No supernovae associated with two long-duration γ-ray bursts

Johan P. U. Fynbo[1], Darach Watson[1], Christina C. Thöne[1], Jesper Sollerman[1,3], Joshua S. Bloom[4], Tamara M. Davis[1], Jens Hjorth[1], Páll Jakobsson[5], Uffe G. Jørgensen[2], John F. Graham[6], Andrew S. Fruchter[6], David Bersier[7], Lisa Kewley[8], Arnaud Cassan[9], José María Castro Cerón[1], Suzanne Foley[10], Javier Gorosabel[11], Tobias C. Hinse[2], Keith D. Horne[12], Brian L. Jensen[1], Sylvio Klose[13], Daniel Kocevski[4], Jean-Baptiste Marquette[14], Daniel Perley[4], Enrico Ramirez-Ruiz[15,16], Maximilian D. Stritzinger[1], Paul M. Vreeswijk[17,18], Ralph A. M. Wijers[19], Kristian G. Woller[2], Dong Xu[1] & Marta Zub[9]

It is now accepted that long-duration γ-ray bursts (GRBs) are produced during the collapse of a massive star[1,2]. The standard 'collapsar' model[3] predicts that a broad-lined and luminous type Ic core-collapse supernova accompanies every long-duration GRB[4]. This association has been confirmed in observations of several nearby GRBs[5–9]. Here we report that GRB 060505 (ref. 10) and GRB 060614 (ref. 11) were not accompanied by supernova emission down to limits hundreds of times fainter than the archetypal supernova SN 1998bw that accompanied GRB 980425, and fainter than any type Ic supernova ever observed[12]. Multi-band observations of the early afterglows, as well as spectroscopy of the host galaxies, exclude the possibility of significant dust obscuration and show that the bursts originated in actively star-forming regions. The absence of a supernova to such deep limits is qualitatively different from all previous nearby long-duration GRBs and suggests a new phenomenological type of massive stellar death.

GRB 060505 and GRB 060614 were detected by the γ-ray Burst Alert Telescope onboard the dedicated GRB satellite Swift on 5.275 May 2006 and 14.530 June 2006, respectively[11,12]. GRB 060505 was a faint burst with a duration of 4 s. GRB 060614 had a duration of 102 s and a pronounced hard-to-soft evolution. Both were rapidly localized by Swift's X-ray telescope. Subsequent follow-up of these bursts led to the discovery of their optical afterglows, locating them in galaxies at low redshift: GRB 060505 at $z = 0.089$ (ref. 13) and GRB 060614 at $z = 0.125$ (refs 14, 15). The relative proximity of these bursts engendered an expectation that a bright supernova would be discovered a few days after the bursts, as had been found just a few months before in another low-redshift Swift burst, GRB 060218 ($z = 0.033$)[9], and in all previous well-observed nearby bursts[1,5–8].

We monitored the afterglows of GRB 060505 and GRB 060614 using a range of telescopes (see Supplementary Information for details). These led to early detections of the afterglows. We continued the monitoring campaign and obtained stringent upper limits on any re-brightening at the position of the optical afterglows up to 12 and 5 weeks after the bursts, respectively. The light curves obtained from this monitoring are shown in Fig. 1. For GRB 060505 we detected the optical afterglow at a single epoch. All subsequent observations resulted in deep upper limits. For GRB 060614 we followed the decay of the optical afterglow in the R-band up to four nights after the burst. In later observations no source was detected to deep limits (see also refs 14, 15 for independent studies of this event). As seen in Fig. 1, the upper limits are far below the level seen in previous supernovae, and in particular previous supernovae associated with long-duration GRBs[5–9]. For both GRBs our 3σ limits around the time of expected maximum of a supernova component are 80–100 times fainter than SN 1998bw would have appeared. The very deep limits for GRB 060505 from 23 May and 30 May places a 3σ upper limit more than 250 times fainter than SN 1998bw at a similar time. Hence, any associated supernova must have a peak magnitude in the R-band fainter than about −13.5.

A concern in any attempt to uncover a supernova associated with a GRB is the presence of a poorly quantified level of extinction along the line of sight. In these cases, however, the levels of Galactic extinction in both directions are fortunately very low: $E(B–V) = 0.02$ (ref. 16). In the case of GRB 060505, our spatially resolved spectroscopy of the host galaxy allows us to use the Balmer emission line ratios to limit the dust obscuration at the location of the burst. The Balmer line ratio is consistent with no internal reddening. In the case of GRB 060614, the detection of the early afterglow in many bands, including the Swift ultraviolet bands[17] UVW1 and UVW2, rules out significant obscuration of the source in the host galaxy and we conclude that there is no significant dust obscuration in either case (see also ref. 15).

