J. Astrophys. Astr. (1993) **14**, 53–63

The Bolometric Light Curve of SN 1993J and the Nature of its Progenitor

A. Ray, K. P. Singh & F. K. Sutaria *Tata Institute of Fundamental Research, Bombay 400 005*

Received 1993 May 27; accepted 1993 June 8

Abstract. We have constructed the bolometric light curve of SN 1993J based on UBVRI(JHK) photometric data obtained from various sources and assuming $A_v = 0$ and a distance modulus of 27.6. Effective temperatures and photosphere radius at various times have been obtained from detailed blackbody fits. The bolometric light curve shows two maxima. The short rise time to the second maximum, and the luminosities at the minimum and the second maximum are used to constrain the properties of the progenitor star. The total mass of the hydrogen envelope M_H, in the star is found to be $\lesssim 0{\cdot}2\ M_\odot$ at the time of explosion, and the explosion ejected about 0.05 $M_\odot$ of Ni^{56}. Thin hydrogen envelope combined with a sufficient presupernova luminosity suggest that the exploding star was in a binary with a probable period range of $5\text{yr} \leqslant P_{orb} \leqslant 11\text{yr}$.

Key words: Stars: Supernovae: SN1993J—techniques: photometry—stars: evolution

1. Introduction

Study of Supernovae (SNe) provide insights to the nature of the progenitor star prior to its explosion. Most SNe, however, take place in distant galaxies and fade away rather quickly. A supernova (SN) in a nearby galaxy is therefore eagerly awaited by astronomers all over the world. One such event (SN1987A) took place in 1987 in our satellite galaxy, the Large Magellanic Cloud. Currently it is SN1993J that exploded in a nearby galaxy M81, which is commanding considerable attention of astronomers.

SN1993J was discovered on the night of 28 March 1993 by an amateur astronomer in Spain, Francisco Garcia, within a day of the explosion (Ripero 1993). Because of its relative nearness (distance = 3.3 Mpc) it has received a substantial coverage over a wide range of the electromagnetic spectrum. SN1993J has been detected quite early on, in the radio (Pooley & Green 1993) and X-ray wavelengths (Zimmermann *et al.* 1993; Tanaka 1993), apart from the infrared, optical and ultraviolet (Sonnebora *et al.* 1993). It was identified as a type II supernova (SN II) based on early detection of hydrogen lines in its spectra (Filippenko 1993a). This supernova like SN1987K is a rare example of a type II SN which seems to be undergoing a metamorphosis into a type Ib SN based on spectroscopic evidence (Filippenko & Matheson 1993). The progenitor suggested for SN1993J, based on archival data of the region in M81 where the explosion took place, is either a K0 supergiant (Perelmuter 1993; Filippenko

1993b), or a late A/early F-type supergiant with some reddening (Humphreys *et al.* 1993).

We present in section 2 the bolometric light curves of SN1993J which have been constructed by us by making detailed black-body fits to optical photometry data, kindly provided by many observers. In section 3 we interpret the unusual bolometric light curve based on simple physical ideas and scaling laws in comparison with SN1987A, and finally discuss our results.

2. Bolometric light curve of SN1993J

We have used the broad-band optical-to-infrared photometry data in the UBVRI (and JHK wherever available e.g. Romanshin 1993; Smith 1993; Morbidelli *et al.* 1993; Odewahn *et al.* 1993; Lawrence 1993; Calamai *et al.* 1993; and Lester *et al.* 1993) bands from the following sources—S. Unger, Z.-Y. Zheng, N. M. Shakhovskoy, A. Filippenko, M. Richmond and their collaborators (private communications). The data incorporate the corrections made upto the writing of this paper. The photometric magnitudes were converted to flux units (ergs cm $^{-2}$ s^{-1} Å^{-1}) using the calibrations provided by Bessell (1979), Wilson *et al.* (1972) and Johnson (1966). We assumed $A_V = 0$ and distance modulus = 27.6.

