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LETTERS

A short γ-ray burst apparently associated with an elliptical galaxy at redshift z = 0.225

N. Gehrels[1], C. L. Sarazin[2], P. T. O'Brien[3], B. Zhang[4], L. Barbier[1], S. D. Barthelmy[1], A. Blustin[5], D. N. Burrows[6], J. Cannizzo[1,7], J. R. Cummings[1,8], M. Goad[3], S. T. Holland[1,9], C. P. Hurkett[3], J. A. Kennea[6], A. Levan[3], C. B. Markwardt[1,10], K. O. Mason[5], P. Meszaros[6], M. Page[5], D. M. Palmer[11], E. Rol[3], T. Sakamoto[1,8], R. Willingale[3], L. Angelini[1,7], A. Beardmore[3], P. T. Boyd[1,7], A. Breeveld[5], S. Campana[12], M. M. Chester[6], G. Chincarini[12,13], L. R. Cominsky[14], G. Cusumano[15], M. de Pasquale[5], E. E. Fenimore[11], P. Giommi[16], C. Gronwall[6], D. Grupe[6], J. E. Hill[6], D. Hinshaw[1,17], J. Hjorth[18], D. Hullinger[1,10], K. C. Hurley[19], S. Klose[20], S. Kobayashi[6], C. Kouveliotou[21], H. A. Krimm[1,9], V. Mangano[12], F. E. Marshall[1], K. McGowan[5], A. Moretti[12], R. F. Mushotzky[1], K. Nakazawa[22], J. P. Norris[1], J. A. Nousek[6], J. P. Osborne[3], K. Page[3], A. M. Parsons[1], S. Patel[23], M. Perri[16], T. Poole[5], P. Romano[12], P. W. A. Roming[6], S. Rosen[5], G. Sato[22], P. Schady[5], A. P. Smale[24], J. Sollerman[25], R. Starling[26], M. Still[1,9], M. Suzuki[27], G. Tagliaferri[12], T. Takahashi[22], M. Tashiro[27], J. Tueller[1], A. A. Wells[3], N. E. White[1] & R. A. M. J. Wijers[26]

Gamma-ray bursts (GRBs) come in two classes[1]: long (>2 s), soft-spectrum bursts and short, hard events. Most progress has been made on understanding the long GRBs, which are typically observed at high redshift ($z \approx 1$) and found in subluminous star-forming host galaxies. They are likely to be produced in core-collapse explosions of massive stars[2]. In contrast, no short GRB had been accurately (<10″) and rapidly (minutes) located. Here we report the detection of the X-ray afterglow from—and the localization of—the short burst GRB 050509B. Its position on the sky is near a luminous, non-star-forming elliptical galaxy at a redshift of 0.225, which is the location one would expect[3,4] if the origin of this GRB is through the merger of neutron-star or black-hole binaries. The X-ray afterglow was weak and faded below the detection limit within a few hours; no optical afterglow was detected to stringent limits, explaining the past difficulty in localizing short GRBs.

The new observations are from the Swift[5] satellite, which features the hard X-ray wide-field Burst Alert Telescope (BAT), and rapid spacecraft slewing to point the narrow-field X-ray Telescope (XRT) and the Ultraviolet-optical Telescope (UVOT) at the burst. On 9 May 2005 at 04:00:19.23 UT, the BAT triggered and located GRB 050509B on board[6]. The BAT location is shown in Fig. 1 (large red circle) and the light curves in Fig. 2. The event is a single short spike with duration of 40 ± 4 ms. The burst has a ratio of 50–100 keV to 25–25 keV fluences of 1.4 ± 0.5, which is consistent with, but in the soft portion of, the short/hard population detected by the first extensive GRB survey made with the Burst and Transient Source Experiment (BATSE). The 15–150 keV fluence is $(9.5 \pm 2.5) \times 10^{-9}$ erg cm^{-2}, which is the lowest imaged by BAT so far and is just below the short GRB fluence range detected by BATSE (adjusted for the different energy ranges of the two instruments).

