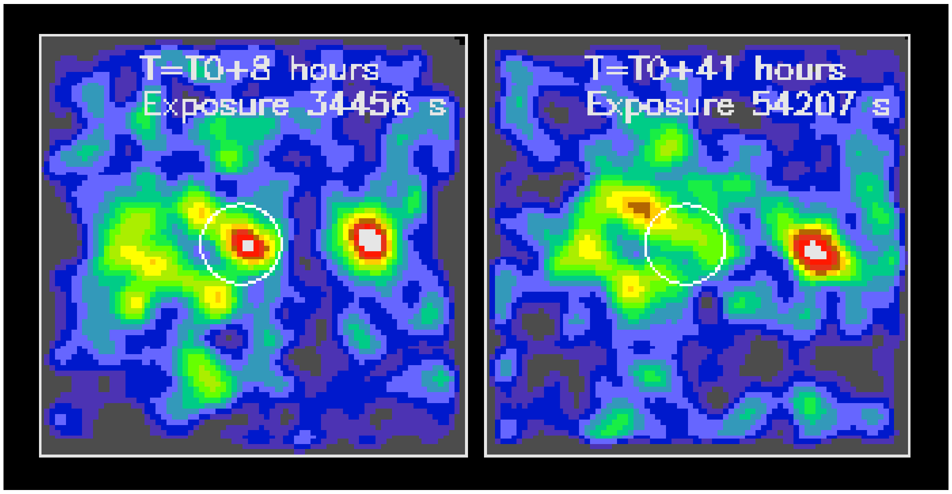

Fig. 14. Images of the GRB970402 field taken by BeppoSAX after eight hours (left) and 1.7 days (right). The GRB afterglow is indicated by the circle.

of GRB970228 and GRB970508. No (variable) optical counterpart has been found at the level of the 23^{rd} magnitude, whereas the GRB970228 optical transient was detected at the 20^{th} magnitude, and GRB970508 peaked at the 19^{th} magnitude.

4.3.2 GRB970402

GRB970402 was detected by the BeppoSAX GRBM and WFC on April 2, 1997, 22:19:39 UT (Ref. 60). The event was very weak and structured, with a total duration of about 150 s. The peak flux in the 40–700 keV range was 2.4×10^{-7} erg cm^{-2} s^{-1}, and in the 2–26 keV 7×10^{-9} erg cm^{-2} s^{-1}. Again, the NFI were pointed to the GRB within eight hours from the event, for a net observing time of 35,000 s. A new X-ray source was detected, 1SAX J1450.1-6920, at the coordinates R.A. = $14^h50^m06^s$, Decl. = –69°20'00", with 50" error radius.[61] The mean flux of the observed source was 2×10^{-13} erg cm^{-2} s^{-1} with an apparent decaying temporal behavior. A new NFI observation was carried out 1.7 days after the GRB for a net exposure time of 53,000 s. The new source 1SAX J1450.1-6920 was only marginally detected with an intensity decreased by a factor of three. In Fig. 14, the images of the two MECS pointings are shown.

The decay law of GRB970402 is well-described by a power law with index (–1.2 ± 0.1), compatible with that observed for the GRB970228 afterglow. From these elements one would expect similar results also from the observations at other wavelengths. In this case, the source location was in a direction near the galactic plane, where the amount of matter along the line of sight gives a pretty high absorption column, especially at optical wavelengths. In fact, optical observations[62] started about one day after the GRB and gave null results. But, because of the galactic absorption, one would have expected a detection in the infrared range (12 and 174 microns). We used the *Infrared Space Observatory* (ISO) to perform a target-of-opportunity observation only 55 hours after the GRB,[63] but again a null result was obtained.

5 Conclusions

As we have seen, BeppoSAX has radically changed our way of looking at GRBs and has probably discovered their origin. Since we generally know very little about the nature of GRBs, we don't feel secure in saying that BeppoSAX has discovered their origin. What we can surely state is that we have discovered the origin of at least two GRBs. What is needed in the future is, of course, a larger number of afterglow detections, with more optical counterparts found and redshifts measured. In this respect, BeppoSAX has created a *method* that we now know is correct in bringing us toward the solution of the mystery.

Following the BeppoSAX example other satellites have set up procedures for rapid GRB follow-up. Of particular interest is the capability of the *All Sky Monitor* instrument onboard the *Rossi X-Ray Timing Explorer* mission, to locate a GRB just like the BeppoSAX/WFC, with more limitations, but with a faster reaction time (due to the fact that unlike BeppoSAX, the RXTE satellite is continuously visible from the ground). This new effort has already resulted in a successful detection of a GRB afterglow [GRB970828 (see Refs. 64 and 65)], thanks to the collaboration with the PCA instrument onboard the same satellite and with the ASCA satellite. The X-ray temporal behavior is again compatible with what was observed in the case of GRB970228, but no optical or radio counterpart has been found.[66] Also, BATSE is getting small enough error boxes to be rapidly explored by the PCA instrument, but the attempts performed so far have given null results, possibly due to the unmatched sensitivity of the PCA with the GRB afterglows.

Acknowledgments

The important results presented here were obtained through the joint effort of all the components of the BeppoSAX Team, with particular regard to the operational teams. In particular, I wish to point out the fundamental contributions by the Mission Director, R. C. Butler; the Mission Scientist, L. Piro; and by E. Costa and F. Frontera, scientists responsible for the WFC/GRBM program on GRBs. Finally, I wish to thank the BATSE team for making their data publicly available.

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