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LETTERS

Relativistic ejecta from X-ray flash XRF 060218 and the rate of cosmic explosions

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Over the past decade, long-duration γ-ray bursts (GRBs)—including the subclass of X-ray flashes (XRFs)—have been revealed[1–3] to be a rare variety of type Ibc supernova. Although all these events result from the death of massive stars, the electromagnetic luminosities of GRBs and XRFs exceed those of ordinary type Ibc supernovae by many orders of magnitude. The essential physical process that causes a dying star to produce a GRB or XRF, and not just a supernova, is still unknown. Here we report radio and X-ray observations of XRF 060218 (associated[4] with supernova SN 2006aj), the second-nearest[5,6] GRB identified until now. We show that this event is a hundred times less energetic but ten times more common than cosmological GRBs. Moreover, it is distinguished from ordinary type Ibc supernovae by the presence of 10^{48} erg coupled to mildly relativistic ejecta, along with a central engine (an accretion-fed, rapidly rotating compact source) that produces X-rays for weeks after the explosion. This suggests that the production of relativistic ejecta is the key physical distinction between GRBs or XRFs and ordinary supernovae, while the nature of the central engine (black hole or magnetar) may distinguish typical bursts from low-luminosity, spherical events like XRF 060218.

On 2006 February 18.15 UT, the Burst Alert Telescope (BAT), a hard X-ray detector aboard the Swift satellite, detected[5] an exceedingly long-duration ($\Delta t \approx 2{,}000$ s) transient. Within 153 s of the γ-ray trigger, the on-board X-ray Telescope (XRT) and Ultra-Violet Optical Telescope (UVOT) identified[5] a counterpart coincident[6] with a dwarf galaxy at $z = 0.0335$. The XRT and BAT data show[5] that the event peaked at a photon energy of 4.9 keV, thus classifying this transient as an X-ray flash: XRF 060218. Distinguished[7] by their soft X-ray dominated spectrum (peak energy, $E_{\rm p} \lesssim 25$ keV versus 250 keV), the subclass of XRFs are otherwise similar (see ref. 8 and references therein) to GRBs in their observational properties.

Using the Very Large Array (VLA), we discovered a radio source at α(J2000) = 03 h 21 min 39.68 s and δ(J2000) = 16° 52′ 01.82″ (±0.02 arcsec in each axis), coincident with the UVOT position. Our monitoring of the radio source showed a power-law decay with $\alpha \approx -0.8$ through $t \approx 22$ days (Table 1), similar to the decay of afterglows seen from GRBs; here $F_\nu \propto t^\alpha$ is the spectral flux density. Over the same period the XRT undertook intensive observations of the source in the X-ray band (0.3–10 keV). We find the X-ray spectral flux density, $F_{\nu,{\rm X}} \propto \nu_{\rm X}^{\beta}$, is fitted by $\beta_{\rm X} = -2.2 \pm 0.2$ with an absorbing hydrogen column density of $N_{\rm H} = 3.9 \pm 0.4 \times 10^{21}$ cm^{-2}, consistent with previously reported[5,9] values.

Separately, we observed the source with the Advanced CCD Imaging Spectrometer (ACIS) instrument aboard the Chandra X-ray Observatory (CXO). These observations began on 2006 February 26.78 and March 7.55 UT ($t \approx 8.8$ and 17.4 days) and lasted about 20 and 30 ks, respectively. The measured count rates are $(1.9 \pm 0.3) \times 10^{-3}$ and $(1.3 \pm 0.3) \times 10^{-3}$ s^{-1}, respectively. Using the XRT model parameters stated above we derive $F_{\rm X} = (4.5 \pm 1.4) \times 10^{-14}$ and $(2.8 \pm 0.9) \times 10^{-14}$ erg cm^{-2} s^{-1} for the unabsorbed flux values. The XRT-CXO data spanning the range from a few minutes to 17 days are well fitted by a simple power-law decay model with temporal index, $\alpha_{\rm X} = -1.1$.

