Discovery of the X-Ray Afterglow of the Gamma-Ray Burst of February 28 1997

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The understanding of the nature of gamma-ray bursts is recognised to be one of the major challenges of high energy astrophysics. These flashes of gamma-rays are isotropically distributed in the sky, but inhomogeneously distributed in space, with a deficit of faint bursts \[1\]. It is not yet known if they are produced in our galaxy or at cosmological distance. Only the detection and identification of their counterpart could provide the needed breakthrough to determine the site and the physics of the gamma-ray burst phenomenon. Here we report the discovery in the X-ray band of the first afterglow of a gamma-ray burst. It was detected and quickly positioned by the Beppo-SAX satellite \[2\] on 1997 February 28 (GRB970228 \[3\]). The X-ray afterglow source was detected \[4\] with the X-ray telescopes aboard the same satellite about eight hours after the burst and faded away in a few days with a power law decay function. The energetic content of the X-ray afterglow results to be a significant fraction of gamma-ray burst energetics. The Beppo-SAX detection and fast imaging of GRB970228 started a multiwavelength campaign that lead to the identification of a fading optical source \[5\] in a position consistent with the X-ray source \[6\].

The main reason of our ignorance on the nature of Gamma-Ray Burst (GRB) sources is the unfavourable combination of an unusual phenomenology and instrumental inadequacy. Gamma-ray telescopes have a poor imaging capability and GRBs only last from a fraction of a second to hundreds of seconds. In any case, after a short time they are no longer detectable in the gamma-ray band even with large detectors. The burst decay is so fast and the positioning uncertainty so large that no search for delayed emission in other wavelengths could so far be successfully attempted \[7\].

The Italian-Dutch Beppo SAX satellite \[8\] includes many experiments in different energy bands and with different fields of view. In particular, the combined presence of an all-sky Gamma-Ray Burst Monitor (GRBM) \[9, 10\], in the 40-700 keV energy
range and two Wide Field Cameras (WFCs) [11], that cover about 5% of the sky, in
the 2-26 keV energy range, with a pixel size of 5 arcminutes, allows an unprecedented
capability of detecting and fast positioning GRBs and starting follow-up observations.

We developed a procedure for fast localization and rapid follow-up GRBs ob-
servation with the Beppo-SAX Narrow Field Instruments (NFIs), a cluster of tele-
scopes pointing the same field of view and covering the large band of 0.1-300 keV
[12, 13, 14, 10], taking advantage of having them aboard the same satellite and under
the same Operation Control Centre.

On 1997 February 28.123620 UT the GRBM onboard selection logics was triggered
by a GRB event. When the data from the whole orbit were transferred to the ground
station and forwarded to the Scientific Operation Centre quick look analysis of WFCs
data at the trigger time showed that a counting excess was also present in one WFC.
The X-ray excess was imaged showing a point-like source. WFC images before and
after the event showed that the source was transient and simultaneous with the burst.
Light curves in the gamma-ray and X-ray band are shown in Figure 1.

The burst position was first determined from a quick look analysis of the WFC
data with an error radius of about 10 arcmin suitable to plan a Target of Opportunity
(TOO1) pointing of the GRB field with Beppo-SAX NFIs. After few hours through
off-line attitude analysis we obtained for the GRB970228 a refined error box of 3
arcmin radius, centered at \( \alpha = 05^h01^m57^s, \delta = 11^\circ46'.4 \) (equinox 2000.0). With
these refined position observations in other wavelengths were solicited.

The first observation by the Narrow Field Instruments of Beppo-SAX started on
February 28.4681, 8 hours only after the GRBM trigger, and ended on 28.8330. The
total exposure time was 14,344 s in the Medium Energy Concentrator Spectrometer
and 8,725 s in the Low Energy Concentrator Spectrometer. In the refined WFC error
box we found only one source: 1SAX J0501.7+1146 with coordinates (equinox 2000.0)
\( \alpha = 05^h01^m44^s \) and \( \delta = 11^\circ46'.7 \) and a 90% confidence error radius of 50 arcseconds.
Since the pointing of NFI was based on the first coarse positioning of the GRB in two of the three medium energy telescopes the source was partially covered by the window support structure. To exclude spurious variability due to pointing drifts, in the analysis we only use data from the LECS and only one out of three MECS units.

