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

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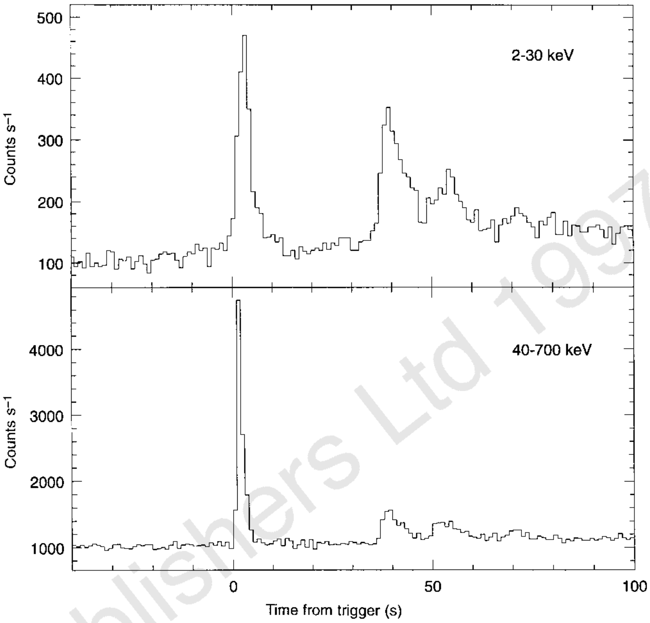

Figure 1 Time profile of GRB970228 in the γ-ray (from the Gamma-Ray Burst Monitor) and X-ray (from the Wide Field Camera) bands. The origin is the trigger time. The first pulse is shorter in γ-rays than in X-rays. Three other pulses follow (at $\sim$35, 50 and 70 s from the trigger) that are much enhanced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

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[1]. 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[2] 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[4] 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[5] of a fading optical transient in a position consistent[6] 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[7].

The Italian–Dutch Beppo-SAX satellite[2,8] 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] in the 2–26 keV energy range, which cover $\sim$5% of the sky with a pixel size of 5 arcmin, 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 observations of GRBs with the Beppo-SAX Narrow Field Instruments (NFIs), a cluster of telescopes pointing towards the same field of view and covering the large band of 0.1–300 keV (refs 10, 12–14), taking advantage of having them aboard the same satellite and under the same Operation Control Centre.

On 1997 February 28.123620 UT the GRBM was triggered by a GRB event (GRB970228). When the data from the whole orbit were transferred to the ground station and forwarded to the Scientific Operation Centre, 'quick-look' analysis of data from the WFCs 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 γ-ray and X-ray band are shown in Fig. 1.

The burst position was first determined from a 'quick-look' analysis of the WFC data with an error radius of $\sim$10 arcmin, suitable for planning a Target of Opportunity pointing (TOO1) of the GRB field with Beppo-SAX NFIs. After few hours, using off-line attitude analysis, we obtained for GRB970228 a refined error box of 3 arcmin radius, centred at right ascension (RA) 05 h 01 min 57 s, declination (dec.) 11° 46.4′ (equinox 2000.0). With this refined position, observations in other wavelengths were solicited.

The first observation by the NFIs of Beppo-SAX started on February 28.4681, only 8 hours after the GRBM trigger, and ended on February 28.8330. The total exposure time was 14,344 s in the Medium Energy Concentrator Spectrometer (MECS) and 8,725 s in the Low Energy Concentrator Spectrometer (LECS). In the refined WFC error box we found only one source: 1SAX J0501.7 + 1146 with coordinates (equinox 2000.0) RA 05 h 01 min 44 s, dec. 11° 46.7′ and a 90% confidence error radius of 50 arcsec.

As the pointing of NFIs was based on the first coarse positioning of the GRB in two of the three medium-energy telescopes, the

