Discovery of an X-ray afterglow associated with the γ-ray burst of 28 February 1997

E. Costa†, F. Frontera‡‡, J. Heise§§, M. Feroci†, J. in’t Zand†, F. Fiore†, M. N. Cinti†, D. Dal Fiume†, L. Nicastro†, M. Orlandini†, E. Palazzi†, M. Rapisarda†, G. Zavattoni†, R. Jager†, A. Parmar†, A. Owens†, S. Molendi†, G. Cusumano†, M. C. Maccarone†, S. Giarrusso†, A. Coletta††, L. A. Antonelli, P. Giommi‡, J. M. Muller§§, L. Piro† & R. C. Butler§§

* Istituto di Astrofisica Spaziale, CNR, Via E. Fermi 21, I-00044 Frascati, Italy † Istituto Tecnologie e Studio Radiazioni Extraterrestri, CNR, Via Gobetti 101, I-40129 Bologna, Italy ‡ Dipartimento di Fisica, Università Ferrara, Via Paradiso 12, I-44100 Ferrara, Italy § Space Research Organization in the Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands † Istituto di Fisica Cosmica e Tecnologie Relative, CNR, Via Bassini 15, I-20133 Milano, Italy †† Istituto di Fisica Cosmica e Applicazioni Informatiche, CNR, Via U. La Malfa 153, I-90139 Palermo, Italy ‡‡ Beppo-SAX Science Operation Center, Via Corrolejo 19, I-00131 Roma, Italy §§ Agenzia Spaziale Italiana, Viale Regina Margherita 202, I-00198 Roma, Italy

Establishing the nature of γ-ray bursts is one of the greatest challenges in high-energy astrophysics. The distribution of these bursts is isotropic across the sky, but inhomogeneous in space, with a deficit of faint bursts. It is currently unknown whether γ-ray bursts are produced in our Galaxy or at cosmological distances. The detection and identification of counterparts at other wavelengths are seen as crucial for resolving the origin of the events. Here we report the detection by the Beppo-SAX satellite of an X-ray "afterglow", associated with the γ-ray burst of 28 February 1997 (GRB970228; ref. 3) — the first such detection for any γ-ray burst. The X-ray transient was found to contain a significant fraction of the total energy of the γ-ray burst and, following the initial detection eight hours after the main burst, faded within a few days with a power-law decay function. The rapid locating of this γ-ray burst instigated a multi-wavelength observational campaign that culminated in the identification of a fading optical transient in a position consistent with the X-ray transient reported here.

The main reason of our ignorance of the nature of γ-ray burst (GRB) sources is the unfavourable combination of an unusual phenomenology and instrumental inadequacy. γ-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 γ-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 has so far been successfully attempted.

The Italian–Dutch Beppo-SAX satellite 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) in the 40–700 keV energy range, and two Wide Field Cameras (WFCs) in the 2–26 keV energy range, which cover ~5% of the sky with a pixel size of 5 arcmin, allows an unprece-
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 \( 4 \times 10^{20} \text{ cm}^{-2} \) and consistent with the Galactic absorption along the line of sight \( 4 \times 10^{20} \text{ cm}^{-2} \), whereas the 0.1–2 keV flux was \( 3.0 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \) and gray to a background of \( 0.1 \text{ counts per pixel} \). Taking into account the correction for the number of telescopes (one in TOO1 and three in TOO2) and the vignetting in TOO1, due to off-axis pointing, the source faded by a factor of \( \sim 20 \) in three days. 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 \( 1 \times 10^{-3} \).

This position is consistent with the GRB error box obtained with WFC, and with the GRB error annulus resulting from the Interplanetary Network (IPN) based on Beppo-SAX GRBM/Ulysses experiments.

No source was present in this position in the ROSAT all-sky survey \( 1SAX\ J0501.7+1146 \) with Beppo-SAX Medium Energy Concentrator Spectrometers (2–10 keV) during the first and second Target of Opportunity observations (TOO1 and TOO2, respectively). White corresponds to 31 counts per pixel, green corresponds to 6 counts per pixel, and gray to a background of 0.1 counts per pixel. Taking into account the correction for the number of telescopes (one in TOO1 and three in TOO2) and the vignetting in TOO1, due to off-axis pointing, the source faded by a factor of \( \sim 20 \) in three days. 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 \( 1 \times 10^{-3} \).