The source energy spectrum in the 0.1-10 keV band is consistent with a power law of photon index $2.1 \pm 0.3$. The hydrogen column density is $3.5^{+3.3}_{-2.3} \times 10^{21}$ cm$^{-2}$ and consistent with the Galactic absorption along the line of sight $1.6 \times 10^{21}$ cm$^{-2}$. The 2-10 keV average source flux during this observation was $(2.8 \pm 0.4) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, while the 0.1-2 keV flux was $(1.0 \pm 0.3) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (note that this corrects the power law photon index, the fluxes and the hydrogen column density quoted in ref. [5]). We also searched for hard X-ray emission (15-100 keV) with the Phoswich Detection System without detecting any line or continuum flux. The 3σ upper limit on the 15-100 keV emission is $4.3 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is higher than the extrapolation from the low energy power law.

We performed a second Target of Opportunity (TOO2) observation of the field with Beppo-SAX NFI, about three days after the GRB970228 occurrence time (from March 3.7345 to March 4.1174). The exposure time was 16,270 s with the MECS and 9,510 s with the LECS. A source at a position consistent with that of 1SAX J0501.7+1146 was detected in the MECS. Assuming the above spectral shape, the 2-10 keV flux was $(1.5 \pm 0.5) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, a factor about 20 lower than in TOO1. The source was not detected in the LECS and the 3σ upper limit in the 0.1-2 keV band was $4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. In Figure 2 we show the MECS image of the source in the first and in the second observation. This position is consistent with the GRB error box obtained with WFC and the GRB error annulus resulting from the Interplanetary Network (IPN) based on Beppo-SAX GRBM/Ulysses experiments [10].

No source was present in this position in the ROSAT All Sky Survey [17] with
a flux upper limit at 2.5 $\sigma$ of $1.9 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, in the range 0.1–2.4 keV, a value compatible with the LECS TOO2 but not with TOO1.

The transient time behaviour and the positional coincidence strongly support the association of SAX J0501.7+1146 with GRB970228. Using the statistics of X-ray sources derived from the GINGA background analysis we estimate that the probability to have by chance in a field of 3 arcmin radius a source of intensity equal or higher than the one we detected is less than $8 \times 10^{-4}$. This probability value is reduced by at least a factor 5 if we take into account the intersection of the error annulus of 30 arcsec half-width derived from IPN for GRB970228 with the WFC and NFI error boxes.

While results of a detailed spectral analysis of 1SAXJ0501.7+1146 and GRB970228 will be reported in another paper (Frontera et al., to be submitted), we devote the rest of this letter to the remarkable time behaviour of the source. Figure 3 shows the 2-10 keV flux evolution during the two TOO observations. The source flux shows a significant decrease within the TOO1 observation. The reduced $\chi^2$ (3 degrees of freedom) for a constant flux is 3.6 corresponding to a probability of 0.13%. We tried to fit data of both observations with a single law. An exponential decay function does not fit the data. The best fit of the TOO1 and TOO2 flux data versus time were obtained with a power law function ($\propto t^{-\alpha}$) (see Fig.3). The best fit index is given by $\alpha = 1.33^{+0.13}_{-0.11}$ ($\chi^2$ per degree of freedom (dof) = 0.7 with 4 dof).

We have also compared the flux and the decay law found for 1SAX J0501.7+1146 with the fluxes measured with GRBM and WFC during the entire gamma-burst and during the following minor pulses shown in Fig. 1. In Fig. 3 (left top) dashed line shows the 2-10 keV Wide Field Cameras flux averaged over 80 s corresponding to the entire burst duration, while the solid line gives the average flux of the three minor pulses. Both fluxes are consistent with the extrapolation of the derived afterglow decay law. This strongly suggests that the X-ray emission detected soon after the
GRB continuously evolves into the X-ray emission of the afterglow.