Black-body spectrum generally gives a fairly good representation of the observed emission from a supernova in its early days (see for example, Menzies *et al.* 1987). The derived fluxes were fitted with a black-body spectrum using the NFIT1D task in the STSDAS* software package. The best fit temperatures and amplitudes were

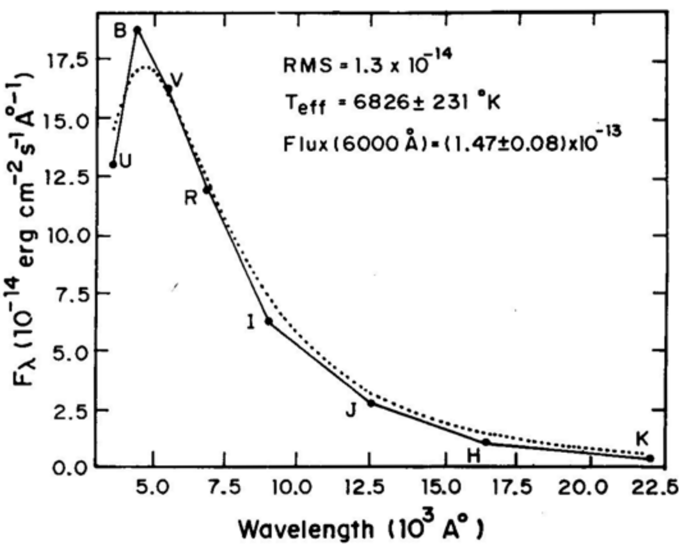

Figure 1. UBVRIJHK photometric data for the 1993 April 14 observations by Zheng *et al.* (April 14.62) along with Romanishin (1993; at April 14·17) are shown fitted with a blackbody curve (dotted line). The best fit parameters with errors and the quality of the fit are indicated.

*The Space Telescope Science Data Analysis System (STSDAS) is distributed by the Space Telescope Science Institute.

estimated based on the downhill simplex method (Press *et al.* 1986). The associated errors were estimated after replicating the data a few times by adding Gaussian noise based on the dispersion of the original data around the fit In Fig. 1, we show one such fit to the UBVRI data of April 14 obtained by Zheng *et al.* (1993) and JHK data on the same day by Romanshin (1993). The best fit parameters were converted to the black-body radius and bolometric luminosity assuming a distance of 3·3 Mpc.

The bolometric light curves thus derived are shown in Figs. 2(a) and (b). The values in Fig. 2(a) are based only on the UBVRI data whereas those in 2(b) are based on the UBVRI and JHK data. The curve marked "Richmond" is constructed from calibrated UBVRI photometry from Leuschner Observatory (University of California at Berkeley) reported by A. Filippenko *et al.* (private communication). The corresponding temperatures and the radii of the photosphere are shown in Figs. 3(a) and (b) and Figs. 4(a) and (b) respectively. Open circles in Figs. 2(b), 3(b) and 4(b) have been primarily compiled with Richmond's $UBV(RI)_C$ data combined with JHK data. One open circle is due to combining Unger's similar data with JHK photometry. Similarly, the filled circles in Figs. 2(b), 3(b) and 4(b) are Johnson band photometry primarily due to Zheng *et al.* combined with JHK data of other observers although several other points similarly marked are due to Shakhovskoy combined with JHK data. Note that the error bars are considerably reduced by the inclusion of the JHK data in the near infra-red. The effect of assuming a non-zero value of extinction would be to increase the luminosity and temperature slightly. The quality of the fits, as measured by the rms deviation, becomes progressively poorer as the supernova cools, and this effect is most noticeable in the U band. The luminosity curve has a distinctive double maximum similar to that observed in SN1987A except that the second maximum is reached in $\sim 20d$ compared to $\sim 90d$ for SN1987A (Catchpole *et al.* 1987). The second maximum also appears to resemble the peak normally seen in some SNe Ib e.g., SN1983N. The derived temperatures show a plateau at ~ 6250 K; in contrast, the temperature in SN1987A showed a plateau at ~ 5500 K. (Catchpole *et al.* 1987). The black-body temperature is higher in SN1993J compared to that in SN1987A at the stages identified as the hydrogen recombination plateau. This, together with Saha ionisation equation imply a higher density at the photosphere compared to SN1987A at the corresponding time or stage. This is consistent with a sharper density profile of SN1993J after explosion. In Fig.4(a) we have drawn lines indicating the rate of expansion of the supernova photosphere. The expansion velocity lies between $10^4 \mathrm{kms}^{-1}$ to $1{\cdot}6 \times 10^4 \mathrm{kms}^{-1}$ on the first few days after the explosion. On 1993 April 2.3 (~$5d$ after the explosion), Wheeler *et al.* (1993) reported the detection of Paschen β line with a width of 10^4 kms $^{-1}$ consistent with the derived velocity from Fig. 4 (see the point marked with a cross). The expansion velocity decreased later and was in the range of 7000 to 10,000 km s^{-1} range, 10 to 30 days after the explosion.

