An optical supernova associated with X-ray flash 060218

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Long-duration gamma-ray bursts (GRBs) are associated with Type Ic supernovae[1] that are more luminous than the average[2–5] and eject material at very high velocities. Less luminous supernovae were not hitherto known to be associated with GRBs, and therefore GRB-supernovae were thought to be rare events[6]. The detection of X-ray flashes (XRFs) – analogues of GRBs, but with lower luminosities and fewer gamma-rays – raised the issue of whether they are also associated with supernovae and whether they are intrinsically weak events or typical GRBs viewed off-axis[7]. Here we report on the optical discovery and follow-up of the Type Ic supernova 2006aj associated with XRF 060218. SN 2006aj was intrinsically less luminous than the GRB-supernovae, but more luminous than many supernovae not accompanied by a GRB. The ejecta velocities derived from our spectra are intermediate between these two groups, which is consistent with the weakness of both the GRB output[8] and the supernova radio flux[9]. Our data, combined with radio and X-ray observations[8–10], suggest that XRF 060218 is an intrinsically weak and soft event, rather than a classical GRB observed off-axis. The discovery of SN 2006aj and its properties extend the GRB-supernova connection to XRFs and to fainter supernovae, implying a common origin. Events such as XRF 060218 probably dominate in number over GRB-supernovae.

The Burst Alert Telescope (BAT) onboard *Swift* detected XRF 060218 on 2006 February 18, 03:34:30 UT[8]. Its spectrum peaked near 5 keV, placing the burst in the XRF subgroup of GRBs. The optical counterpart of the burst was detected ∼200 s later by the *Swift* Ultraviolet/Optical Telescope, and was subsequently observed by

ground-based telescopes[11]. The closeness of the event[12] made XRF 060218 an ideal candidate for spectroscopic observations of a possible associated supernova.

We observed XRF 060218 with the European Southern Observatory's (ESO) 8.2m Very Large Telescope (VLT) and the University of California's Lick Observatory Shane 3 m telescope (Lick) starting 21 February 2006. Table 1 in the Supplementary Information shows the log of the observations. Spectroscopy was performed nearly daily for seventeen days (see Figure 1 in the Supplementary Information). Broad absorption lines detected in our first spectrum resembled those of broad-lined Type Ic supernovae, thus providing the first definite case of a supernova associated with an XRF[13]. This is the earliest spectroscopy of a GRB-supernova, and in fact one of the earliest for any supernova. Based on its early decline, we estimate that the contribution of the fading afterglow of XRF 060218 to the supernova emission is not significant at the epoch of our first spectrum[11,12].

The high-dispersion spectrum taken with the VLT Ultraviolet and Visual Echelle Spectrograph (UVES) near the epoch of supernova maximum exhibits several narrow emission and absorption lines. From the former we obtained an accurate measurement of the host-galaxy redshift, $z = 0.03342 \pm 0.00002$ (heliocentric corrected), corresponding to a distance of ~ 140 Mpc (using a Hubble constant of $H_0 = 73$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.72$, and $\Omega_m = 0.28$). We constrained the total extinction toward the supernova from the equivalent widths of the interstellar Na I D absorption lines[14] to be $E_{B-V} = 0.13 \pm 0.02$ mag (P.A.M., manuscript in preparation). The extinction is mainly due to our Galaxy, and its value is consistent with that derived using infrared dust maps[15]. We used this value to correct the light curve of SN 2006aj (Figure 1).

It is interesting to compare the properties of SN 2006aj with those of other Type Ic supernovae. The three well-observed, low-redshift GRB-supernovae (SN 1998bw, 2003dh and 2003lw) are striking for their similarities. They are ∼5-6 times more luminous and ∼30 times more energetic than typical type-Ic supernovae[16]. The peak luminosities and the kinetic energies of the GRB-supernovae differ by no more than 30%. At maximum light, SN 2006aj is dimmer than these supernovae by about a factor of 2, but it is still a factor of 2 to 3 more luminous than other broad-lined Ic supernovae not associated with GRBs and normal (i.e, narrow-lined) supernovae Ic (Figure 1).