Both GRBs were located in star-forming galaxies. The host galaxy of GRB 060505 has an absolute magnitude of about $M_B = -19.6$ and the spectrum displays the prominent emission lines typically seen in star-forming galaxies. The two-dimensional spectrum shows that the host galaxy emission seen at the position of the afterglow is due to a compact H II region in a spiral arm of the host (see the Supplementary Information for details). We estimate a star-formation rate of

[1]Dark Cosmology Centre, [2]Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark. [3]Department of Astronomy, Stockholm University, AlbaNova, S-10691 Stockholm, Sweden. [4]Department of Astronomy, University of California at Berkeley, 601 Campbell Hall, Berkeley, California 94720, USA. [5]Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield, Hertfordshire, AL10 9AB, UK. [6]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218, USA. [7]Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead CH41 1LD, UK. [8]University of Hawaii, Institute of Astronomy, 2680 Woodlawn Drive, Honolulu, Hawaii 96822, USA. [9]Astronomisches Rechen-Institut (ARI), Zentrum für Astronomie der Universität Heidelberg (ZAH), Mönchhof Str. 12-14, 69120 Heidelberg, Germany. [10]School of Physics, University College Dublin, Dublin 4, Ireland. [11]Instituto de Astrofísica de Andalucía (CSIC), Apartado de Correos, 3004, E-18080 Granada, Spain. [12]SUPA Physics/Astronomy, University of St Andrews, St Andrews, KY16 9SS, Scotland, UK. [13]Thüringer Landessternwarte Tautenburg, Sternwarte 5, 07778 Tautenburg, Germany. [14]Institut d'Astrophysique de Paris, UMR70951 CNRS, Université Pierre et Marie Curie, 98 bis boulevard Arago, 75014 Paris, France. [15]Institute for Advanced Study, Einstein Drive, Princeton, New Jersey 08540, USA. [16]Department of Astronomy and Astrophysics, University of California, Santa Cruz, California 95064, USA. [17]European Southern Observatory, Alonso de Córdova 3107, Casilla 19001, Vitacura. [18]Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile. [19]Astronomical Institute 'Anton Pannekoek', Faculty of Science, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands.

$1M_{\odot}$ yr^{-1} (where $M_{\odot}$ is the mass of the Sun) and a specific rate of about $4M_{\odot}$ yr^{-1} $(L/L^{*})^{-1}$ (assuming an absolute magnitude corresponding to the B-band luminosity L^{*} of $M^{*}_{B} = -21$). The host galaxy of GRB 060614 is significantly fainter with an absolute magnitude of about $M_{B} = -15.3$. This is one of the least luminous GRB host galaxies ever detected, to our knowledge. We detect emission lines from hydrogen and oxygen and infer a star-formation rate of $0.014M_{\odot}$ yr^{-1} (see Supplementary Information for details). The specific star-formation rate is $3M_{\odot}$ yr^{-1} $(L/L^{*})^{-1}$. Sub-L^{*} and star-forming host galaxies like these two are ubiquitous among long-duration GRB host galaxies[18]. For comparison, the specific star-formation rates of the four previously studied nearby ($z < 0.2$) long-duration GRB host galaxies are 6, 7, 25 and $39M_{\odot}$ yr^{-1} $(L/L^{*})^{-1}$ (refs 19, 20).

