A type IIb model for supernova 1993J

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SPECTRAL analyses of supernovae have allowed them to be broadly divided into two classes, type I and type II. Supernova 1993J was identified[1–3] as a type II supernova following the detection of a weak hydrogen line in its early spectrum. But the optical light curve[4] of SN1993J is atypical for this class of supernova, with the intensity rising to a second maximum after the initial outburst. The light curve around the second maximum more closely resembles that of the type Ib supernova 1983N (ref. 5), the progenitor of which may have been a helium star[6]. Here we show that the secondary brightening and subsequent decay of the light curve can be explained by the radioactive decay of ^{56}Co; combined with the early spectrum, this suggests that the progenitor may have been a red supergiant with an unusually thin hydrogen-rich envelope. If this model is correct, the spectrum will rapidly evolve from type II to type Ib, in which case SN1993J would be classified as a type IIb supernova[7,8]. We suggest that the progenitor was in a binary system, and had lost most of its hydrogen envelope to the companion star before the explosion.

The light curve of SN1993J quickly reached the first maximum, declined in ~5 days, rose to the second maximum in ~10–15 days depending on the wavelength, and then declined again[4]. Such a light curve with two peaks is distinctly different from those of previously known type II supernovae which show either a long plateau (type II-P) or a relatively monotonic decline without a clear plateau (type II-L)[9]. The light curves of these type II supernovae have been well modelled with the explosion of massive red-supergiant stars (except for the blue supergiant progenitor of SN1987A). The explosion of such massive stars ($\gtrsim$8 solar masses ($M_\odot$)) is triggered by the gravitational collapse that forms a neutron star (or a black hole) and a shock wave. The shock wave propagates through the surface to heat up the extended hydrogen-rich envelope. Subsequent diffusive release of internal energy forms a light curve whose plateau duration depends on the mass and the initial radius of the progenitor's envelope[10,11]. However, those ordinary massive red-supergiant models cannot explain the unusual light curve of SN1993J.

The important clue to the understanding of the nature of SN1993J has been provided by its bolometric light curve, which has been constructed[4] using BVI photometry and bolometric corrections derived from models and SN1987A (the filled circles in Figs 1 and 2); the distance to SN1993J and the extinction are assumed to be 3.3 Mpc and $A_v = 0.4$ mag, respectively. Since the observed bolometric luminosity is the rate of total energy output integrated from the ultraviolet to the infrared bands, it can be compared with the theoretical bolometric luminosity to identify the energy source of the unusual light curve of SN1993J

Because there is no resemblance between SN1993J and other type II supernovae, we extend the comparison to include type I supernovae. In Fig. 1 we plot the observed bolometric light curves of SN1993J (filled circles) and SN1993N (open circles) which is the best observed type Ib supernova[5]. It is striking that the light curve around the second maximum of SN1993J is in excellent agreement with that of SN1983N

As the basic features of type Ib supernova light curves have been explained with the helium star models[6,12–14], we calculate the explosions of helium stars with masses of $M_\alpha = 3.3$, 4 and 6 $M_\odot$, which are presumed to form from the main-sequence stars with $M_{ms} = 13$, 15 and 20 $M_\odot$, respectively[15]. These helium stars undergo gravitational collapse to form a neutron star and generate a shock wave as in type II supernovae. In our hydrodynamical calculations, parameters such as the neutron star mass and the initial energy given to the shock wave are chosen to produce the kinetic energy of explosion $E = 1 \times 10^{51}$ erg s^{-1} and 0.075 $M_\odot$ of ^{56}Ni, which is synthesized in explosive nucleosynthesis behind the shock wave. Rayleigh–Taylor instabilities are found to take place during the shock propagation[16], which induces some mixing of ^{56}Ni from the deepest layer to the helium envelope. In these models, the radioactive decays of ^{56}Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe power the light curve of SN1993J around the second maximum. (Shock heating effect does not appear in the early light curve because of small initial radii.) If ^{56}Ni is well mixed through the surface, the second maximum is reached earlier because of earlier heating by the radioactive decays. Also, the light curve declines faster because of faster escape of γ-rays before thermalization occurs. Because the degree of ^{56}Ni mixing has not been accurately determined, we calculate two cases for each helium star[6], one with nearly homogeneous mixing and one without mixing. In Fig. 1 are shown the theoretical curves for $M_\alpha = 3.3$–6 $M_\odot$, with and without mixing. It is seen that the light curves of the 3.3 $M_\odot$ and 4 $M_\odot$ models without mixing are in good agreement with SN1993J.