3. Nature of the progenitor

3.1 *Basic Physics Involved*

We now relate the behaviour of the bolometric light curves presented above to the nature of the progenitor using simple ideas explained in detail by McCray & Li (1988); Arnett (1982); and Woosley *et al* (1988).

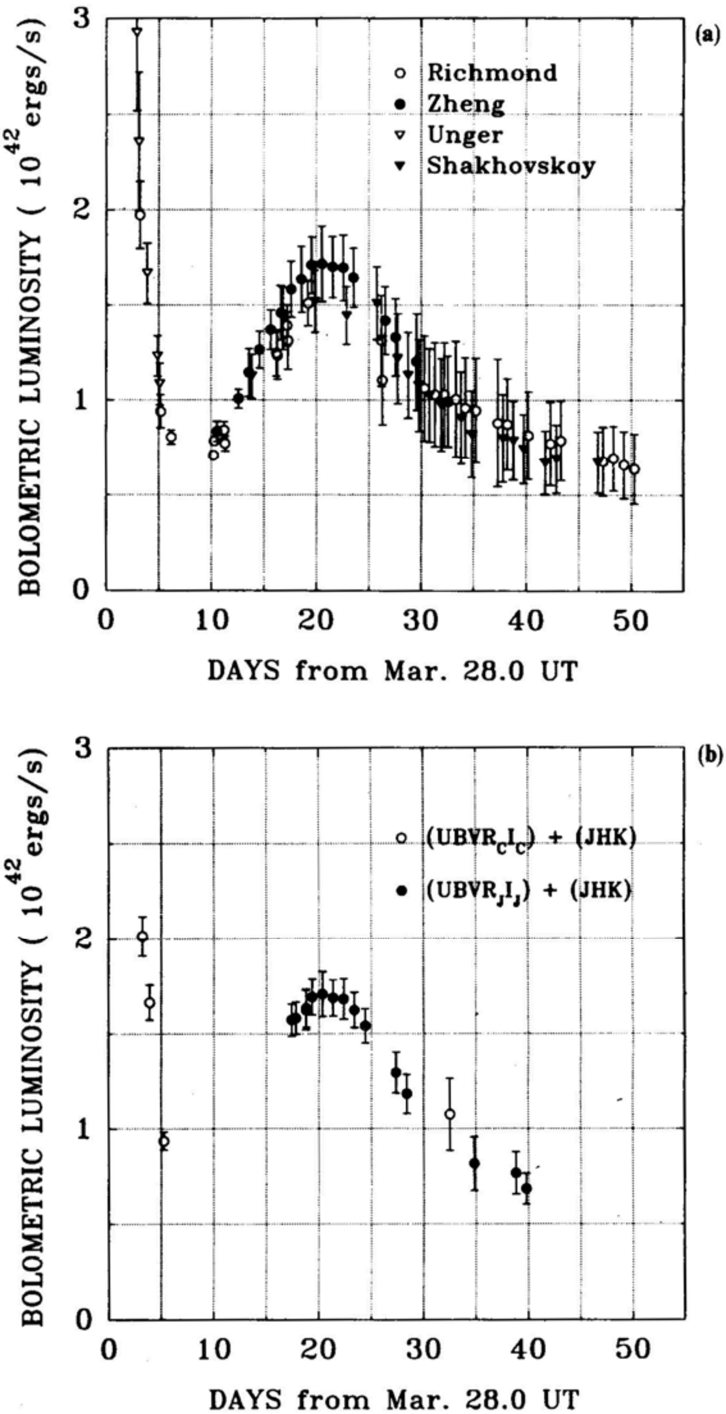

Figure 2. Bolometric luminosity of SN1993J on different days based on the data indicated in the Figure. In (**a**) we show the luminosity derived from fitting only the UBVRI data whereas in (**b**) we show the derived values obtained by the addition of the available JHK data. See text for elaboration of symbols.

