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The progenitor of supernova 1993J: a stripped supergiant in a binary system?

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SUPERNOVA 1993J in the spiral galaxy M81 is the brightest supernova since SN1987A and, like the latter, appears to be another 'peculiar' type II supernova. The available photometry[1,2] of the supernova region before the explosion requires the presence of at least two supergiants (one of early spectral type and the other of late type), but the actual progenitor has yet to be identified. Here we show that the explosion of a late-type supergiant can explain the initial sharp peak in the supernova light curve, provided that the star had lost almost all of its hydrogen-rich envelope before the explosion. In our model, the secondary brightening of the supernova, ~10 days later, is then a consequence of the radioactive decay of ^{56}Ni (and subsequently ^{56}Co) produced in the explosion. The progenitor could have lost its hydrogen-rich envelope either in a strong stellar wind or, as seems more likely, through mass transfer to a companion star. In the latter case, the companion should reappear after the supernova photosphere has receded, the system having become a binary composed of a neutron star with a massive stellar companion.

The early light curve of SN1993J is characterized by a very sharp initial peak (lasting for less than ten days) followed by a less rapid secondary brightening, which was qualitatively similar to the secondary brightening observed in SN1987A. The unusual initial peak and the absence of an extended plateau phase relegate SN1993J to the category of peculiar supernovae. Humphreys *et al.*[1] have identified a candidate progenitor consistent with the position of the supernova. Combining their ultraviolet–blue–visible–red (UBVR) photometry with the infrared (I) magnitude obtained by Blakeslee and Tonry[2], they concluded (personal communication) that the colours of the apparent progenitor require the presence of at least two bright stars. The results of these fits are sensitive to the assumed visual extinction, A_V, and also to the assumed reddening law. Nevertheless, the presence of two supergiants of comparable brightness is required for all values of A_V for which good fits can be found ($A_V \lesssim 2$). One star is an early-type supergiant (most likely a late-B to early-A supergiant), the other a late-type supergiant (most likely a G to early-K supergiant). The bolometric magnitudes (M) of both stars are in the range of -6 to -8, with best-fit values of -7 to -7.5 (for an assumed distance modulus, $(m—M)_0$, of 27.6). These best-fit values imply main-sequence masses of ~ 15 solar masses ($M_\odot$) but the masses could have been as low as 8 $M_\odot$ and as large as 20 $M_\odot$ (larger masses would require very large bolometric corrections and/or a very large value for $A_V + (m—M)_0$).

The image of the candidate progenitor appears extended on some plates[2]. This suggests that, at the distance of M81, the two stars are separated by at least a few light years and that it is unlikely that the two stars are gravitationally bound to each other (that is, form a binary system). However, this does not rule out that the progenitor was in a close binary, because the presence of one or more additional stars is consistent with the photometric fits. In fact, this is *a priori* quite probable, because the majority of massive stars are believed to be members of binary systems (see for example, refs 3, 4). The likely presence of two supergiants in the field of SN1993J raises the question of which of the two stars was the actual progenitor. An early-type supergiant is an unlikely candidate for a (bright) type II supernova[5,6] (although SN1987A violated this theoretical expectation), whereas an ordinary red supergiant probably produces a more normal type II supernova[5,6]. Furthermore, the spectral type of the late (G to early K) component is significantly earlier than the typical spectral type of a massive red supergiant (early to mid M; ref. 7). As we shall show below, however, a red supergiant progenitor can account for the early light curve, provided that it had lost almost all of its hydrogen-rich envelope before the supernova event (that is, provided it was a 'stripped' supergiant).

We previously carried out a detailed study of supernovae with stripped red-supergiant progenitors (which we refer to as type II (stripped) supernovae; see refs 8, 9 and J.J.L.H. *et al.* manuscript submitted). We found that supernovae of this type differ from ordinary type II-P supernovae (which have red-supergiant progenitors with large hydrogen-rich envelopes) in two important respects. (1) The plateau phase of the light curve, which corresponds to the phase where the hydrogen-recombination front

