

A giant outburst two years before the core-collapse of a massive star

A. Pastorello¹, S. J. Smartt¹, S. Mattila¹, J. J. Eldridge¹, D. Young¹, K. Itagaki², H. Yamaoka³, H. Navasardyan⁴, S. Valenti^{5,6}, F. Patat⁵, I. Agnoletto^{4,7}, T. Augusteijn⁸, S. Benetti⁴, E. Cappellaro⁴, T. Boles⁹, J.-M. Bonnet-Bidaud¹⁰, M. T. Botticella¹¹, F. Bufano^{4,7}, C. Cao¹², J. Deng^{12,13}, M. Dennefeld¹⁴, N. Elias-Rosa^{4,15}, A. Harutyunyan^{4,7}, F. P. Keenan¹, T. Iijima¹⁶, V. Lorenzi¹⁷, P. A. Mazzali^{18,19}, X. Meng¹², S. Nakano²⁰, T. B. Nielsen⁸, J. V. Smoker¹, V. Stanishev²¹, M. Turatto⁴, D. Xu¹² & L. Zampieri⁴

The death of massive stars produces a variety of supernovae, which are linked to the structure of the exploding stars^{1,2}. The detection of several precursor stars of type II supernovae has been reported (see, for example, ref. 3), but we do not yet have direct information on the progenitors of the hydrogen-deficient type Ib and Ic supernovae. Here we report that the peculiar type Ib supernova SN 2006jc is spatially coincident with a bright optical transient⁴ that occurred in 2004. Spectroscopic and photometric monitoring of the supernova leads us to suggest that the progenitor was a carbon-oxygen Wolf–Rayet star embedded within a helium-rich circumstellar medium. There are different possible explanations for this pre-explosion transient. It appears similar to the giant outbursts of luminous blue variable stars (LBVs) of 60–100 solar masses³, but the progenitor of SN 2006jc was helium- and hydrogen-deficient (unlike LBVs). An LBV-like outburst of a Wolf–Rayet star could be invoked, but this would be the first observational evidence of such a phenomenon. Alternatively, a massive binary system composed of an LBV that erupted in 2004, and a Wolf–Rayet star exploding as SN 2006jc, could explain the observations.

SN 2006jc was discovered in UGC 4904 on 2006 October 9.75 UT at magnitude 13.8 (ref. 4). The early spectrum was that of a hydrogen-poor event with strong, narrow He I emission lines^{6–9} superimposed on a broad-line spectrum of a type Ic supernova. In 2004, an optical transient was reported to the Central Bureau for Astronomical Telegrams (CBAT) which, when retrospectively compared with the SN 2006jc discovery images, appeared to be spatially coincident with the new supernova⁴. The 2004 transient was much fainter than SN 2006jc (magnitude ~ 18) and remained visible for only a few days after discovery. This event was never independently confirmed, and CBAT did not issue an official object designation. Given the new, bright supernova discovery, the nature of this transient (which we name UGC 4904-V1, that is, variable 1 in UGC 4904) has become intriguing. We have aligned the images containing the two transients using differential astrometry of 21 nearby stars, and find that UGC 4904-V1 and SN 2006jc are indeed coincident to within the

uncertainties (Fig. 1). In Supplementary Information, we give a comprehensive description of the method, the error analysis and a demonstration that the probability that these two events are chance coincidences is negligible.

We monitored the light curve and spectral evolution of SN 2006jc during the first ~ 2 months after discovery (Figs 2 and 3). An independent data set was presented in ref. 10. The object was discovered a few days past maximum, but its brightness is still comparable with that of the most luminous type Ic supernovae (Fig. 2), namely $M_R < -18.3$ mag, adopting a host galaxy distance of 25.8 ± 2.6 Mpc and a total reddening $E(B - V) = 0.05$ (see Supplementary Information). However, SN 2006jc declines faster than most type Ib/c supernovae and the optical spectra are unusual. The broad emission lines commonly observed in type Ic supernovae are detected, although with an atypical profile (see Supplementary Information). In addition, prominent and relatively narrow (full-width at half-maximum, FWHM, $\sim 2,200$ km s⁻¹) He I emission lines are observed, hence the classification of SN 2006jc as a peculiar type Ib event^{6–10}. Although very rare, objects like SN 2006jc have been observed before: SN 1999cq¹¹ and SN 2002ao^{10,12} (Fig. 2b). The detection of narrow He I lines suggests that SN 2006jc-like events should be more properly classified as type Ibn, in analogy to the similar nomenclature (type IIn) used for supernovae that show narrow hydrogen emission lines. Another property of the spectra of SN 2006jc (in common with SN 1999cq and SN 2002ao) is the blue colour, which remains almost constant over the entire observational period.

