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

S. Yu. Sazonov¹² A. A. Lutovinov¹ & R. A. Sunyaev¹²

Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117997 Moscow, Russia Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85740 Garching bei München, Germany

Much of progress in gamma-ray bursts (GRBs) has come from the studies of di

Much of progress in gamma-ray bursts (GRBs) has come from the studies of distant events (redshift $z \sim 1$). The brightest GRBs are the most collimated events and seen across the Universe due to their brilliance. It has long been suspected that nearest (and most common) events have been missed because they are not so collimated or under-energetic or both. Here we report soft γ -ray observations of GRB 031203, the nearest event to date (z=0.106; ref. 2). This event with a duration of 40 s and peak energy of > 190 keV appears to be a typical long duration GRB. However, the isotropic γ -ray energy $\lesssim 10^{50}\,\mathrm{erg}$, about three orders of magnitude smaller than the cosmological population. This event as well as the other nearby but somewhat controversial event GRB 980425 are clear outliers for the much discussed isotropic-energy peak-energy relation^{3,4} and luminosity spectral-lag relations. Radio calorimetry shows that both these events are under-energetic explosions. We conclude that there does indeed exist Much of progress in gamma-ray bursts (GRBs) has come from the studies of distant 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 detected⁸ a pulse of 40 s-duration. This event, GRB 031203, was localized by on-board software and the 2.5-arcmin position rapidly disseminated. The event with a simple profile (Figure 1) appears to be a typical long duration GRB. Likewise the spectrum is also typical (Figure 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, $E_{\text{peak}} > 190 \,\text{keV}$ (90% confidence; see Figure 2).

We found no evidence for significant spectral evolution on short (seconds) time scales. 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).

2 Sazonov, Lutovinov & Sunyaev

Watson et al.¹⁰ have suggested that GRB 031203 is an X-ray flash (XRF). XRFs are defined^{11,12} either by $E_{\text{peak}} < 50 \,\text{keV}$ or a larger 2–30 keV fluence (S_X) compared to that in the traditional GRB band, 30–400 keV (S_γ) . The high- E_{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, $F_X = (2.6 \pm 1.3) \times 10^{-6} \,\text{erg cm}^{-2} \,\text{keV}^{-1}$, inferred from modelling of a dust-scattered echo.¹³ As can be seen from Figure 2 the soft X-ray emission is well above an extrapolation of the INTEGRAL spectrum (which predicts $0.36 < S_X/S_\gamma < 0.53$, depending on the precise value of E_{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 ($\lesssim 1,000 \,\text{s}$) 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 $(2.0 \pm 0.4) \times 10^{-6} \,\mathrm{erg}\,\mathrm{cm}^{-2}$. Adopting the redshift of 0.1 (ref. 2) and the currently popular cosmological parameters $[(H_0, \Omega_{\mathrm{m}}, \Omega_{\Lambda}) = (75 \,\mathrm{km}\,\mathrm{s}^{-1}\,\mathrm{Mpc}^{-1}, 0.3, 0.7)]$. we find that the isotropic energy equivalent is $(4 \pm 1) \times 10^{49} \,\mathrm{erg}$. Defining $\epsilon_{\gamma,\mathrm{iso}}$ to be the isotropic energy equivalent over the 20–2000 keV band, we find $6 \times 10^{49} \,\mathrm{erg} < \epsilon_{\gamma,\mathrm{iso}} < 1.4 \times 10^{50} \,\mathrm{erg}$; where the range reflects the observational uncertainty in the spectrum above 200 keV (see Figure 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 predicts⁴ $E_{\rm peak} \sim 10\,\rm keV$, 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 (Figure 3).

GRB 031203, however, shares some properties with GRB 980425 associated with a nearby (z = 0.0085) SN 1998bw.^{14,15} This event was also severely underenergetic, $\epsilon_{\gamma,\rm iso} \sim 10^{48}$ erg and violated the $\epsilon_{\gamma,\rm iso}$ - $E_{\rm peak}$ relation. Curiously, GRB 98425 was also a single pulse¹⁶ 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 prime interest to understand their origin and relation to the more distant cosmological events. Are these

events genuinely low energy explosions¹⁵ ("sub-energetic" model) or a typical GRB viewed away from its axis ("off-axis" model)?