XRF 060218 is most interesting because it is nearby, at a distance $d \approx 145$ Mpc. Indeed it is second only to GRB 980425/SN 1998bw[1], at just 36 Mpc. Similar to GRB 980425, XRF 060218 is also associated[4] with a type Ic supernova explosion, SN 2006aj. The isotropic prompt energy release[5] $E_{\gamma,{\rm iso}} = (6.2 \pm 0.3) \times 10^{49}$ erg, is at least a hundred times fainter than typical GRBs but comparable to another nearby event, GRB 031203[10,11] ($z = 0.106$). Similarly, the radio and X-ray luminosities are 10^3 and 10^2 times fainter than those of cosmological GRBs, respectively.

Radio observations directly probe the ejecta and environments of stellar explosions because the blastwave (velocity v) shocks the circumstellar medium and accelerates relativistic electrons that give rise to radio synchrotron emission. For radio sources dominated by synchrotron self-absorption, the brightness temperature is $T_{\rm B} \lesssim 4 \times 10^{10}$ K. As can be seen from Fig. 1, at day 5 the radio emission peaks between 1.4 GHz and 4.9 GHz. Applying the basic equipartition analysis (see ref. 2) we find, at this epoch, that the radius of the radio-emitting region is $r \approx 3 \times 10^{16}$ cm, the ejecta kinetic energy is $E_{\rm K} \approx 2 \times 10^{48}$ erg and the circumburst particle density is $n \approx 5$ cm^{-3}. The blastwave thus expands with a Lorentz factor of $\Gamma = (1 - \beta^2)^{-1/2} \approx 2.3$; here $\beta \equiv v/c$.

The early, steady decay of the radio emission indicates[12] that it cannot be attributed to a collimated jet directed away from our line-of-sight. Moreover, on a timescale of $t_{\rm NR} \approx 7.3(E_{\rm K,48}/n_0)^{1/3}$ days, the blastwave becomes[13] sub-relativistic ($\Gamma\beta < 1$), at which point it effectively assumes spherical geometry, even if the initial explosion was biconical. Independently, noting the absence of a 'jet break' in the radio light-curve (to 22 days) and applying the standard formulation[14] we find the opening angle, $\theta_j \gtrsim 1.4$ radians. Thus, on several grounds, the radio data argue for a quasi-spherical ejecta with 10^{48} erg coupled to mildly relativistic material. In addition, our

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Table 1 | Radio observations made with the VLA and the Ryle telescope†

Epoch (UT)	Δt (days)	$F_{1.43}$ (μJy)	$F_{4.86}$ (μJy)	$F_{8.46}$ (μJy)	$F_{15.0}$ (μJy)	$F_{22.5}$ (μJy)
2006 Feb 20.02	1.87	–	78 ± 70	453 ± 77	–	–
2006 Feb 21.14	3.00	–	–	381 ± 60	–	250 ± 52
2006 Feb 21.77†	3.62	–	–	–	350 ± 350	–
2006 Feb 21.97	3.83	–	287 ± 56	269 ± 40	–	–
2006 Feb 22.99	4.85	25 ± 25	328 ± 61	280 ± 47	–	–
2006 Feb 25.12	6.97	134 ± 145	80 ± 47	164 ± 39	46 ± 141	–
2006 Feb 26.09	7.94	–	32 ± 32	30 ± 30	–	–
2006 Feb 28.10	9.95	–	–	39 ± 25	–	–
2006 Mar 2.23	12.08	70 ± 70	–	–	–	–
2006 Mar 3.03	12.88	–	–	15 ± 15	–	–
2006 Mar 6.89	16.74	–	–	75 ± 13	–	–
2006 Mar 10.01	19.86	–	–	48 ± 14	–	–
2006 Mar 12.11	21.96	–	–	87 ± 39	–	–
2006 Mar 15.04	24.91	–	–	20 ± 20	–	–
2006 Mar 20.86	30.71	–	–	32 ± 20	–	–
2006 Mar 24.96	34.81	–	–	15 ± 18	–	–
2006 Mar 26.85	36.70	69 ± 69	5 ± 37	–	–	–
2006 Mar 31.89	41.74	–	–	22 ± 22	–	–
2006 Apr 9.84	50.70	–	–	25 ± 25	–	–
2006 Jun 2.67	104.52	–	–	17 ± 21	–	–