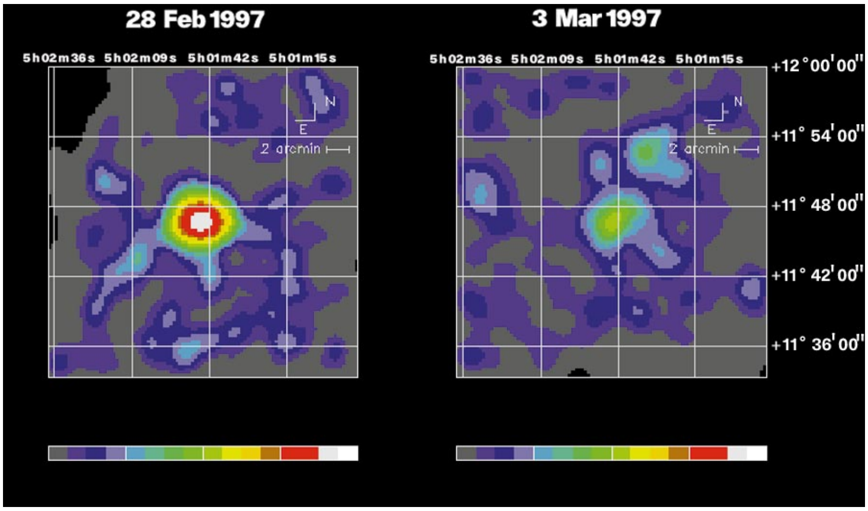

Figure 2 False-colour images of the source 1SAX J0501.7 + 1146, as detected in the error box of GRB970228 with Beppo-SAX Medium Energy Concentrator Spectrometer (2–10 keV) during the first and second Target of Opportunity observations (TOO1 and TOO2, respectively). White corresponds to 31 counts per pixel^2, green corresponds to 6 counts per pixel^2 and grey to a background of 0–1 counts per pixel^2. 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 ~20 in three days. From the ASCA faint sources data[33], 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 1×10^{-3}.

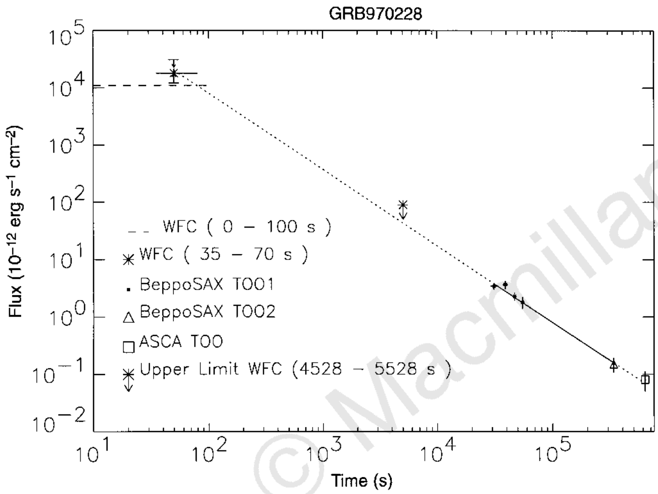

Figure 3 Variation of source flux with time in the 2–10 keV range. Data from the TOO1 observation are grouped into four points of 8,000-s duration each. Data from TOO2 are grouped in one point only due to the lower statistics. The zero time is taken at the GRBM trigger time. Data are fitted by a power law ($\propto t^{-1.32}$). This law is shown as a solid 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 $(8 \pm 0.3) \times 10^{-14}$ erg cm^{-2} 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 2.3×10^{-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~5,000 s after the burst, for an exposure time to the source of 1,000 s.

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 ± 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 1.6×10^{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}, whereas the 0.1–2 keV flux was $(1.0 \pm 0.3) \times 10^{-12}$ erg cm^{-2} s^{-1} (note that the power-law photon index, the fluxes and the hydrogen column density quoted in ref. 5 are not correct). 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 4.3×10^{-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 observation (TOO2) of the field with Beppo-SAX NFIs, 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 8,510 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 ~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 4×10^{-13} erg cm^{-2} s^{-1}. In Fig. 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 with the GRB error annulus resulting from the Interplanetary Network (IPN) based on Beppo-SAX GRBM/Ulysses experiments[15].

No source was present in this position in the Rosat all-sky survey[16] with a flux upper limit at 2.5σ of 1.9×10^{-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 1SAX J0501.7 + 1146 with GRB970228. Using the statistics of X-ray sources derived from the GINGA background analysis[17] we estimate that the probability to have by chance in a field of 3 arcmin radius a source of intensity equal to or higher than the one we detected is $< 8 \times 10^{-4}$. This probability value is reduced by a factor of at least 5 if we take into account the intersection of the error annulus of 30-arcsec half-width derived from IPN for GRB970228[15,18] with the WFC and NFI error boxes.

Although results of a detailed spectral analysis of 1SAX J0501.7 + 1146 and GRB970228 will be reported elsewhere (F. Frontera *et al.*, manuscript in preparation), we examine here 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 χ^2 (3 degrees of freedom, d.o.f.) 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 was obtained with a power-law function ($\propto t^{-\alpha}$) (see Fig. 3). The best-fit index is given by $\alpha = 1.33^{+0.13}_{-0.11}$ (χ^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 γ-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 1.1×10^{-5} erg cm^{-2}. The X-ray fluence measured by WFC in the 2–10 keV band was $\sim 1.2 \times 10^{-6}$ erg cm^{-2}, that is ~11% of the γ-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 ~40% of the energy in the γ-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[3,4], 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[5,26–30] 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, GRB970111[31], had a γ-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 γ-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. ☐

Received 9 April; accepted 22 May 1997.

