The massive binary companion star to the progenitor of supernova 1993J

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The massive star that underwent a collapse of its core to produce supernova (SN)1993J was subsequently identified as a non-variable red supergiant star in images of the galaxy M81 taken before explosion[1,2]. It showed an excess in ultraviolet and B-band colours, suggesting either the presence of a hot, massive companion star or that it was embedded in an unresolved young stellar association[1]. The spectra of SN1993J underwent a remarkable transformation from the signature of a hydrogen-rich type II supernova to one of a helium-rich (hydrogen-deficient) type Ib[3,4]. The spectral and photometric peculiarities were best explained by models in which the 13–20 solar mass supergiant had lost almost its entire hydrogen envelope to a close binary companion[5–7], producing a 'type IIb' supernova, but the hypothetical massive companion stars for this class of supernovae have so far eluded discovery. Here we report photometric and spectroscopic observations of SN1993J ten years after the explosion. At the position of the fading supernova we detect the unambiguous signature of a massive star: the binary companion to the progenitor.

Images of SN1993J were acquired on 28 May 2002 using the Advanced Camera for Surveys (ACS) on board the Hubble Space Telescope (HST). These observations were primarily carried out in the ultraviolet and blue spectral regions, where the flux of a hot star companion would be most prominent. A F330W (U-band) image of SN1993J is shown in Fig. 1. The high angular resolution of these images (0.025″ per pixel) allowed for the complete separation of unrelated surrounding stars from the supernova, including the discovery of a previously blended star near to the supernova (star G of Fig. 1; see Table 1 for details). The blending of stars E–G with the supernova (as in previous lower-resolution HST images[8]) would lead to the supernova appearing bluer. The stars surrounding the supernova, which are isolated by the exquisite resolution of the ACS images, would be blended with the supernova flux in lower-spatial-resolution ground-based observations. Recently the contributions of the surrounding blue stars to the U- and B-band magnitudes of the supernova progenitor have been estimated from lower-resolution HST archive images[8]. This study concluded that although a significant fraction of the progenitor U-band flux could be explained by the contamination of these stars in the ground-based point spread function, within 1σ errors, a hot massive companion star would be compatible with the progenitor and the late-time images. We have conducted a similar analysis with the higher-spatial-resolution and deeper ACS images. A gaussian weighting scheme, which is a function of angular distance of the stars from the supernova and the wavelength-dependent seeing, was applied to simulate the contribution of each object to the photometry of the supernova progenitor[1]. We found that these stars, assuming a K0Ia progenitor, clearly would not have had sufficient flux to be solely responsible for the ultraviolet excess reported for the progenitor[1,8]. In a similar fashion this photometry provided an estimate of the flux contribution of these surrounding stars to the ground-based spectroscopy of SN1993J.

Spectroscopy of SN1993J was acquired using the LRIS-B spectrometer on the Keck I telescope, covering 3,400–5,400 Å, on 1 March 2003 (Fig. 2). The spectrum in general is typical of supernovae at late times that show evidence for the interaction of the ejecta with a dense circumstellar medium[9]. It is dominated by a series of broad, box-like emission lines, which have been interpreted to be due to ejecta shocks in a thin spherical shell[10]. However, the high signal-to-noise ratio of the LRIS-B spectrum in the near-ultraviolet illustrates two peculiar features not detected before: a rising ultraviolet continuum and narrow absorption lines consistent with a hot star spectrum superimposed on the flux from the young supernova remnant. The maximum contribution of the surrounding stars to the observed spectrum, again simulating the effects of ground-based seeing conditions with a gaussian weighting function, was calculated to be 18%. The variability of star A[2,8] (see Fig. 1), given its magnitude and distance from the supernova, has a negligible effect on this analysis. The strength and width of the absorption lines, and the rising shape of the blue continuum suggest that the observed flux is composed of a pseudo-continuum from the supernova ejecta emission and flux from a hot star that is unresolved from the supernova on the ACS images. The point spread function of SN1993J is perfectly consistent with a single stellar source, and conservatively we have estimated that the separation of the star and the supernova must be closer than 0.015 arcseconds (0.3 parsecs), or else we would clearly detect asymmetries in the spatial profile. The observed B-band stellar density of M81 in the vicinity of SN1993J implied a probability of 1 in 2,000 of a single randomly located and unrelated star fortuitously lying so close to the supernova as to be unresolved.