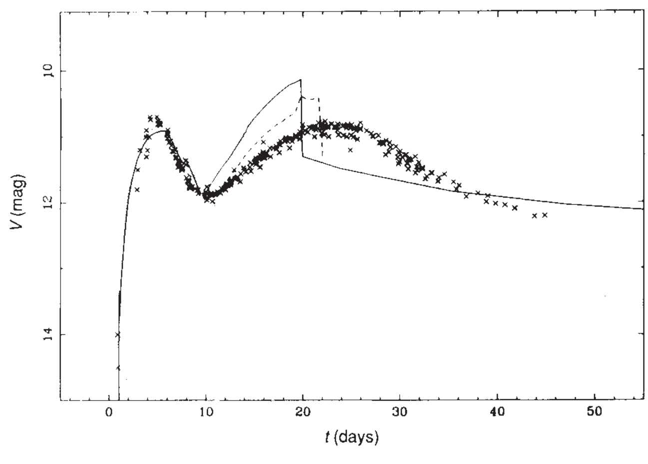

FIG. 1 Comparison of theoretical visual light curves with observations of SN1993J (apparent visual magnitude (V) plotted against time (t) in days since the explosion; 1993 March 26.0 UT corresponds to $t=0$). The crosses represent observed V magnitudes, as compiled by T. Kato (personal communication). The theoretical light curves assume a distance modulus to M81 of $(m-M)_0=27.6$ and a visual extinction $A_V=0.8$ mag. The bolometric corrections were calculated by assuming a hydrostatic stellar atmosphere and by adopting a constant effective temperature of 5,000 K after the secondary peak. The progenitor in all three cases, is a red supergiant (of spectral type K) which had an initial main-sequence mass of 15 $M_\odot$, but had lost all but 0.2 $M_\odot$ of its hydrogen-rich envelope. The solid curve shows the visual light curve for a model with an explosion energy $E=9\times10^{50}$ erg plus energy from the radioactive decay of 0.15 $M_\odot$ of ^{56}Ni (produced in the explosion) and its decay product, ^{56}Co. The dotted curve represents a model with $E=10^{51}$ erg and no nickel. The third model (shown as a dashed curve) is similar to the first model, except that the opacity law has been modified to smooth the secondary rise of the light curve (using the formalism in ref. 16).

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recedes through the ejecta, becomes shorter as the residual envelope mass of the progenitor star decreases. When the envelope mass is less than $\sim 0.5\ M_{\odot}$, there is no distinct plateau phase, and the early light curve is characterized by a single, well-defined peak. (2) If radioactive nickel is produced during the supernova (this depends on the original mass of the progenitor and the details of the explosion mechanism), the energy released from the decay of nickel (and subsequently cobalt) produces a short, but visible, secondary maximum. The observed light curve of SN1993J seems to show both of these predicted features. It is also worth noting that the spectral type of a stripped supergiant will be significantly earlier than the spectral type of a red supergiant with a large hydrogen-rich envelope (spectral type K rather than M), which is in excellent agreement with the photometric constraints discussed above.

We therefore performed a series of hydrodynamical calculations to investigate the possible range of parameters for a stripped-supergiant progenitor of SN1993J. (Technical details of our calculations can be found in the references listed above.) Our main result is that the observed early visual light curve of SN1993J can be fitted very well with the explosion of a progenitor star with a main-sequence mass of $15\ M_{\odot}$, which suffered severe mass loss and had a residual hydrogen envelope mass of $\sim 0.2\ M_{\odot}$ and an explosion energy $E \simeq 9 \times 10^{50}$ erg. Furthermore, if it found that the light curve of SN1993J after ~ 40 days is following the exponential decay of cobalt, then both the secondary peak of the light curve and the exponential decay can be understood as the result of $\sim 0.1\ M_{\odot}$ of nickel that was produced in the supernova and confined to the inner regions of the ejecta (the exact amount of nickel depends sensitively on the assumed reddening and the distance to M81).

In Fig. 1 we display the observed visual light curve of SN1993J and compare it with a few theoretical light curves we have calculated. The first peak in the light curve within ~ 10 days after the explosion is mostly produced by the initial expansion of the supernova ejecta (that is, it took only ~ 10 days for all of the hydrogen to recombine). If no nickel had been produced in the supernova, the light curve would have dropped rapidly and faded away after the initial peak (the dotted curve in Fig. 1). With the additional energy from the radioactive decay of $0.15\ M_{\odot}$ of nickel, however, the light curve (the solid curve in Fig. 1) then rises to a secondary maximum (in 25 days) and drops to follow the exponential decay curve of cobalt. (The cause of the secondary peak is very similar to that inferred for the secondary peak in SN1987A.) It is apparent that our calculated light curve rises more sharply to the secondary maximum and fades more rapidly thereafter than is observed. This is similar to the situation in SN1987A and is caused by several effects we did not consider, in particular the effects of Doppler broadening on the opacities and the effects of mixing of hydrogen and nickel through the ejecta during the explosion. (A detailed discussion of these issues and a more detailed comparison of our models with the observations will be published elsewhere; J.J.L.H. *et al*., manuscript in preparation.)

