An apparently normal γ-ray burst with an unusually low luminosity

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Much of the progress in understanding γ-ray bursts (GRBs) has come from studies of distant events (redshift $z \approx 1$). In the brightest GRBs, the γ-rays are so highly collimated that the events can be seen across the Universe. It has long been suspected that the nearest and most common events have been missed because they are not as collimated or they are under-energetic (or both)[1]. Here we report soft γ-ray observations of GRB 031203, the nearest event to date ($z = 0.106$; ref. 2). It had a duration of 40 s and peak energy of >190 keV, and therefore appears to be a typical long-duration GRB. The isotropic γ-ray energy of $\leq 10^{50}$ erg, however, is about three orders of magnitude smaller than that of the cosmological population. This event—as well as the other nearby but somewhat controversial GRB 980425—is a clear outlier from the isotropic-energy/peak-energy relation[3,4] and luminosity/spectral-lag relations[5,6] that describe the majority of GRBs. Radio calorimetry shows that both of these events are under-energetic explosions[7]. We conclude that there does indeed exist a large population of under-energetic events.

On 2003 December 3 at 22:01:28 UTC, IBIS, a hard X-ray coded aperture mask imager on the INTEGRAL satellite, detected[8] a pulse of 40 s duration. This event, GRB 031203, was localized by on-board software and the 2.5-arcmin position rapidly disseminated[9]. The event, with a simple profile (Fig. 1), appears to be a typical long-duration GRB. Likewise the spectrum is also typical (Fig. 2). A single power law model with photon index $\alpha = -1.63 \pm 0.06$ provides an adequate fit. We place a lower limit on the spectral peak energy, $E_{\rm peak} > 190$ keV (90% confidence; see Fig. 2).

We found no evidence for significant spectral evolution on short (seconds) timescales. Next, we cross-correlated the light curves in two energy ranges (soft, 20–50 keV, and hard, 100–200 keV) and detected a marginal lag of 0.24 ± 0.12 in the usual sense (harder emission preceding the softer emission).

Watson *et al.*[10] have suggested that GRB 031203 is an X-ray flash (XRF). XRFs are defined[11,12] either by $E_{\rm peak} < 50$ keV or by a larger 2–30 keV fluence ($S_{\rm X}$) compared to that in the traditional GRB band, 30–400 keV (S_γ). The high-$E_{\rm peak}$ soft γ-ray spectrum measured by INTEGRAL provides direct evidence that GRB 031203 is a GRB rather than an XRF. The case for an XRF was made by a very high value of flux at 1 keV, $F_{\rm X} = (2.6 \pm 1.3) \times 10^{-6}$ erg cm^{-2} keV^{-1}, inferred from modelling of a dust-scattered echo[13]. As can be seen from Fig. 2 the soft X-ray emission is well above an extrapolation of the INTEGRAL spectrum (which predicts $0.36 < S_{\rm X}/S_\gamma < 0.53$, depending on the precise value of $E_{\rm peak}$) and thus it must have an origin different from the process producing the soft γ-ray pulse. It is possible that the echo was caused by the early ($\lesssim 1{,}000$ s) afterglow. We note however that the inferred soft X-ray fluence is inversely proportional to the assumed dust column and extrapolation of our spectrum to keV energies is consistent with the lower soft X-ray fluence (due to a higher dust column) advocated by Prochaska *et al.*[2].

The burst fluence in the 20–200 keV band is $(2.0 \pm 0.4) \times 10^{-6}$ erg cm^{-2}. Adopting the redshift of 0.1 (ref. 2) and the currently popular cosmological parameters '$(H_0, \Omega_{\rm m}, \Omega_\Lambda) = (75\,{\rm km\,s^{-1}\,Mpc^{-1}}, 0.3, 0.7)$', we find that the isotropic energy equivalent is $(4 \pm 1) \times 10^{49}$ erg. Defining $\epsilon_{\gamma,{\rm iso}}$ to be the isotropic energy equivalent over the 20–2000 keV band, we find 6×10^{49} erg $< \epsilon_{\gamma,{\rm iso}} < 1.4 \times 10^{50}$ erg; where the range reflects the observational uncertainty in the spectrum above 200 keV (see Fig. 2).