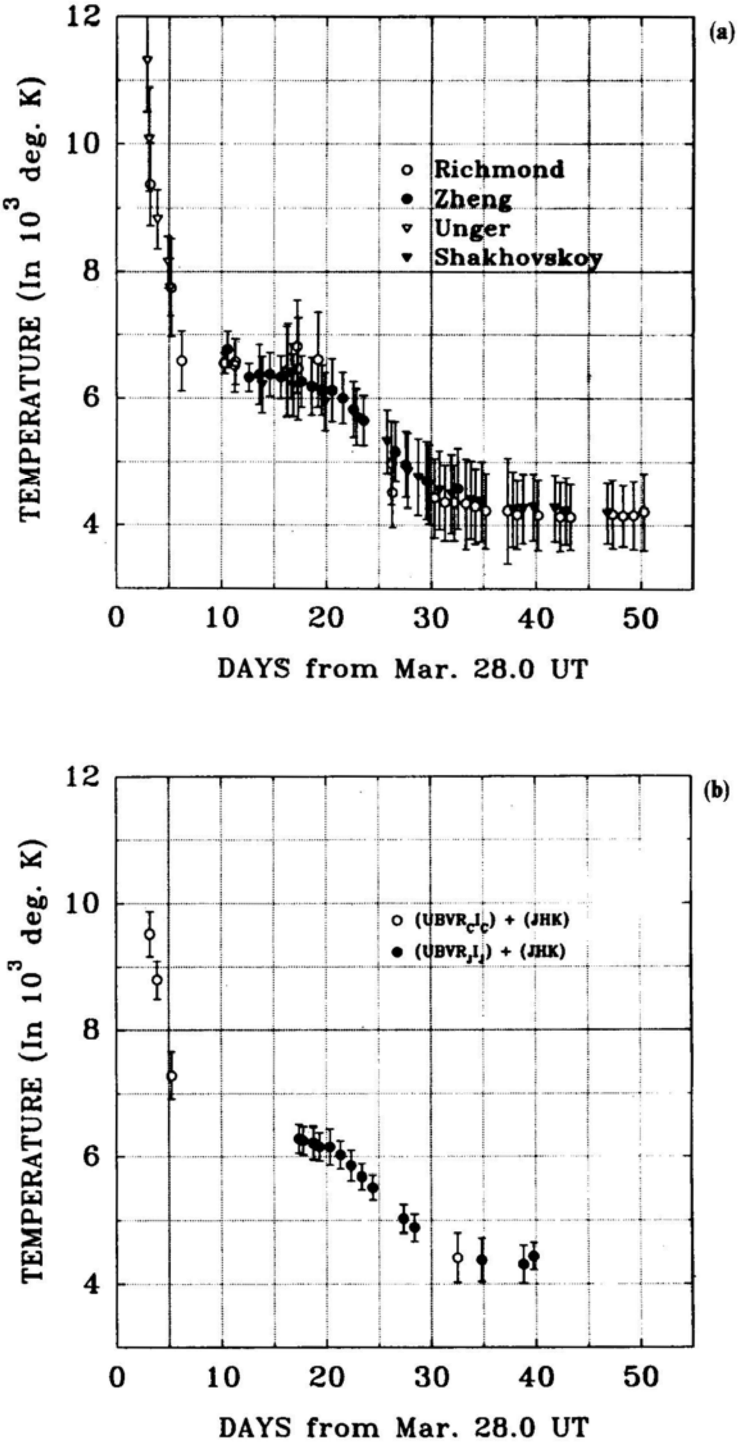

Figure 3. Photospheric temperatures derived for SN1993J. The values based on UBVRI data alone are shown in (**a**), and those including both the optical and near-IR data are shown in (**b**) as in Fig.2(b).