The blue spectral continuum, the presence of narrower lines superimposed on broad spectral features (Fig. 3) and the strong X-ray emission¹³ are normally interpreted as a signature of interaction between supernova ejecta and the circumstellar medium (CSM). The presence of prominent He I lines and the simultaneous lack of conspicuous hydrogen features suggest a helium-rich composition of the CSM, while the abundance of hydrogen must be modest. There is no evidence of broad helium components, suggesting that the progenitor of SN 2006jc had entirely lost its helium envelope and was a

¹Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, UK. ²Itagaki Astronomical Observatory, Teppo-cho, Yamagata 990-2492, Japan. ³Department of Physics, Kyushu University, Fukuoka 810-8560, Japan. ⁴INAF Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy. ⁵European Southern Observatory (ESO), Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany. ⁶Dipartimento di Fisica, Università di Ferrara, via del Paradiso 12, I-44100 Ferrara, Italy. ⁷Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 2, I-35122 Padova, Italy. ⁸Nordic Optical Telescope, Apartado 474, E-38700 Santa Cruz de la Palma, Tenerife, Spain. ⁹Coddenham Astronomical Observatory, Peel House, Coddenham, Suffolk, IP6 9QY, UK. ¹⁰Service d'Astrophysique, DSM/DAPNIA/SAp, CE Saclay, F-91191 Gif-sur-Yvette Cedex, France. ¹¹Dipartimento di Scienze della Comunicazione, Università degli Studi di Teramo, Viale Crucoli 122, I-64100 Teramo, Italy. ¹²National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China. ¹³Centre de Physique des Particules de Marseille, CNRS-IN2P3 and University Aix Marseille II, Case 907, 13288 Marseille Cedex 9, France. ¹⁴Institut d'Astrophysique de Paris, CNRS, and Université P. et M. Curie, 98bis Bd Arago, F-75014 Paris, France. ¹⁵Universidad de La Laguna, Av. Astrofísico Francisco Sánchez s/n, E-38206 La Laguna, Tenerife, Spain. ¹⁶INAF Osservatorio Astronomico di Padova, Sezione di Asiago, Via dell'Osservatorio 8, I-36012 Asiago (Vicenza), Italy. ¹⁷Fundación Galileo Galilei-INAF, Telescopio Nazionale Galileo, E-38700 Santa Cruz de la Palma, Tenerife, Spain. ¹⁸Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85741 Garching bei München, Germany. ¹⁹INAF Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-34131 Trieste, Italy. ²⁰Computing & Minor Planet Section (Center for AstroDynamics) of the Oriental Astronomical Association, Sumoto, Hyogo-Ken, 656-0011, Japan. ²¹Department of Physics, Stockholm University, AlbaNova University Center, SE-10691 Stockholm, Sweden.

carbon-oxygen Wolf–Rayet star (WC or WO)¹⁰. Fast-moving ejecta produce the broad lines of intermediate-mass elements, whose width increases with time (from about 4,000 to 9,000 km s⁻¹), whereas the slow-moving CSM produces moderately narrow (about 2,200 km s⁻¹) He I emissions. In addition to these prominent features, weak, very narrow (~500 km s⁻¹) P Cygni absorptions attributed to He I and O I (and, possibly, H α) are visible in the highest resolution spectra, and are indicative of further undisturbed, slowly moving shells originating from previous mass loss episodes (Supplementary Information). Severe mass loss is necessary to remove the outer helium and hydrogen layers, and to produce a massive carbon-oxygen core.

