nature Vol 438|15 December 2005|doi:10.1038/nature04238

LETTERS

The afterglow and elliptical host galaxy of the short γ-ray burst GRB 050724

E. Berger[1], P. A. Price[2], S. B. Cenko[3], A. Gal-Yam[4], A. M. Soderberg[4], M. Kasliwal[4], D. C. Leonard[4], P. B. Cameron[4], D. A. Frail[5], S. R. Kulkarni[4], D. C. Murphy[1], W. Krzeminski[6], T. Piran[7], B. L. Lee[8], K. C. Roth[9], D.-S. Moon[3], D. B. Fox[4], F. A. Harrison[3], S. E. Persson[1], B. P. Schmidt[10], B. E. Penprase[11], J. Rich[10], B. A. Peterson[10] & L. L. Cowie[2]

Despite a rich phenomenology, γ-ray bursts (GRBs) are divided[1] into two classes based on their duration and spectral hardness—the long-soft and the short-hard bursts. The discovery of afterglow emission from long GRBs was a watershed event, pinpointing[2] their origin to star-forming galaxies, and hence the death of massive stars, and indicating[3] an energy release of about 10^{51} erg. While theoretical arguments[4] suggest that short GRBs are produced in the coalescence of binary compact objects (neutron stars or black holes), the progenitors, energetics and environments of these events remain elusive despite recent[5–8] localizations. Here we report the discovery of the first radio afterglow from the short burst GRB 050724, which unambiguously associates it with an elliptical galaxy at a redshift[9] $z = 0.257$. We show that the burst is powered by the same relativistic fireball mechanism as long GRBs, with the ejecta possibly collimated in jets, but that the total energy release is 10–1,000 times smaller. More importantly, the nature of the host galaxy demonstrates that short GRBs arise from an old (>1 Gyr) stellar population, strengthening earlier suggestions[5,6] and providing support for coalescing compact object binaries as the progenitors.

On receipt of the Swift X-ray localization[10] of the short-hard burst GRB 050724 (duration, $T_{90} = 3 \pm 1$ s dominated by an initial spike of 0.25 s; hardness ratio, F(50–100 keV)/F(25–50 kev) = 0.9 ± 0.1; ref. 11) we initiated observations in the radio, near-infrared (NIR) and optical bands at the Very Large Array, the Baade 6.5-m Magellan telescope, and the Swope 40-inch telescope (see Table 1). Within the overall uncertainty of the X-ray position we discovered a point-like radio source and confirmed that it is the radio afterglow by its subsequent variability. Contemporaneous digital image subtraction of our optical and NIR frames from the first and second nights revealed a variable source coincident with the radio afterglow, which we identify as the optical afterglow; this was subsequently confirmed[12] elsewhere. The afterglow is coincident with a bright galaxy, identified[13] in earlier optical imaging, demonstrating that it is the host galaxy; see Fig. 1.

Motivated by this association, we used the Gemini Multi-Object Spectrograph on the Gemini North telescope to obtain a spectrum of the host galaxy from which we measure a redshift, $z = 0.257$, confirming other measurements[9]; see Fig. 2. At this redshift the fluence[10] of the burst, $F_\gamma \approx 6.3 \times 10^{-7}$ erg cm^{-2} (15–350 keV), translates to an isotropic-equivalent energy release, $E_{\gamma,\rm iso} \approx 4 \times 10^{50}$ erg; this includes a bolometric correction of a factor of four, the average ratio of the 20–2,000 keV to the 25–300 keV luminosity in the BATSE short burst sample. The X-ray luminosity of the afterglow at $t = 10$ h, a proxy[14] for the kinetic energy of the blast wave, is $L_{X,\rm iso} \approx 4.2 \times 10^{44}$ erg s^{-1}. Both of these quantities are at least an order of magnitude lower[3,15] than for the long GRBs.