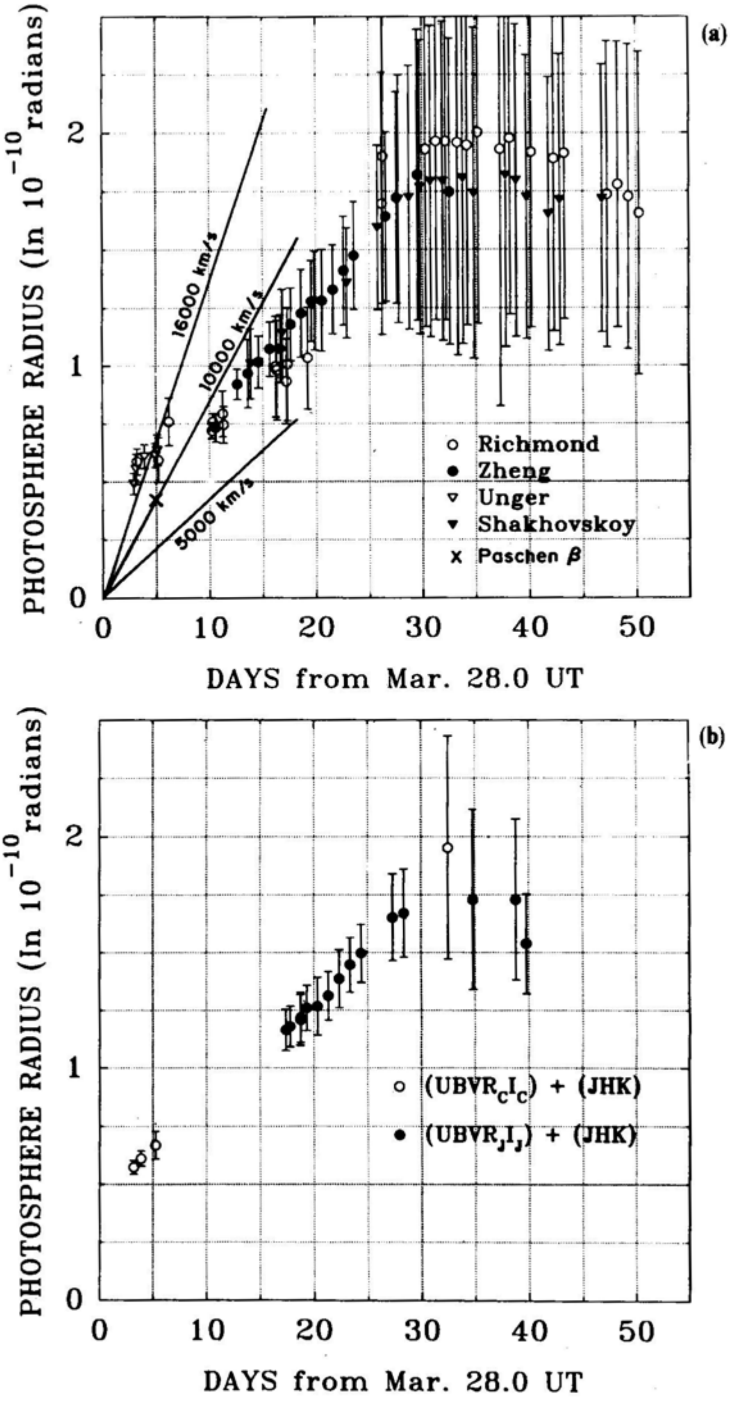

Figure 4. Radii of the photosphere corresponding to the Figs. 2(a) and (b) and 3(a) and (b) are shown here in (**a**) and (**b**) respectively. Lines have been drawn to indicate different velocities of expansion. Also indicated by an X is the velocity interpreted from the widths of the Paschen β line on April 2nd.