The narrow stellar lines observed in the SN1993J spectrum were compared with lines from observed spectra of late-O and early-B standard stars and TLUSTY[11,12] model stellar spectra, with appropriate parameters[13,14]. The comparison was conducted in the wavelength region of the U-band, least affected by the strong supernova

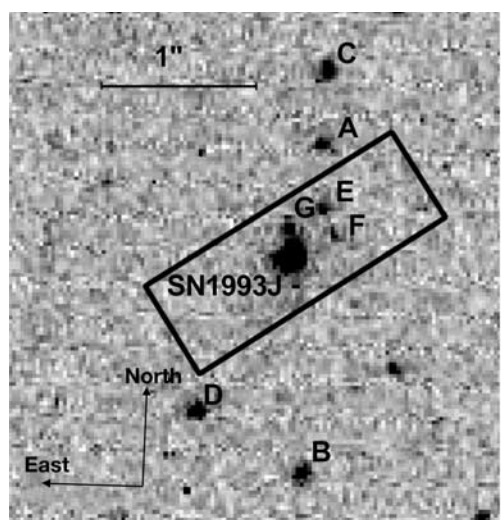

Figure 1 An HST ACS High Resolution Camera (HRC) F330W (~U-band) image of SN1993J. The image was a 1,200-s exposure, acquired on 28 May 2002—9.17 yr post-explosion, observed for program GO9353. The spatial resolution of the HRC allows the clear separation of stars E–G from the supernova (adopting the nomenclature of ref. 8). The photometric magnitudes of the stars measured in the ACS filters[24] are listed in Table 1. These magnitudes were used to calculate, and remove, the contamination of the faint surrounding blue stars to the ground-based spectrum of SN1993J. The box is an example of the area of sky sampled in the lower-spatial-resolution ground-based spectroscopy. The width is 0.7″ (the slit width employed with the LRIS spectrograph), and the length is 1.8″ (the aperture diameter used to extract the object spectrum down to a level of 10% of the peak flux). The slit was positioned at the angle of parallax and during the night rotated between angles −162° and 106° (east of north). The optical spectrum presented in Fig. 2 is effectively a sum of the flux of all objects within this box.

Table 1 **Photometric magnitudes of SN1993J and nearby stars**

Star	Distance from supernova (pc)	Near-ultraviolet (F250W)		U		B		V	
A	12.9	22.99	(0.05)	23.05	(0.08)	23.78	(0.02)	22.56	(0.01)
B	25.0	22.76	(0.05)	22.89	(0.06)	23.12	(0.01)	23.05	(0.01)
C	21.1	22.52	(0.05)	22.98	(0.08)	23.78	(0.01)	23.80	(0.01)
D	20.8	22.15	(0.06)	22.87	(0.07)	23.84	(0.01)	23.95	(0.01)
E	6.0	23.39	(0.07)	23.68	(0.08)	24.12	(0.01)	24.17	(0.01)
F	5.1	23.73	(0.12)	24.2	(0.18)	25.04	(0.01)	24.85	(0.01)
G	2.8	22.79	(0.19)	23.54	(0.08)	24.44	(0.02)	24.42	(0.01)
1993J	–	19.93	(0.04)	20.7	(0.05)	21.08	(0.01)	20.27	(0.01)

Star numbers are as identified on Fig. 1, using the nomenclature of ref. 8. The distances of the stars, in parsec, are calculated from the centre of the SN1993J point spread function. Magnitudes are F250W Vegamag, in the ACS photometric system[24] and U, B and V Johnson magnitudes, transformed from the original ACS photometric system. Bracketed numbers indicate the uncertainty, in magnitudes, of the preceding magnitude. The colours of the surrounding stars imply they are of early type, in the range O9–B3. Photometry of 24 other stars, within 106 pc of SN1993J, were used to determine the reddening by comparing observed colours (U–B) and (B–V) with intrinsic colours, yielding a colour excess E(B–V) = 0.2 and hence a V-band extinction $A_v = 0.62$, assuming a standard galactic reddening law, which is in good agreement with previously determined values[10]. An accurate distance to the galaxy of 3.63 ± 0.14 Mpc from Cepheid variables is available[23].

emission lines. Main-sequence stars were immediately excluded because their luminosities were too low to produce lines of sufficient strength to match those in the SN1993J spectrum. The strengths of the lines in the SN1993J spectrum, with respect to the continuum, were weaker than those in the stellar spectra owing to the continuum of the supernova. The continuum of the supernova, in units of the B supergiant flux at each H I line, was calculated by adding excess continuum to the stellar spectra until the renormalized H I line strengths matched those observed in the SN1993J spectrum. In addition, the continua ratio was calculated for He I lines, in order to identify those types which gave consistent matches with the values calculated for the H I lines assuming a normal He abundance. B-type supergiants of type B5 and later were eliminated by this method. Early B-supergiants (B0–B4) provided the best consistent fit to the H I and He I lines. The average ratio of the continua, for all the H I lines, was calculated for each spectral type: for B0Ia it was 1, for B1Ia 1.9, for B2Ia 1.9, for B3Ia 2.3 and for B4Ia 3 (where the contribution due to the surrounding stars is already subtracted). From the ACS U- and B-band fluxes of the supernova plus the companion, and the relative fluxes of the companion required to