Swift slewed promptly and XRT started acquiring data 62 s after the burst (T+62 s, where T is the BAT trigger time). Ground-processed data revealed an uncatalogued X-ray source near the centre of the BAT error circle containing 11 photons (5.7σ significance due to near-zero background in image) in the first 1,640 s of integration time. The XRT position is shown with respect to the Digitized Sky Survey (DSS) field in Fig. 1. A *Chandra* target-of-opportunity observation of the XRT error circle was performed on 11 May at 4:00 UT for 50 ks, with no sources detected in the XRT error circle. The light curve combining BAT, XRT and *Chandra* data are shown in Fig. 3. The UVOT observed the field starting at T+60 s. No new optical/ultraviolet sources were found in the XRT error circle to V-band magnitude > 19.7 for $t < 300$ min.

Swift has provided the first accurate localization of a short GRB. No optical afterglow was detected to stringent limits (R-band magnitude > 25 at 25 h; ref. 7). When the XRT error circle is plotted on the R-band image we obtained[8] with the Very Large Telescope (VLT), several faint objects are seen in the error circle, some of which are extended and could be high-redshift galaxies[9,10]. It is possible the burst occurred in one of these. However, the centre of the XRT error circle lies only 9.8″ away from the centre of the large E1 elliptical

[1]NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. [2]Department of Astronomy, University of Virginia, Charlottesville, Virginia 22903-0818, USA. [3]Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK. [4]Department of Physics, University of Nevada, Las Vegas, Nevada 89154-4002, USA. [5]Mullard Space Science Laboratory, University College London, Dorking RH5 6NT, UK. [6]Department of Astronomy and Astrophysics, Penn State University, University Park, Pennsylvania 16802, USA. [7]Joint Center for Astrophysics, University of Maryland, Baltimore County, Baltimore, Maryland 21250, USA. [8]National Research Council, 2101 Constitution Ave NW, Washington DC 20418, USA. [9]Universities Space Research Association, 10211 Wincopin Circle, Suite 500, Columbia, Maryland 21044-3432, USA. [10]Department of Astronomy, University of Maryland, College Park, Maryland 20742, USA. [11]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA. [12]INAF—Osservatorio Astronomico di Brera, Via Bianchi 46, I-23807 Merate, Italy. [13]Universita degli studi di Milano Bicocca, Piazza delle Scienze 3, I-20126 Milano, Italy. [14]Department of Physics and Astronomy, Sonoma State University, Rohnert Park, California 94928, USA. [15]INAF—Istituto di Astrofisica Spaziale e Cosmica, Via Ugo La Malfa 153, I-90146 Palermo, Italy. [16]ASI Science Data Center, Via Galileo Galilei, I-00044 Frascati, Italy. [17]SP Systems Inc., 7500 Greenway Center Drive, Greenbelt, Maryland 20770, USA. [18]Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark. [19]UC Berkeley Space Sciences Laboratory, Berkeley, California 94720-7450, USA. [20]Thüringer Landessternwarte Tautenburg, Sternwarte 5, D-07778 Tautenburg, Germany. [21]NASA/Marshall Space Flight Center, NSSTC, XD-12, 320 Sparkman Drive, Huntsville, Alabama 35805, USA. [22]Institute of Space and Astronautical Science, JAXA, Kanagawa 229-8510, Japan. [23]Universities Space Research Association, NSSTC, XD-12, 320 Sparkman Drive, Huntsville, Alabama 35805, USA. [24]Office of Space Science, NASA Headquarters, Washington DC 20546, USA. [25]Stockholm Observatory, Department of Astronomy, AlbaNova, 106 91 Stockholm, Sweden. [26]Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands. [27]Department of Physics, Saitama University, Sakura, Saitama 338-8570, Japan.