The resemblance between the observed and calculated light curves shown in Fig. 1 strongly indicate that the hydrogen-rich envelope of SN1993J contains a very small mass, so that it has little influence on the light curve shape powered by the radioactive decays in the core. If the hydrogen-rich envelope were as massive as ~10 $M_\odot$ (which is the case for a typical red-supergiant as described earlier), it would take ~100 days until the hydrogen-rich envelope becomes transparent. This is demonstrated by the dotted line in Fig. 2, for the model which has the 10.6 $M_\odot$ envelope on top of the 4 $M_\odot$ helium core.

To estimate how small the envelope mass should be, we construct an explosion model which has a helium core of $M_\alpha = 4$ $M_\odot$ and a hydrogen-rich envelope of mass $M_{env} = 0.89$ $M_\odot$. (Its pre-

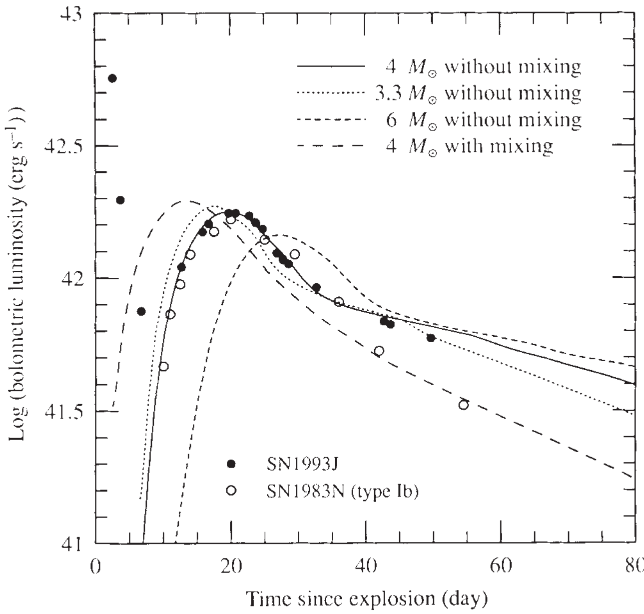

FIG. 1 The bolometric light curves of SN1993J (filled circles)[4], the type IIb supernova 1983N (open circles)[5], and the He star models with various masses and degrees of ^{56}Ni mixing.

supernova radius and helium mass fraction are $R=300$ solar radii ($R_\odot$) and $Y=0.8$.) The hydrodynamics of explosion is simulated as in the helium star models and the model parameters are chosen to produce $E=1.2\times10^{51}$ erg s^{-1} and 0.075 $M_\odot$ ^{56}Ni. Uniform mixing of ^{56}Ni in the helium core is assumed. The calculated bolometric light curve (the solid line in Fig. 2) shows two peaks as in SN1993J. The light curve around the first maximum is due to the shock heating of the envelope. Starting from the light curve minimum, the effect of heating by the ^{56}Co decay appears and produces the second peak. In this model, the hydrogen-rich envelope does not become transparent until the second peak, and the agreement with the SN1993J curve is not as successful as in the helium star models. This indicates that the envelope mass should be less than ~0.9 $M_\odot$. Further explorations of the correct model for SN1993J are underway for various combinations of the envelope models and core models[17].

If the helium star models in Fig. 1 give the correct interpretation of the light curve around the second maximum, the mass of ^{56}Ni synthesized in SN1993J is ~0.075 $M_\odot$ with a factor of ~2 uncertainty (due to the estimates of the extinction and distance). Because of the thin hydrogen-rich envelope, SN1993J may be called a type IIb supernova[7] as future spectral development may follow SN1987K, which changed from type II to type Ib (ref. 8). Depending on their abundances, line features of helium, oxygen, and calcium will appear due to radioactive excitation.

Possible progenitors that have a thin hydrogen-rich envelope include (1) an AGB star[18], (2) a very massive star with the main-sequence mass $\gtrsim30$ $M_\odot$ (and $M_\alpha\gtrsim10$ $M_\odot$) that has lost most of the envelope in a red supergiant wind becoming almost a Wolf–Rayet star[19], and (3) a binary star which has a 3–6 $M_\odot$ helium core and lost most of its envelope to the companion star.

The AGB model would probably result in more like the monotonic decline type supernova (type II-L) because of the large initial radius as well as very small total ejecta mass[11,20], although a helium rich envelope model may not be precluded[18]. To distinguish the other two models, the mass of the helium core can be constrained from the date of the second maximum, which is ~20 d. For more massive helium stars, heat generated by the radioactive decay takes longer to diffuse out by means of electron scattering. Accordingly the helium star models with masses $\gtrsim6$ $M_\odot$ reach the light curve maximum after day 25. Even with the large scale mixing of ^{56}Ni, the 6 $M_\odot$ model shows a maximum at day 20 (ref. 6). Therefore, the helium core mass would be in the range of 3–6 $M_\odot$, which favours the binary scheme. Further information on the decline rate of the light curve would provide more accurate determination of the helium core mass and the degree of the ^{56}Ni mixing as seen in Fig. 1. For longer terms the decline of the bolometric light curve will be slowed down by two effects. First, the time scale of energy emission due to recombination of ions will become longer than that of energy input from the radioactive decay (which mostly goes into ionization[21].) Second, possible pulsar activity may heat up the ejecta.