Normal type Ic supernovae rise to a peak in approximately 10-12 days and have photospheric expansion velocities of ∼10000 km s^{-1} at ∼10 days. Previously known GRB-supernovae showed a longer risetime (14–15 days) and had, at an epoch of ∼10 days, velocities of ∼25000 km s^{-1} (see Figures 1 and 2). If XRF 060218 and SN 2006aj occurred simultaneously, SN 2006aj rose as fast as normal supernovae Ic, and declined also comparatively fast. At the same time, the photospheric expansion velocity derived from spectral modelling is intermediate between the GRB-supernovae and other supernovae Ic, broad-lined or narrow-lined, that were not associated with GRBs (Figure 2). Asymmetry in the supernova explosion may modify the observed luminosity with respect to the intrinsic one, depending on the orientation of the symmetry axis, by no more than 25% (ref. 17).

We conclude that SN 2006aj is intrinsically dimmer than the other 3 GRB-supernovae. In addition, it is associated with the softest (but not the weakest) of the four local events connected with supernovae[8], and it has mildly relativistic ejecta[8,9], thus appearing to be an intermediate object between GRB-supernovae and other type Ic

supernovae, both broad-lined and narrow-lined, not accompanied by a GRB.

All together, these facts point to a substantial diversity between supernovae associated with GRBs and supernovae associated with XRFs. This diversity may be related to the masses of the exploding stars. In a companion paper, the parameters of the explosion are derived from models of the supernova optical light curves and spectra, and a relatively low initial mass, 20 $M_{\odot}$, is proposed, evolving to a 3.3 $M_{\odot}$ CO star[18]. This mass is smaller than those estimated for the typical GRB-supernovae[19].

GRBs and GRB-supernovae are aspherical sources. If XRF060218 was a normal GRB viewed off-axis, the observed soft flux was emitted at large angles with respect to its jet axis. If the associated SN 2006aj is aspherical, then it is also probably seen off-axis. Alternatively, XRF 060218 may have been intrinsically soft, whether it was an aspherical explosion viewed on axis or a spherical event. Various independent arguments, like the chromatic behaviour of the multiwavelength counterpart of XRF 060218[8], the absence of a late radio rebrightening[9] and the compliance of XRF 060218 with the empirical correlation between peak energy and isotropic energy[10], favour the latter possibility.

Together with the observation of other underluminous, relatively nearby XRFs and GRBs – GRB 980425 (ref. 2), XRF 030723 (refs. 20,21), XRF 020903 (ref. 22), and GRB 031203 (refs. 23,24), some definitely and some probably associated with supernovae – the properties of XRF 060218 suggest the existence of a population of events less luminous than "classical" GRBs, but possibly much more numerous and with lower radio luminosities[9]. Indeed, these events may be the most abundant form of X- or gamma-ray explosive transient in the Universe, but instrumental limits allow us to detect them only

locally, so that several intrinsically sub-luminous bursts may remain undetected. The fraction of supernovae that are associated with GRBs or XRFs may be higher than currently thought.

By including this underluminous population and assuming no correction for possible collimation, which may vary from object to object, we obtain a local GRB rate of 110^{+180}_{-20} Gpc^{-3}yr^{-1}, compared to 1 Gpc^{-3}yr^{-1} estimated from the cosmological events only (see Supplementary Information for details). In particular, for the detection threshold of *Swift*, we expect a few bursts per year within $z = 0.1$ and with luminosities as low as that of GRB 980425. The low-energy GRB population could be part of a continuum of explosion phenomena that mark the collapse of a stellar core, with normal supernovae at one end and classical GRBs at the other.

REFERENCES

1. Filippenko, A. V. Optical spectra of supernovae. *Annu. Rev. Astron. Astrophys.* **35**, 309–355 (1997).

2. Galama, T. J. *et al.* An unusual supernova in the error box of the γ-ray burst of 25 April 1998. *Nature* **395**, 670–672 (1998).