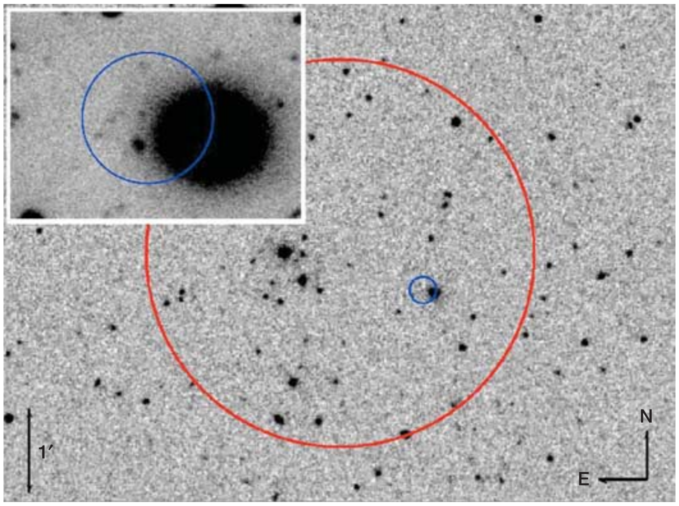

Figure 1 | Optical images of the region of GRB 050509B showing the association with a large elliptical galaxy. The Digitized Sky Survey image. The large red circle is the BAT position error circle, and the smaller blue circle is the XRT position error circle. The BAT position is 12 h 36 m 18 s, +28° 59′ 28″ (J2000) with a 2.3′ error radius (90% containment). The XRT, operating in its most sensitive 'photon counting' mode, derived a position of 12 h 36 m 13.58 s, +28° 59′ 01.3″ (J2000), with a positional accuracy of 9.3″ (90% containment radius; larger than the typical XRT 4″ accuracy, owing to weakness of burst). This position takes into account the low counting statistics, cluster emission in the field and astrometric corrections[10] to the 2MASS coordinate system. Many of the extended objects are likely to be galaxies in the cluster NSC J123610+28590131. The inset shows a blow-up of the region of the XRT error circle from an R-band image obtained[8] using FORS2 on the 8.2-m VLT-Antu telescope at the European Southern Observatory/Paranal on 11 May UT, 1.85 days after the burst. The extended source to the right (west) is the luminous elliptical galaxy 2MASX J12361286+285858026, which we suggest to be the likely host of the burst. Other objects in the error circle are not identified, but appear to be faint galaxies either associated with the same cluster as the elliptical galaxy or at higher redshift. The VLT image consists of fifteen 3-min frames taken under good conditions (~1″ seeing).