GRB 031203, an event with spectrum similar to cosmological GRBs, is the least energetic (in terms of $\epsilon_{\gamma,{\rm iso}}$) long-duration GRB. Clearly, γ-ray luminosities and energy releases vary widely, spanning at least four orders of magnitude. Furthermore it is of considerable interest to note that GRB 031203 violates two much discussed relations in GRB astrophysics: (1) the $\epsilon_{\gamma,{\rm iso}}$–$E_{\rm peak}$ relation and (2) the luminosity–spectral lag relation. For GRB 031203, the first relation predicts[4] $E_{\rm peak} \approx 10$ keV, in gross disagreement with the analysis presented here. Long spectral lags are expected from the second relation[5,6] when in fact we see virtually no lag (Fig. 3).

GRB 031203, however, shares some properties with GRB 980425, which is associated with a nearby ($z = 0.0085$) supernova, SN 1998bw (refs 14, 15). This event was also severely underenergetic, $\epsilon_{\gamma,{\rm iso}} \approx 10^{48}$ erg, and violated the $\epsilon_{\gamma,{\rm iso}}$–$E_{\rm peak}$ relation. Curiously, GRB 98425 was also a single pulse[16] but without a cusp.

To summarize, the two nearest long-duration events, GRB 031203 and GRB 980425, are clearly sub-energetic in the γ-ray band. Their proximity (and hence implied abundance) makes it of great interest to understand their origin and relation to the more distant cosmological events. Are these events genuinely low-energy explosions[15] ('sub-energetic' model) or a typical GRB viewed away from its axis ('off-axis' model)?

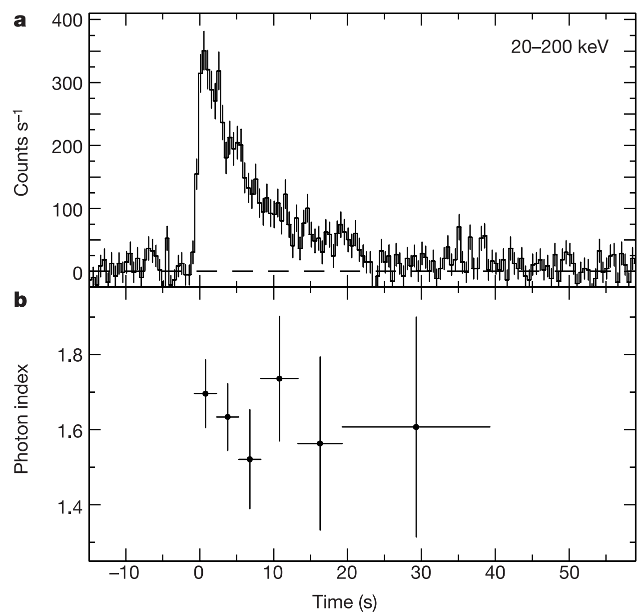

Figure 1 The temporal profile of GRB 031203 and its evolution. **a**, The profile in the 20–200 keV energy range obtained with the IBIS/ISGRI detector on board INTEGRAL. The binning is 0.5 s. Time is measured relative to burst trigger. A background level (136 counts s^{-1}) was estimated from a 200-s interval preceding the trigger and then subtracted from the profile. Vertical error bars indicate poissonian noise. The profile can be classified as a FRED ('fast rise exponential decay') with a rise time of about 1 s and an *e*-folding time of 8 ± 0.5 s. The peak flux is 2.6 photons cm^{-2} s^{-1} corresponding to 2.4×10^{-7} erg cm^{-2} s^{-1} in the 20–200 keV band. Two X-ray sources present in the field of view (Vela X-1 and 4U 0836–429) contribute only ~15 counts s^{-1} to the total count rate (before background subtraction). Imaging analysis of IBIS data revealed no source at the position of GRB 031203 during half an hour before, or one day after, the burst. The corresponding 3σ upper limits (in the 20–200 keV band) are $\sim 10^{-9}$ erg cm^{-2} s^{-1} and $\sim 10^{-10}$ erg cm^{-2} s^{-1}, respectively. **b**, The evolution of the photon index during the duration of the burst. The spectrum over 20–200 keV is fitted to a single power law with index α; the bin width varies from 2.5 s near the burst peak to 20 s during the decay phase. Vertical bars indicate 1σ uncertainties.