The minimum initial Lorentz factor of the ejecta is between 80 and 160, based[10] on a peak flux, $f_{\rm p} \approx 3.9$ photons cm^{-2} s^{-1}, and the duration of the initial hard spike[11] of 0.25 s. This large value, similar to those inferred[16] for long GRBs, indicates a relativistically expanding fireball, which in turn produces the afterglow emission. GRB 050724 is the first short burst with radio, optical/NIR and X-ray afterglows, and we are therefore in a unique position to derive the properties of the fireball and burst environment. Using a standard synchrotron power-law spectrum[17] fit to the afterglow data at

Table 1 | Afterglow observations of GRB 050724 in the radio, optical, and near-infrared bands

Epoch (UT)	Δt (h)	Telescope	Band	Flux (μJy)
Jul 25.01	11.6	Magellan/PANIC	K	38.7 ± 1.4
Jul 25.98	34.9	Magellan/PANIC	K	<4.6
Jul 25.02	12.0	Swope 40-inch	I	8.4 ± 0.2
Jul 25.11	14.2	Swope 40-inch	I	11.1 ± 0.9
Jul 26.05	36.7	Swope 40-inch	I	<4.0
Jul 25.09	13.7	VLA	8.46	173 ± 30
Jul 26.21	40.5	VLA	8.46	465 ± 29

For the radio observations we list the observing band in GHz, while for the optical and NIR data we list the filter. In all Very Large Array (VLA) observations we used the extra-galactic sources 3C 286 and J1626 − 298 for flux and phase calibration, respectively. The data were reduced and analysed using the Astronomical Image Processing System, and the flux density and uncertainty were measured from the resulting maps. The NIR data were obtained with Persson's Auxilliary Nasmyth Infrared Camera and consisted of sixty-six 20-s images at each epoch. The individual images were processed in the standard manner and corrected for distortion. Astrometry was performed relative to nine 2-Micron All-Sky Survey (2MASS) sources resulting in an astrometric accuracy of about 0.1″. The optical observations consisted of two 900-s images in the first two epochs and three 900-s images in the third epoch. The data were processed in the standard manner, and astrometry was performed relative to 65 USNO (United States Naval Observatory) stars, resulting in an root-mean-square (r.m.s.) uncertainty of about 0.15″. Photometry of the NIR afterglow was performed using the 'NN2' method[27]. Errors in the subtracted fluxes were measured from the r.m.s. deviation of fluxes within apertures randomly distributed over the background of the subtracted images. Flux calibration was performed relative to sources from the 2MASS catalogue; our resulting absolute calibration is limited by statistical errors in the faint catalogue sources to an accuracy of about 5%. Photometry of the optical afterglow was performed using image subtraction, and the flux measurements carry a systematic uncertainty of about 0.15 mag, which affects all epochs in the same manner. Therefore, the observed re-brightening between 12 and 14.2 h is significant at about 3σ. The optical and NIR fluxes are not corrected for Galactic extinction (see Fig. 3).

[1]Carnegie Observatories, 813 Santa Barbara Street, Pasadena, California 91101, USA. [2]Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822, USA. [3]Space Radiation Laboratory 220-47, [4]Caltech Optical Observatories 105-24, California Institute of Technology, Pasadena, California, 91125 USA. [5]National Radio Astronomy Observatory, PO Box 0, Socorro, New Mexico 87801, USA. [6]Las Campanas Observatory, Carnegie Observatories, Casilla 601, La Serena, Chile. [7]Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel. [8]Department of Astronomy and Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada. [9]Gemini Observatory, 670 N. Aohoku Place Hilo, Hawaii 96720, USA. [10]RSAA, ANU, Mt Stromlo Observatory, via Cotter Rd, Weston Creek, ACT 2611, Australia. [11]Pomona College Department of Physics and Astronomy, 610 N. College Ave, Claremont, California 91711, USA.