We used the standard continuum mode with 2 × 50-MHz bands (VLA) and 350-MHz bandwidth (Ryle). At 22.5 GHz we used referenced pointing scans to correct for the systematic 10–20-arcsec pointing errors of the VLA antennas. We used the extra-galactic sources 3C 48 (J0137+331) and 3C 147 (J0542+498) for flux calibration, while the phase was monitored using J0319+190 (VLA) and J0326+1521 (Ryle). The data were reduced and analysed using the Astronomical Image Processing System. The flux density and uncertainty were measured from the resulting maps by fitting a gaussian model to the afterglow emission.

observations at 104 days show no evidence for a late-time increase in the radio flux, thus constraining the presence of additional ejecta components (off-axis jets; Fig. 2) spreading into our line-of-sight.

As can be seen from Fig. 1, the above synchrotron model is unable to explain the strong X-ray emission. Attributing the emission to scattering of supernova optical photons by the mildly relativistic ejecta requires an optical depth of $\tau \approx 10^{-4}$, too large to be produced by the shocked electrons which provide $\tau = nr\sigma_T \approx 10^{-7}$; here σ_T is the Thomson cross-section. We must therefore seek an entirely different origin for the observed X-rays.

At day 1, the steep X-ray spectrum roughly connects to the peculiar optical/ultraviolet component ($\beta_{OX} \approx -2$) observed[5] to peak on this timescale. A similar steep near-infrared spectrum was seen[15] in GRB 031203 at $t = 0.4$ days. Given that both GRB 031203 and XRF 060218 are sub-energetic events[11,10], we suggest that this mysterious steep component is ubiquitous among sub-energetic GRBs and speculate that a central engine is the origin of this intense, long-lived emission. One particularly attractive possibility is a rapidly rotating (period P), highly magnetized (field strength B) neutron star: a magnetar. The spin-down power, $\dot{E} = 10^{45}(P/10)^{-4}(B/10^{15})^2\,\mathrm{erg\,s^{-1}}$, where P is in milliseconds and B is in gauss, can explain the peculiar optical to X-ray integrated luminosity at 1 day, while the temporal evolution requires a braking index lower than three (magnetic dipole). We note that similarly low braking indices are measured for young Galactic pulsars (ref. 16 and references therein).

Combining the sky coverage and detection thresholds of γ-ray missions, we estimate the following sensitivity to the two exemplars