In the off-axis model, 17 $\epsilon_{\gamma, \rm iso} \propto \delta^n$ with $n \sim 2-3$ where $\delta = \gamma^{-1}[1-\beta\cos(\theta-\theta_j)]^{-1}$ 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 θ_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 to 30 times smaller than the on-axis value δ_0 . The true peak energy is then $(\delta_0/\delta) \times (1+z) \times E_{\rm peak} > 2\,{\rm MeV}$ – 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 underenergetic, $\lesssim 10^{50}\,{\rm erg}$. Likewise, radio calorimetry of SN 1998bw at early or late 18 find $\lesssim 10^{50}\,{\rm erg}$. Thus we conclude that GRB 031203 and GRB 980425 are intrinsically sub-energetic events.

With peak count rate of 1.3 photon cm⁻² s⁻¹ (50–300 keV), GRB 031203 could have been detected by BATSE out $z \sim 0.25$. 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 $\epsilon_{\gamma,\rm iso} \sim 10^{53}$ 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.

Received 14 July 2018; Accepted draft.

- MacFadyen, A. I., Woosley, S. E. & Heger, A. Supernovae, Jets, and Collapsars. Astrophys. J. 550, 410–425 March 2001.
- 2. Prochaska, J. X., Bloom, J. S., Chen, H., Hurley, K. C., Melbourne, J. et al. The host galaxy of GRB 031203: implications of its low metallicity, low redshift, and starburst nature. ApJ (in press) (2004).
- Amati, L., Frontera, F., Tavani, M., in't Zand, J. J. M., Antonelli, A. et al. Intrinsic spectra and energetics of BeppoSAX gamma-Ray bursts with known redshifts. Astr. Astrophys. 390, 81–89 (2002).

- 4 Sazonov, Lutovinov & Sunyaev
- 4. Lamb, D. Q., Donaghy, T. Q. & Graziani, C. A unified jet model of X-ray flashes and γ -ray bursts. New Astronomy Review 48, 459–464 (2004).
- Norris, J. P., Marani, G. F. & Bonnell, J. T. Connection between energy-dependent lags and peak luminosity in gamma-ray bursts. Astrophys. J. 534, 248–257 (2000).
- Schaefer, B. E., Deng, M. & Band, D. L. Redshifts and luminosities for 112 gamma-ray bursts. Astrophys. J. 563, L123–L127 (2001).
- 7. Soderberg, A. M., Kulkarni, S. R., Berger, E., Fox, D. W., Sako, M. *et al.* The sub-energetic GRB 031203 as a cosmic analogue to GRB 980425. submitted to Nature (2004).
- 8. Mereghetti, S. & Götz, D. GRB 031203: further analysis of INTEGRAL data. *GRB Circular Network* **2460**, (2003).
- Götz, D., Mereghetti, S., Beck, M., Borkowski, J. & Mowlavi, N. GRB 031203: a long GRB detected with INTEGRAL. GRB Circular Network 2459, (2003).
- Watson, D., Hjorth, J., Levan, A., Jakobsson, P., O'Brien, P. T. et al. A Very Low Luminosity X-Ray Flash: XMM-Newton Observations of GRB 031203. Astrophys. J. 605, L101–L104 (2004).
- 11. Heise, J., in't Zand, J., Kippen, R. M. & Woods, P. M. in *Gamma-ray Bursts in the Afterglow Era* (eds Costa, E., Frontera, F. & Hjorth, J.) 16–21 (Springer, 2001).
- 12. Barraud, C., Olive, J.-F., Lestrade, J. P., Atteia, J.-L., Hurley, K. et al. Spectral analysis of 35 GRBs/XRFs observed with HETE-2/FREGATE. Astr. Astrophys. 400, 1021–1030 (2003).
- 13. Vaughan, S., Willingale, R., O'Brien, P. T., Osborne, J. P., Reeves, J. N. et al. The discovery of an evolving dust-scattered X-ray halo around GRB 031203. Astrophys. J. 603, L5–L8 (2004).
- 14. Galama, T. J., Vreeswijk, P. M., van Paradijs, J., Kouveliotou, C., Augusteijn, T. et al. An unusual supernova in the error box of the gamma-ray burst of 25 April 1998. Nature 395, 670–672 (1998).
- Kulkarni, S. R., Frail, D. A., Wieringa, M. H., Ekers, R. D., Sadler, E. M. et al. Radio emission from the unusual supernova 1998bw and its association with the gamma-ray burst of 25 April 1998. Nature 395, 663–669 (1998).
- Bloom, J. S., Kulkarni, S. R., Harrison, F., Prince, T., Phinney, E. S. et al. Expected characteristics of the subclass of supernova gamma-ray bursts. Astrophys. J. 506, L105–L108 (1998).