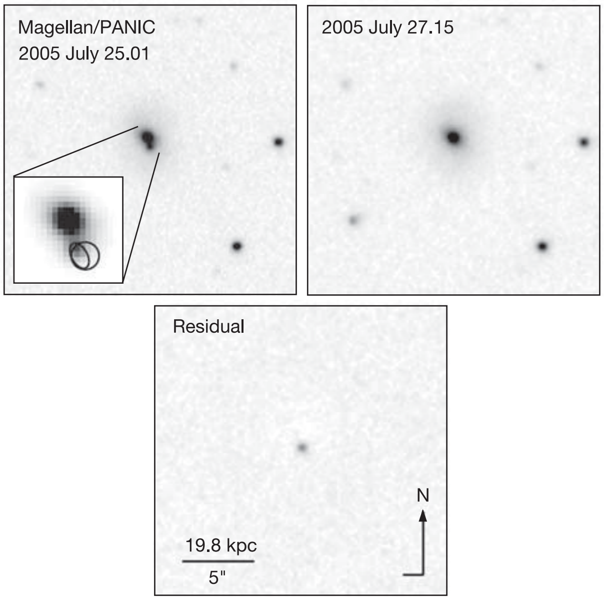

Figure 1 | Near-infrared *K*-band images of the afterglow and host galaxy of GRB 050724. The afterglow has completely faded between 11.6 and 34.9 hours after the burst, indicating a flux decay rate of $\alpha < -1.9$ ($F_\nu \propto t^\alpha$). The position of the NIR afterglow is $\alpha = 16$ h 24 min 44.38 s, $\delta = -27°\ 32'\ 27.5''$, with an uncertainty of about 0.1″ in each coordinate. The inset shows the VLA radio position (ellipse; $\alpha = 16$ h 24 min 44.37 s, $\delta = -27°\ 32'\ 27.5''$) and the Chandra X-ray position[28] (circle; $\alpha = 16$ h 24 min 44.36 s, $\delta = -27°\ 32'\ 27.5''$). These positions are fully consistent within the measurement uncertainty: the radio–NIR offset is $\Delta\alpha = 0.12 \pm 0.11''$, $\Delta\delta = 0.19 \pm 0.21''$, while the X-ray–NIR offset is $\Delta\alpha = 0.28 \pm 0.22''$ and $\Delta\delta = 0.01 \pm 0.22''$. The host galaxy brightness corrected for Galactic extinction is $K = 14.88 \pm 0.03$ mag (3.5″ aperture). Using standard cosmological parameters ($\Omega_m = 0.27$, $\Omega_\lambda = 0.73$, $H_0 = 71\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$) the absolute magnitude is $M_K = -24.7$ (mag), including a *k*-correction factor of 1.05 mag. This suggests that the host is a bright galaxy with a luminosity, $L \approx 1.6\ L^*$ by comparison to the luminosity function derived[29] from the 2dF Galaxy Redshift Survey and 2MASS; see also ref. 9. The host magnitude in the optical I-band is $I = 18.63 \pm 0.2$ mag, indicating a red $I - K \approx 2.56 \pm 0.2$ mag. The radial surface brightness distribution, measured using elliptical isophotes, follows a de Vaucouleurs $r^{1/4}$ profile with an effective radius of 6 kpc and a central surface brightness of $\mu_K \approx 19.5\ \mathrm{mag\ arcsec^{-2}}$. The ellipticity of the host is about 0.17, indicating an E2 Hubble classification.