The 2004 outburst of UGC 4904-V1 reached a peak magnitude of $M_R \approx -14.1$, and we offer a few possible explanations of the event. Giant outbursts of LBVs^{14,15} are well documented transients with a similar peak magnitude and sharp decline (Fig. 4 and Supplementary Information). LBVs are massive blue stars that show significant optical variability, due to unstable atmospheres and episodic mass loss. The only Galactic star well observed during such an eruption is η Carinae (in 1837–57; ref. 14), which has a current mass of approximately 90 solar masses (90 M_\odot) and an initial mass of around 150 M_\odot (ref. 16). Other LBVs in the local Universe that have shown giant outbursts of similar magnitude to UGC 4904-V1 are likely to have had initial masses in the range 60–100 M_\odot (Supplementary Information). However, despite the fact that the magnitude of the 2004 outburst of UGC 4904-V1 was similar to that of a typical LBV, an LBV scenario raises two problems. It is at odds with current stellar evolutionary theory, which predicts that massive stars do not undergo core-collapse in the LBV stage, and also that the subsequent

Wolf–Rayet star should have a lifetime of more than 200,000 years (refs 1, 2). Additionally, all the known LBVs that have undergone outbursts still have hydrogen- and helium-rich atmospheres^{14,16} (Supplementary Information). The progenitor of SN 2006jc was different, because prominent hydrogen lines were not detected in early supernova spectra (Fig. 3). One could then propose that the progenitor star has been a Wolf–Rayet star for this timescale, and that the 2004 event was an LBV-like eruption of a Wolf–Rayet star¹⁰. In this case we need to invoke a novel explosion mechanism, as no carbon-oxygen star has ever been observed to produce such a bright outburst.

It is unquestionable that SN 2006jc is not a typical supernova, and hence this post-LBV channel is probably not the preferred one that produces type Ib or Ic supernovae, and the rarity of such events could be due to the high progenitor mass. If this scenario is true, then it has interesting implications. A star of 60–100 M_\odot has a carbon-oxygen core of mass 15–25 M_\odot as it enters the Wolf–Rayet phase^{1,2} (Supplementary Information). The core-collapse of such an object is predicted to form a black hole by fall-back, producing a low yield of ⁵⁶Ni and hence resulting in a very faint and under-energetic explosion¹⁷. However, although powered by the ejecta–CSM interaction, SN 2006jc is a high-luminosity event, and a plausible model for the production of a bright supernova from a black-hole-forming core is a jet-powered supernova^{2,17,18}. Such events in helium- and hydrogen-free stars are the working models for long duration γ -ray bursts¹⁷.

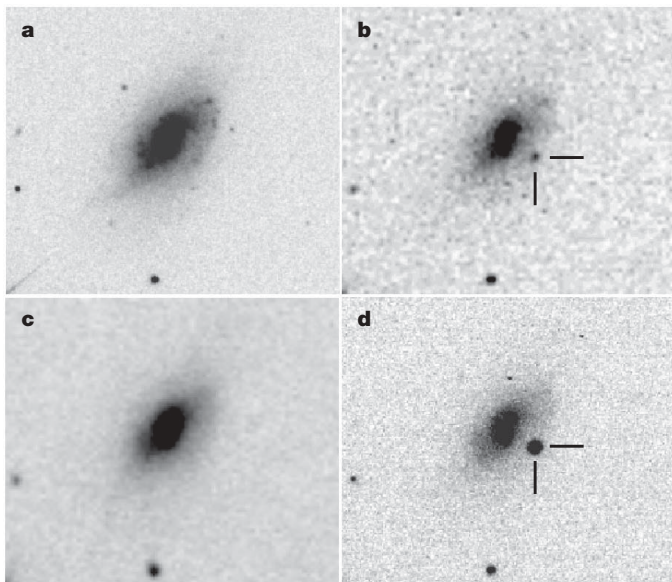


Figure 1 | The transients UGC 4904-V1 and SN 2006jc. Sequence of images of UGC 4904 rebinned to a pixel scale of 0.53 arcsec. **a**, r' band image of UGC 4904 from the Sloan Digital Sky Survey obtained on 2001 December 20. No transient is visible. **b**, Detection of UGC 4904-V1 on 2004 October 16 by K.I. (magnitude 19.13 ± 0.19), using a 0.60-m $f/5.7$ reflector and Bitran-CCD (Kodak KAF 1001E). The transient was detected in five epochs between 2004 October 14 and 2004 October 23. The original image has a pixel size of 1.44 arcsec, and seeing of 2.2 arcsec. **c**, Another image obtained by K.I. (2006 September 21), showing no transient detection. **d**, R-band frame (original pixel scale of 0.473 arcsec, seeing of 2.0 arcsec) taken on 2006 October 29 with the Asiago 1.82-m Telescope equipped with AFOSC. We find that the two transients are coincident to within 0.1 arcsec, and the total error budget (including the uncertainty in the position measurements and the error of the geometric transformation) is 0.3 arcsec (see Supplementary Information). The transient UGC 4904-V1 was not detected before 2004 October 2001 or after 2004 November 2007, and it is not a moving object, as there is no apparent motion between the five epochs in which it was detected.