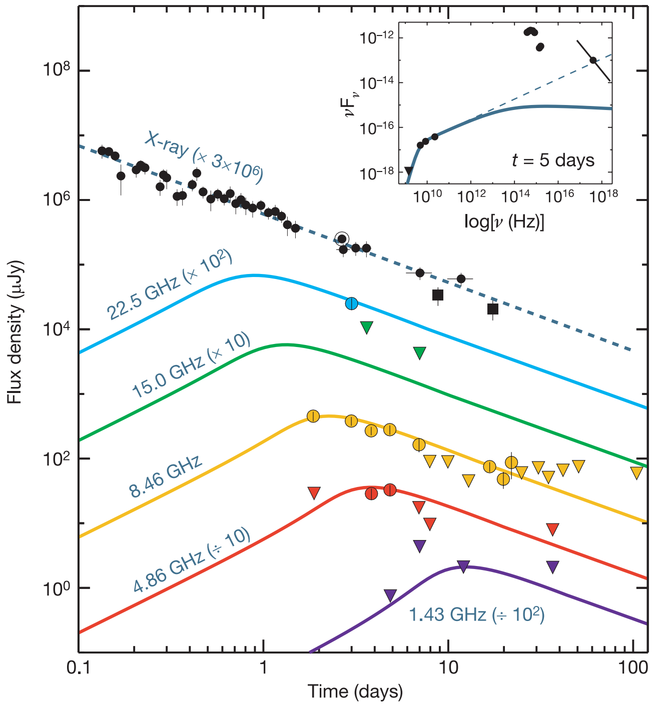

Figure 1 | Radio and X-ray light-curves of XRF 060218. Radio measurements are summarized in Table 1. Upper limits are given as 3σ (inverted triangles). Error bars are 1σ. Solid lines are models of synchrotron emission from a spherical shock expanding into a wind-blown circumstellar medium ($n \propto r^{-2}$). At $t = 5$ days the radio spectrum peaks near 4 GHz owing to the synchrotron self-absorption frequency, ν_a. We assume that the energy density is partitioned between the relativistic electrons (energy distribution $N(\gamma) \propto \gamma^{-p}$ with $p \approx 2.1$) and magnetic field as $\varepsilon_e = \varepsilon_B = 0.1$. We find that $E_K \approx 2 \times 10^{48}$ erg is coupled to ejecta with $\Gamma \approx 2.3$. The expansion, $r \propto t^m$, appropriate[25] for a core-collapse supernova explosion with a distribution of ejecta velocities, is fitted with $m \approx 0.85$. We infer a progenitor mass loss rate of $2 \times 10^{-7} M_\odot\,\mathrm{yr}^{-1}$ (for wind velocity, $v_w \approx 10^3\,\mathrm{km\,s^{-1}}$). These parameters constrain the characteristic synchrotron frequency, $\nu_m \approx 0.3$ GHz, and the synchrotron cooling frequency $\nu_c \approx 10^{14}$ Hz, at $t = 5$ days and thus $\nu_m < \nu_a$; consistent with the observed radio spectrum (inset, solid grey curve). A nearly identical fit is obtained for a trans-relativistic GRB blastwave expanding into a constant-density circumstellar medium[26] for parameters: $E_K \approx 1.2 \times 10^{48}$ erg, $n = 10^2\,\mathrm{cm^{-3}}$, $\varepsilon_e = \varepsilon_B = 0.1$ and $p = 2.1$; in this case the mildly relativistic ejecta is assumed to expand with a single bulk Lorentz factor. These values constrain the geometry of the ejecta to be effectively spherical, $\theta_j \gtrsim 1.4$. The X-ray flux (XRT, circles; XMM, circled dot, scaled to XRT spectral model; CXO, squares) is significantly brighter than an extrapolation of the above model, as shown by the unusually flat radio to X-ray spectral index, $\beta_{RX} \approx -0.5$ (inset, grey dashed line), and the steep X-ray spectrum $\beta_X \approx -2.2$ (inset, black line), instead of $\beta_X \approx -1.1$ for typical GRBs. We suggest that the integrated optical to X-ray luminosity ($10^{44}\,\mathrm{erg\,s^{-1}}$; 2–$10^4$ eV) can be attributed to the spin-down power of a magnetar. By day 5, the optical/ultraviolet spectrum is dominated by the thermal supernova emission (inset).

of low-energy events (GRB 980425 and XRF 060218): 3.8×10^{-3} (BeppoSAX), 1.2×10^{-3} (HETE-2) and $3.7 \times 10^{-3}\,\mathrm{Gpc}^3\,\mathrm{yr}$ (Swift). Thus, the true rate of sub-energetic GRBs is $230^{+490}_{-190}\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (90% confidence range; see Supplementary Information I), about ten times more abundant than typical bright GRBs[17], for which we use a mean inverse beaming factor of $< f_{\mathrm{b}}^{-1} > \sim 100$; here $f_{\mathrm{b}} \equiv 1 - \cos\theta_j$. Separately, we note that sub-energetic GRBs could not be strongly beamed or the true rate of such events would exceed the local ($d \lesssim 100$ Mpc) rate[18,19] of type Ibc supernovae, $9^{+3}_{-5} \times 10^3\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.

Spectroscopy of the nearest GRB-associated supernovae (SN 1998bw, SN 2003dh, SN 2003lw and now SN 2006aj) reveals (see ref. 4 and references therein) remarkably broad absorption lines (indicative of fast ejecta) and may suggest that all GRB–supernovae are broad-lined. Locally, broad-lined events comprise[20] 5% of type Ibc supernovae. Thus, the rate of broad-lined events and sub-energetic GRBs are comparable, suggesting that all broad-lined supernovae harbour a long-lived central engine.

Radio observations of an extensive sample of 144 optically selected local type Ibc supernovae, however, suggest[21,12] a different picture (Fig. 2). Not a single supernova (broad-lined or otherwise) shows strong early radio emission comparable to that seen in SN 1998bw and SN 2006aj. Thus, we constrain the volumetric rate of such events to be $\lesssim 300\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (see Supplementary Information II), consistent with the rate of sub-energetic GRBs inferred above. Focusing on the broad-lined supernovae, less than one in three are similar to GRBs, indicating that broad lines cannot be used as a reliable proxy for a central engine.