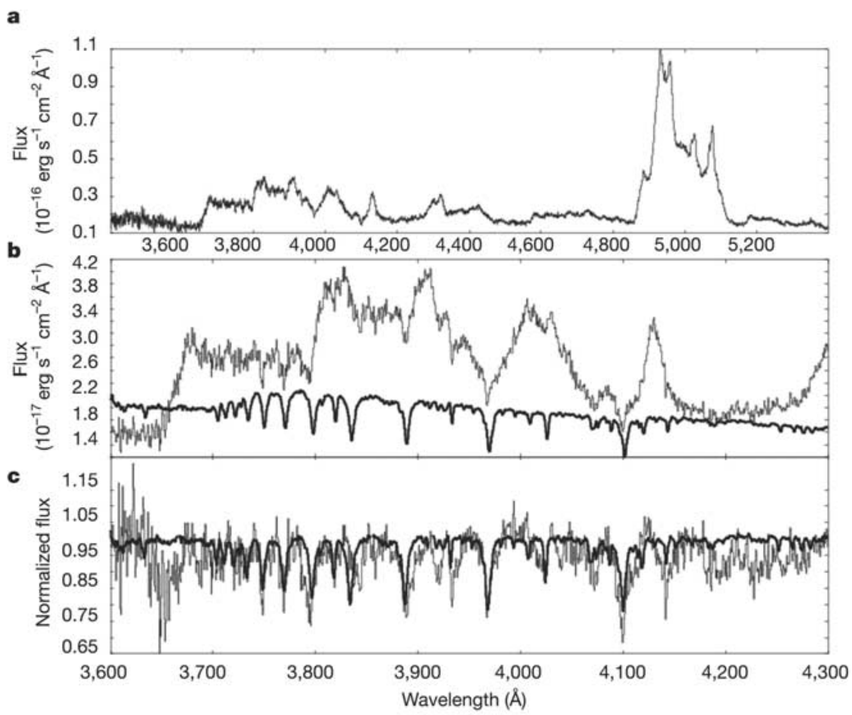

Figure 2 Near-ultraviolet spectra of SN1993J. **a**, Flux-calibrated ground-based blue spectrum of SN1993J. The spectrum was acquired with Keck I LRIS-B spectrometer (1 March 2003, 9.93 yr post-explosion) using the 600/4,000 grism (with instrumental resolution 2.4 Å and signal-to-noise ratio ranging from 15–30). Seeing during the 5.5-hr total exposure time was between 0.7 and 1.2 arcseconds. The spectrum is dominated by broad, box-like emission line profiles which are characteristic of interaction between the supernova ejecta and the circumstellar medium[9,10]. However, the near-ultraviolet region shows a series of narrow absorption features. **b**, Flux spectra of SN1993J (thin line) and a B-supergiant (bold line) HD168489 (B1Ia, $T_{\rm eff} \approx 23.3 \times 10^3$ K and $\log L/L_\odot = 5$). The stellar spectrum was scaled to the distance of M81, with a reddening of E(B–V) = 0.2 and a radial velocity shift of $-120\,{\rm km}^{-1}$. The series of sharp absorption features are coincident with the H I Balmer series and the He I line at 3,819.7 Å. The absorption lines are conspicuously narrower than the [O III] (wavelengths, $\lambda = 4{,}959$ and 5,007 Å) and [S II] ($\lambda = 4{,}068$ and 4,072 Å) emission lines (3,200 km s^{-1})—implying that the absorption lines do not arise from the supernova ejecta itself. The flux contribution from the contaminating stars A–G (18%) cannot reproduce the strength of the absorption lines observed. **c**, Normalized spectra of SN1993J (thin line) and the B1Ia Galactic standard star HD168489, which has been renormalized for an excess continuum ratio of 0.8, in units of the combined continuum fluxes of the companion and surrounding stars. The supernova continuum was normalized by estimating the position of the continuum and applying a series of short spline fits. The H I Balmer and He I absorption lines are best matched by early-B type supergiant spectra (B0–B4). The average ratios, in the range 3,600–4,000 Å, and the total measured ACS flux in the F330W filter allowed a calculation[14] of the parameters of the unresolved hot star component: $\log L/L_\odot = 5 \pm 0.3$, $\log T_{\rm eff} = 4.3 \pm 0.1$.

