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Letter to the Editor

Type IIb supernova 1993J in M81: the explosion of a ~4M$_\odot$ star in a close binary system

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Abstract. A study of the recently discovered Type IIb supernova 1993J in the galaxy M81 indicates that the mass of the ejected envelope was $\sim$ 2.4 M$_\odot$ including a hydrogen mass of $\sim$ 0.75 M$_\odot$, the explosion energy was $\sim$ 1.6 10^{51} ergs, and the mass of radioactive ^{56}Ni nuclides was $\sim$ 0.06 M$_\odot$. In our model, the outburst of supernova 1993J is interpreted as the explosion of a $\sim$ 4 M$_\odot$ red supergiant undergoing core collapse and leaving a neutron star in a binary system. The progenitor is supposed to have a helium core mass of $\sim$ 3 M$_\odot$ corresponding to a $\sim$ 12 M$_\odot$ main-sequence star. Supernova 1993J reveals physical similarities with Type II-P supernova 1987A and adds evidence to the scenario that Type Ib supernovae originate from moderately massive stars on the main sequence which have lost their hydrogen envelopes in interacting binary systems.

Key words: supernovae : supernova 1993J

1. Introduction

Supernova (SN) 1993J in the galaxy M81 (NGC 3031) was discovered at a very early epoch in its evolution (Garcia 1993a). Soon after its discovery it was classified as a Type II supernova (SN II) (Filippenko 1993a; Garnavich & Ann 1993). Further extensive photometric observations revealed an unprecedented visual light curve with two distinct maxima (see IAU Circulars). The very early radio observations (Weiler et al. 1993; Pooley & Green 1993) and the x-ray emission discovered somewhat later (Zimmermann et al. 1993; Tanaka 1993) are distinguishing features of SN 1993J. It was clear immediately that SN 1993J is quite different from the classical variety of Type II supernovae (SNe II) in these fundamental aspects. Moreover, spectra of SN 1993J show the onset of a remarkable transformation from the characteristics of SNe II to those of SNe Ib and therefore allow Filippenko et al. (1993) to call SN 1993J a "SN IIb". The comprehensive observational data of SN 1993J may provide significant clues to the presupernova stellar evolution and the physics of the supernova explosion as will be discussed in this paper.

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Since the occurrence of SN 1987A supernova research has been experiencing a second boost. Several groups were prepared to compute light curves and synthetic spectra when SN 1993J was discovered. By day 50 Bartunov et al. (1993), Höflich et al. (1993), Podsiadlowski et al. (1993), Shigeyama et al. (1993), Utrobin (1993b), and Woosley (1993) were able to represent hydrodynamic models of this event. A general characteristic of these models is the relatively low hydrogen mass of the expelled envelope. This implies that very likely the progenitor of SN 1993J has lost most of its hydrogen-rich envelope prior to the explosion. Based on observational data alone Schmidt et al. (1993) reached the same conclusion. Höflich et al. (1993) modelled the progenitor by a cool massive single star with an initial mass of $\sim 25 - 30$ M$_\odot$ on the main sequence which lost a major fraction of its hydrogen envelope through a stellar wind. Podsiadlowski et al. (1993), Shigeyama et al. (1993), Utrobin (1993b), and Woosley (1993) in contrast reached conclusions that SN 1993J is produced by a star with an initial main-sequence mass in the range of $\sim 12 - 15$ M$_\odot$ which lost most of its hydrogen-rich envelope during a close binary evolutional phase. Similarly, Filippenko et al. (1993) argued that the progenitor of SN 1993J was probably a massive star with the initial mass of $\sim 10 - 20$ M$_\odot$ that transferred most of its hydrogen envelope to a physically bound companion.

In this letter we present a hydrodynamic study of SN 1993J, the main aim being to reproduce the visual light curve with two distinct maxima. The input physics, hydrodynamic model, a comparison with the available observational data on SN 1993J, and the nature of its progenitor are described in Sect. 2. Section 3 contains a discussion of the obtained results and the physical relation between SNe Ib, SNe IIb, and SNe II-P.

