

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

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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’ model³ predicts that a broad-lined and luminous type Ic core-collapse supernova accompanies every long-duration GRB⁴. 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 observed¹². 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 bands¹⁷ 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

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$1M_{\odot} \text{ yr}^{-1}$ (where M_{\odot} is the mass of the Sun) and a specific rate of about $4M_{\odot} \text{ yr}^{-1} (L/L^*)^{-1}$ (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 gal-

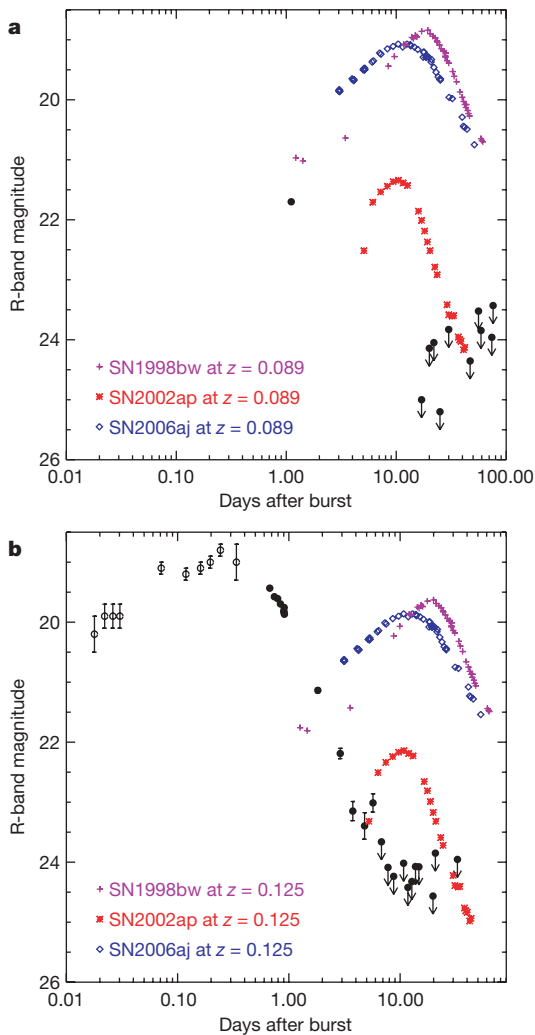


Figure 1 | No supernova associated with two nearby γ -ray bursts. Light curves of supernovae SN 1998bw, SN 2002ap and SN 2006aj, as they would have appeared at the redshift of GRB 060505 (a, top) and at the redshift of GRB 060614 (b, bottom). We also plot our afterglow detection in both cases (filled 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 Circulars²⁹ (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 970508³⁰. In the Supplementary Information we provide further details on the observations and data analysis. Error bars are 1σ .

axies ever detected, to our knowledge. We detect emission lines from hydrogen and oxygen and infer a star-formation rate of $0.014M_{\odot} \text{ yr}^{-1}$ (see Supplementary Information for details). The specific star-formation rate is $3M_{\odot} \text{ yr}^{-1} (L/L^*)^{-1}$. Sub- L^* and star-forming host galaxies like these two are ubiquitous among long-duration GRB host galaxies¹⁸. 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 $39M_{\odot} \text{ yr}^{-1} (L/L^*)^{-1}$ (refs 19, 20).

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.

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

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