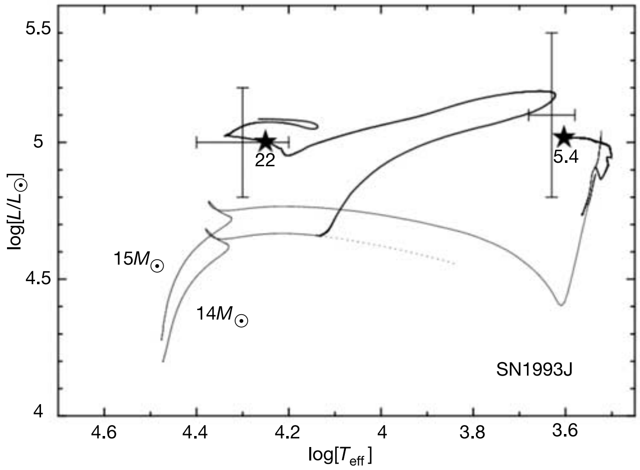

Figure 3 Hertzsprung–Russell diagram illustrating the evolution of the progenitor binary of SN1993J. The system initially consists of two stars of mass $15M_\odot$ and $14M_\odot$ in an orbit of 5.8 yr. The thin lines show the evolution of both components before the beginning of mass transfer, the bold lines during the mass-transfer phase. The more massive component fills its Roche lobe and starts to transfer mass to the companion after the exhaustion of central helium when ascending the red-supergiant branch for the second time (called 'case C' mass transfer; alternatively mass transfer may already start on the first ascent of the red-supergiant branch; 'case BC' mass transfer). The mass transfer rate is initially very high, reaching a peak of $4 \times 10^{-2} M_\odot\,\mathrm{yr}^{-1}$ (the accretion rate onto the secondary was limited to $2 \times 10^{-2} M_\odot\,\mathrm{yr}^{-1}$). Once the primary has transferred most of its envelope, it detaches from its Roche lobe and subsequently continues to lose mass owing to a strong stellar wind, assumed to be $4 \times 10^{-5} M_\odot\,\mathrm{yr}^{-1}$ (ref. 25) at the time of the explosion. Because of the similar masses, the secondary is already somewhat evolved and is near the end of its hydrogen-core burning phase or just beyond (and hence is not being rejuvenated by accretion[15,16]). The numbers along the tracks give the masses of the two components at selected phases. At the time of the explosion of the primary (indicated by asterisks), the primary has a mass of $5.4M_\odot$ (with a helium-exhausted core of $5.1M_\odot$), the secondary has a mass of $22M_\odot$. The error bars show the parameters of the two components, as determined in this work.

produce these narrow lines, the luminosity and temperature of the companion star were calculated to be: $\log L/L_\odot = 5 \pm 0.3$ and $\log T_{\mathrm{eff}} = 4.3 \pm 0.1$ (where subscript $\odot$ refers to the Sun, and our best estimate is a B2Ia star). The uncertainties were determined from the range of atmospheric parameters that would provide appropriate simultaneous matches to the observed lines. The pre-explosion photometry was used to further constrain the companion parameters. The luminosity of the B0Ia star requires a U-band magnitude too bright to be compatible with the pre-explosion U-band luminosity of the progenitor binary system. The nature of the progenitor, considering the blend of the progenitor and the companion in the pre-explosion photometry, is restricted to be a K-supergiant with parameters $\log L/L_\odot = 5.1 \pm 0.3$ and $\log T_{\mathrm{eff}} = 3.63 \pm 0.05$.

The most important implication of these results is that it confirms that the progenitor of SN1993J was a member of a binary system which has lost most of its hydrogen-rich envelope by interaction with its companion star[5–7]. Figure 3 illustrates the evolutionary tracks of both components, the mass-losing one and the mass-accreting one, in the Hertzsprung–Russell (H–R) diagram. The model is very similar to the ones proposed originally[5–7]. The system initially consists of two stars of comparable masses (15 and $14M_\odot$) with an orbital period of 5.8 yr. At the time of the supernova explosion the locations of both stars in the H–R diagram are close to the observationally inferred ones. Note that the subsequent evolution of the companion star would be very different from a star evolved in isolation, and it would most probably end its evolution as a blue supergiant rather than a red supergiant, producing a supernova like SN1987A[15–18] (see Fig. 3). An overabundance of He would be a signature of the accretion onto the companion from the progenitor and the supernova, and we would expect that the He abundance could be determined at much later times once the supernova has faded sufficiently[19,20].

The narrow lines in the SN1993J spectrum are at a velocity of $-120\,\mathrm{km\,s^{-1}}$ relative to the rest frame. This velocity is consistent with the rotational velocity curve of M81 at the position of SN1993J[10,21] and with a low kick velocity to the companion in a long-period binary. At the time of the explosion the orbital period of the system is ~25 yr, and the companion has an orbital velocity of $\sim 6\,\mathrm{km\,s^{-1}}$. The companion is expected to move with this velocity relative to its neighbourhood if the system is disrupted as a result of the supernova, or with the post-supernova binary system velocity ($\sim$20–40 $\mathrm{km\,s^{-1}}$) if the system remains bound[22]. □

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