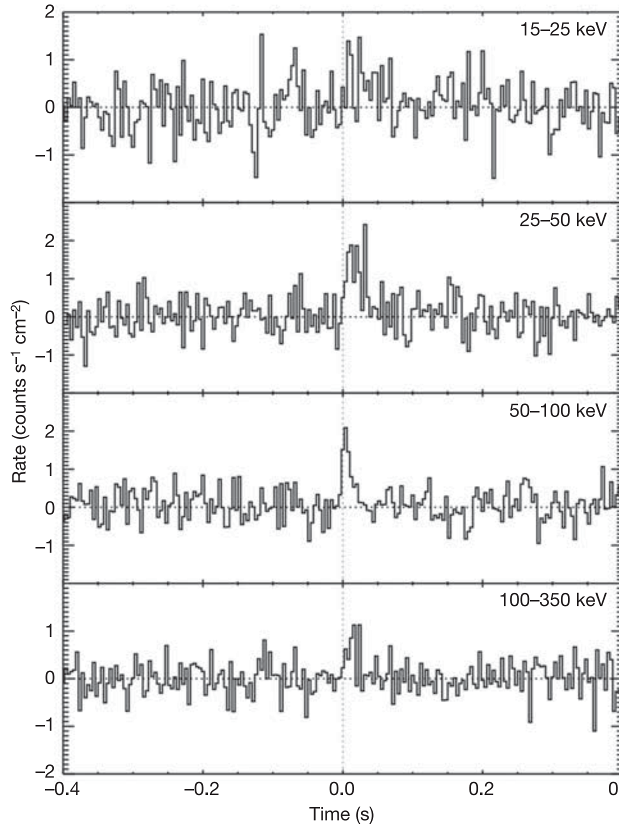

Figure 2 | BAT light curves for the short GRB 050509B, showing the short duration of this GRB. The light curves are given in four photon energy bands with the band identified in the upper right of each panel. The peak has a duration of 40 ± 4 ms (90% containment of counts). There is no detectable emission except from $T-30$ ms to $T+30$ ms, confirming the 'short' aspect of this burst. The successful trigger criterion for the GRB was in the 25–100 keV band. The peak count rate measured by BAT is ~2,100 counts s^{-1} in the 15–150 keV band at $T+5$ ms. The BAT data (40 ms of data centred on $T+23$ ms) are well fitted by a simple power-law model with a photon index of 1.5 ± 0.4, a normalization at 50 keV of $(2.0 \pm 0.5) \times 10^{-2}$ photons cm^{-2} s^{-1} keV^{-1} and a peak flux of 2.53 ± 0.33 photons cm^{-2} s^{-1} (all in 15–150 keV and 90% confidence level).

galaxy 2MASX J12361286+2858580 (ref. 10) at a redshift of 0.225 (ref. 11), which is located in the cluster NSC J123610+285901 (refs 12, 13). This is a luminous giant elliptical galaxy; its 2 Micron All Sky Survey (2MASS) magnitude of $K = 14.1$ corresponds to a luminosity of $4 \times 10^{11} L_{\odot} \approx 3L^*$, where $L_{\odot}$ is the luminosity of the Sun and L^* is the luminosity of a typical galaxy, assuming standard cosmology. Our *Chandra* image shows that this is the central dominant galaxy in one of two merging subclusters in this bimodal cluster. Although caution is always prudent for a posteriori statistics, the association with this galaxy seems unlikely to be coincidental. The probability of a random location being within 10″ of a galaxy with an apparent magnitude at least this bright is $\sim 10^{-3}$. Moreover, galaxies this luminous are relatively rare; the comoving number density[14] of galaxies at least this luminous is $\sim 5 \times 10^{-5}$ Mpc^{-3}; the probability of lying within 10″ of a randomly located one at $z \leq 0.225$ is $\sim 10^{-4}$. Note that this is the first GRB of ~80 with accurate optical localizations to be near a bright elliptical on the sky.

The likely association between GRB 050509B and 2MASX J12361286+2858580 is difficult to understand if the GRB resulted from any mechanism involving recent star formation. The galaxy type for the suggested host galaxy is very different from those found for long GRBs; their hosts are typically subluminous and blue[15] and show strong emission lines associated with star formation[16]. As is true of most giant ellipticals in clusters, 2MASX J12361286+2858580 has no indications of ultraviolet or optical line emission[10]. Our UVOT images clearly detect the galaxy in the optical, but not in the ultraviolet (UVM2 220-nm and UVW2 188-nm filters), as expected for an elliptical galaxy—implying little or no contribution from young, hot stars. The 3σ upper limit at 188 nm gives a limit to the star-formation rate[17] of $< 0.2 M_{\odot}$ yr^{-1}, where $M_{\odot}$ is the mass of the Sun. It is improbable that we will find a massive-star core collapse or young magnetar in this galaxy. In addition, the isotropic energy of $1.1 \times 10^{48} k$ erg (15–150 keV, $z = 0.225$, where the k-correction factor is typically 1 to 10) is $> 10^2$ times higher than that of the 27 December 2004 giant flare from SGR 1806−20 (refs 18, 19). Thus, it is unlikely that this burst was an SGR-type flare.

