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The sub-energetic γ-ray burst GRB 031203 as a cosmic analogue to the nearby GRB 980425

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Over the six years since the discovery[1] of the γ-ray burst GRB 980425, which was associated[2] with the nearby (distance ~40 Mpc) supernova 1998bw, astronomers have debated fiercely the nature of this event. Relative to bursts located at cosmological distance (redshift $z \approx 1$), GRB 980425 was under-luminous in γ-rays by three orders of magnitude. Radio calorimetry[3,4] showed that the explosion was sub-energetic by a factor of 10. Here we report observations of the radio and X-ray afterglow of the recent GRB 031203 (refs 5–7), which has a redshift of $z = 0.105$. We demonstrate that it too is sub-energetic which, when taken together with the low γ-ray luminosity[7], suggests that GRB 031203 is the first cosmic analogue to GRB 980425. We find no evidence that this event was a highly collimated explosion viewed off-axis. Like GRB 980425, GRB 031203 appears to be an intrinsically sub-energetic γ-ray burst. Such sub-energetic events have faint afterglows. We expect intensive follow-up of faint bursts with smooth γ-ray light curves[8,9] (common to both GRB 031203 and 980425) to reveal a large population of such events.

On 3 December 2003 at 22:01:28 UT, the INTEGRAL satellite detected[5,7] a seemingly typical long-duration ($\Delta t \approx 20$ s) γ-ray burst. Within 6 h, the Newton X-ray Multiple Mirror (XMM) observatory detected[10,11] an X-ray source with flux (2–10 keV band) $F_X = (3.95 \pm 0.09) \times 10^{-13}$ erg cm^{-2} s^{-1}, fading gradually $\propto t^{\alpha}$ with $\alpha = -0.4$. Using the Very Large Array (VLA), we discovered a radio source at right ascension $\alpha(\mathrm{J2000}) = 08$ h 02 min 30.18 s and declination $\delta(\mathrm{J2000}) = -39° \, 51' \, 03.51''$ (± 0.1 arcsec in each axis), well within the 6-arcsec radius error circle of the XMM source. A subsequent XMM observation[12] confirmed the gradual decay of the X-ray source. From our analysis of the XMM data, we find the flux $\propto t^{-0.4}$ between the two epochs and the spectral flux density, $F_{\nu,X} \propto \nu^{\beta}$, is fitted by $\beta = -0.81 \pm 0.05$ with an absorbing column density, $N_H = 6.2 \times 10^{21}$ cm^{-2}. Taken