3. Hjorth, J. *et al.* A very energetic supernova associated with the γ-ray burst of 29 March 2003. *Nature* **423**, 847–850 (2003).

4. Stanek, K.Z. *et al.* Spectroscopic discovery of the supernova 2003dh associated with GRB 030329. *Astrophys. J.* **591**, L17–L20 (2003).

5. Malesani, D. *et al.* SN 2003lw and GRB 031203: a bright supernova for a faint Gamma-Ray Burst. *Astrophys. J.* **609**, L5–L8 (2004).

6. Woosley, S. E. & Bloom, J. The Supernova Gamma-Ray Burst connection. *Annu. Rev. Astron. Astrophys.* **44**, 507–556 (2006).

7. Granot, J., Ramirez-Ruiz E. & Perna R. Afterglow observations shed new light on the nature of X-Ray Flashes. *Astrophys. J.* **630**, 1003–1014 (2005).

8. Campana, S. *et al.* The shock break-out of GRB 060218/SN 2006aj. *Nature* in press, preprint available at http://arXiv.org/astro-ph/0603279 (2006).

9. Soderberg, A.M. *et al.* Relativistic ejecta from XRF 060218 and the complete census of cosmic explosions. *Nature* in press, preprint available at http://arXiv.org/astro-ph/0604389 (2006).

10. Amati, L., Frontera, F., Guidorzi, C. & Montanari, E. GRB 060218: Ep,i - Eiso correlation. *GCN Circ.* 4846 (2006).

11. Modjaz, M. *et al.* Early-time photometry and spectroscopy of the fast evolving SN 2006aj associated with GRB 060218. *Astrophys. J.* **645**, L21–L24 (2006).

12. Mirabal, N., Halpern, J.P., An, D., Thorstensen, J.R. & Terndrup, D.M. GRB 060218A/SN 2006aj: a gamma-ray burst and prompt supernova at $z = 0.0335$. *Astrophys. J.* **643**, L99–L102 (2006).

13. Masetti, N., Palazzi, E., Pian, E. & Patat, F. GRB 060218: VLT spectroscopy. *GCN Circ.* 4803 (2006).

14. Guenther, E.W., Klose, S., Vreeswijk, P.M., Pian, E. & Greiner, J. GRB 060218/SN 2006aj, high resolution spectra. *GCN Circ.* 4863 (2006).

15. 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).

16. Mazzali, P.A. *et al.* Models for the type Ic hypernova SN 2003lw associated with GRB 031203. *Astrophys. J.* **645**, 1323–1330 (2006).

17. Maeda, K., Mazzali, P.A. & Nomoto, K. Optical emission from aspherical supernovae and the hypernova SN 1998bw. *Astrophys. J.* **645**, 1331–1344 (2006).

18. Mazzali, P.A. *et al.* A neutron star-driven X-Ray Flash associated with SN 2006aj. *Nature* in press, preprint available at http://arXiv.org/astro-ph/0603567 (2006).

19. Woosley, S.E. & Heger, A. *et al.* The progenitor stars of Gamma-Ray Bursts. *Astrophys. J.* **637**, 914–921 (2006).

20. Fynbo, J.P.U. *et al.* On the afterglow of the X-Ray Flash of 2003 July 23: photometric evidence for an off-axis Gamma-Ray Burst with an associated supernova? *Astrophys. J.* **609**, 962–971 (2004).

21. Tominaga, N. *et al.* Supernova light-curve models for the bump in the optical counterpart of X-Ray Flash 030723. *Astrophys. J.* **612**, L105–L108 (2004).

22. Soderberg, A.M. *et al.* An HST Search for Supernovae Accompanying X-Ray Flashes. *Astrophys. J.* **627**, 877–887 (2005).

23. Sazonov, S. Y., Lutovinov, A. A. & Sunyaev, R. A. An apparently normal gamma-ray burst with an unusually low luminosity. *Nature* **430**, 646–648 (2004).