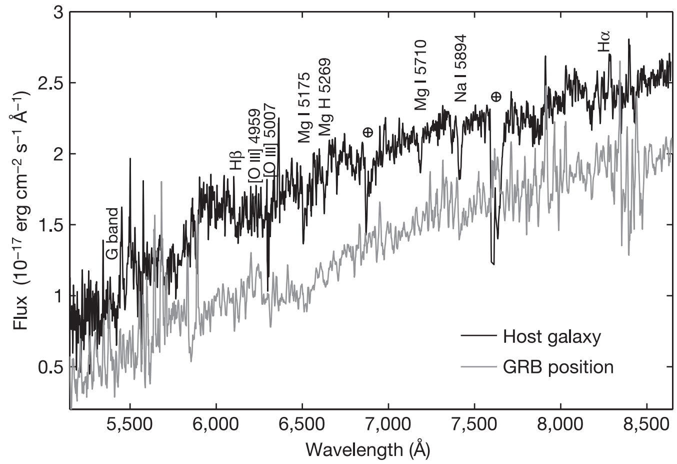

Figure 2 | Optical spectra of the host galaxy of GRB 050724. The black line shows a spectrum taken through the centre of the host galaxy with the Gemini Multi-Object Spectrograph on the Gemini North telescope on 2005 July 27 UT. The observations consisted of $4 \times 1{,}800$ s integrations through a 1″ wide slit. The spectrum was processed with the standard gmos reduction tasks in IRAF (Image Reduction and Analysis Facility) before subtracting the sky, and extracting the spectra. Flux calibration was achieved through an archival observation of a spectrophotometric standard star, taken with a slightly different instrumental set-up; as such, the flux calibration is not completely accurate, but is indicative. We detect the Na D lines in absorption at a mean redshift of $z = 0.257 \pm 0.001$, confirming another measurement[9]. We also detect absorption lines corresponding to Mg b (5174), MgH (5269) and Mg I (5710). We place a 3σ limit of about $1.5 \times 10^{-17}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ on the flux of Hα, corresponding at the redshift of the host to a limit of $< 0.02\,M_\odot\,\mathrm{yr^{-1}}$. The lack of a prominent Hβ absorption feature indicates[19] a stellar population older than ~1 Gyr. The grey line is a spectrum obtained at the position of GRB 050724 with the Low-Resolution Imaging Spectrometer on the Keck II telescope on 2005 July 28 UT. A slit position angle of 90° was chosen to minimize contribution from the galaxy light. This allows us to place constraints on any residual star formation at the position of the GRB. The observation consisted of a single 2,240 s exposure with a 1.5″ wide slit. Flux calibration was performed using the spectrophotometric standard BD + 17°4708 (red) and BD + 28°4211 (blue). The shape of the spectrum is not completely accurate because of slit losses, but the lack of detectable Hα emission allows us to place a limit of $0.03\,M_\odot\,\mathrm{yr^{-1}}$ on the star-formation rate at the position of the GRB.

$t = 12$ h we find an isotropic-equivalent kinetic energy of $E_{K,\mathrm{iso}} \approx 1.5 \times 10^{51}$ erg, a density of $n \approx 0.1\ \mathrm{cm^{-3}}$, and fractions of energy in the relativistic electrons and magnetic field of $\epsilon_e \approx 0.04$ and $\epsilon_B \approx 0.02$, respectively; a mild degeneracy between n and $E_{K,\mathrm{iso}}$ marginally accommodates a density as low as $0.02\ \mathrm{cm^{-3}}$ and an energy as high as 3×10^{51} erg (see Fig. 3). A comparison of $E_{\gamma,\mathrm{iso}}$ and $E_{K,\mathrm{iso}}$ indicates a radiative efficiency of about 20%, similar to the long GRBs.

The fading rate of the NIR afterglow emission between 12 and 35 hours after the burst is steeper than $F_\nu \propto t^{-1.9}$ (Table 1). This is suggestive of a collimated explosion, or jet[18]. The flat or rising optical light curve between 12 and 14.2 h, suggests that the jet break time is ~1 d, corresponding to an opening angle[3], $\theta_j \approx 0.15$ rad (for $n = 0.1\ \mathrm{cm^{-3}}$). In this framework the true energy release is $E_\gamma \approx 4 \times 10^{48}$ erg and $E_K \approx 1.7 \times 10^{49}$ erg, two orders of magnitude below the energy release of long GRBs. We note that jet breaks are achromatic, and our tentative claim can be tested with additional radio data. We conclude from this discussion that GRB 050724 is powered by the same fireball mechanism as long GRBs, with similar micro-physical properties. The fundamental difference is that the total energy release is a few orders of magnitude smaller than in long GRBs.