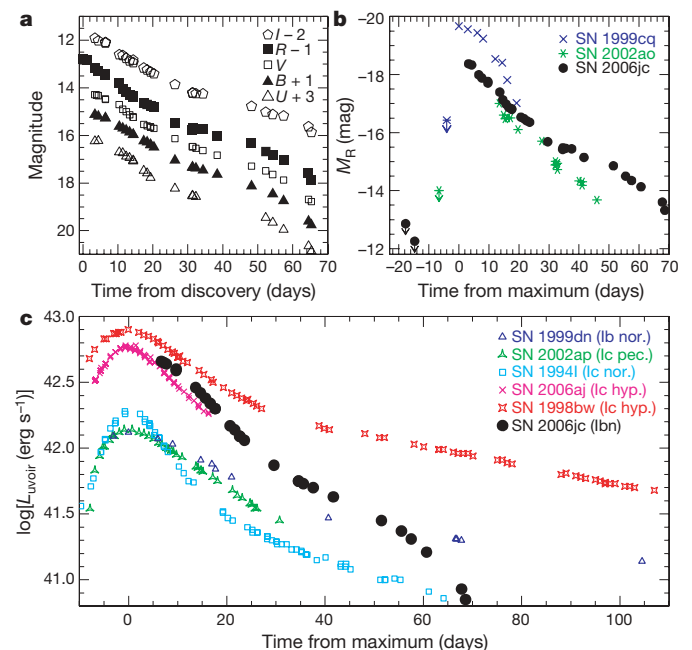


Figure 2 | Light curve of SN 2006jc. **a**, $UBVR$ light curves of SN 2006jc. No significant colour evolution is visible from the available multiband photometry. **b**, The R-band absolute light curve of SN 2006jc is compared with unfiltered light curves of two similar interacting type Ibc events: SN 1999cq and SN 2002ao (refs 10, 11, 24). The phases are estimated from the epochs of the approximated light curve maxima. The pre-explosion limit of SN 1999cq was very close (~4 days) to the discovery epoch, which strongly constrains the epoch of this explosion and suggests (at least for this supernova) a very steep rise to maximum light, supporting the idea that the ejecta are strongly interacting with a CSM. **c**, Comparison between the quasi-bolometric (uvoir) light curve of SN 2006jc and those of a sample of hydrogen-deficient core-collapse supernovae: SN 1999dn (normal type Ib, S.B. *et al.*, manuscript in preparation), SN 1994I (normal type Ic, ref. 25), SN 2002ap (high-velocity, moderate luminosity ('peculiar') type Ic, ref. 26), and the hypernovae SN 2006aj and SN 1998bw (either associated with an X-ray flash or a γ -ray burst; refs 27–29 and references therein). The light curves of SN 2006jc and hypernova SN 2006aj peak in-between the luminous hypernova SN 1998bw and more normal type Ib/c supernovae, although the ejecta–CSM interaction might power significantly the observed light curve of SN 2006jc.