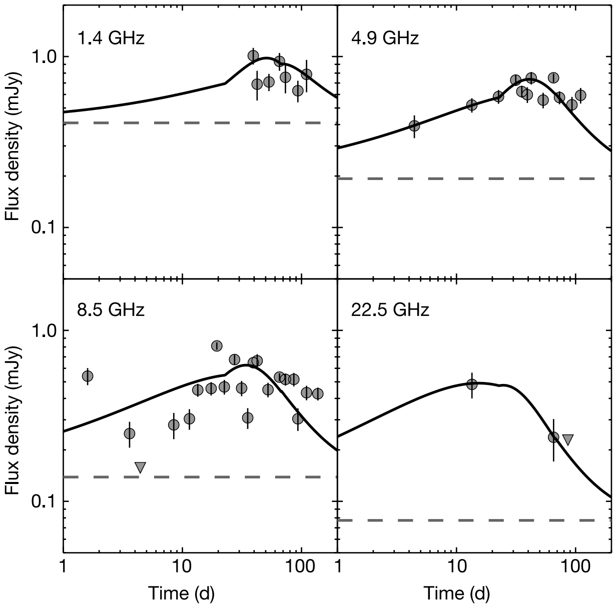

Figure 1 Radio light curves of the afterglow of GRB 031203. All measurements (circles) are summarized in Table 1 and include 1σ error bars. Triangles represent 2σ upper limits. The solid lines are models of synchrotron (afterglow) emission from spherical ejecta expanding into a uniform circumburst medium[19]. The models include a contribution from the host galaxy, which is well fitted by $F_{\mathrm{host}} \approx 0.4(\nu/1.4\,\mathrm{GHz})^{-0.6}$ mJy (dashed lines) and is consistent with the star-formation rate inferred[6] from optical spectroscopy of the host. In applying the models, the X-ray observations are considered upper limits because they are probably dominated by (non-synchrotron) emission arising from the associated supernova SN 2003lw, as evidenced by the unusually slow flux decay at early time and the flat spectral index ($F_{\nu,X} \propto t^{-0.4}\nu^{-0.8}$ as opposed to $\propto t^{-1}\nu^{-1.3}$ for GRBs). This was also the case for the X-ray emission[1] of GRB 980425/SN 1998bw ($F_{\nu,X} \propto t^{-0.2}\nu^{-1}$). For our best-fit model, we find $\chi_r^2 = 8.9$ (38 degrees of freedom), dominated by interstellar scintillation. The blastwave transitions to the non-relativistic regime at $t_{\mathrm{NR}} \approx 23$ d. From the derived synchrotron parameters (at $t = 1$ d): $\nu_a \approx 3.2 \times 10^8$ Hz, $\nu_m \approx 3.6 \times 10^{12}$ Hz and $F_{\nu a} \approx 0.04$ mJy we find an isotropic afterglow energy, $E_{\mathrm{AG,iso}} \approx 1.7 \times 10^{49}\,\nu_{c,15.5}^{1/4}$ erg, a circumburst density $n \approx 0.6\,\nu_{c,15.5}^{3/4}$ cm^{-3} and the fractions of energy in the relativistic electrons (energy distribution $N(\gamma) \propto \gamma^{-p}$ with $p \approx 2.6$) and magnetic field of $\epsilon_e \approx 0.4\,\nu_{c,15.5}^{1/4}$ and $\epsilon_B \approx 0.2\,\nu_{c,15.5}^{-5/4}$, respectively. Here, $\nu_c = 3 \times 10^{15}\,\nu_{c,15.5}$ is the synchrotron cooling frequency, which is roughly constrained by the (non-synchrotron) SN 2003lw X-ray emission. Extrapolation of the synchrotron model beyond ν_c underestimates the observed X-ray flux by a factor of $\lesssim 10$, which is comparable to the discrepancy for SN 1998bw (found by extrapolating the radio model by Li and Chevalier[4] ($p = 2.5$, $\epsilon_B = 10^{-3}$) beyond ν_c and comparing with the X-ray data[1] at $t \sim 12$ d).

Table 1 **Radio observations made with the Very Large Array**

Epoch (UT)	Δt (d)	$F_{1.43}$ (mJy)	$F_{4.86}$ (mJy)	$F_{8.46}$ (mJy)	$F_{22.5}$ (mJy)
2003 Dec. 5.52	1.60	–	–	0.540 ± 0.062	–
2003 Dec. 7.52	3.60	–	–	0.249 ± 0.043	–
2003 Dec. 8.35	4.43	–	0.393 ± 0.060	0.053 ± 0.052	–
2003 Dec. 12.38	8.46	–	–	0.280 ± 0.049	–
2003 Dec. 15.37	11.45	–	–	0.304 ± 0.042	–
2003 Dec. 17.38	13.46	–	0.520 ± 0.050	0.448 ± 0.039	0.483 ± 0.083
2003 Dec. 21.35	17.43	–	–	0.457 ± 0.041	–
2003 Dec. 23.37	19.45	–	–	0.811 ± 0.040	–
2003 Dec. 26.40	22.48	–	0.583 ± 0.054	0.467 ± 0.046	–
2003 Dec. 31.33	27.41	–	–	0.675 ± 0.045	–
2004 Jan. 4.33	31.41	–	0.728 ± 0.055	0.459 ± 0.047	–
2004 Jan. 8.26	35.34	–	0.624 ± 0.050	0.308 ± 0.043	–
2004 Jan. 12.29	39.37	1.011 ± 0.113	0.598 ± 0.063	0.647 ± 0.045	–
2004 Jan. 15.35	42.43	0.689 ± 0.136	0.749 ± 0.063	0.664 ± 0.061	–
2004 Jan. 25.24	52.32	0.710 ± 0.082	–	0.450 ± 0.044	–
2004 Jan. 26.34	53.42	–	0.556 ± 0.058	–	–
2004 Feb. 7.24	65.32	0.937 ± 0.112	0.751 ± 0.045	0.533 ± 0.028	0.273 ± 0.066
2004 Feb. 15.22	73.30	0.756 ± 0.147	0.576 ± 0.050	0.517 ± 0.042	–
2004 Feb. 28.13	86.21	–	–	0.517 ± 0.047	0 ± 0.114
2004 Mar. 6.17	93.25	0.631 ± 0.091	0.522 ± 0.058	0.304 ± 0.046	–
2004 Mar. 23.13	110.21	0.787 ± 0.169	0.593 ± 0.062	0.432 ± 0.042	–
2004 Apr. 19.07	137.15	–	–	0.426 ± 0.037	–

Observations commenced on 5 December 2003 UT. For all observations, we used the standard continuum mode with 2 × 50 MHz bands. At 22.5 GHz we used referenced pointing scans to correct for the systematic 10–20 arcsec pointing errors of the Very Large Array (VLA) antennas. We used the extra-galactic sources 3C 147 (J0542+498) and 3C 286 (J1331+305) for flux calibration, while the phase was monitored using J0828−375. The data were reduced and analysed using the Astronomical Image Processing System. The flux density and 1σ uncertainty were measured from the resulting maps by fitting a gaussian model to the afterglow emission.

together, the transient X-ray and radio emission are suggestive of afterglow emission.