2. Observations of SN 1993J and hydrodynamic model

In order to compare calculated light curves with the observed ones, we adopt a distance modulus of $27^m\!.6$ to M81 (Freedman & Madore 1988). No reddening conditions are taken into account because of their uncertainties (see e.g., Wamsteker et al. 1993;

Richmond 1993). Note that theoretical light curves might be easily adjusted to reddening of a few tenths of a magnitude.

The input physics in hydrodynamic model discussed below is the same as in the work of Utrobin (1993a), in addition taking into account negative hydrogen ions and line blocking effects in the expanding envelope (Karp et al. 1977). The composition is assumed to be a mixture of hydrogen, helium, and an "average" heavy element. Their Rosseland mean opacity is evaluated in the hydrogenic approximation, allowing for Thomson scattering by free electrons. The contribution of the negative hydrogen ion to the opacity is calculated according to Doughty & Fraser (1966). The expansion opacity is treated as an additive opacity for the "average" heavy element. The enhancement of the opacity due to line blocking effects becomes significant as temperature decreases (Müller & Höflich 1991). For the model discussed below, for example at day $\sim$ 40, the inner layers of the expanding envelope are characterized by a density of $\sim 3\ 10^{-14}$ g cm^{-3}, a temperature of $\sim 5\ 10^3$ K, and an expansion parameter, which is equal to the reciprocal of the relative Doppler shift of a photon between electron scatterings, of $\sim 10^3$. It results in an expansion opacity of ~ 0.04 cm^2 g^{-1}(Müller & Höflich 1991). Therefore, in the inner layers an additive opacity of heavy elements of 0.04 cm^2 g^{-1}is adopted. Note that the inner layers contain more heavy elements (Fig. 4) than the solar mixture depleted in hydrogen used by Müller & Höflich (1991) so that the adopted value is quite reasonable. An investigation of SN 1993J has been carried out similar to that of SN 1987A (Utrobin 1993a). A central core of 1.4 $M_\odot$ in the initial model is assumed to stay behind as a neutron star and the rest of the outer envelope is ejected by the explosion. The explosion of the star is assumed to be triggered by an instantaneous energy release near the edge of the central core at epoch zero. In addition, energy is deposited by the γ-rays released in the subsequent decays of radioactive ^{56}Ni and ^{56}Co . The γ-ray energy deposition is calculated in the approximation suggested by Sutherland & Wheeler (1984) with an effective γ-ray absorption opacity of 0.03 cm^2 g^{-1}.

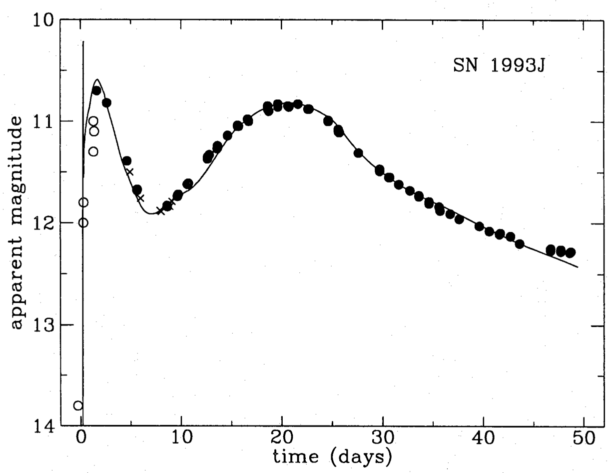

Fig. 1. Theoretical and observed visual light curves of SN 1993J for the first 50 days. Open circles are the visual and unfiltered CCD observations of Neely (1993), Garcia (1993a,b), Rodriguez (1993), and Pujol (1993). Crosses are the V observations of Kato (1993) and solid circles are those of Filippenko (1993c)