We now turn to the nature of the progenitor system, as revealed from the properties of the host galaxy. The spectrum indicates that the host is an early-type galaxy[9], with a stellar population that is older than ~1 Gyr, based on the lack of detectable Balmer Hβ absorption[19]. From the limit on Hα emission we find that the overall star-formation rate is $< 0.02\,M_\odot\,\mathrm{yr^{-1}}$, and more importantly, at the location of GRB 050724 we place a limit of $< 0.03\,M_\odot\,\mathrm{yr^{-1}}$ (Fig. 2). The red colour and surface brightness profile of the galaxy indicate an elliptical (E2) classification. The position of GRB 050724 is offset by about $2{,}570 \pm 80$ pc from the centre of the host, corresponding to $0.4r_e$, where $r_e \approx 6$ kpc is the host galaxy's effective radius. This offset is smaller[20] than for 80% of the long bursts.

The association of the burst with an elliptical galaxy dominated by an old stellar population is unlike any of the long GRBs localized to date, which invariably occur[21] in star-forming galaxies. This leads us to conclude that the progenitor of GRB 050724 was not a massive star, but was instead related to an old stellar population. Theoretical considerations suggest[4] that short bursts arise from the coalescence of binary systems undergoing angular momentum loss via gravitational radiation. Both neutron star–neutron star and neutron star–black hole systems have been proposed, leading to a prediction[22] of a wide distribution of coalescence timescales (~10^7 – 10^{10} yr) and hence offsets (few to 10^3 kpc). For delayed mergers, the median redshift is predicted[23] to be lower compared to the bulk of the star-formation activity, that is $z \ll 1$.

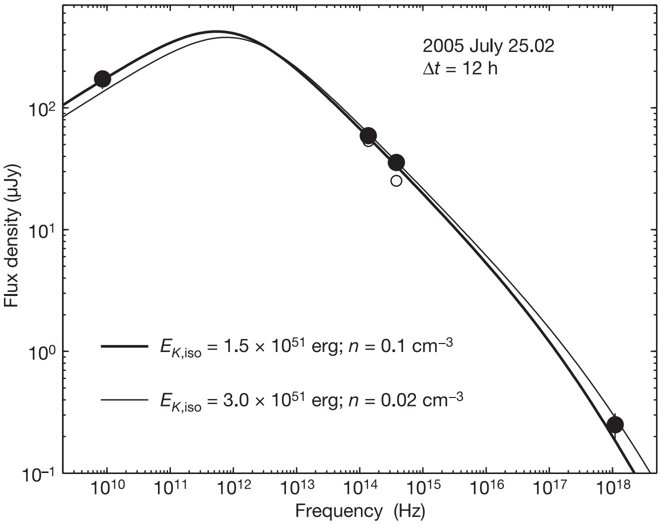

Figure 3 | Radio to X-ray spectral energy distribution of the afterglow emission 12 h after the burst. **In the optical and NIR bands the open circles are the measured fluxes without a correction for Galactic extinction. We find that the Galactic extinction along the line of sight required for reconciling the optical, NIR and X-ray fluxes is $A_V \approx 2.7$ mag, about 35% higher than the tabulated value[30]. The inferred extinction is in very good agreement with the increased hydrogen column density, $N_{\mathrm{H}} \approx 5.6 \times 10^{21}\,\mathrm{cm}^{-2}$, inferred[11] from the X-ray afterglow, and it indicates that the excess absorption has a Galactic, rather than host galaxy, origin. The lines are synchrotron models[17] of the afterglow emission. We find a best-fit solution with an energy of $E_{K,\mathrm{iso}} \approx 1.5 \times 10^{51}$ erg, a density of $n \approx 0.1\,\mathrm{cm}^{-3}$, and fractions of energy in the relativistic electrons and magnetic field of $\epsilon_{\mathrm{e}} \approx 0.04$ and $\epsilon_{\mathrm{B}} \approx 0.02$, respectively. A slight degeneracy between the energy and density is shown by the thin line, which marginally fits the data.**