The SN starts with a core collapse and proceeds with a shock imparting kinetic energy (~ 10^{51} E_{51} ergs) to its envelope which consists mainly of hydrogen. Assuming the homologous expansion of a uniform density envelope having uniform energy deposition from the shock wave passing through the star, one can write down the equations for the velocity, density and the outer radius of the expanding gaseous envelope. Given the initial radius of the star, the interior temperature just after the blast can be calculated from the total thermal energy E_{51}. Initially for a few days, the SN is opaque and the interior temperature falls inversely as the radius. Using these parameters and the diffusion theory (Chernoff et *al.* 1988), and assuming surface opacity $k = 40\ A_{100}$ cm^2 gm^{-1} (i.e. 100 times Thompson value—because of many overlapping *UV* lines near the photosphere with substantial differential velocity), one can estimate the early luminosity and temperature of the expanding photosphere. Here, A_{100} is a measure of uncertainty in κ. Then the luminosity is

$$L(t) = (5.9 \times 10^{41}\,\mathrm{ergs\,s^{-1}}) A_{100}^{-1/2} M_{10}^{-1/4} E_{51}^{3/4} t_d^{-1} \times \left[\frac{R_0}{R_{87A}}\right] \quad (1)$$

and the surface temperature is

$$T_p(t) = (2.8 \times 10^4\,{}^\circ\mathrm{K}) A_{100}^{-1/8} \left[\frac{R_0}{R_{87A}}\right]^{1/4} E_{51}^{-1/16} M_{10}^{3/16} t_d^{-3/4}$$

where R_o is the radius of the progenitor, t_d is the number of days after the explosion, $R_{87A} = 3 \times 10^{12}$ cm is the radius of the progenitor of SN1987A, and M_{10} is the mass of the envelope in 10 $M_\odot$ units. Equivalently the expression for the luminosity at this stage can be expressed with the following scaling:

$$L(t) = (3.7 \times 10^{41}\,\mathrm{ergs\,s^{-1}}) A_{100}^{-1/2} E_{51} M_{10}^{-1/2} \left(\frac{V}{10{,}000\,\mathrm{km/s}}\right)^{-1/2} \left(\frac{R_0}{3 \times 10^{12}}\right) t_d^{-1} \quad (2)$$

In case estimates of the early photospheric velocities exist (e.g. from the expanding photospheric method, see 4(a) and 4(b) or from the width of a deep lying IR line which is emitted close to the photosphere, e.g., the Paschen β–line seen on April 2–3 (Wheeler *et al.* 1993)) the above form can also be used to estimate the relevant quantities of the explosion (see below).

As an example for SN1987A, at $t_d = 5$,

$L \sim 1.2 \times 10^{41}$ erg s^{-1} for $E_{51} = M_{10} = 1$

$T_p \sim 8500^\circ$ K for $E_{51} = M_{10} = 1$

which compares very well with the observed values for SN1987A.

When T_p reaches 5000–7000°K, the ionized hydrogen in the envelope starts recombining. For lower temperatures the opacity declines sharply and the above equations no longer apply. The luminosity is then controlled by a hydrogen "recombination front" moving into the interior in the mass coordinate i.e., "eating" into the envelope. The luminosity of SN photosphere is ≈ mass flow rate times the trapped photon energy release from recombination i.e.,

$$L_{\mathrm{bol}} = \varepsilon(x,t)\, M(t) \quad (3)$$

Here ε is the radiation energy density per unit mass, x is the fractional radius $x = r/R(t) = v(r)/V$ and if energy loss through diffusion is small (a good approximation initially, e.g. $t_d < 100$ for SN1987A—see McCray & Li (1988) we have,

$$\varepsilon(x,t) = \varepsilon(x,0)\left[\frac{R(0)}{R(t)}\right].$$

If the energy deposited by the initial blast is uniformly distributed throughout the hydrogen envelope then we have, in addition,

$$\varepsilon(x,0) = E_0 / 2M_{\mathrm{env}}$$

where E_0 is the total energy of the explosion (kinetic + thermal).