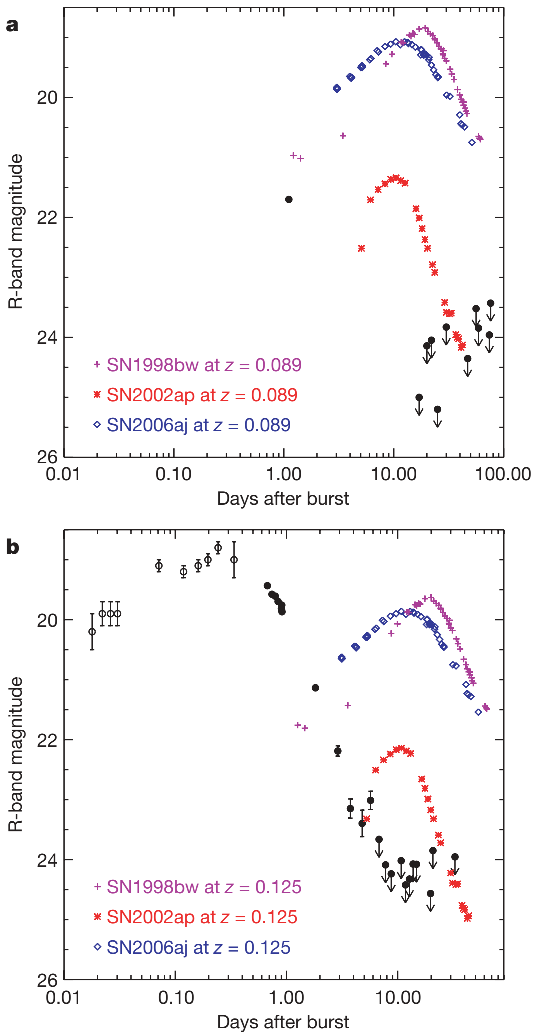

Figure 1 | No supernova associated with two nearby γ-ray bursts. Light curves of supernovae SN 1998bw, SN 2002ap and SN 2006aj, as they would have appeared at the redshift of GRB 060505 (**a**, top) and at the redshift of GRB060614 (**b,** bottom). We also plot our afterglow detection in both cases (filled circles) and subsequent 3σ upper limits. We conclude that neither GRB 060505 nor GRB 060614 were associated with significant supernova emission down to very faint limits hundreds of times less luminous than the archetypal SN 1998bw. GRB 060505 was monitored with the Danish 1.5 m telescope, the Very Large Telescope and the Keck telescope over a period of 12 weeks, which allowed us to detect the afterglow on the first night after the burst and thereafter obtain very strict upper limits on associated supernova emission. GRB 060614 was observed with the Danish 1.5 m telescope almost every night up to 5 weeks after the burst, which enabled us to monitor the decay of the optical afterglow, and finally to detect the host galaxy. For GRB 060614 the early light curve is populated with data reported in the GRB Coordinates Network Circulars[29] (open circles). These supernova-less GRBs share no obvious characteristics in their prompt emission. GRB 060505 was one of the least luminous bursts discovered by Swift, with an isotropic-equivalent energy release of 1.2×10^{49} erg. It had a relatively short duration, and was single-peaked with a very faint afterglow. GRB 060614 was about a hundred times more luminous with an isotropic-equivalent energy release of 8.9×10^{50} erg, and it showed strong spectral evolution. Its optical afterglow brightened over the first day[17,29], reminiscent of GRB 970508[30]. In the Supplementary Information we provide further details on the observations and data analysis. Error bars are 1σ.

All spectroscopically confirmed supernova-GRBs have peak magnitudes within half a magnitude of SN 1998bw[1,2], and all photometrically identified supernova-GRBs have peak magnitudes within one and a half magnitudes of SN 1998bw[1,21,22]. For X-ray flashes there has been evidence that associated supernovae span a somewhat wider range of luminosities[9,23–25], but still within the range of non-GRB-selected type Ic supernovae. The available data on all type Ic supernovae (including those unrelated to GRBs) show a distribution from roughly two magnitudes fainter in the V band than SN 1998bw to perhaps half a magnitude brighter[1,2,12]. The faintest type Ic supernova known is SN 1997ef (classified as a broad-line supernova); but even a supernova as faint as this would easily have been detected in our observations of GRB 060505 and GRB 060614 (SN 2002ap shown in Fig. 1 had a luminosity similar to that of SN 1997ef). Any supernova associated with these two long-duration GRBs must therefore have been not only fainter than any supernova previously associated with a GRB or XRF but also substantially fainter than any non-GRB-related type Ic supernova seen until now.

The non-appearance of a supernova in these cases is a surprise and indicates that we have uncovered GRBs with quite different properties from those studied previously. It is possible that the origin of these bursts lies in one of the many supernova-less GRB progenitors suggested before the definitive association between GRBs and supernovae. Also, in a variant of the original collapsar model 'fallback'-formed black holes or progenitors with relatively low angular momentum could produce supernova-less GRBs[26–28]. Of the six long-duration GRBs or X-ray flashes known to be at low redshift ($z < 0.2$), two now have no associated supernova, so the fraction of supernova-less GRBs could be substantial.