On the other hand, 2MASX J12361286+2858580 is a very propitious site for a neutron star–neutron star or neutron star–black hole merger. As *Chandra* observations have shown[20], giant ellipticals, especially those dominant in their cluster, have large populations of low-mass X-ray binaries containing accreting neutron stars and black holes. Further, a high fraction ($\gtrsim$50%) of the low-mass X-ray binaries in ellipticals are located in globular clusters[21] because close binary systems containing at least one compact object can easily be formed dynamically in globular clusters. Although there is less direct evidence that close neutron star–neutron star binaries can form easily in globular clusters, the double-neutron-star system PSR B2127+11C in the Galactic globular cluster M15 is an example of such a binary[22], and has a merger lifetime of $\sim 2 \times 10^8$ yr. In fact, of

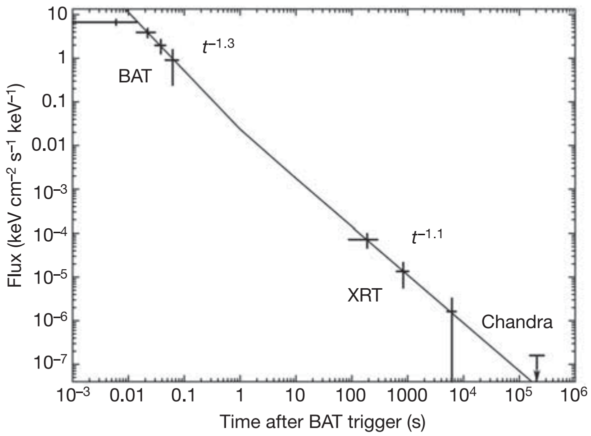

Figure 3 | X-ray afterglow light curve for GRB 050509B showing weak flux falling off to undetectability after 10^4 s. The decline in the 1-keV X-ray emission from GRB 050509B from BAT, XRT and Chandra data is shown. The BAT points were calculated by extrapolating the BAT spectrum with measured photon index Γ (flux = constant × $E^{-\Gamma}$) of 1.5 down to 1 keV. The XRT fluxes are unabsorbed values derived by fixing the photon index to 1.5 (that is, that found by the BAT) and using the Galactic column density of 1.5×10^{20} cm^{-2}. The initial flux is $(3.57 \pm 1.08) \times 10^{-13}$ erg cm^{-2} s^{-1} between 0.3 and 10 keV. The XRT time decay index α (flux = constant × time$^{-\alpha}$) is 1.10 (0.57 to 2.36; 90% confidence) and the BAT index is 1.34 (0.27 to 2.87; 90% confidence). The BAT index is poorly constrained because the burst is so short. The BAT and XRT data are also consistent at the 90% confidence level with a single decay index of 1.20 (1.12 to 1.29). The Chandra 99% confidence flux upper limit lies above the decay curves. The error bars in the figure are at the 1σ 68% confidence level.

all galaxy types, large ellipticals (particularly cluster dominants) are the most likely place to find double compact binary systems, owing to their large populations of globular clusters.

The centre of the XRT error circle is in the outer regions of the elliptical galaxy, although the circle extends nearly to the galaxy centre. A location at large radius would be consistent with the binary merger model for short GRBs[23]. Neutron star–neutron star binaries often obtain significant kick velocities (100–1,000 km s^{-1}) from the supernova that creates each neutron star[24]. If we ignore the effects of the galactic potential, a neutron star–neutron star binary moving at 1,000 km s^{-1} would travel 100 kpc in 10^8 yr. The projected distance of the centre of the XRT position from the centre of the galaxy is about 35 kpc; the range over the error circle is about 2–70 kpc. Thus, the neutron star–neutron star binary might have reached this distance before merging, even if it started from a more central location. Alternatively, the binary may have formed in a globular cluster; globular clusters have a broader radial distribution than field stars in ellipticals, which could explain the large projected radius of the GRB.