3.2 *Application to SN1993J*

From the bolometric light curve of SN1993J (Fig. 2), after the minimum at $t_d \sim 8$, we derive

$$L(t) = (6{\cdot}2 \times 10^{41}\ \mathrm{erg/s})\ e^{(td-8)/10.6} \tag{4}$$

valid for the period $8d \leqslant t_d \leqslant 19d$. Integrating the Equation (3) and using (4), we then derive the mass of the hydrogen envelope in SN1993J,

$$M(t) = \frac{2M_{\mathrm{env}}}{E_0 R_0}\int_0^t L(t)R(t)\mathrm{d}t$$

$$\approx 1.4 M_\odot \frac{M_{10}^{1/2} E_{51}^{-1/2}}{\left(\frac{R_0}{R_{87\mathrm{A}}}\right)}\left[1 + \left(\frac{(t_d - 8)}{10.6} - 1\right)e^{(t_d - 8)/10.6}\right]$$

At $t_d = 19\ d$, i.e. near the second maximum, this implies

$$E_{51}^{1/2}(M_{93\mathrm{J}}/\mathrm{M}_\odot)^{1/2}\left(\frac{R(0)}{3 \times 10^{12}}\right) = 0.49 \tag{5}$$

This is really an upper limit as it is assumed that the increase in luminosity in the 11 days after the first minimum, is due to hydrogen recombination only. Here $M_{93\mathrm{J}}$ is the mass of the hydrogen envelope of SN1993J and $R(0)$ is its initial radius at the time of explosion.

The minimum in the bolometric luminosity occurs at $t_d = 8$ for both SN1993J and SN1987A with the following values for the luminosity

$$L1993\mathrm{J} = 6{\cdot}25 \times 10^{41}\mathrm{ergs}^{-1}$$

$$L1987\mathrm{A} = 1{\cdot}8 \times 10^{41}\ \mathrm{erg\ s}^{-1}$$

We compare the two SNe at the minimum of the bolometric light curve using equation (1) and then by combining with equation (5), we get, (for $E_{51} = 1$; $M_{87\mathrm{A}} = 10\ \mathrm{M}_\odot$),

$$M_{93\mathrm{J}} \sim 0{\cdot}15\ \mathrm{M}_\odot$$

It is also possible to fit the time dependence of early ($\leqslant$ 6 days) bolometric luminosity curve derived from Unger's data to an expression like equation (2) where the data on the velocity of the photosphere can be supplemented from Fig 4 (a) and Wheeler *et al.* (1933). For an energy of explosion $E_{51} \sim 3$, the mass of the hydrogen envelope from this fit turns out to be ~ 0.1 $M_\odot$ which is close to the value obtained in the preceding paragraph by comparing the minima of the two SNe: SN1993J and SN1987A.

The amount of hydrogen in the envelope of the progenitor was therefore unusually small, unlike the progenitors of normal type II SNe. The SN type of 1993 J appears to be changing to that of type Ib (based upon spectroscopic evidence, see Filippenko & Matheson 1993) after the early appearance of H lines that had put it in the type II category. The presupernova star of SN1993J was a supergiant (see section 1) and the mass of its Helium core based on the luminosites of the progenitor field stars is in the range 3–5 $M_\odot$ so that its mass on the Main Sequence expected to be ~ 10–20 $M_\odot$. Since normally, for a $M_{\rm MS} \approx 20 M_\odot$ the $M_{\rm H} \sim 11$–$14 M_\odot$, the question arises as to why so little hydrogen is left in the envelope at the time of explosion. A probable answer to this question is that the progenitor could have lost its envelope via mass transfer to a companion star in binary. A possible scenario for the binary system in SN1993J is one in which the progenitor was a red supergiant when Roche Lobe Overflow started, and followed the evolutionary sequence of the C^1 D^2 channel as presented in Rathnasree & Ray (1992). This would avoid spiral in of the two stars in a common envelope. This is also consistent with the asymmetry of SN1993J indicated by the polarization measurements (Jannuzi *et al.* (1993), Trammel *et al.* (1993)). In this scenario, the possible period of such a binary with $M_{\rm MS}$ (primary) ~ 18 $M_\odot$ at the time of explosion of the primary $P_{\rm orb}$ is in the range of 511 yr. Then Kepler's law,

$$P_{\rm yr}^2 = \frac{a_{\rm AU}^3}{\left(\dfrac{M_{\rm total}}{M_\odot}\right)}$$

gives for $P = 10$ yr,

$$a_{\rm AU}\,(10{\rm yr}) \simeq 13.5{\rm AU}.$$

At this distance, the SN shock travelling at ~ 10,000 km/s would engulf the companion in ~2 days.