The commonality between the three nearest events (GRB 980425, XRF 060218, GRB 031203) is their substantial ($E_{\mathrm{K}} \gtrsim 10^{48}$ erg) mildly relativistic ($\Gamma \gtrsim 2$) ejecta and a smooth pulse profile for the prompt emission. These two clues lead us to suggest that the primary physical distinction between GRBs or XRFs and ordinary supernovae is the velocity profile of the ejecta. For the latter, hydrodynamic collapse

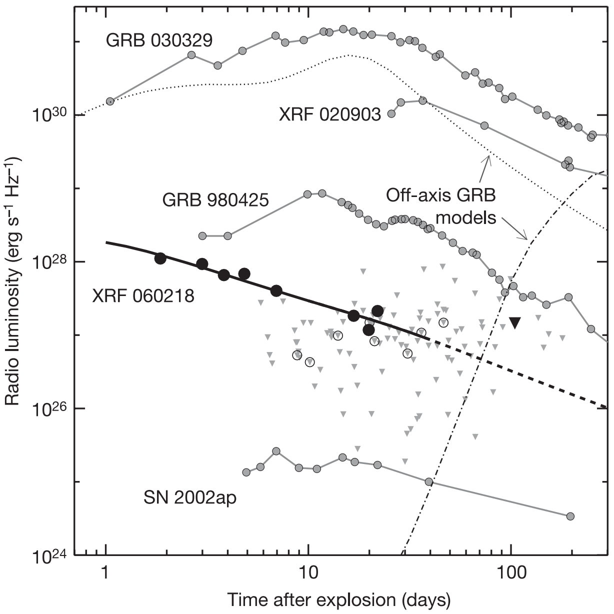

Figure 2 | **Radio observations for a large sample of local type Ibc supernovae.** Since 1999 we have been monitoring the radio emission from optically selected type Ibc supernovae with the VLA. We use radio luminosity as a proxy for mildly relativistic ejecta to quantify the fraction of type Ibc supernovae powered by central engines. Our observations of 144 supernovae show that most type Ibc supernovae do not produce strong radio emission and therefore show no evidence for a central engine. For comparison, we include the radio afterglows for nearby ($z \lesssim 0.25$) GRB 980425 and GRB 030329, and XRF 020903, all three of which show[2,8,27] evidence for an engine-driven explosion. XRF 060218 is intermediate between GRBs and the broad-lined SN 2002ap, demonstrating that broad lines are not a reliable proxy for strong radio emission. Radio limits for other local broad-lined supernovae (encircled triangles) show that less than one in three of these events may have a radio luminosity comparable to XRF 060218 or GRB 980425 (90% confidence level). In addition, we show two 8.5-GHz model light curves for a typical GRB viewed away from the collimation axis. Both models adopt typical GRB parameters (see ref. 12 and references therein) of $\Gamma = 100$, $E_{\mathrm{K,iso}} = 10^{53}$ erg, $n = 1\,\mathrm{cm}^{-3}$, $\varepsilon_{\mathrm{e}} = \varepsilon_{\mathrm{B}} = 0.1$ and $p = 2.1$. In the first model we assume that the observed γ-ray and radio emission are produced by a GRB jet viewed from an angle $\theta_{\mathrm{obs}} = 2\theta_j$; here θ_{obs} is the angle between our line-of-sight and the jet axis. In this scenario, the observed prompt emission properties (Δt, E_{p}, $E_{\gamma,\mathrm{iso}}$) are related to the intrinsic values through the quantity $D \equiv [\Gamma(\theta_{\mathrm{obs}} - \theta_j)]^{-2}$. For $D \approx 0.02$, the intrinsic properties for XRF 060218 would be typical for GRBs: $\Delta t \approx 40$ s, $E_{\mathrm{p}} \approx 250$ keV, $E_{\gamma,\mathrm{iso}} \approx 10^{53}$ erg, and $\theta_j \approx 4°$. The resulting off-axis model (dotted line) is a factor of 10^3 brighter than the observed XRF 060218 radio light-curve and can therefore be ruled out. In the second model, we assume that in addition to the quasi-spherical mildly relativistic ejecta component producing the observed radio emission, XRF 060218 also harbours a strongly collimated relativistic jet directed significantly away from our line-of-sight. In this scenario, we expect[13,12] a late-time radio re-brightening as the jet becomes non-relativistic and spreads sideways into our line-of-sight. Adopting $\theta_j = 4°$ we find that our latest radio limit (104 days; black triangle) rules out an off-axis GRB with $\theta_{\mathrm{obs}} \lesssim 60°$ (dash-dotted line). We conclude that the XRF 060218 ejecta was quasi-spherical and intrinsically sub-energetic.