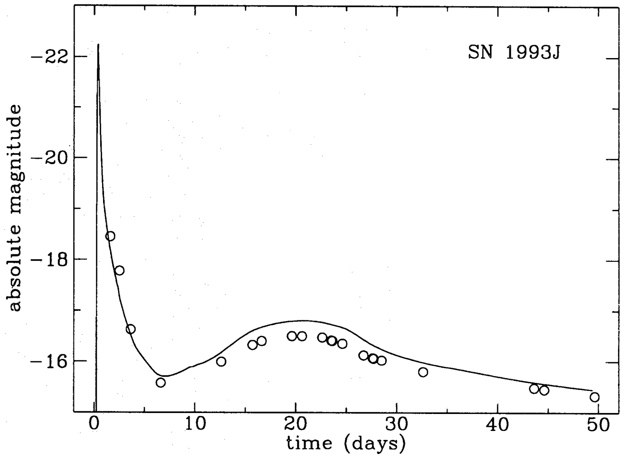

Fig. 2. Comparison of the theoretical light curve with the bolometric light curve of SN 1993J estimated by Schmidt et al. (1993) and reduced to an extinction of $A_V=0^m_.0$ (open circles)

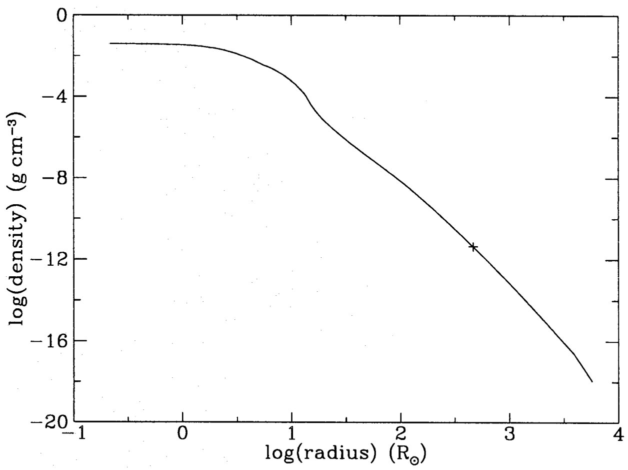

Fig. 3. Density profile with respect to radius for the presupernova model. The central core of 1.4 $M_\odot$ is omitted. The cross indicates the position of the photosphere

A good agreement between the hydrodynamic model and the available observational data on SN 1993J (Figs. 1 and 2) leads us to conclude that its progenitor had a photospheric radius of $\sim 460\ R_\odot$, the mass of ejected envelope was around 2.4 $M_\odot$, and that the explosion energy was near 1.6 10^{51} ergs. To obtain the visual light curve with two distinct maxima (Fig. 1), we need a progenitor model with a relatively dense core within a radius of $\sim 20\ R_\odot$ and its outer layers with a mass of $\sim 0.1\ M_\odot$

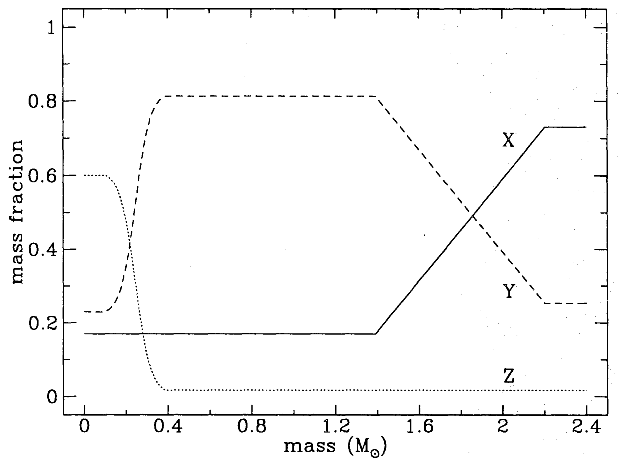

Fig. 4. The mass fraction of hydrogen (X), helium (Y), and heavy elements (Z) in the ejected envelope. The total mass of hydrogen, helium, and heavy elements in the ejecta is 0.75 $M_\odot$, 1.47 $M_\odot$, and 0.18 $M_\odot$, respectively