In addition to monitoring the afterglow in various radio bands (Table 1 and discussion below) we obtained an observation of the source with the Advanced CCD Imaging Spectrometer (ACIS) instrument on board the Chandra X-ray observatory. The Chandra observations began on 22 January 2004 at 21:35 UT and lasted about 22 ks. We detected a faint source, count rate in the 2–10 keV band of $5.6 \times 10^{-4}\,\mathrm{s}^{-1}$, at $\alpha(\mathrm{J2000}) = 08\,\mathrm{h}\ 02\,\mathrm{min}\ 30.159\,\mathrm{s}$ and $\delta(\mathrm{J2000}) = -39^\circ\ 51'\ 03.51''$ (±0.18 arcsec in each axis), precisely coincident with the VLA source. Using the XMM model parameters stated above, we obtain $F_X = 6.4 \times 10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, implying a faster decline ($\alpha = -1 \pm 0.1$) between the second XMM and Chandra observations.

The primary interest in this burst is that the radio and X-ray afterglows coincide at the sub-arcsecond level[13] with a nearby ($z = 0.1055$) galaxy[6], making it the nearest GRB with the exception of the peculiar GRB 980425[2]. At this redshift, the isotropic γ-ray energy release is 10^2 times smaller[7] than that of the nearest classical event GRB 030329 ($z = 0.169$)[14] and yet a factor of 10^2 larger[1,2] than that of GRB 980425.

The afterglow properties of GRB 031203 also seem to be intermediate between classical cosmological GRBs and GRB 980425: the isotropic X-ray luminosity of GRB 031203 at $t \approx 10\,\mathrm{h}$ is $L_X = 9 \times 10^{42}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, nearly 10^3 times fainter than that observed[15] for classical GRBs but a factor of 10^2 brighter[1] than that of GRB 980425. In the centimetre band, the peak luminosity is $L_{\nu,8.5\,\mathrm{GHZ}} \approx 10^{29}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}$, fainter[16] by a factor of 10^2 than that of most radio afterglows but comparable[3] to that of GRB 980425. As L_X and the peak radio luminosity of an afterglow can be used[17,15] as rough proxies for the afterglow energy, the data suggest that GRBs 031203 and 980425 are sub-energetic in comparison with classical GRBs.

As a next step, we applied the simplest afterglow model[18,19] (a spherical relativistic blastwave shocking a constant density circumburst medium and accelerating relativistic electrons: the afterglow emission arises from synchrotron emission of shocked electrons) to the afterglow data and obtain a satisfactory fit (Fig. 1). On the timescales best probed by the radio data—days to months—we see no evidence for a collimated (jet) geometry commonly seen[20] in the afterglows of cosmological GRBs.