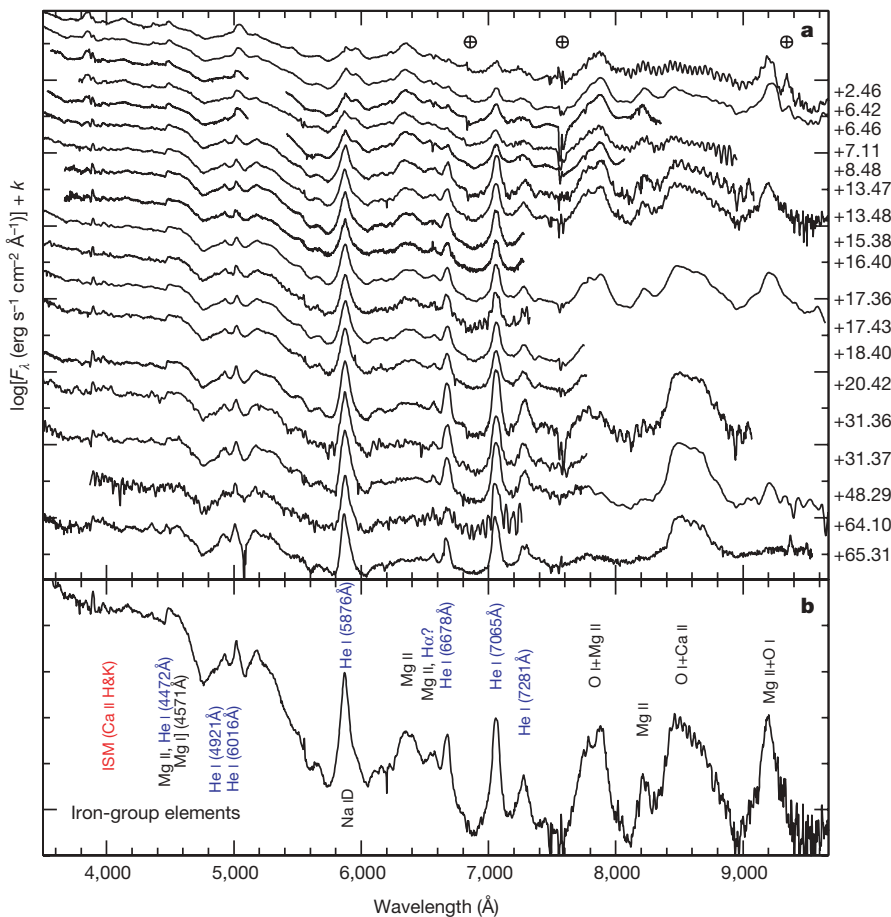


Figure 3 | Spectra of SN 2006jc and line identification. **a, b,** Spectral evolution of SN 2006jc (**a**) and identification of the main features in the spectrum at +14.38 days (**b**). All spectra have been shifted to the host galaxy rest wavelength. For clarity, the spectra have been shifted in the y axis (flux, in logarithmic scale) by an arbitrary constant k . The numbers on the right indicate the phase from the discovery (days). The spectra are dominated by a blue pseudo-continuum and broad lines (FWHM about 4,000–9,000 km s⁻¹, depending on the phase; black labels) of intermediate-mass elements: Na I D, O I 7,774 Å and O I 9,264 Å (both blended with Mg II), Ca II IR triplet (blended with O I 8,446 Å) and a number of Mg II lines (the most prominent being at wavelengths (Å) 4,481, 6,347 and 6,546; and 7,877–7,896, 8,214–8,235 and 9,218–9,244. In addition the spectra show narrower (FWHM ~2,200 km s⁻¹) He I emissions (blue labels), strengthening with time. Narrow, weak interstellar Ca II H&K lines are also visible (labelled in red). Moreover, the earliest spectra show some narrow unidentified emission lines in the blue region (for example, at 3,850 Å), and a weak, narrow H α absorption is possibly detected, replaced by a weak component in pure emission in the latest spectra. This detection suggests that a small amount of hydrogen is present in the helium-dominated circumstellar environment of SN 2006jc. The nature of the flux excess in the blue region is unclear, possibly linked with the ejecta–CSM interaction (as observed in many type II_n supernovae, for example, SN 1997cy), but might also result from a strong contribution from Fe II lines¹⁰. Earth signs (crossed circles) mark telluric features.

As an alternative to the single star scenario, one could propose a massive binary system with two stars entering the final, violent, stages of their evolution. One of the components could have undergone a classical LBV outburst in 2004, while the companion was an evolved Wolf–Rayet star that collapsed to give SN 2006jc. The interaction of the ejecta within a complex, circumstellar environment shaped by the strong stellar winds of massive stars could explain the numerous gas

shells detected in the spectra (Supplementary Information). It has recently been suggested that η Carinae has a hot companion (around 30M_⊙), which is a nitrogen-rich late O-type or Wolf–Rayet star¹⁹. A similar scenario (a pair of 30M_⊙ and 50M_⊙ stars) was proposed for HD 5980, an LBV + Wolf–Rayet star binary in the Small Magellanic Cloud²⁰. In neither of these cases is the Wolf–Rayet star a WC or WO, as it is still nitrogen- and helium-rich, but a more evolved system is a