The X-ray emission for GRB 050509B is faint, being the weakest afterglow of any of the 15 GRBs that XRT has promptly observed (a factor of ~200 weaker than the XRT average). For BATSE bursts, studies were done of the post-burst emission by summing large numbers of GRB lightcurves[25,26]. The post-burst emission was found to be weaker for short bursts than for long events, consistent with the GRB 050509B. For typical shock parameters, the early X-ray afterglow emission is probably below the cooling frequency[27]; in this regime, the weak afterglow is consistent with the low-density medium around an evolved compact binary progenitor. A more critical factor to define the low X-ray flux may be the small energy injection involved, as the prompt emission for GRB 050509B is also the weakest of the BAT GRBs. If the redshift is 0.225, then the afterglow is >100 times less luminous than that of typical long-burst afterglows and the isotropic energy is $\sim 10^{-4}$ that of typical long GRBs (about the same as the lowest-luminosity, unusual GRB 980425).

Before Swift's observations, it was predicted[28] that short GRBs would have faint optical afterglows, particularly so if they occurred in low-density regions like those around evolved stars. This prediction is consistent with the lack of optical detection to stringent limits for GRB 050509B, although we bear in mind that this burst is weak compared to other short GRBs. It is likely that the X-ray afterglow will remain a key to understanding short bursts.

The X-ray afterglow from this short GRB can constrain outflow parameters. The fact that the X-rays are fading as early as 62 s puts a limit on the initial Lorentz factor of $\Gamma_0 \geq 70 n_{-2}^{-1/8} E^{1/8}$ for $z = 0.225$ (n_{-2} is ambient density in units of 10^{-2} cm^{-3}, and E is the isotropic energy in units of 10^{48} erg), showing that short GRBs are highly relativistic events.

Another interesting aspect of the localization of GRB 050509B is that the burst is faint and yet has a bright galaxy in its error circle. There are five previous short GRBs with fluences one to three orders of magnitude larger than GRB 050509B that have had their arcminute-sized error boxes searched for bright galaxies[29,30]. There are galaxies in each error box of brightness comparable to or less than 2MASX J12361286+2858580, but none much brighter—as one might expect for these brighter GRBs. This does not contradict a merger model for short GRBs, because, although giant elliptical galaxies are a rich environment for mergers, most would occur in the more numerous, fainter, star-forming galaxies. Thus star-forming galaxies harbour both massive stars and evolved binaries, whereas ellipticals have almost no star formation and are highly deficient in short-lived massive stars. The detection of GRB 050509B near an elliptical galaxy is an important observation for short bursts because the association with a large elliptical galaxy is evidence against a collapsar origin, whereas an association with a star-forming galaxy would have left the question unanswered. There may be more than one origin of short GRBs, but this particular short event has a high probability of being unrelated to star formation and of being caused by a binary merger.

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1. Kouveliotou, C. *et al.* Identification of two classes of gamma-ray bursts. *Astrophys. J.* **413**, L101–L104 (1993).
2. van Paradijs, J., Kouveliotou, C. & Wijers, R. A. M. J. Gamma-ray burst afterglows. *Annu. Rev. Astron. Astrophys.* **38**, 379–425 (2000).
3. Eichler, D., Livio, M., Piran, T. & Schramm, D. N. Nucleosynthesis, neutrino bursts and gamma-rays from coalescing neutron stars. *Nature* **340**, 126–127 (1989).
4. Mochkovitch, R., Hernanz, M., Isern, J. & Martin, X. Gamma-ray bursts as collimated jets from neutron star/black hole mergers. *Nature* **361**, 236–237 (1993).
5. Gehrels, N. *et al.* The Swift gamma ray burst mission. *Astrophys. J.* **611**, 1005–1020 (2004).
6. Hurkett, C. *et al.* Swift detection of GRB050509B: A short duration burst. *GCN Circ.* **3381** (2005).
7. Cenko, S. B. *et al.* GRB050509B: No optical variability in XRT error circle. *GCN Circ.* **3409** (2005).
8. Hjorth, J. *et al.* GRB050509B: Optical observations with the VLT. *GCN Circ.* **3410** (2005).
9. Cenko, S. B. *et al.* GRB050509B: Further analysis of Keck LRIS images. *GCN Circ.* **3401** (2005).
10. Bloom, J. S. *et al.* Closing in on a short-hard burst progenitor: constraints from early-time optical imaging and spectroscopy of a possible host galaxy of GRB050509B. *Astrophys. J.* (submitted).
11. Prochaska, J. X. *et al.* Keck/DEIMOS spectrum of possible host galaxy for GRB050509B. *GCN Circ.* **3390** (2005).
12. Kennea, J. A. *et al.* GRB050509B: Swift XRT Position. *GCN Circ.* **3383** (2005).
13. Gal, R. R. *et al.* The Northern Sky Optical Cluster Survey. II. An objective cluster catalog for 5800 square degrees. *Astron. J.* **125**, 2064–2084 (2003).
14. Kochanek, C. S. *et al.* The K-band galaxy luminosity function. *Astrophys. J.* **560**, 566–579 (2001).
15. Le Floc'h, E. *et al.* Are the hosts of gamma-ray bursts sub-luminous and blue galaxies? *Astron. Astrophys.* **400**, 499–510 (2003).
16. Vreeswijk, P. M. *et al.* VLT Spectroscopy of GRB 990510 and GRB 990712: Probing the faint and bright ends of the gamma-ray burst host galaxy population. *Astrophys. J.* **546**, 672–680 (2001).