**Figure 2** False-colour images of the source \( 1SAX\ J0501.7+1146 \), as detected in the error box of GRB970228 with Beppo-SAX Medium Energy Concentrator Spectrometer (2–10 keV) during the first and second Target of Opportunity observations (TOO1 and TOO2, respectively). White corresponds to 31 counts per pixel, green corresponds to 6 counts per pixel, and gray to a background of 0.1 counts per pixel. Taking into account the correction for the number of telescopes (one in TOO1 and three in TOO2) and the vignetting in TOO1, due to off-axis pointing, the source faded by a factor of \( \sim 20 \) in three days. 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 \( 1 \times 10^{-3} \).

**Figure 3** Variation of source flux with time in the 2–10 keV range. Data from the TOO observations are grouped into four points of 8,000 s duration each. Data from TOO 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 \( (x \pm 10^{-12}) \text{ erg cm}^{-2} \text{ s}^{-1} \). This law is shown as a solid sloping line at lower right. The forward extrapolation of the same law is consistent with the flux detected by ASCA\( ^{34} \) on March 7.028 of \( (8 \pm 0.03) \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \) (averaged value for SIS and GIS detectors), in same energy range. The same law extrapolated backwards (dotted line) to the approximate time of the GRB (described by arrows in the top left) is a good match with the average flux of \( 2.3 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \) detected by WFC in the three minor pulses of Fig. 1 from 35 to 70 s. Also shown is the \( 3 \sigma \) upper limit of the source flux obtained with WFC ~5,000 s after the burst, for an exposure time to the source of 1,000 s.

This position is consistent with the GRB error box obtained with WFC, and with the GRB error annulus resulting from the Interplanetary Network (IPN) based on Beppo-SAX GRBM/Ulysses experiments.

No source was present in this position in the ROSAT all-sky survey \( 1SAX\ J0501.7+1146 \) with Beppo-SAX Medium Energy Concentrator Spectrometers (2–10 keV) during the first and second Target of Opportunity observations (TOO1 and TOO2, respectively). White corresponds to 31 counts per pixel, green corresponds to 6 counts per pixel, and gray to a background of 0.1 counts per pixel. Taking into account the correction for the number of telescopes (one in TOO1 and three in TOO2) and the vignetting in TOO1, due to off-axis pointing, the source faded by a factor of \( \sim 20 \) in three days. 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 \( 1 \times 10^{-3} \).

The transient time behaviour and the positional coincidence strongly support the association of \( 1SAX\ J0501.7+1146 \) with Beppo-SAX Medium Energy Concentrator Spectrometers (2–10 keV) during the first and second Target of Opportunity observations (TOO1 and TOO2, respectively). White corresponds to 31 counts per pixel, green corresponds to 6 counts per pixel, and gray to a background of 0.1 counts per pixel. Taking into account the correction for the number of telescopes (one in TOO1 and three in TOO2) and the vignetting in TOO1, due to off-axis pointing, the source faded by a factor of \( \sim 20 \) in three days. 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 \( 1 \times 10^{-3} \).

The transient time behaviour and the positional coincidence strongly support the association of \( 1SAX\ J0501.7+1146 \) with Beppo-SAX Medium Energy Concentrator Spectrometers (2–10 keV) during the first and second Target of Opportunity observations (TOO1 and TOO2, respectively). White corresponds to 31 counts per pixel, green corresponds to 6 counts per pixel, and gray to a background of 0.1 counts per pixel. Taking into account the correction for the number of telescopes (one in TOO1 and three in TOO2) and the vignetting in TOO1, due to off-axis pointing, the source faded by a factor of \( \sim 20 \) in three days. 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 \( 1 \times 10^{-3} \).

This position is consistent with the GRB error box obtained with WFC, and with the GRB error annulus resulting from the Interplanetary Network (IPN) based on Beppo-SAX GRBM/Ulysses experiments.