24. Soderberg, A.M. *et al.* The sub-energetic gamma-ray burst GRB 031203 as a cosmic analogue to the nearby GRB 980425. *Nature* **430**, 648–650 (2004).

25. Sauer, D.N., *et al.* The properties of the "standard" type Ic supernova 1994I from spectral models. *Mon. Not. R. Astr. Soc.* **369**, 1939–1948 (2006).

26. Mazzali, P.A. *et al.* Properties of Two Hypernovae Entering the Nebular Phase: SN 1997ef and SN 1997dq. *Astrophys. J.* **614**, 858–863 (2004).

27. Tomita, H., *et al.* The optical/near-infrared light curves of SN 2002ap for the first 1.5 years after discovery. *Astrophys. J.* **644**, 400–408 (2006).

28. Deng, J., Tominaga, N., Mazzali, P.A., Maeda, K. & Nomoto, K. On the light curve

and spectrum of SN 2003dh separated from the optical afterglow of GRB 030329. *Astrophys. J.* **624**, 898–905 (2005).

29. Cobb, B.E., Bailyn, C.D., van Dokkum, P.G. & Natarajan, P. SN 2006aj and the nature of low-luminosity gamma-ray bursts. *Astrophys. J.* **645**, L113–L116 (2006).

30. Cardelli, J.A., Clayton, G.C. & Mathis, J.S. The relationship between infrared, optical, and ultraviolet extinction. *Astrophys. J.* **345**, 245–256 (1989).

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

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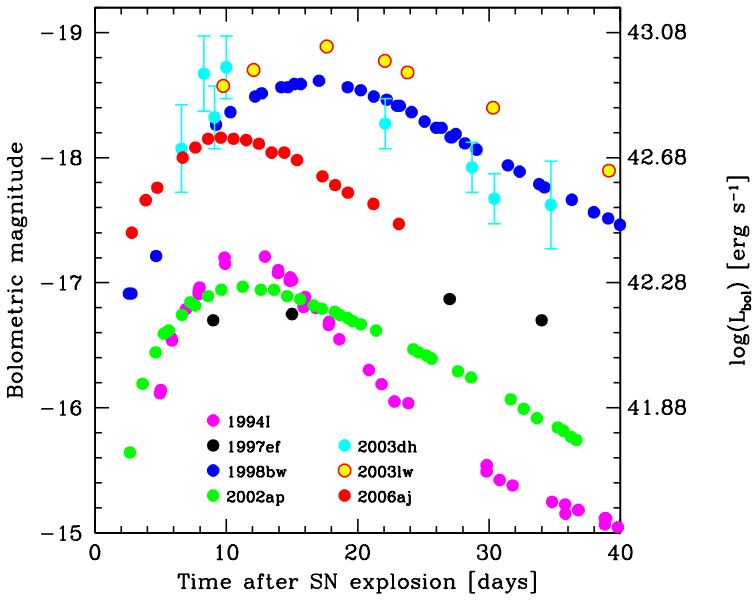


Fig. 1.— **Bolometric light curves of Type Ic Supernovae.** We report, as a function of time, the luminosity and corresponding absolute magnitude of the four spectroscopically identified supernovae associated with GRB/XRFs, namely SN 1998bw (GRB 980425, $z = 0.0085$), 2003dh (GRB 030329, $z = 0.168$), 2003lw (GRB 031203, $z = 0.1055$), and 2006aj (XRF 060218, $z = 0.03342$); of 2 broad-lined supernovae (not accompanied by a GRB), 1997ef and 2002ap; and of the normal, intensively monitored SN 1994I. All represented supernovae are Type Ic. The light curves, reported in their rest frame, have been constructed in the 3000–24000 Å range, taking into account the Galactic and, where appropriate, the host galaxy extinction[16,25–28]. For SN 2006aj, we used the optical light curves obtained during our monitoring and the near-infrared data reported by ref. 29, and a total extinction value of $E_{B-V} = 0.13$ mag (see text). We adopted the extinction curve of ref. 30 with $R_V = 3.1$. The galaxy contribution has also been subtracted where significant. The initial time has been assumed to coincide with the XRF detection time, 2006 Feb 18.149 UT. The systematic errors (about 0.2 mag) have been omitted, for clarity. The shape of the light curve of SN 2006aj is strikingly similar to that of SN 2002ap, as are indeed the spectra[18].