- 17. Yamazaki, R., Yonetoku, D. & Nakamura, T. An off-axis jet model for GRB 980425 and low-energy gamma-ray bursts. *Astrophys. J.* **594**, L79–L82 (2003).
- 18. Soderberg, A. M., Frail, D. A. & Wieringa, M. H. Constraints on Off-Axis Gamma-Ray Burst Jets in Type Ibc Supernovae from Late-Time Radio Observations. *Astrophys. J.* **607**, L13–L16 May 2004.
- Paciesas, W. S., Meegan, C. A., Pendleton, G. N., Briggs, M. S., Kouveliotou, C. et al. The fourth BATSE gamma-ray burst catalog (revised). Astrophys. J. Supp. Series 122, 465–495 (1999).
- 20. Mazets, E. P. & Golenetskii, S. V. Recent results from the gamma-ray burst studies in the KONUS experiment. *Astrophys. Space Sci.* **75**, 47–81 (1981).
- Kuznetsov, A. V., Syunyaev, R. A., Terekhov, O. V., Yakubtsev, L. A., Barat, C. et al. SIGNE:2 MP9 data for the powerful gamma-ray burst of 1983 Aug 1. Soviet Astronomy Letters 12, 315–318 (1986).
- 22. Fenimore, E. E., Epstein, R. I., Ho, C., Klebesadel, R. W., Lacey, C. *et al.* The intrinsic luminosity of gamma-ray bursts and their host galaxies. *Nature* **366**, 40–42 (1993).
- 23. Lutovinov, A. A., Molkov, S. V. & Revnivtsev, M. G. The First Results of Observations of the Transient Pulsar SAX J2103.5+4545 by the INTEGRAL Observatory. *Astronomy Letters* **29**, 713–718 (2003).
- 24. Revnivtsev, M. G., Sunyaev, R. A., Varshalovich, D. A., Zheleznyakov, V. V., Cherepashchuk, A. M. et al. A hard X-ray survey of the Galactic-Center region with the IBIS telescope of the INTEGRAL observatory: a catalog of sources. Astronomy Letters 30, 430–435 (2004).
- 25. Mazets, E. P., Golenetskii, S. V., Ilinskii, V. N., Gurian, I. A., Aptekar, R. L. et al. Cosmic gamma-ray burst spectroscopy. Astrophys. Space Sci. 82, 261–282 (1982).
- Band, D., Matteson, J., Ford, L., Schaefer, B., Palmer, D. et al. BATSE observations of gamma-ray burst spectra. I - Spectral diversity. Astrophys. J. 413, 281–292 (1993).
- 27. Schaefer, B. E. Gamma-ray burst Hubble diagram to z=4.5. Astrophys. J. 583, L67–L70 (2003).

 Correspondence and requests for materials should be addressed to S. Yu. Sazonov (e-mail: sazonov@mpa-garching.mpg.de).

Acknowledgements

This work is based on a Core Programme pointed observation (PI: S. Yu. Sazonov) with *INTEGRAL*, an ESA project with instruments and science data centre funded by ESA member states (especially

6 Sazonov, Lutovinov & Sunyaev

the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA. The authors thank Mikhail Revnivtsev and Eugene Churazov for help in the data analysis, and Shri Kulkarni for useful suggestions.