These arguments suggest that the progenitor of SN1993J was in a binary system and lost most of its envelope to the companion star. The progenitor may have become detached from the Roche lobe as a result of the reversal of the mass ratio. In the binary scheme, the asymmetry of SN1993J inferred from the polarization[22] and line features[23] may be naturally explained by the binary interaction.

The hydrogen-poor model for SN1993J would lead to several interesting predictions depending on the chemical composition in the core. (1) At a distance of 3.3 Mpc, the Compton Gamma Ray Observatory (CGRO) could detect the line γ-rays from supernovae of type Ia, Ib and Ic, but not from ordinary type II-P (refs 24–26). If SN1993J has a small enough hydrogen-rich envelope, produced more than ~0.15 $M_\odot$ ^{56}Ni, and underwent mixing, the observations of line γ-rays from SN1993J with CGRO could be just possible around day 100. (2) SN1993J could form a helium-rich supernova remnant, which might look like the helium-rich Crab Nebula[27] if most of heavy elements form dust grains in the remnant. SN1054 was visible during the day for about a month[28], which could happen with SN1993J if its light curve continues to decline.

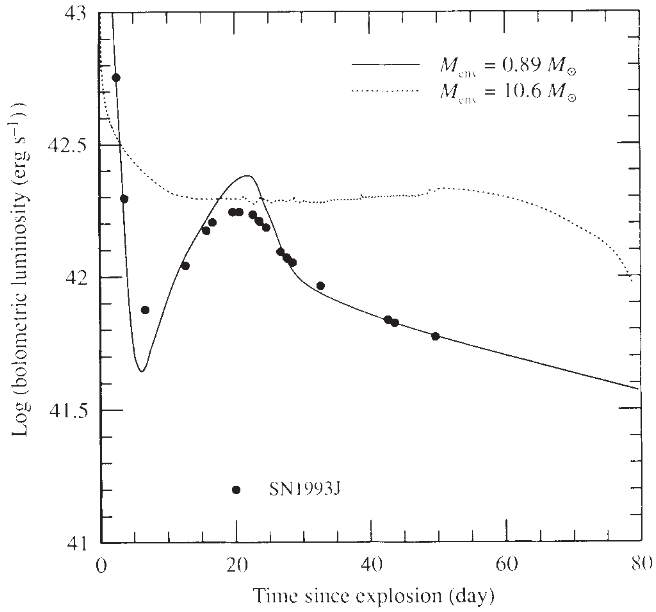

FIG. 2 The calculated bolometric light curves for two models, with envelopes of different masses M_{env} on top of the same 4 $M_\odot$ helium core. The solid and the dotted lines show the cases with $M_{env}=0.89$ and 10.6 $M_\odot$, respectively. The bolometric light curve of SN1993J is shown by the filled circles[4].

In summary, we suggest that SN1993J is a supernova that occurred in a binary system and may be classified as a type IIb supernova.

Note added in proof: After this paper had been submitted Filippenko and Matheson[29] reported the emergence of prominent helium line features in the spectra of SN1993J, supporting our prediction for the spectral development from type II to type Ib. □

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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

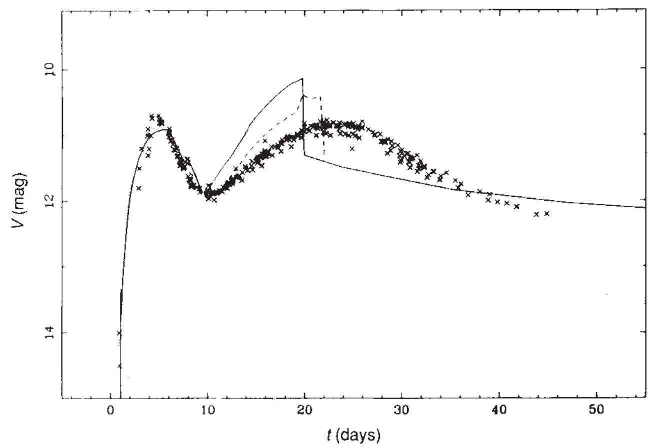

FIG. 1 Comparison of theoretical visual light curves with observations of SN1993J (apparent visual magnitude (V) plotted against time (t) in days since the explosion; 1993 March 26.0 UT corresponds to $t=0$). The crosses represent observed V magnitudes, as compiled by T. Kato (personal communication). 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).