The transient time behaviour and the positional coincidence strongly support the association of \( 1SAX\ J0501.7+1146 \) with Beppo-SAX Medium Energy Concentrator Spectrometers (2–10 keV) during the first and second Target of Opportunity observations (TOO1 and TOO2, respectively). White corresponds to 31 counts per pixel, green corresponds to 6 counts per pixel, and gray to a background of 0.1 counts per pixel. Taking into account the correction for the number of telescopes (one in TOO1 and three in TOO2) and the vignetting in TOO1, due to off-axis pointing, the source faded by a factor of \( \sim 20 \) in three days. 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 \( 1 \times 10^{-3} \).
not fit the data. The best fit of the TOO1 and TOO2 flux data versus time was obtained with a power-law function (\(\xi(t)\)) (see Fig. 3). The best-fit index is given by \(\alpha = 1.33^{+0.06}_{-0.11}\) (\(x^2\) per d.o.f. = 0.7 with 4 d.o.f.).

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 \(\gamma\)-ray burst and during the following minor pulses shown in Fig. 1. In Fig. 3 (top left), the dashed line shows the 2–10 keV flux averaged over 100 s corresponding to the entire burst duration, whereas the solid horizontal line gives the average flux of the three minor pulses. Both fluxes are consistent with the backward 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 an implication for the energetics of the event. The GRB fluence measured by GRBM in the 40–700 keV band was \(1.1 \times 10^{-8} \text{ erg cm}^{-2}\). The X-ray fluence measured by WFC in the 2–10 keV band was \(1.2 \times 10^{-8} \text{ erg cm}^{-2}\), that is \(\sim 11\%\) 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, for the window 2–10 keV, a fluence which is \(\sim 40\%\) of the energy in the \(\gamma\)-ray burst itself in the band 40–700 keV. The X-ray afterglow is not only the low-energy tail of the GRB phenomenon but is also 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 affect models of GRBs and constrain their parameters. Indeed the fast detection of GRB970228, promptly communicated to the scientific community, triggered both the Beppo-SAX NFI follow-up and observations in the radio,\(^{19,20}\) and optical bands.\(^{21-25}\) These observations lead to cogent limits to the radio emission and to the detection\(^{26-30}\) 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, GRB970113\(^{31}\), had a \(\gamma\)-ray fluence about four 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 \(R = 22.6\) (ref. 32).

The Beppo-SAX measurement, in addition to discovering 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 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 the unambiguous identification of the GRB sources.

Recent discoveries of objects orbiting beyond Neptune\(^{1-3}\) have emphasized that our understanding of the distribution and dynamics of material in the outer Solar System is very incomplete. This trans-neptunian population—known as the Kuiper belt—is thought to act as a relatively stable reservoir of objects that could become short-period comets\(^{4-6}\), although there may be other regions of stability in the outer Solar System that could also supply such comets. Here I use numerical simulations to identify one such long-lived region between the orbits of Uranus and Neptune. I show that in the region 24–27 \(\text{au}\) from the Sun, about 0.3 per cent of an initial population of small bodies moving on low-eccentricity, low-inclination orbits could survive for the age of the Solar System. The actual existence of this hypothetical belt is not precluded by currently available observational limits, and there could be as much as \(\sim 5 \times 10^{-4}\) Earth masses of material populating this region—comparable to the mass of the asteroid belt between Mars and Jupiter.

Numerical investigations show there are few such regions in the outer Solar System where material could survive for the age of Solar System without being ejected through the gravitational influence of the giant planets.\(^{12,13}\) In a recent study\(^{7}\), a few thousand test particles, starting from circular orbits in the plane of the Solar System from \(5\) to \(50\) \(\text{au}\) from the Sun, were numerically integrated for times up to 800 Myr. Later work extended this to 4.5 \(\text{Gyr}\) for the regions between the outer planets and to 1 \(\text{Gyr}\) beyond Neptune.\(^{11}\) During the integrations, any test particle that entered the gravitational sphere of influence of a planet\(^{12}\) was removed from the simulation. Such test particles are typically ejected from the Solar System in another \(10^6-10^7\) \(\text{yr}\) (ref. 13). The results are shown in Fig. 1. The green points mark the close encounter times as a function of semimajor axis; the red points indicate those test particles that survived the full...