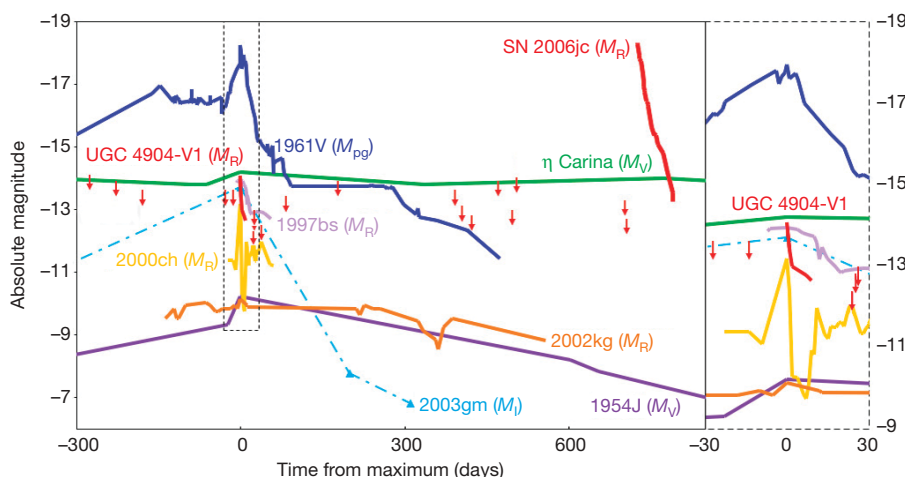


Figure 4 | R-band light curves of UGC 4904-V1 and SN 2006jc compared with those of giant outbursts of LBVs. The figure (without SN 2006jc) was first shown in ref. 15 (see references therein), and has since been supplemented with data from ref. 30. Although all of the extragalactic transients were originally given supernova labels, they are now commonly accepted as giant outbursts of LBVs and not core-collapse supernovae. SN 2002kg (which is the well known variable NGC 2403-V37) was not a giant outburst, but is part of fairly common S Doradus variability of LBVs. The

down-arrows are upper limits for UGC 4904-V1. Owing to many of the images of UGC 4904 having limiting magnitudes in the range 19–20, we have only detected the peak of the outburst. With a peak magnitude of about $M_R = -14.1$ and such a sharp decline, a plausible explanation for UGC 4904-V1 is a giant LBV-like outburst (Supplementary Information), although alternatives are presented in the text. The magnitudes of each object shown in this figure are in different bands, depending on the available data. M_{pg} , photographic magnitude.

possible progenitor. Also, the system has only undergone moderate amplitude outbursts, reaching $M_V = -10.6$, significantly fainter than UGC 4904-V1. Theoretical models of pre-supernova evolution in massive binary systems show that type Ib/c supernovae can be produced, and a higher-mass system than that calculated in ref. 21 could be plausible, although a physically consistent scenario needs a detailed calculation.

Further observational and theoretical studies are required to determine which scenario is the more likely. The detection in very late spectra of SN 2006jc of more prominent, narrow hydrogen lines from the CSM (S.M. *et al.*, manuscript in preparation) might support a single, massive star scenario. Moreover, line profile measurements may determine the asphericity of the ejecta and explosion²², and radio modulations could eventually show that an LBV phase recently occurred²³. Finally, deep high-resolution images from the Hubble Space Telescope could probe the presence of the possible binary companion, and a detailed comparison with the few similar supernovae^{10,11} may help to provide additional clues to the progenitor scenario.