The old age of the host's stellar population, the lack of detectable current star formation at the position of the burst, and the low redshift compared to most long GRBs point to a binary progenitor that had a coalescence time of $\gtrsim 1$ Gyr. The small offset, however, suggests that the kick velocity imparted to the system was probably too small to unbind it from the host. In this context a comparison to two recent short GRBs is illustrative. GRB 050509b was possibly associated[5,6] with an elliptical galaxy at $z = 0.225$, but the poor localization (9.3″ radius[6]) also allowed an association with higher-redshift star-forming galaxies. The results on GRB 050724 now support the claimed association with the elliptical galaxy. On the other hand, GRB 050709 was precisely localized within 3 kpc of a star-forming galaxy[24] at $z = 0.16$. While this association does not allow a definitive argument against a massive star origin, it suggests that the progenitors of short GRBs occur in diverse environments, and with a range of coalescence timescales. This scenario is similar to that of type Ia supernovae[25].

We conclude with the following intriguing possibilities. First, the isotropic-equivalent prompt energy release appears to correlate with the burst duration, such that the luminosity is nearly constant, $L_{\gamma,\mathrm{iso}} \approx (3\text{–}15) \times 10^{50}$ erg. This may explain why the afterglow of the 40-ms duration GRB 050509b was significantly fainter than those of GRBs 050709 and 050724. Second, the small offsets and low redshifts of the latter two bursts may contrast with population synthesis models, which predict[22,23] 90% of the offsets to be >10 kpc, and a median redshift $z \approx 0.5$–1. Finally, if the beaming inferred for GRB 050724 is typical of the short burst population, then this implies that the true event rate of short bursts is about fifty times higher than observed. This suggests that $\lesssim 10\%$ of neutron star–neutron star and neutron star–black hole binaries[26] end their lives in GRB explosions. The continued detection of short GRBs by Swift will allow these conclusions to be tested through the distribution of energies, jet angles and offsets.

Received 3 August; accepted 14 September 2005.