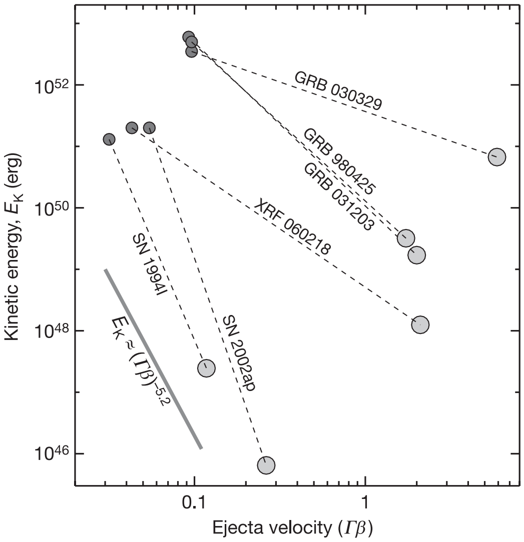

Figure 3 | **Energy as a function of velocity for GRBs, XRFs, and type Ibc supernovae.** Optical data (small dark circles) probe (see refs 28, 29 and references therein) the slowest ejecta in supernova explosions, which typically carry the bulk of the kinetic energy ($E_{\mathrm{K}} = 0.3\,M_{\mathrm{ej}}v_{\mathrm{ej}}^2 \approx 10^{51}$ erg). On the other hand, radio observations (large light circles) trace[2,11,21,25,27] only the fastest ejecta in the explosion. For GRB 030329 and GRB 031203, $\Gamma \propto t^{-3/8}$; we adopt the bulk velocity of the relativistic ejecta at day 1 as inferred from radio modelling. For GRB 980425, XRF 060218, SN 2002ap and SN 1994I the bulk velocity is roughly constant on the timescale probed by the radio observations; we adopt the velocity at the radio peak time. Standard hydrodynamic collapse results[30] in a kinetic energy profile, $E_{\mathrm{K}} \propto (\Gamma\beta)^{-5.2}$ (grey line), and thus a negligible fraction of the kinetic energy may be coupled to mildly relativistic ejecta, consistent with the radio observations of local type Ibc supernovae 1994I and 2002ap. In the case of typical GRBs (such as GRB 030329), however, the kinetic energy of the mildly relativistic ejecta is nearly comparable to that of the slower material, indicating the presence of a central engine. Because the origin of the relativistic flow is separate from the supernova, there is probably not a continuous distribution of matter between the two data points but rather distinct ejecta components. Sub-energetic bursts such as XRF 060218 are intermediate between these two classes and may indicate that their central engines are different than those of typical GRBs. We conclude that the minimum criteria for producing GRBs and XRFs is a mildly relativistic ($\Gamma \gtrsim 2$), quasi-spherical ejecta carrying at least 10^{48} erg.

requires that the ejecta energy is concentrated at low velocities, $E_K \propto (\Gamma\beta)^{-5.2}$. In comparison, the shallow velocity profiles inferred for GRBs and XRFs indicate that some other agent (an engine) enables coupling of copious energy to the relativistic material (Fig. 3).

We conclude by noting that magnetars constitute[22] about 10% of the Galactic neutron-star birth-rate, and thus a similar fraction of type Ibc supernovae. This rate is similar to that of the sub-energetic GRBs. Furthermore, magnetars produce long-lived emission (see ref. 23 and references therein) and have been suggested[24] previously as candidate GRB progenitors. We therefore speculate that a magnetar central engine is what distinguishes sub-energetic GRBs from the cosmological bursts, which are thought to be powered by a black hole.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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