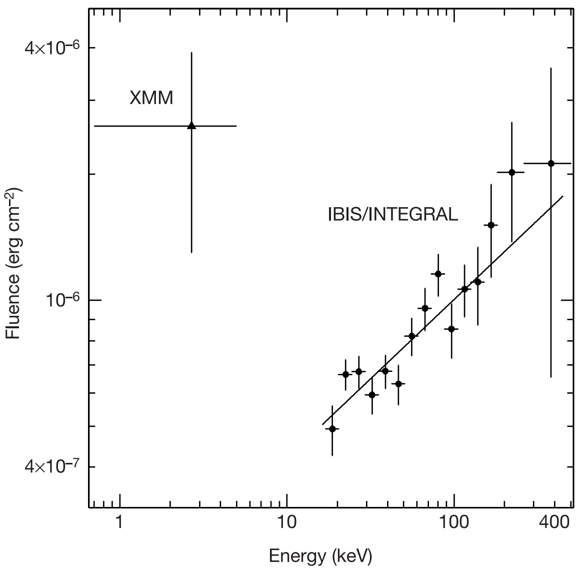

Figure 2 Spectral energy distribution of GRB 031203 shown in νF_ν units. The data points in the 17–500 keV range were obtained from the data of the IBIS/ISGRI detector for the first 20 s of the burst, when 80% of its total energy was emitted. Scattering and absorption in the interstellar medium of our Galaxy and the host galaxy of GRB 031203 has negligible effect (<1%) on observed flux at photon energies above 20 keV. The energy bin width varies from 3 keV at 17 keV to 250 keV at 500 keV. Vertical bars indicate 1σ statistical uncertainties. We considered a single power law model (photon index, α). Our method[23,24] consisted of constructing images in predefined energy intervals followed by normalizing the resulting source fluxes to the corresponding fluxes of the Crab nebula for a similar position in the field of view. Analysis of an extensive set of Crab calibration observations has shown that the source absolute flux can be recovered with an accuracy of 10% and the systematic uncertainty of relative flux measurement in different energy channels is less than 5%. The latter uncertainty was included in the modelling of the spectrum. The best-fit power law model with $\alpha = -1.63 \pm 0.06$ (1σ uncertainty, χ^2/d.o.f. = 14.8/15) is shown by the line. We also considered a double power law model (the so-called 'Band' model[25,26]). Setting the high-energy power law index to -2 we are able to place a lower limit to the peak energy, $E_{\rm peak} > 190$ keV (90% confidence level). The data point towards the top left corner of the figure is the soft X-ray (0.7–5 keV) fluence, $F_{\rm X}$, inferred[10,13] from the dust scattered haloes discovered in XMM-Newton observations. The vertical bars indicate 1σ uncertainties.

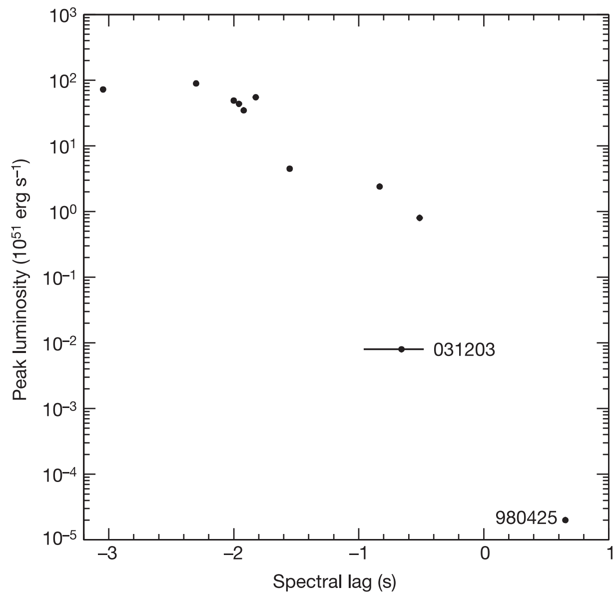

Figure 3 Spectral lag versus luminosity for cosmological and low-redshift GRBs. The data for cosmological bursts (unlabelled points), with measured redshifts ranging between $z = 0.84$ and 4.5, are adopted from ref. 27. The lag is defined between the burst profiles at 25–50 keV and 100–300 keV, and the luminosity is calculated over the 50–300 keV band at the burst peak, assuming isotropic emission. Also plotted are the data for GRB 980425 ($z = 0.0085$)[6], and GRB 031203 ($z = 0.1055$, this work). In the latter case, the peak luminosity measured with INTEGRAL was converted to the 50–300 keV range, and the lag (shown with 1σ error bars) was determined between the 20–50 keV and 100–200 keV bands. All the lags have been corrected for cosmological time dilation. The luminosities are given for a cosmology with (H_0, $\Omega_{\rm m}$, Ω_Λ) = (65 km s^{-1} Mpc^{-1}, 0.3, 0.7).