Figure 1. The temporal profile of GRB 031203 and its evolution. Top – 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 count 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 photon 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 count 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 nor 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. Bottom – b. The evolution of the photon index across 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.

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. Vertical bars indicate 1- σ 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, $\chi^2/\text{dof} = 14.8/15$) 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, $E_{\rm peak} > 190\,{\rm keV}$ (90% confidence level). The cross towards the top left corner of the figure is the soft X-ray (0.7–5 keV) fluence, F_X inferred^{10,13} from the dust scattered halos discovered in XMM-Newton observations.

8

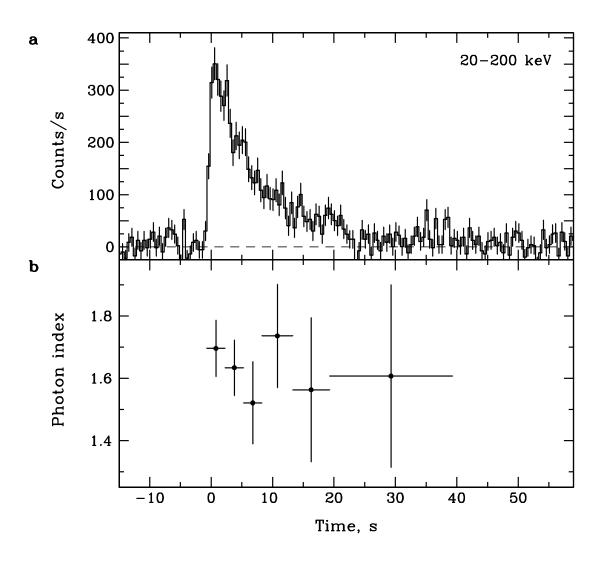


Figure 1.

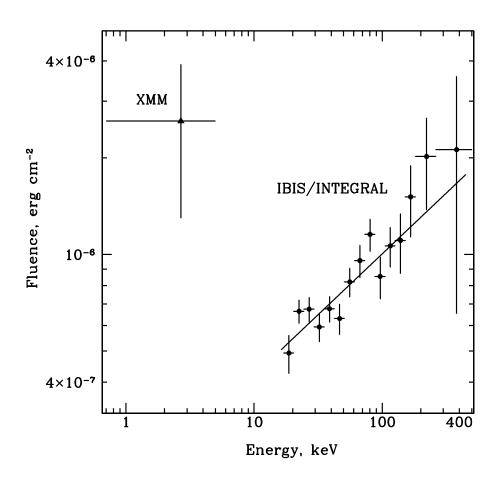


Figure 2.

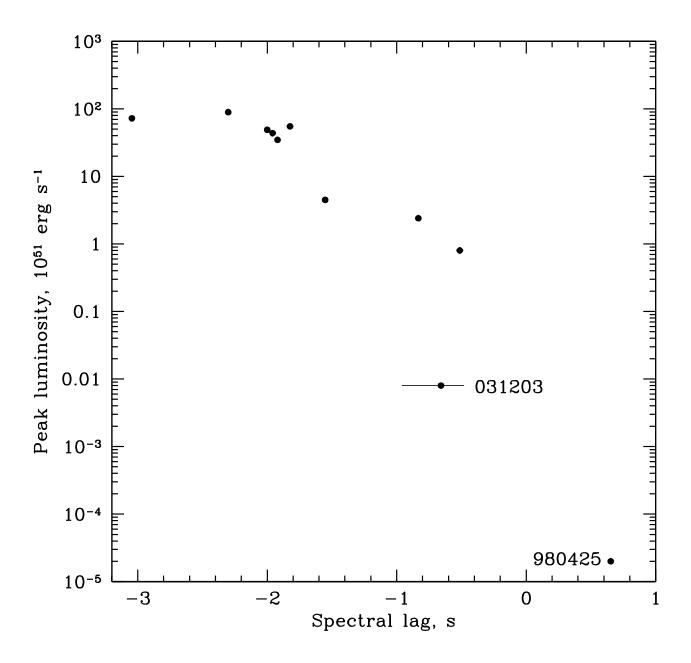


Figure 3.