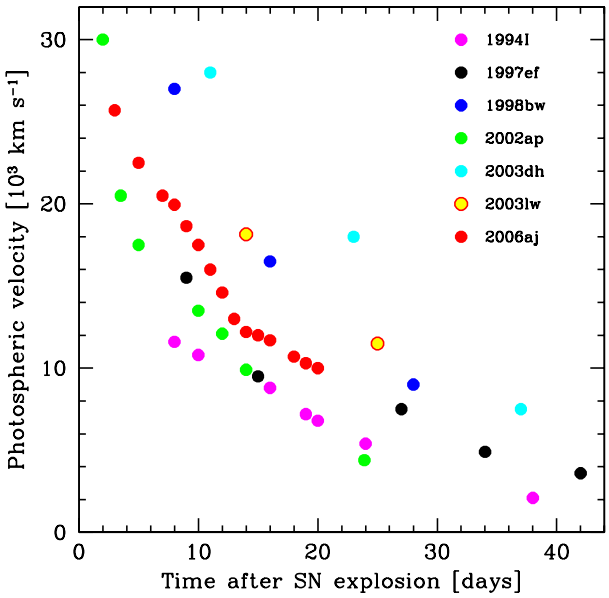


Fig. 2.— **Photospheric expansion velocities of Type Ic Supernovae.** The time profiles of the expansion velocities of the same seven supernovae represented in Fig. 1 are reported. The velocities have been determined through models of the spectra at the various epochs[16,18,25,26].

Supplementary Information for "An optical supernova associated with X-ray flash 060218"

1 Supplementary Table

In this Table we present the log of the observations, with details on the acquisition, and part of the photometric results. Low-resolution spectra of SN 2006aj have been obtained with the ESO VLT UT1 and UT2 telescopes, equipped with the FOcal Reducer Spectrographs (FORS1 and FORS2), and with the Lick telescope, equipped with the Kast Dual-Beam Spectrograph (KDBS) with the D55 dichroic. A high-resolution spectrum of the source was acquired with the VLT UT2 equipped with UVES. Photometry in the $BVRI$ bands has been performed simultaneously with each spectrum with the VLT and with the 0.76 m Katzman Automatic Imaging Telescope (limited to the Lick+KDBS observation), except on March 8, when only BVR photometry was acquired[31]. Spectroscopic monitoring was discontinued on 10 March 2006, due to Sun elevation constraints. However, photometry was performed for a few more days with the VLT. In Column 1 we report the observation date, in Column 2 the telescope and instrument used, in Column 3 the observing setup, in Column 4 the exposure times of the spectra, in Column 5 the seeing during the spectrum acquisition, in Column 6 the magnitudes not corrected for the Galactic and intrinsic extinction, nor for the host-galaxy flux contribution, and in Column 7 the same magnitudes reported in Column 6, but corrected for the host-galaxy flux. The associated errors are 1σ uncertainties.

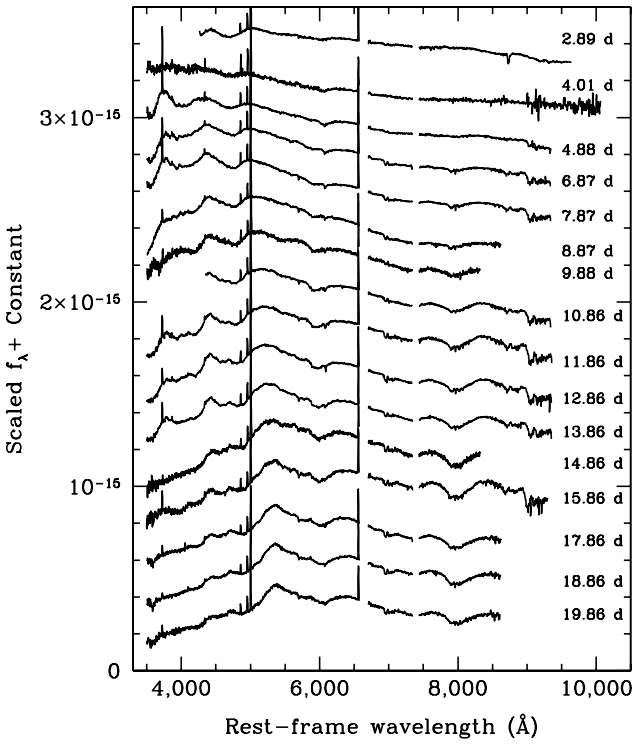
Supplementary Table 1: Summary of observations of SN 2006aj.