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- Eldridge, J. J. & Tout, C. A. The progenitors of core-collapse supernovae. *Mon. Not. R. Astron. Soc.* **353**, 87–97 (2004).
- Heger, A. *et al.* How massive single stars end their life. *Astrophys. J.* **591**, 288–300 (2003).
- Smartt, S. J. *et al.* Detection of a red supergiant star of a type II-plateau supernova. *Science* **303**, 499–503 (2004).
- Nakano, S. *et al.* Possible supernova in UGC 4904. *CB Electron. Teleg.* **666** (2006).
- Smith, N. & Owocki, S. P. On the role of continuum-driven eruptions in the evolution of very massive stars and population III stars. *Astrophys. J.* **645**, L45–L48 (2006).
- Crotts, A. *et al.* Supernova 2006jc in UGC 4904. *CB Electron. Teleg.* **672**, 1 (2006).
- Fesen, R., Milisavljevic, D. & Rudie, G. Supernova 2006jc in UGC 4904. *CB Electron. Teleg.* **672**, 2 (2006).
- Benetti, S. *et al.* Supernova 2006jc in UGC 4904. *CB Electron. Teleg.* **674**, 2 (2006).
- Modjaz, M. *et al.* Supernova 2006jc in UGC 4904. *CB Electron. Teleg.* **677**, 1 (2006).
- Foley, R. J. *et al.* SN 2006jc: A Wolf-Rayet star exploding in a dense He-rich circumstellar medium. *Astrophys. J.* **657**, L105–L108 (2007).
- Matheson, T. *et al.* Helium emission lines in the type IC supernova 1999CQ. *Astron. J.* **119**, 2303–2310 (2000).
- Filippenko, A. V. & Chornock, R. Supernovae 2002ao, 2002ap, 2002ar, 2002au, 2002av. *IAU Circ.* **7825** (2002).
- Immler, S., Modjaz, M. & Brown, P. J. Detection of SN 2006jc in X-rays with Chandra. *Astron. Tel.* **934** (2006).
- Davidson, K. & Humphreys, R. M. Eta Carinae and its environment. *Annu. Rev. Astron. Astrophys.* **35**, 1–32 (1997).
- Van Dyk, S. V. *et al.* The type II_n supernova 2002kg: The outburst of a luminous blue variable star in NGC 2403. *Publ. Astron. Soc. Pacif.* (submitted); preprint at (<http://arXiv.org/astro-ph/0603025>) (2006).
- Hillier, D. J. *et al.* On the nature of the central source in η Carinae. *Astrophys. J.* **553**, 837–860 (2001).
- MacFadyen, A. I., Woosley, S. E. & Heger, A. Supernovae, jets, and collapsars. *Astrophys. J.* **550**, 410–425 (2001).
- Nomoto, K. *et al.* in *A Massive Star Odyssey: From Main Sequence to Supernova* (eds van der Hucht, K., Herrero, A. & Esteban, C.) 395 (Proc. IAU Symp. 212, Astronomical Society of the Pacific, San Francisco, 2003).
- Iping, R. C. *et al.* Detection of a hot binary companion of η Carinae. *Astrophys. J.* **633**, L37–L40 (2006).
- Koenigsberger, G., Kurucz, R. L. & Georgiev, L. The photospheric absorption lines in the ultraviolet spectrum of the multiple system HD 5980. *Astrophys. J.* **581**, 598–609 (2002).
- Podsiadlowski, Ph., Joss, P. C. & Hsu, J. J. L. Presupernova evolution in massive interacting binaries. *Astrophys. J.* **391**, 246–264 (1992).
- Mazzali, P. A. *et al.* An asymmetric energetic type Ic supernova viewed off-axis, and a link to gamma ray bursts. *Science* **308**, 1284–1287 (2005).
- Kotak, R. & Vink, J. S. Luminous blue variables as the progenitors of supernovae with quasi-periodic radio modulations. *Astron. Astrophys.* **460**, L5–L8 (2006).
- Llasset, J. M. SN 2002ao. (<http://www.astrosurf.com/snweb/2002/02ao/02aoMeas.htm>) (14 June 2002).
- Richmond, M. W. *et al.* UBVR photometry of the type IC SN 1994I in M51. *Astron. J.* **111**, 327–339 (1996).
- Mazzali, P. A. *et al.* The type Ic hypernova SN 2002ap. *Astrophys. J.* **572**, L61–L65 (2002).
- Pian, E. *et al.* An optical supernova associated with the X-ray flash XRF 060218. *Nature* **442**, 1011–1013 (2006).
- Mazzali, P. A. *et al.* A neutron-star-driven X-ray flash associated with supernova SN 2006aj. *Nature* **442**, 1018–1020 (2006).
- Patat, F. *et al.* The metamorphosis of SN 1998bw. *Astrophys. J.* **555**, 900–917 (2001).
- Maund, J. R. *et al.* Faint supernovae and supernova impostors: Case studies of SN 2002kg/NGC 2403–V37 and SN 2003gm. *Mon. Not. R. Astron. Soc.* **369**, 390–406 (2006).

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

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