From our modelling we confirm that the blast wave is sub-

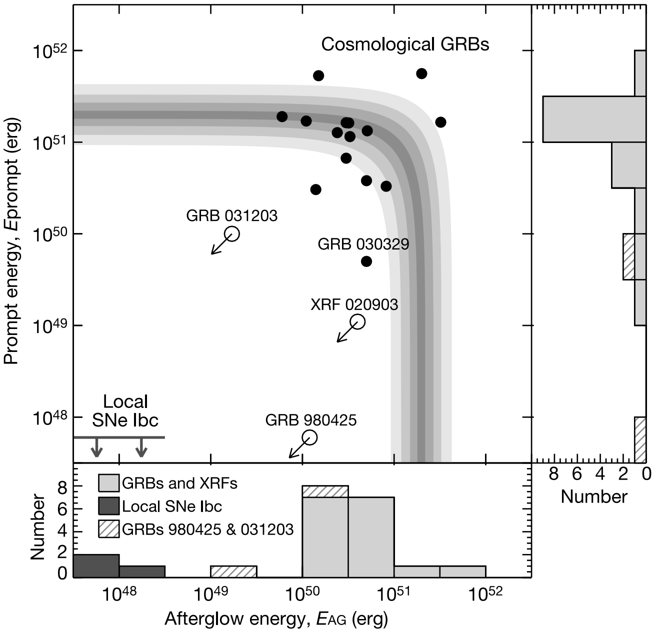

Figure 2 Two-dimensional energy plot for cosmic explosions. The energy in the prompt emission, E_{prompt}, and in the afterglow, E_{AG}, have been corrected[20,26,27] for beaming based on the jet-break time observed for each burst, except in the cases of GRB 980425[4,3], X-ray flash (XRF) 020903[28] and GRB 031203 for which there is no evidence for a collimated outflow. For these three cases, we plot the isotropic values of E_{prompt} and E_{AG} and use an arrow to indicate they represent upper limits on both axes. The arcs mark lines of constant $E_{\mathrm{prompt}} + E_{\mathrm{AG}}$ as a guide to the reader. Most cosmological GRBs tend to cluster[27] around $E_{\mathrm{prompt}} + E_{\mathrm{AG}} \approx 2 \times 10^{51}$ erg, while GRBs 031203 and 980425, the nearest two bursts in the sample, are clearly sub-energetic. With the exception of SN 1998bw, associated with GRB 980425, there are no local Ibc supernovae with detected γ-ray emission, but the kinetic energy in the ejecta (excluding the photospheric energy yield) is generically found[29] to be $E_{\mathrm{AG}} \lesssim 3 \times 10^{48}$ erg (bottom left corner). Histograms of E_{AG} and E_{prompt} are shown in the bottom and side panels, respectively, for cosmological GRBs and local Ibc supernovae (SNe). The striped energy bins show the locations of GRBs 980425 and 031203.

energetic, finding an inferred afterglow energy of $E_{\rm AG} \approx 1.7 \times 10^{49}$ erg. The circumburst particle density, $n \approx 0.6\,{\rm cm}^{-3}$, is not atypical of that inferred[17] for other GRBs. The blastwave is expected to become[21] non-relativistic on a timescale $t_{\rm NR} \approx 34(E_{\rm AG,50}/n_0)^{1/3}$ d, where we adopt the notation $q \equiv 10^x q_x$. The observational signatures[22] of this transition, a steeper decay of the spectral peak frequency ($\nu_{\rm m} \propto t^{-1.5} \rightarrow t^{-3}$) and an increase in the spectral peak flux ($F_{\nu_{\rm m}} \propto t^0 \rightarrow t^{3/5}$) are consistent with the data (Fig. 1).

Here we use $E_{\rm AG}$ to denote the kinetic energy remaining in the blast wave after the prompt γ-ray energy release. In turn, the γ-ray emission arises from ultra-relativistic (bulk Lorentz factor $\Gamma \gtrsim 100$) ejecta within the blastwave. Thus, a more complete picture of the explosion energy is visualized through a two-dimensional plot of $E_{\rm prompt}$, the beaming-corrected prompt energy release, versus $E_{\rm AG}$ (Fig. 2).

The two nearest events, GRBs 031203 and 980425, are clearly sub-energetic outliers in Fig. 2. Furthermore, we note several additional similarities: GRBs 031203 and 980425 (1) show no evidence for jets[3]; (2) possess simple γ-ray light curves[1,7], (3) violate[7] the $E_{\rm prompt} - E_{\rm peak}$ relation[23] with respect to cosmological ('classical') bursts; and (4) are outliers in the luminosity–spectral lag relation[9]. This discussion motivates the question: How are these two events related to cosmological GRBs?

It has been suggested (see, for example, ref. 24) that all GRB explosions have the same energetics and explosion geometry. In this framework, sub-energetic bursts are simply events viewed away from the jet axis. Such bursts should have a soft $E_{\rm peak}$ and also exhibit a rise in the inferred $E_{\rm AG}$ as shocked ejecta eventually come into our line of sight. For GRB 031203, $E_{\rm peak} > 190$ keV (ref. 7), comparable to cosmological GRBs for which we have observational evidence favouring an on-axis viewing angle. Moreover, we see no evidence for an increase in $E_{\rm AG}$ during the timescale of the radio observation (~150 d). Similarly, there is no evidence that $E_{\rm AG}$ is increasing for GRB 980425, despite dedicated radio monitoring[25] of the source since 1998. With no indication of their being off-axis explosions, we at present conclude that GRBs 031203 and 980425 are intrinsically sub-energetic events.

Astronomers have had to wait six years to discover a sub-energetic event similar to GRB 980425, despite a large population of such events (as implied by their proximity). The bulk of the population has escaped our attention owing to their faint γ-ray and afterglow emission, which challenge our current detection limits. The Swift satellite mission, with its higher γ-ray sensitivity (compared to current missions) and improved localization capability (enabling rapid identification of afterglow counterparts), is expected to revolutionize our understanding of cosmic explosions. □

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Two-dimensional geometry of spin excitations in the high-transition-temperature superconductor $YBa_2Cu_3O_{6+x}$

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The fundamental building block of the copper oxide superconductors is a Cu_4O_4 square plaquette. The plaquettes in most of these materials are slightly distorted to form a rectangular lattice, for which an influential theory predicts that high-transition-temperature (high-T_c) superconductivity is nucleated in 'stripes' aligned along one of the axes[1–3]. This theory received strong support from experiments that indicated a one-dimensional character for the magnetic excitations in the high-T_c material $YBa_2Cu_3O_{6.6}$ (ref. 4). Here we report neutron scattering data on 'untwinned' $YBa_2Cu_3O_{6+x}$ crystals, in which the orientation of the rectangular lattice is maintained throughout the entire