In the off-axis model[17], $\epsilon_{\gamma,\rm iso} \propto \delta^n$ with $n \approx 2$–3, where $\delta = \gamma^{-1}[1 - \beta\cos(\theta - \theta_{\rm j})]^{-1}$ is the so-called Doppler factor; here, $v = c\beta$ is the velocity of the shocked ejecta, c is the velocity of light, $\gamma = (1 - \beta^2)^{-1/2}$, θ is the angle between the observer and the principal axis of the explosion and $\theta_{\rm j}$ is the opening angle of the explosion ('jet'). If we wish to make GRB 031203 to have isotropic energies similar to cosmological GRBs then δ should be ~10–30 times smaller than the on-axis value δ_0. The true peak energy is then $(\delta_0/\delta) \times (1 + z) \times E_{\rm peak} > 2$ MeV — making GRB 031203 one of the hardest bursts. A second consequence is that the afterglow should brighten as the ejecta slows down. Soderberg *et al.*[7] do not see any rebrightening, and furthermore the afterglow is faint, indicating that the explosion was under-energetic, $\lesssim 10^{50}$ erg. Likewise, radio calorimetry of SN 1998bw at early[15] or late[18] times finds $\lesssim 10^{50}$ erg. Thus we conclude that GRB 031203 and GRB 980425 are intrinsically sub-energetic events.

With a peak count rate of 1.3 photons cm^{-2} s^{-1} (50–300 keV), GRB 031203 could have been detected by BATSE out to $z \approx 0.25$. So as not to significantly distort the observed (nearly flat) burst intensity distribution at low fluxes, less than ~300 underluminous bursts like GRB 031203 can be present in the BATSE catalogue[19], including up to ~20 located at $z < 0.1$. On the other hand, a 'typical' GRB with $\epsilon_{\gamma,\rm iso} \approx 10^{53}$ erg would have a fluence of 10^{-3} erg cm^{-2} if it occurred as close as GRB 031203. Only a few such bright bursts have been observed in the ~30 years of GRB observations[20–22], suggesting a large population of events like GRB 031203 (see also ref. 2). We eagerly await the launch of the Swift mission, which with its increased sensitivity should detect and localize many (×10 the current rate) under-energetic events like GRB 031203. □

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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

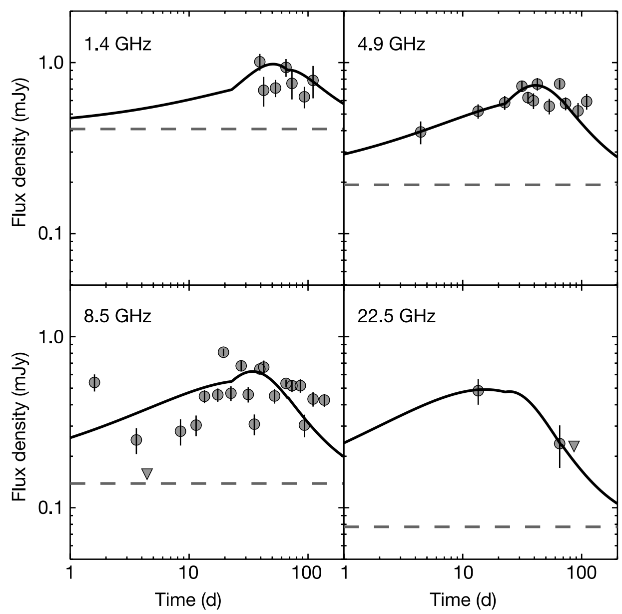

Figure 1 Radio light curves of the afterglow of GRB 031203. All measurements (circles) are summarized in Table 1 and include 1σ error bars. Triangles represent 2σ upper limits. The solid lines are models of synchrotron (afterglow) emission from spherical ejecta expanding into a uniform circumburst medium[19]. The models include a contribution from the host galaxy, which is well fitted by $F_{\rm host} \approx 0.4(\nu/1.4\,\mathrm{GHz})^{-0.6}$ 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 $\chi^2_r = 8.9$ (38 degrees of freedom), dominated by interstellar scintillation. The blastwave transitions to the non-relativistic regime at $t_{\rm NR} \approx 23$ 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, $E_{\rm AG,iso} \approx 1.7 \times 10^{49}\, \nu_{c,15.5}^{1/4}$ 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).