having a density profile close to that of a n = 4.95 polytrope out to the radius of 6400 $R_\odot$ (Fig. 3). The first visual peak is emitted by these outer layers after a strong shock wave has propagated through the envelope and has heated it (Figs. 1 and 2). The second visual peak is powered by the radioactive decay of ^{56}Ni and ^{56}Co nuclides. Good fits can be obtained if the bulk of the radioactive material is confined to the innermost layers of ejected envelope and if the mass of radioactive nuclides is $\sim$ 0.055 $M_\odot$. In addition, a shell with a positive gradient of hydrogen abundance and a negative gradient of helium is necessary to reproduce the smooth second peak of the observed visual light curve and hydrogen has to be mixed into the inner layers of the envelope (Fig. 4).

We conclude this section with some further remarks on the nature of the progenitor of SN 1993J. According to Filippenko (1993b) and Humphreys et al. (1993), a star-like object identified at the progenitor position had characteristics of a red supergiant. The presupernova model is consistent with this red supergiant. Note that the outer extended shell with relative low density in the presupernova model (Fig. 3) might be produced by a superwind during a few last years just before the supernova outburst.

A low amount of $\sim$ 0.2 $M_\odot$ of heavy elements in the ejected envelope (Fig. 4) may be considered as evidence that a neutron star is left behind. The ejected envelope of 2.4 $M_\odot$ and a neutron star of 1.4 $M_\odot$ correspond to a 3.8 $M_\odot$ progenitor. The helium core of $\sim$ 3 $M_\odot$ in the presupernova model (Fig. 4) presumably stems from a $\sim$ 12 $M_\odot$ main-sequence star (Woosley & Weaver 1986a). So the progenitor must have lost most of its hydrogen-rich envelope prior to the explosion either by stellar winds or by binary mass transfer.

Stars of $\sim$ 12 $M_\odot$ are thought to have too low mass loss to lose their hydrogen envelope before core collapse without the mass transfer. Modern standard evolution of a single moderately massive star with an initial mass of 15 $M_\odot$ results in a hydrogen-rich star of $\sim$ 12.8 $M_\odot$ at the time of carbon exhaustion in the center (Maeder 1987). On the other hand, in a close binary system, the primary component with the initial mass of 12 $M_\odot$ evolves to a hydrogen-poor star of $\sim$ 3 $M_\odot$ at the end of helium burning in the core (de Loore & De Greve 1992). Thus, most probably the progenitor has been a member of interacting binary system. A binary system is known to remain bound after a supernova explosion when a mass ejected in the explosion is less than a half of the total mass of the system. In the case of SN 1993J, this implies a companion star more massive than the Sun and it is more than likely. Hence, the system is definitely to become a binary system involving a neutron star.

3. Discussion and conclusions

To reproduce the first very sharp peak and the second smooth peak of the visual light curve observed (Fig. 1), hydrogen should be of cosmic abundance near the surface and should be mixed down in mass but with decreasing mass fraction (Fig. 4). Such a deep mixing of hydrogen is not unprecedented. For example, in the late spectra of SN 1987A there was evidence for mixing of hydrogen down to a velocity of $\sim$ 600 km s^{-1}(Chugai 1991). It should be emphasized that the use of more realistic expansion opacities may decrease the hydrogen content in the inner region and could increase the mass fraction of heavy elements.

It is striking that the low mass of $\sim$ 0.2 $M_\odot$ of heavy elements in the ejecta (Fig. 4) is in a good agreement with presupernova models of stars with a helium core mass of $\sim$ 3 $M_\odot$ (Woosley & Weaver 1986b; Nomoto & Hashimoto 1988). This fact is of great importance, and more observational evidence is needed to confirm it. From this point of view the two Type IIb SN 1987K and SN 1993J are worth to consider. Schlegel & Kirshner (1989) found that the oxygen mass of SN 1987K appeared to be $\sim$ 0.3 $M_\odot$ and that layers of oxygen expanded with a characteristic velocity of 6300 $\pm$ 490 km s^{-1}. Our model of SN 1993J implies that the oxygen mass is at most $\sim$ 0.2 $M_\odot$ and that oxygen-rich layers expand with velocities less than $\sim$ 4600 km s^{-1}. Thus, the model discussed here suggests that the oxygen mass in SN 1993J is less than that in SN 1987K and that oxygen-rich layers in SN 1993J expand with velocities less than those in SN 1987K. Following the prediction of Filippenko et al. (1993), we add that strong and broad emission lines of [O I] but probably somewhat weaker and narrower than in SN 1987K will dominate the spectrum of SN 1993J at late times. Moreover, Hα line will be weak or absent.