1. Kouveliotou, C. *et al.* Identification of two classes of gamma-ray bursts. *Astrophys. J.* **413,** L101–L104 (1993).
2. Pian, E. *et al.* Hubble Space Telescope Imaging of the optical transient associated with GRB 970508. *Astrophys. J.* **492,** L103–L106 (1998).
3. Frail, D. A. *et al.* Beaming in gamma-ray bursts: Evidence for a standard energy reservoir. *Astrophys. J.* **562,** L55–L58 (2001).
4. Katz, J. I. & Canel, L. M. The long and the short of gamma-ray bursts. *Astrophys. J.* **471,** 915–920 (1996).
5. 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 GRB 050509b. Preprint at ⟨http://arXiv.org/astro-ph/0505480⟩ (2005).
6. Gehrels, N. *et al.* A short γ-ray burst apparently associated with an elliptical galaxy at redshift z = 0.225. *Nature* **437,** 851–854 (2005).
7. Fox, D. B. *et al.* The afterglow of GRB 050709 and the nature of the short-hard γ-ray bursts. *Nature* **437,** 845–850 (2005).
8. Hjorth, J. *et al.* The optical afterglow of the short γ-ray burst GRB 050709. *Nature* **437,** 859–861 (2005).
9. Prochaska, J. X. *et al.* GRB 050724: secure host redshift from Keck. *GCN Circ.* **3700** (2005).
10. Krimm, H. *et al.* GRB050724: refined analysis of the Swift-BAT possible short bursts. *GCN Circ.* **3667** (2005).
11. Barthelmy, S. D. *et al.* An origin for short γ-ray bursts unassociated with current star formation. *Nature* doi:10.1038/nature04392 (this issue).
12. D'Avanzo, P. *et al.* GRB050724: VLT observations of the variable source. *GCN Circ.* **3690** (2005).
13. Bloom, J. S., Dupree, A., Chen, H.-W. & Prochaska, J. X. GRB050724: GMOS imaging and spectroscopy. *GCN Circ.* **3679** (2005).
14. Freedman, D. L. & Waxman, E. On the energy of gamma-ray bursts. *Astrophys. J.* **547,** 922–928 (2001).
15. Berger, E., Kulkarni, S. R. & Frail, D. A. A standard kinetic energy reservoir in gamma-ray burst afterglows. *Astrophys. J.* **590,** 379–385 (2003).
16. Lithwick, Y. & Sari, R. Lower limits on Lorentz factors in gamma-ray bursts. *Astrophys. J.* **555,** 540–545 (2001).
17. Granot, J. & Sari, R. The shape of spectral breaks in gamma-ray burst afterglows. *Astrophys. J.* **568,** 820–829 (2002).
18. Sari, R., Piran, T. & Halpern, J. P. Jets in gamma-ray bursts. *Astrophys. J.* **519,** L17–L20 (1999).
19. Dressler, A. & Gunn, J. E. Spectroscopy of galaxies in distant clusters. II—The population of the 3C 295 cluster. *Astrophys. J.* **270,** 7–19 (1983).
20. Bloom, J. S., Kulkarni, S. R. & Djorgovski, S. G. The observed offset distribution of gamma-ray bursts from their host galaxies: a robust clue to the nature of the progenitors. *Astron. J.* **123,** 1111–1148 (2002).
21. Christensen, L., Hjorth, J. & Gorosabel, J. UV star-formation rates of GRB host galaxies. *Astron. Astrophys.* **425,** 913–926 (2004).
22. Fryer, C. L., Woosley, S. E. & Hartmann, D. H. Formation rates of black hole accretion disk gamma-ray bursts. *Astrophys. J.* **526,** 152–177 (1999).
23. Guetta, D. & Piran, T. The luminosity and redshift distributions of short-duration GRBs. *Astron. Astrophys.* **435,** 421–426 (2005).
24. Price, P. A. GRB 050709: spectroscopy. *GCN Circ.* **3605** (2005).
25. van den Bergh, S. The frequency of SN IA in galaxies of different Hubble type. *Publ. Astron. Soc. Pacif.* **102,** 1318–1320 (1990).
26. Phinney, E. S. The rate of neutron star binary mergers in the universe—Minimal predictions for gravity wave detectors. *Astrophys. J.* **380,** L17–L21 (1991).
27. Barris, B. J., Tonry, J. L., Novicki, M. C. & Wood-Vasey, W. M. The NN2 flux difference method for constructing variable object light curves. Preprint at ⟨http://arXiv.org/astro-ph/0507584⟩ (2005).
28. Burrows, D. *et al.* GRB 050724: Chandra observations of the X-ray afterglow. *GCN Circ.* **3697** (2005).
29. Cole, S. *et al.* The 2dF galaxy redshift survey: near-infrared galaxy luminosity functions. *Mon. Not. R. Astron. Soc.* **326,** 255–273 (2001).
30. Schlegel, D. J., Finkbeiner, D. P. & Davis, M. Maps of dust infrared emission for use in estimation of reddening and cosmic microwave background radiation foregrounds. *Astrophys. J.* **500,** 525–553 (1998).

Acknowledgements We are, as always, indebted to S. Barthelmy and the GCN. GRB research at Carnegie and Caltech is supported in part by funds from NASA. E.B. and A.G.Y. are supported by NASA through Hubble Fellowship grants awarded by the Space Telescope Science Institute, which is operated by AURA, Inc., for NASA. The VLA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Author Information Reprints and permissions information is available at npg.nature.com/reprintsandpermissions. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to E.B. (eberger@ociw.edu).