1. Zeh, A., Klose, S. & Hartmann, D. H. A systematic analysis of supernova light in gamma-ray burst afterglows. *Astrophys. J.* **609**, 952–961 (2004).
2. Woosley, S. E. & Bloom, J. S. The supernova–gamma-ray burst connection. *Annu. Rev. Astron. Astrophys.* **44**, 507–556 (2006).
3. Woosley, S. E. Gamma-ray bursts from stellar mass accretion disks around black holes. *Astrophys. J.* **405**, 273–277 (1993).
4. MacFadyen, A. I. & Woosley, S. E. Collapsars: Gamma-ray bursts and explosions in "failed supernovae". *Astrophys. J.* **524**, 262–289 (1999).
5. Galama, T. J. *et al.* An unusual supernova in the error box of the gamma-ray burst of 25 April 1998. *Nature* **395**, 670–672 (1998).
6. Hjorth, J. *et al.* A very energetic supernova associated with the γ-ray burst of 29 March 2003. *Nature* **423**, 847–850 (2003).
7. Stanek, K. Z. *et al.* Spectroscopic discovery of the supernova 2003dh associated with GRB 030329. *Astrophys. J.* **591**, L17–L20 (2003).
8. Malesani, D. *et al.*, *Astrophys. J.* **609**, L5–L8 (2004).
9. Pian, E. *et al.* An optical supernova associated with X-ray flash 060218. *Nature* **442**, 1011–1013 (2006).
10. Hullinger, D. *et al.* GRB 060505 BAT refined analysis. *GCN Circ.* **5142** (2006).
11. Gehrels, N, *et al.* A new γ-ray burst classification scheme from GRB 060614. *Nature* doi:10.1038/nature05376 (this issue); preprint at ⟨http://arxiv.org/astro-ph/0610635⟩ (2006).
12. Richardson, D., Branch, D. & Baron, E. Absolute magnitude distributions and light curves of stripped-envelope supernovae. *Astron. J.* **131**, 2233–2244 (2006).
13. Ofek, E. O. *et al.* GRB 060505 − OT candidate + galaxy spectrum. *GCN Circ.* **5123** (2006).
14. Gal-Yam, A. *et al.* A novel explosive process is required for the γ-ray burst GRB 060614. *Nature* doi:10.1038/nature05373 (this issue); preprint at ⟨http://arxiv.org/astro-ph/0608257⟩ (2006).
15. Della Valle, M. *et al.* An enigmatic long-lasting γ-ray burst not accompanied by a bright supernova. *Nature* doi:10.1038/nature05374 (this issue); preprint at ⟨http://arxiv.org/astro-ph/0608322⟩ (2006).

16. 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).
17. Holland, S. T. GRB 060614: Swift/UVOT Observations. *GCN Circ.* **5255** (2006).
18. Fruchter, A. S. *et al.* Long gamma-ray bursts and core-collapse supernovae have different environments. *Nature* **441,** 463–468 (2006).
19. Sollerman, J. *et al.* On the nature of nearby GRB/SN host galaxies. *New Astron.* **11,** 103–115 (2005).
20. Sollerman, J. *et al.* Supernova 2006aj and the associated X-ray flash 060218. *Astron. Astrophys.* **454,** 503–509 (2006).
21. Soderberg, A. M. *et al.* An HST study of the supernovae accompanying GRB 040924 and GRB 041006. *Astrophys. J.* **636,** 391–399 (2006).
22. Ferrero, P. *et al.* The GRB 060218/SN 2006aj event in the context of other gamma-ray burst supernovae. *Astron. Astrophys.* **457,** 857–864 (2006).
23. Levan, A. *et al.* A deep search with the Hubble Space Telescope for late-time supernova signatures in the hosts of XRF 011030 and XRF 020427. *Astrophys. J.* **622,** 975–985 (2005).
24. Soderberg, A. M. *et al.* An HST search for supernovae accompanying X-ray flashes. *Astrophys. J.* **627,** 877–887 (2005).
25. 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).
26. Fryer, C. L., Young, P. A. & Hungerford, A. L. Explosive nucleosynthesis from GRB and hypernova progenitors: direct collapse versus fallback. *Astrophys. J.* **650,** 1028–1047 (2006).
27. Heger, A. *et al.* How massive single stars end their life. *Astrophys. J.* **591,** 288–300 (2003).
28. MacFadyen, A. I. in *AIP Conf. Proc. 662: Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission (November 2001)* (eds Ricker, G. R. & Vanderspek, R. K.) 202–205 (American Institute of Physics, Melville, New York, 2003).
29. Schmidt, B. P. *et al.* SSO 1m observations. *GCN Circ.* **5258** (2006).
30. Pedersen, H. *et al.* Evidence for diverse optical emission from gamma-ray burst sources. *Astrophys. J.* **496,** 311–315 (1998).

Acknowledgements We acknowledge benefits from collaboration within the EU FP5 Research Training Network ''Gamma-Ray Bursts: An Enigma and a Tool''. The Dark Cosmology Centre is funded by the DNRF. The observations presented here have been obtained from the ESO La Silla-Paranal observatory and from the Gemini Observatory. The Gemini Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (USA), the Particle Physics and Astronomy Research Council (UK), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil), and CONICET (Argentina).