1. Fishman, G. J. & Meegan, C. A. Gamma ray bursts. *Annu. Rev. Astron. Astrophys.* **33,** 415–458 (1995).
2. Boella, G. *et al.* Beppo SAX, the wide band mission for X-ray astronomy. *Astron. Astrophys. Suppl. Ser.* **122,** 299–307 (1997).
3. Costa, E. *et al. IAU Circ.* No. 6572 (1997).
4. Costa, E. *et al. IAU Circ.* No. 6576 (1997).
5. van Paradijs, J. *et al.* Transient optical emission from the error box of the γ-ray burst of 28 February 1997. *Nature* **386,** 686–688 (1997).
6. Frontera, F. *et al. IAU Circ.* No. 6637 (1997).
7. Vrba, F. *Searches for gamma-ray bursts counterparts: current status and future prospects.* 565–574 (AIP Proc. 384, Am. Inst. Phys., Huntsville, AL, 1996).
8. Piro, L., Scarsi, L. & Butler, R. C. in *X-Ray and EUV/FUV Spectroscopy and Polarimetry* (ed. Fenischi, S.) 169–181 (SPIE 2517, San Diego, 1995).
9. Costa, E. *et al.* The gamma-ray burst monitor onboard SAX. *Adv. Space Res.* (submitted).
10. Frontera, F. *et al.* The high energy instruments PDS on-board the BeppoSAX X-ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.* **122,** 357–369 (1997).
11. Jager, R. *et al.* The Wide Field cameras onboard the BeppoSAX X-ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.* (submitted).
12. Parmar, A. *et al.* The low energy concentrator spectrometer on-board the BeppoSAX X-ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.* **122,** 309–326 (1997).
13. Boella, G. *et al.* The medium energy concentrator spectrometer on-board the BeppoSAX X-ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.* **122,** 327–340 (1997).
14. Manzo, G. *et al.* The high pressure gas scintillation proportional counter on-board the BeppoSAX X-ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.* **122,** 341–356 (1997).
15. Hurley, K. *et al.* 3rd Interplanetary Network localization, time history, fluence, and peak flux of the February 28, 1997 gamma-ray burst. *Astrophys. J. Lett.* (in the press).
16. Boller, T. *et al. IAU Circ.* No. 6580 (1997).
17. Warwick, R. & Stewart, G. in *Proc. 23rd ESLAB Symp. on Two-Topics in X-Ray Astronomy* (eds Hunt, J. & Batteick, B.) 727–731 (SP-296, ESA, Bologna, 1989).
18. Cline, T. L. *et al. IAU Circ.* No. 6593 (1997).
19. Galama, T. J. *et al. IAU Circ.* No. 6574 (1997).
20. Frail, D. A. *et al. IAU Circ.* No. 6576 (1997).
21. Metzger, R. M. *et al. IAU Circ.* No. 6588 (1997).
22. Pedersen, H. *et al. IAU Circ.* No. 6580 (1997).
23. Wagner, *et al. IAU Circ.* No. 6581 (1997).
24. Tonry, J. L. *et al. IAU Circ.* No. 6620 (1997).
25. Metzger, M. R. *et al. IAU Circ.* No. 6631 (1997).
26. Guarnieri, A. *et al.* Earliest detection of an optical transient following the gamma-ray burst GRB970228. *Astron. Astrophys. Lett.* (submitted).
27. Margon, B. *et al. IAU Circ.* No. 6618 (1997).
28. Pedichini, F. *et al. IAU Circ.* No. 6635 (1997).
29. Sahu, K. *et al. IAU Circ.* No. 6606 (1997).
30. Sahu, K. *et al. IAU Circ.* No. 6619 (1997).
31. Costa, E. *et al. IAU Circ.* No. 6533 (1997).
32. Castro-Tirado, A. *et al. IAU Circ.* No. 6598 (1997).
33. Georgentopoulos, I. *et al.* ASCA observations of deep ROSAT fields I: the nature of the X-ray source populations. *Mon. Nat. R. Astron. Soc.* (in the press).
34. Yoshida, A. *et al. IAU Circ.* No. 6593 (1997).

Acknowledgements. This research is supported by the Italian Space Agency (ASI) and Consiglio Nazionale Ricerche of Italy. Beppo-SAX is a joint program of ASI and the Netherlands Agency for Aerospace Programs (NIVR). We thank the staff at the Beppo-SAX Scientific Operation Centre and the Operation Control Centre for their contributions to the GRB research program.

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A possible long-lived belt of objects between Uranus and Neptune

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Recent discoveries of objects orbiting beyond Neptune[1–5] 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[6–9], 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 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[7,10]. 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 AU from the Sun, were numerically integrated for times up to 800 Myr. Later work extended this to 4.5 Gyr for the regions between the outer planets and to 1 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 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