It should be noted that in the present model of SN 1993J the bulk of the radioactive material is confined to the inner layers of ejected envelope expanding with velocities less than $\sim$ 2600 km s^{-1}. This is consistent with an expansion velocity of 2500 $\pm$ 1000 km s^{-1}derived from infrared observations of iron emission lines at 1.6 μm in Type Ib SN 1983N (Graham et al. 1986).

Our hydrodynamic model of SN 1993J indicates that most likely it was a core collapse supernova rather than a thermonuclear explosion. Unfortunately, the modern theory of core collapse and bounce of $8-15\ M_\odot$ main-sequence stars remains controversial and no satisfactory concrete mechanism has been proposed so far (Woosley & Weaver 1986a; Hillebrandt 1991). So SN 1993J and the well-studied Type II-P SN 1987A should be compared. First, the explosion energy of $\sim 1.6\ 10^{51}$ ergs is roughly equal to that of SN 1987A (Woosley 1988; Shigeyama & Nomoto 1990; Utrobin 1993a). Second, the mass of radioactive ^{56}Ni is close to that of SN 1987A (see e.g., Bouchet et al. 1991). Note that no reddening was included in the model discussed implying that the radioactive ^{56}Ni mass in the ejecta of SN 1993J could be somewhat higher than $0.055\ M_\odot$. For example, an extinction of $A_V=0\overset{m}{.}4$ would result in a mass of radioactive ^{56}Ni of $\sim 0.06\ M_\odot$ (Schmidt et al. 1993). Thus, there are strong arguments in favor of a fundamental similarity between the explosions of SNe IIb and SNe II-P.

A characteristic transformation of SN 1987K as well as of SN 1993J from spectra of SNe II to those of SNe Ib suggests that SNe IIb are genetically related to SNe Ib (Filippenko 1988; Filippenko et al. 1993). Wheeler & Levreault (1985) defining a new subclass of SNe Ib concluded that SNe Ib, similar to SNe II, come from core collapse in moderately massive stars which, in contrast to SNe II, lost their hydrogen envelopes due to strong stellar winds or binary mass transfer and which had masses as low as $3\ M_\odot$ at the time of the explosion. According to Ensman & Woosley (1991), the majority of SNe Ib result from hydrogen-stripped stars of $4-7\ M_\odot$ undergoing mass transfer in interacting binary systems. Shigeyama et al. (1990) argued that SNe Ib and typical SNe II-P originate from a similar mass range on the main sequence and that the progenitors of SNe Ib in contrast to those of SNe II are most probably helium stars of $3-4\ M_\odot$ which are produced by the moderately massive stars in binary systems. The results of our investigation of SN 1993J are consistent with the above hypothesis for the origin of SNe Ib and hence strengthens it. Moreover, a physical similarity of SNe Ib, SNe IIb, and SNe II-P becomes more evident now.