17. Madau, P., Pozzetti, L. & Dickinson, M. The star formation history of field galaxies. *Astrophys. J.* **498,** 106–116 (1998).
18. Hurley, K. *et al.* An exceptionally bright flare from SGR 1806–20 and the origin of short duration gamma-ray bursts. *Nature* **434,** 1098–1103 (2005).
19. Palmer, D. M. *et al.* A giant gamma-ray flare from the magnetar SGR 1806–20. *Nature* **434,** 1107–1109 (2005).
20. Sarazin, C. L., Irwin, J. A. & Bregman, J. N. Resolving the mystery of X-ray-faint elliptical galaxies: Chandra X-ray observations of NGC 4697. *Astrophys. J.* **544,** L101–L105 (2000).
21. Sarazin, C. L. *et al.* Low-mass X-ray binaries and globular clusters in early-type galaxies. *Astrophys. J.* **595,** 743–759 (2003).
22. Anderson, S. B. *et al.* Discovery of two radio pulsars in the globular cluster M15. *Nature* **346,** 42–44 (1990).
23. Bloom, J. S., Sigurdsson, S. & Pols, O. R. The spatial distribution of coalescing neutron star binaries; implications for gamma-ray bursts. *Mon. Not. R. Astron. Soc.* **305,** 763–769 (1999).
24. Willems, B., Kalogera, V. & Henninger, M. Pulsar kicks and spin tilts in the close double neutron stars PSR J0737–3039, PSR B1534 + 12, and PSR B1913 + 16. *Astrophys. J.* **616,** 414–438 (2004).
25. Lazatti, D., Ramirez-Ruiz, E. & Ghisellini, G. Possible detection of hard X-ray afterglows of short gamma-ray bursts. *Astron. Astrophys.* **379,** L39–L43 (2001).
26. Connaughton, V. BATSE Observations of gamma-ray burst tails. *Astrophys. J.* **567,** 1028–1036 (2002).
27. Panaitescu, A. & Kumar, P. Analytic light curves of gamma-ray burst afterglows: homogeneous versus wind external media. *Astrophys. J.* **543,** 66–76 (2000).
28. Panaitescu, A., Kumar, P. & Narayan, R. Observational prospects for afterglows of short-duration gamma-ray bursts. *Astrophys. J.* **561,** L171–L174 (2001).
29. Nakar, E. *et al.* The distance of short-hard GRBs and the SGR connection. Preprint at ⟨http://arXiv.org/astro-ph 0502148⟩ (2005).
30. Hurley, K. *et al.* Afterglow upper limits for four short-duration, hard spectrum gamma-ray bursts. *Astrophys. J.* **567,** 447–453 (2002).

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