Our explosion model for SN1993J makes two firm predictions for the immediate further evolution of the supernova. (1) Because of the low mass of the hydrogen-rich ejecta, the late supernova spectrum should resemble that of a type Ib/Ic supernova (that is, the supernova should transform itself from a type II to a type Ib/Ic supernova similar to SN1987K; ref. 10). At the time of submission of this letter, this prediction may already have come true[11]. (2) There should, in the near future, be a resurgence of the X-ray flux from SN1993J, because the γ-rays produced by the decay of cobalt should soon be able to escape as X-rays (the degradation of their energies is due to multiple Compton scatterings as the photons diffuse through the ejecta). Such X-rays have been observed in SN1987A, but, at the distance of M81, this resurgence may not be detectable..

There are two principal evolutionary schemes that can explain the existence of a progenitor with a small hydrogen-rich envelope. The first is one in which the progenitor lost most of its hydrogen-rich envelope in a strong stellar wind. Theoretical models of stellar winds in post-main-sequence stars[12] indicate that an initial main-sequence mass $\gtrsim 25\ M_{\odot}$ would then be required. Such masses are higher than the probable mass implied by the photometric fits (although one cannot exclude such masses with a high degree of confidence). Moreover, this single-star scenario would require that the initial mass of the progenitor fell within a very narrow range, because otherwise the progenitor would have been either a normal red supergiant or a Wolf–Rayet star.

A more probable scheme is one in which the progenitor was a member of a close binary system and underwent stable case C mass transfer[13–15]. In this case, the progenitor (the primary of the binary) fills its Roche lobe while on the asymptotic giant branch (that is as a red supergiant after helium core-burning) and loses most of its envelope in a dynamically stable mass-transfer phase (see ref. 15 for details). The companion star will have accreted a significant fraction of the transferred mass and thereby become substantially more luminous (in fact, it may have become more luminous than the primary). When the mass in the hydrogen-rich envelope has decreased below a certain critical value ($\sim 0.3\ M_{\odot}$ for a progenitor mass of $\sim 15\ M_{\odot}$), the envelope of the progenitor will shrink significantly, so that the star will no longer fill its Roche lobe and mass transfer will cease. The primary will initially still have the appearance of an ordinary red supergiant but will have only a residual hydrogen-rich envelope with a mass of at most a few tenths of a solar mass. Subsequently, the residual envelope will be slowly eroded by a stellar wind; however, even for a mass-loss rate $\dot{M} \simeq 10^{-5}\ M_{\odot}\mathrm{yr}^{-1}$, it will take several times 10^4 yr before the envelope has been completely lost. Because this timescale is of the same order as the remaining evolutionary timescale after the case C mass-transfer phase, a remnant hydrogen-rich envelope may still be left at the time of the supernova explosion. Thus, this scenario would avoid the fine-tuning required in a single-star scenario for a stripped-supergiant progenitor; it only requires case C mass transfer, which occurs for a fairly large range of orbital periods (between ~ 1 and ~ 30 yr for typical binary parameters).

The binary scheme described above makes a number of testable predictions. The companion of the original binary system should initially disappear from view below the photosphere of the supernova, but it should ultimately reappear after the photosphere has receded sufficiently. We emphasize that, because of the mass transfer, the companion may have been more luminous than the progenitor. In this case, neither the early-type supergiant nor the late-type supergiant would have been the progenitor and both stars should still be present after the explosion. Even before the optical reappearance of the companion, it may make its presence known as an additional energy source in the light curve (provided that the supernova did not produce a luminous Crab-like pulsar). Also, the binary is likely to remain bound after the supernova explosion, because much less than half the total mass of the system should have been ejected in the explosion. Hence, the system should now have become a binary composed of a neutron star (or black hole) in a significantly eccentric orbit (with an eccentricity $e \simeq 0.1$–0.5) with a massive stellar companion. The most straightforward confirmation of the proposed scheme would be the detection of the collapsed remnant as a pulsar displaying orbital Doppler shifts in its pulse period.

Finally, we note that our binary scheme suggests a possible evolutionary link between this supernova and SN1987A. In this scheme, the companion accretes several solar masses from the primary. If this accretion takes place after the main-sequence phase of the companion (as would be the case if the companion is a bright supergiant), the future evolution of the companion will be drastically altered. The companion is then likely to explode as a blue supergiant (in 10^5 to 10^6 yr from now) and this second supernova will resemble SN1987A (ref. 15).