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References

Bartunov O.S., Blinnikov S.I., Pavlyuk N.N., Tsvetkov D.Yu., 1993, A&A (submitted)
Bouchet P., Danziger I.J., Lucy L.B., 1991. In: Danziger I.J., Kjär K. (eds.) Proc. ESO/EIPC Workshop, Supernova 1987A and other supernovae. ESO, Garching, p. 281
Chugai N.N., 1991, SvA 35, 171
de Loore C., De Greve J.P., 1992, A&AS 94, 453
Doughty N.A., Fraser P.A., 1966, MNRAS 132, 267
Ensman L., Woosley S.E., 1991. In: Woosley S.E. (ed.) The tenth Santa Cruz Workshop, Supernovae. Springer-Verlag, New York, p. 556
Filippenko A.V., 1988, AJ 96, 1941
Filippenko A.V., 1993a, IAU Circ. 5731
Filippenko A.V., 1993b, IAU Circ. 5737
Filippenko A.V., 1993c, private communication
Filippenko A.V., Matheson T., Ho L.C., 1993, ApJ (submitted)
Freedman W.L., Madore B.F., 1988, ApJ 332, L63
Garcia F., 1993a, IAU Circ. 5731
Garcia F., 1993b, IAU Circ. 5733
Garnavich P., Ann H.B., 1993, IAU Circ. 5731
Graham J.R., Meikle W.P.S., Allen D.A., Longmore A.J., Williams P.M., 1986, MNRAS 218, 93
Hillebrandt W., 1991. In: Danziger I.J., Kjär K. (eds.) Proc. ESO/EIPC Workshop, Supernova 1987A and other supernovae. ESO, Garching, p. 55
Höflich P., Langer N., Duschinger M., 1993, A&A (submitted)
Humphreys R.M., Aldering G.S., Bryja C.O., Thurmes P.M., 1993, IAU Circ. 5739
Karp A.H., Lasher G., Chan K.L., Salpeter E.E., 1977, ApJ 214, 161
Kato T., 1993, IAU Circs. 5747, 5750, 5755
Maeder A., 1987, A&A 173, 247
Müller E., Höflich P., 1991. supernovae. In: Danziger I.J., Kjär K. (eds.) Proc. ESO/EIPC Workshop, Supernova 1987A and other supernovae. ESO, Garching, p. 379
Neely A., 1993, IAU Circ. 5740
Nomoto K., Hashimoto M., 1988, Phys. Rep. 163, 13
Podsiadlowski Ph., Hsu J.J.L., Joss P.C., Ross R.R., 1993, Nat (submitted)
Pooley G.G., Green D.A., 1993, IAU Circ. 5751
Pujol P., 1993, IAU Circ. 5731
Rodriguez D., 1993, IAU Circ. 5731
Richmond M., 1993, IAU Circ. 5739
Schlegel E.M., Kirshner R.P., 1989, AJ 98, 577
Schmidt B.P., Kirshner R.P., Eastman R.G., et al. , 1993, Nat (submitted)
Shigeyama T., Nomoto K., 1990, ApJ 360,242
Shigeyama T., Nomoto K., Tsujimoto T., Hashimoto M., 1990, ApJ 361, L23
Shigeyama T., Suzuki T., Kumagai S., et al. , 1993, ApJ (submitted)
Sutherland P.G., Wheeler J.C., 1984, ApJ 280, 282
Tanaka Y., 1993, IAU Circ. 5753
Utrobin V., 1993a, A&A 270, 249
Utrobin V., 1993b, Proc. IAU Coll. 145, Supernovae and supernova remnants (submitted)
Wamsteker W., Rodriguez P.M., Gonzalez R., Sonneborn G., Kirshner R., 1993, IAU Circ. 5738
Weiler K.W., Smarek R.A., Van Dyk S.D., Panagia N., 1993, IAU Circ. 5752
Wheeler J.C., Levreault R., 1985, ApJ 294, L17
Woosley S.E., 1988, ApJ 330, 218
Woosley S.E., 1993, Proc. IAU Coll. 145, Supernovae and supernova remnants (submitted)
Woosley S.E., Weaver T.A., 1986a, ARA&A 24, 205
Woosley S.E., Weaver T.A., 1986b. In: Audouze J., Mathieu N. (eds.) Proc. NATO Workshop, Nucleosynthesis and its implications on nuclear and particle physics. Reidel, Dordrecht, p. 145
Zimmermann H.U., Lewin W., Magnier E., et al. , 1993, IAU Circ. 5750

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