Date (2006 UT)	Telescope+ Instrument	Setup	Integr. Time (s)	Seeing (arcsec)	V magnitude	V_{sub} magnitude
Feb 21.041	UT1+FORS2	300V+GG435	1800	1.70	18.17 ± 0.03	18.36 ± 0.04
Feb 22.159	Lick+KDBS	D55+600/4310 +300/7500	6000	2.02	17.92 ± 0.08	18.06 ± 0.09
Feb 23.026	UT1+FORS2	300V	1800	1.68	17.80 ± 0.03	17.93 ± 0.03
Feb 25.023	UT1+FORS2	300V	1800	1.13	17.58 ± 0.03	17.68 ± 0.03
Feb 26.016	UT1+FORS2	300V	1800	1.08	17.51 ± 0.03	17.61 ± 0.03
Feb 27.023	UT2+FORS1	300V	1800	1.77	17.46 ± 0.03	17.55 ± 0.03
Feb 28.025	UT2+FORS1	300V	2593	1.14	17.45 ± 0.03	17.54 ± 0.03
Mar 01.009	UT1+FORS2	300V+GG435	1800	1.14	17.45 ± 0.03	17.54 ± 0.03
Mar 02.007	UT1+FORS2	300V	1800	1.63	17.47 ± 0.03	17.56 ± 0.03
Mar 03.010	UT1+FORS2	300V	1800	1.12	17.51 ± 0.03	17.61 ± 0.03
Mar 04.009	UT1+FORS2	300V	1800	1.26	17.56 ± 0.03	17.66 ± 0.03
Mar 04.021	UT2+UVES	Dic. 1/390B +564R	2100	1.26		
Mar 05.027	UT2+FORS1	300V	1350	0.83	17.60 ± 0.03	17.71 ± 0.03
Mar 06.014	UT1+FORS2	300V	1800	1.70	17.68 ± 0.03	17.79 ± 0.03
Mar 08.007	UT2+FORS1	300V	1800	1.89	17.86 ± 0.03	18.00 ± 0.03
Mar 09.013	UT2+FORS1	300V	1800	0.95	17.92 ± 0.03	18.06 ± 0.03
Mar 10.013	UT2+FORS1	300V	1560	1.40	18.01 ± 0.03	18.17 ± 0.03

2 Supplementary Figure and Legend

In this Figure we report the VLT FORS1/2 and Lick spectra of SN 2006aj taken at a resolution of 3.4 Å/pixel (FORS1), 2.6 Å/pixel (FORS2), and 1.9/4.6 Å/pixel (Lick, blue and red sides, respectively), reduced to rest frame and scaled up by arbitrary factors for clarity. For each spectrum the time elapsed since XRF 060218 explosion (Feb 18.149, 2006) is indicated, in days. The spectroscopic and photometric data (see Supplementary Table 1) were reduced following standard procedures within the IRAF and MIDAS data reduction packages, respectively. IDL routines were also used for the reduction of the Lick spectrum. Telluric absorption features have been removed. To account for slit losses, the spectra were normalized to the simultaneous V-band photometry: each spectrum was convolved with the response function of the Bessell V filter and the scaling factor was determined by comparison with the V-band measured magnitude. Finally, the contribution of the host-galaxy continuum was subtracted from the spectra and photometry, by linearly interpolating its fluxes[32–34]. No correction for interstellar reddening was applied to the spectra. Owing to the large airmass at which the observations were performed, the relative flux calibration of the spectra shortward of ∼4500 Å is not completely reliable. The low-contrast features visible in some VLT spectra longward of ∼9000 Å are also not meaningful. The spectra show broad absorption lines indicative of high-velocity ejecta, comparable to those present in other energetic Type Ic supernovae[35], although not as high as in typical GRB-supernovae[36–40]. Superimposed on the spectra are emission lines from the host galaxy. Using the Hα and [O II] line luminosities we derive[41] a star-formation rate of ∼0.06 $M_\odot$ yr^{-1}.