This result has a straight implication in terms of the energetics of the event. The GRB fluence measured by GRBM in 40–700 keV was $1.1 \times 10^{-5}$ erg cm$^{-2}$. The X-ray fluence measured by WFC in 2–10 keV was about $1.2 \times 10^{-6}$ erg cm$^{-2}$, that is about 11% of the gamma-ray fluence. If we assume that the three last pulses in Fig.1 are part of the afterglow by integrating the power law from 35 s to infinity we find, in the window 2-10 keV, a fluence which is about 40% of the energy in the gamma burst itself in the band 40–700 keV. The X-ray afterglow is not only the low energy tail of the GRB phenomenon but it is a significant channel of energy dissipation of the event on a completely different timescale.

The well established power law decay function of the GRB remnant flux, the consistency of its extrapolation with the X-ray flux at the time of the burst, and the energetic content in X-rays are the main results of our discovery. They will significantly impact on GRB models of and constrain their parameters. Indeed the fast detection of GRB970228, promptly communicated to the scientific community [3, 9], triggered both the Beppo-SAX NFI follow-up and observations in the radio [21, 22] and optical bands [23, 24, 26, 27]. These observations lead to cogent limits to the radio emission and, most, to the detection [5, 28, 29, 30, 31, 32] of an optical transient, in a position consistent with that of 1SAX J0501.7+1146 that faded in a few days. We note, however, that a previous GRB detected by Beppo-SAX, GRB970111 [33], had a gamma-ray fluence six times larger than GRB970228 and an undetectable X-ray emission 16 hours after the burst. No fading optical source was detected at a level of magnitude B=23 and R=22.6 [34].

The Beppo-SAX measurement, in addition to the discovery of a relevant delayed X-ray emission, has thus provided the link missing for 25 years between the gamma-ray phenomenology and the ultimate location capability of X-ray, optical and radio astronomy. We expect more future detections of GRBs by Beppo-SAX GRBM/WFC,
along with their follow-up observations. We hope that the existence of X-ray/optical afterglows and their rapid detection will contribute to unambiguously identify the GRB sources.

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FIGURE CAPTIONS

Fig.1. Time profile of GRB970228 in the Gamma-ray (from the Gamma Ray Burst Monitor) and X-ray (from the Wide Field Camera) bands. The origin is the trigger time. The first pulse is short in Gamma-rays than in X-rays. Three other pulses follow (at around 35, 50 and 70s from the trigger) that are much more enhanced in the X-ray band. The total burst duration is about 80s.

Fig.2 Images of the source, 1SAX J0501.7+114, as detected with Beppo-SAX Medium Energy Concentrator Spectrometer (2–10 keV) in the error box of GRB90228 during a first and a second Beppo-SAX Target of Opportunity observation. From the ASCA faint sources data the probability that the source detected during the second pointing is coincident by chance with the position of 1SAX J0501.7+1146 is of the order of $1 \times 10^{-3}$. From one pointing to the other the source is faded by a factor 20 in three days.

Fig.3. Source flux with time in the 2-10 keV range. Data from the TOO1 are grouped into 4 points of 8000 s duration each. Data from the TOO2 are grouped in one point only due to the lower statistics. The zero time is taken at the GRBM trigger time. Data are fitted by a power law ($\propto t^{-1.32}$). This law is shown as a solid line. The forward extrapolation of the same law is consistent with the flux detected by ASCA on March 7.028 of $(8 \pm 0.3) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (averaged value for SIS and GIS detectors), in same energy range.

The same law extrapolated backward at the time of the GRB (described by arrows in the left top) is well matched with the average flux of $2.3 \times 10^{-8}$ erg cm$^{-2}$s$^{-1}$ detected by WFC in the three minor pulses of Fig.1 from 35 to 70 s.

Also shown is the 3σ upper limit of the source flux obtained with WFC 5000 s after the burst for an exposure time to the source of 1000 s.
GRB970228

- WFC (0 - 100 s)
- WFC (35 - 70 s)
- BeppoSAX TOO1
- BeppoSAX TOO2
- ASCA TOO
- Upper Limit WFC (4528 - 5528 s)

10^{-2} \text{ erg sec}^{-1} \text{ cm}^{-2}

Time (sec)