3.3 *Amount of Ni Ejected*

The light curve around the second maximum is powered by the radioactive decay of $Ni^{56} \rightarrow Co^{56}$. We can use the bolometric light curve (Fig. 2) to estimate the amount of Ni^{56} in SN1993J by following the prescription of Arnett (1982) based on the first law of thermodynamics, radiative diffusion, radioactive decay and hydrodynamic expansion. The solution for the surface luminosity is

$$L(t) = \varepsilon_{\rm Ni}\, M_{\rm Ni}\, \Lambda(x,y)$$

where, *A(x,y)* is a dimensionless integral given by Arnett (1982), $\varepsilon_{\rm Ni} = q_{\rm Ni} / \tau_{\rm Ni}$ and is equal to 4·78 × l0 ergs g^{-1} s^{-1}, and M_{Ni} is the mass of the Ni^{56} at t = 0. A characteristic time is

$$\tau_m \equiv \sqrt{2\tau_d \tau_h} \equiv \text{Risetime} \sim 10d$$

Here,

$$x = \frac{t}{\tau_m} \quad y = \frac{\tau_m}{2\tau_{Ni}} \quad \text{and} \quad xy = t/2\tau_{Ni},$$

and τ_d and τ_h are the diffusion time and the .hydrodynamic time at t = 0 (i.e., when the shock hits the surface of the presupernova star).

At the peak, SN 1993J had,

$$L_{peak} \sim 1{\cdot}6 \times 10^{42} \text{ erg s}^{-1}$$

Since $\tau_m \sim$ 10.5; τ_{Ni} = 8.8d, using the peak for Λ from the graph for $y \gtrsim 1/2$ (Arnett 1982), we get

$$M_{Ni^{56}} = 0{\cdot}05 \ M_\odot.$$

In comparison, SN1987A was powered in the radioactive phase by 0.07 $M_\odot$ of $Co^{56}(Ni^{56})$.

In summary, we have presented a bolometric light curve of SN1993J based on available photometric data. We interpret it on the basis of simple physical ideas and using scaling laws in comparison with one of the best studied examples of SNe viz., SN 1987A. This simple technique gives a fairly good estimate of many useful properties of the progenitor of SN1993J which can be further refined by using detailed stellar structure and explosion calculations. The interesting results obtained from this preliminary study are—

- The progenitor of SN1993J had a very small amount of hydrogen envelope at the time of explosion,
- Its light curve is powered by ~ 0.05 $M_\odot$ of Ni^{56}.

The small hydrogen envelope can be explained if the progenitor was in a binary system and lost most of its mass due to Roche lobe overflow. It also implies that SN 1993J is transforming from a type II SN in the early days to more like type Ib SN at present which seems to be supported independently by spectroscopic evidence (Filippenko & Matheson 1993). Results of this paper were also presented at the IAU Colloquium No. 145 on “Supernovae and Supernova Remnants”, May 2429, 1993 at Xian, China (Ray, Singh and Sutaria 1993).

Acknowledgements

We are thankful to S. Unger, Z.-Y. Zheng, N. M. Shakhovskoy, Yu. Efimov, A. Filippenko, M. Richmond and all their collaborators for providing their photometry data prior to publication.

In case of data published in IAU circulars that have been subsequently revised, we have taken the revised version as reported in the periodic photometric updates managed byA. Filippenko, T. Kato and R. Wijersupto nearly the date, of submission.

After the paper was accepted by the editors we received revised, calibrated data from the 30 inch telescope of Leuschner Observatory, University of California, Berkeley (A. Filippenko *et al).* The points marked "Richmond" in Figures 2 to 4 (a and b) make use of the revised, calibrated data.

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