Fig. 3.— **Supplementary Figure 1: Spectra of SN 2006aj acquired with the VLT and Lick telescopes.**



3 Supplementary Methods

The rate of low luminosity GRBs and XRFs.

If the low-redshift GRBs are really typical of the global GRB population, then their discovery within the current time and sky coverage must be consistent with the local GRB explosion rate as deduced from the very large BATSE GRB sample. In this section, we study under which conditions low-redshift events can be derived from a luminosity function that is consistent with the $\log N - \log S$ relationship for "classical" cosmological bursts.

All local rate estimates made prior to the discovery of GRB 031203 were derived under the hypothesis that classical bursts greatly exceed a minimum luminosity, $L_{\rm min}$, of about 5×10^{49} erg s^{-1}. It was not until the discovery of GRB 031203 that it became clear that the three nearby bursts, 980425, 030329 and 031203, were not consistent with a population of bursts with luminosities greatly exceeding that of GRB 980425 (refs. 42,43). The discovery by *Swift* of the underluminous XRF 060218 slightly after one year of operation gives further credence to this hypothesis. A unified picture can therefore only be achieved by extending down the luminosity function.

The luminosity function used here is based on an extension down to the lowest luminosities consistent with the BATSE cumulative distribution of the number of GRBs as a function of their fluence ($\log N - \log S$), and at the same time gives the correct number of low-redshift events as collected by BATSE, *HETE-II* and *Swift*.

The luminosity function is characterized by a smoothed broken power-law,

$$\Phi(L) = \Phi_0 \left[\left(\frac{L}{L_b} \right)^{\alpha} + \left(\frac{L}{L_b} \right)^{\beta} \right]^{-1}, \quad (1)$$

where L is the isotropic equivalent luminosity and does not take into account the effects of collimation. The number of bursts with a peak flux $> P$ is then given by:

$$N(>P) = \int_{L_{\rm min}}^{L_{\rm max}} \Phi(L) d\log L \int_0^{z_{\rm max}(L,P)} \frac{R_{\rm GRB}(z)}{1+z} \frac{dV(z)}{dz} dz \quad (2)$$

where $dV(z)/dz$ is the comoving volume element, which in a flat ΛCDM universe, is given by

$$\frac{dV}{dz} = \frac{c}{H_0} \frac{D_L^2}{(1+z)^2} \frac{1}{(\Omega_M (1+z)^3 + \Omega_\Lambda)^{1/2}}. \quad (3)$$

That such an analysis will be possible follows from the currently-favored idea that GRBs trace the star formation history of the Universe: $R_{\rm GRB}(z) = R_{\rm SFR}(z)$. An analytic formula for the cosmic star formation rate per unit comoving volume is adopted here, as given in ref. 44.

The shape of the luminosity function is constrained here by two different methods. First, similarly to ref. 42 we fit the model to the peak flux distribution observed by BATSE (all 2204 bursts from the GUSBAD catalog) by assuming an average *rest frame* GRB spectrum with a peak energy of 200 ± 50 keV and a low (high) energy photon index of -1 ± 0.5 (-2 ± 0.5). The model predictions are then compared to the redshift and luminosities of GRBs detected by BATSE, *HETE-II* and *Swift*, where the sensitivity curves of all three instruments have been used[45]. The individual constraints are subsequently combined to derive the luminosity function's best-fit parameters.