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Note added in proof: After this work had been completed, we became aware that two other groups, K. Nomoto *et al.*[17] and S. E. Woosley *et al.* (preprint) independently arrived at a model for SN1993J which, in many respects, is similar to the one presented here. □

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Evidence for surface heterogeneity on Titan

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UNLIKE all other planetary satellites, Saturn's moon Titan has a massive atmosphere[1–8]. At visible wavelengths, a thick stratospheric haze hides the surface from view. The emission from Titan in the infrared is largely from methane, nitrogen and hydrogen also in the stratosphere[4]. In the near-infrared, however, the extinction from haze decreases, and narrow windows exist in which the atmosphere absorbs only weakly[9–14], and through which we might therefore catch a glimpse of the surface. Within two of these windows, Lemmon *et al.*[15,16] recently observed a difference in Titan's albedo when the satellite was at eastern and western elongation with respect to Saturn. Although these observations could be taken to imply that Titan's surface is heterogeneous (and therefore is not covered by a global methane–ethane ocean as predicted previously[7]), they could also be explained by transient clouds. Here I present observations from two more rotational periods which record the same albedo difference, indicating that the heterogeneity is most unlikely to be associated with transient features and must be intrinsic to the surface. These results also imply that Titan is locked in a synchronous orbit about Saturn.

Ultraviolet, visible, infrared and radar observations of Titan have revealed an atmosphere consisting of nitrogen (1.44 bar), methane (~0.05 bar), hydrogen (~0.006 bar), trace amounts of many organic compounds, and a ubiquitous haze[1–6]. In the near-infrared, at several spectral regions, Titan's atmosphere appears optically thin[10–14,17,18]. Evidence for seeing Titan's surface at these windows would be provided if Titan displayed a variable albedo that correlated with its rotation period. Titan's rotation period is unknown; however, it is probably synchronized with Titan's orbital period, because this configuration (having the lowest tidal energy) is observed for most satellites[19]. In this case, opposite hemispheres face the Earth when Titan is at opposite elongations in its orbit about Saturn.

Using NASA's Infrared Telescope Facility on Mauna Kea, equipped with the Cooled Grating Array Spectrometer[20], I observed Titan at opposite elongations in 1989 and 1990 (Table 1). I found that Titan's albedo at its eastern elongation was $11\pm10\%$, $20\pm10\%$, $13\pm7\%$, and $8\pm6\%$ greater than that at its western elongation at 4,900, 6,300, 7,800 and 9,300 cm^{-1}, respectively (Figs 1, 2). At 4,900 and 9,300 cm^{-1}, these differ-

TABLE 1 Observations and albedo ratios

Observations*† (this work)

Wavenumber (cm^{-1})	Date (UT)	Nearest elongation	Time from elongation	Air mass‡
4,000–5,100	1990 July 25 09 h	Eastern	+51 h	1.33–1.40
4,000–5,100	1990 July 15 10 h	Western	−2 h	1.37–1.47
5,600–6,800	1989 July 5 10 h	Eastern	+9 h	1.55–1.65
5,600–6,800	1989 July 13 10 h	Western	+5 h	1.32–1.35
7,500–9,400	1989 July 5 09 h	Eastern	+8 h	1.40–1.44
7,500–9,400	1989 July 13 09 h	Western	+4 h	1.38–1.41

Ratio of Titan's leading to trailing hemisphere albedos

Wavenumber (cm^{-1})	Observations§ (this work) Ratio	Date	Lemmon *et al.*‖ Ratio	Date	τ_{haze}	Ratio (haze removed)
4,900	1.12 ± 0.04	1990	—	—	0.14–0.17	1.19–1.21
6,300	1.20 ± 0.10	1989	—	—	0.18–0.20	1.30–1.38
7,800	1.13 ± 0.07	1989	1.22 ± 0.03	1992	0.23–0.50	1.21–1.30
9,300	1.09 ± 0.03	1989	1.14 ± 0.03	1992	0.23–0.50	1.21–1.30

* Resolving power: 138–120, 200–171 and 140–120 at 4,000–5,100, 5,600–6,800 and 7,500–9,400 cm^{-1}, respectively.
† Calibration stars: SAO162229 and SAO188337 in 1989 and 1990, respectively.
‡ The air mass, $1/\cos\theta$, where θ is the zenith angle, is a measure of the relative pathlength viewed through the Earth's atmosphere during the observations.
§ At 4,900 and 9,300 cm^{-1}, spectrally degraded observations were used to compute the ratio. Detailed dates in upper part of Table.
‖ Detailed dates given in text.

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