The major uncertainty in the above method concerns $L_{\rm min}$, which we fix to be equal to the luminosity of GRB 980425. By using $L_{\rm max} = 6 \times 10^{52}$ erg s^{-1}, $L_{\rm b} = 9 \times 10^{50}$

erg s^{-1}, $\alpha = 0.3$, $\beta = 0.95$ in Equations (1) and (2) above we obtain the best statistical description of the data and a local GRB rate of 110^{+180}_{-20} $Gpc^{-3}yr^{-1}$.

The local rate of events that give rise to GRBs is therefore at least one hundred times the rate estimated from the cosmological events only (i.e. those observed by BATSE). Interestingly, we find that a single power-law description for the luminosity function is rejected with fairly high confidence and that an intrinsic break in the luminosity function is indeed required.

Obviously, the above calculation is only sketchy and should be taken as an order of magnitude estimate at present, as the observed redshift distributions are likely to be plagued by severe selection effects. It should, however, improve as more bursts with known redshifts are detected. This estimate is nonetheless consistent with the current rate of low-redshift events and is broadly in agreement with conclusions from earlier statistical studies[42].

4 Supplementary Notes

We report here the references for the previous Supplementary Section 3.

REFERENCES

31. Ferrero, P. *et al.* The GRB 060218/SN 2006aj event in the context of other Gamma-Ray Burst supernovae. *Astron. Astrophys.* submitted, preprint available at http://arXiv.org/astro-ph/0605058 (2006).

32. Modjaz, M. *et al.* Early-time photometry and spectroscopy of the fast evolving SN 2006aj associated with GRB 060218. *Astrophys. J.* **645**, L21–L24 (2006).

33. Cool, R.J. *et al.* GRB 060218: SDSS pre-burst observations. *GCN Circ.* 4777 (2006).

34. Hicken, M. *et al.* GRB 060218: refined photometric calibration of comparison stars. *GCN Circ.* 4898 (2006).

35. Foley, R.J. *et al.* Optical photometry and spectroscopy of the SN 1998bw-like type Ic supernova 2002ap. *Publ. Astron. Soc. Pacific* **115**, 1220–1235 (2003).

36. Galama, T. J. *et al.* An unusual supernova in the error box of the γ-ray burst of 25 April 1998. *Nature* **395**, 670–672 (1998).

37. Hjorth, J. *et al.* A very energetic supernova associated with the γ-ray burst of 29 March 2003. *Nature* **423**, 847–850 (2003).

38. Stanek, K.Z. *et al.* Spectroscopic discovery of the supernova 2003dh associated with GRB 030329. *Astrophys. J.* **591**, L17–L20 (2003).

39. Matheson, T. *et al.* Photometry and spectroscopy of GRB 030329 and its associated supernova 2003dh: the first two months. *Astrophys. J.* **599**, 394–407 (2003).

40. Malesani, D. *et al.* SN 2003lw and GRB 031203: a bright supernova for a faint Gamma-Ray Burst. *Astrophys. J.* **609**, L5–L8 (2004).

41. Kennicutt, R.C. Star formation in galaxies along the Hubble sequence. *Annu. Rev. Astron. Astrophys.* **36**, 189–232 (1998).

42. Guetta, D., Perna, R., Stella, L. & Vietri, M. Are all Gamma-Ray Bursts like GRB 980425, GRB 030329, and GRB 031203? *Astrophys. J.* **615**, L73–L76 (2004).

43. Coward, D.M. Simulating a faint gamma-ray burst population. *Mon. Not. R. Astr. Soc.* **360**, L77–L81 (2005).

44. Porciani, C. & Madau, P. On the Association of Gamma-Ray Bursts with Massive Stars: Implications for Number Counts and Lensing Statistics *Astrophys. J.* **548**, 522–531 (2001).

45. Band, D.L. Comparison of the Gamma-Ray Burst Sensitivity of Different Detectors *Astrophys. J.* **588**, 945–951 (2003).

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