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SN 1993J in M 81: Photometry and Spectrophotometry

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Abstract. CCD photometric and spectrophotometric observations of the peculiar type IIb supernova 1993J in M 81 (NGC 3031) were made from Vainu Bappu Observatory, Kavalur during the first two months since the outburst of the supernova. The spectroscopic evolution was similar to other type II supernovae during the early phases, but lines of helium strengthened later indicating that the supernova was turning into type Ib like SN1987K. The lines due to Ba II and Sc II were weaker than in SN 1987A appeared together with lines of helium indicating that there was no significant mixing in the hydrogen envelope. We use the absorption velocities together with photometric radii to make an estimate of the distance to M 81 using the Baade-Wesselink (expanding photosphere) method.

Key words: Supernovae: spectra—supernovae: photometry—supernovae: distances—supernovae: SN 1993J—galaxies: M 81 (NGC 3031).

1. Introduction

Spectrophotometry in the ultraviolet, optical and infrared bands of radiation constitutes the most important data on supernova (SN) outbursts since most of radiation is emitted in these bands around the time of maximum. The classification of supernovae has also been based canonically on optical spectroscopic information. While the basic classification scheme of type I (without the lines due to hydrogen) and type II (showing hydrogen lines in emission) has survived over several decades since Zwicky's initial suggestion, deviants from this scheme are becoming apparent during the last decade. SN 1983N in M 83 (NGC 5236), type I according to the above definition, did not show the dip at 6150 Å attributed to blue-shifted absorption of Si II which was seen in all type I supernovae till then. Instead, it showed lines of helium (Richter & Sadler 1983; Prabhu 1985). This class of SN is growing in number and has now been termed type Ib. Type Ic has also been identified with the SN that shows lines due to oxygen instead of silicon. The early expectations on the homogeneity of type I SN have been growing thin even in the case of their light curves (Branch 1981), a fact that casts aspersions on their utility as distance candles.

Type II SN light curves have been classified into plateau-type (P) and linear-type (L). Though this class was never considered to be a homogeneous one, the subluminous type II SN 1987A in LMC with very large initial expansion velocity and a secondary maximum in the light curve, and SN 1987K which turned from type II near maximum to type Ib at late times, have shown the diversity of phenomena that can take place in SN II (Harkness & Wheeler 1990; Filippenko 1991). It is thus important to study individual SN in detail in order to understand the physical phenomena involved. The discovery of SN 1993J in a nearby M 81 by F. Garcia (Ripero 1993) on March 28, 1993 provided such an opportunity since it reached a maximum brightness of $V \sim 10$. Though the SN started as type II, as time progressed it became evident that it was peculiar with a good resemblance to SN 1987K. We will call this a type IIb SN following Woosley, Pinto & Ensman (1988).

We present here a brief report on the results on SN 1993J based on observations obtained with the 1-m and 2.3-m telescopes at the Vainu Bappu Observatory (VBO), Kavalur. The detailed results will be published elsewhere.

2. Photometry

CCD images of the region around SN 1993J were obtained on a total of 11 nights between April 14 and May 23, 1993 at the prime focus of the 2.3-m Vainu Bappu telescope, generally in *BVR* bands and on two nights also through *I* band. The photometry was carried out differentially with respect to star B (Corwin 1993) as the comparison star and star A as the check star. The colour corrections were made using the transformation equations of Anupama *et al.* (1993). The corrections needed were negligible during the early days when the colours of SN were similar to those of star B, but became very significant as the SN became progressively redder. The results are plotted in Fig. 1 together with other magnitudes available through the nova network (T. Kato, personal communication) and IAU Circulars.

Based on pre-discovery and subsequent observations available in the literature we adopt the date of outburst as March 28, 1993. The initial rise was followed by a sharp drop to $V = 11.9$ on April 5. The SN then brightened slowly to $V = 10.8$ till April 18 and declined thereafter. This behaviour resembles the light curve of SN 1987A though the latter was about 1.4 mag fainter in absolute brightness in *V* band, and reached the

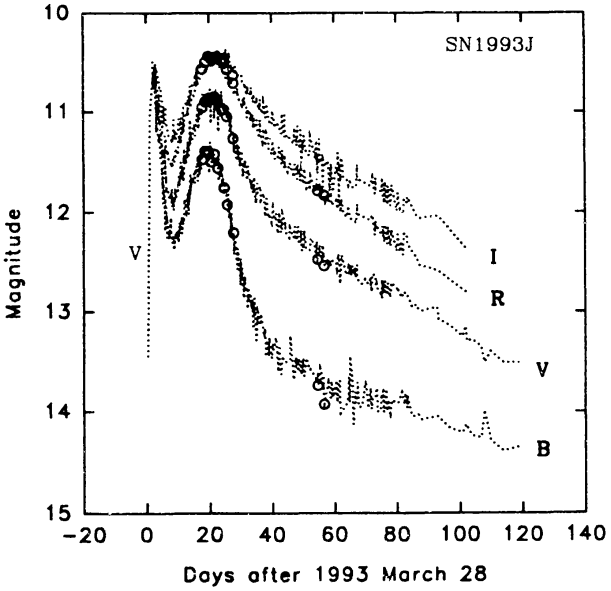

Figure 1. The light curves of SN 1993J in *BVRI* bands. The dotted lines denote the observations from other sources available through the nova network and IAU Circulars. VBO observations are shown by open circles.

second peak ~ 90 days since the outburst compared to only ~ 20 days in the case of SN 1993J. The models of SN outburst constructed soon after the outburst of SN 1987A (cf., Woosley 1991) qualitatively explain such light curves and require a low-mass hydrogen envelope (Ray, Singh & Sutaria 1993). The SN according to this model brightens quickly due to the deposition of the shock energy. This is followed by a sharp drop as the expanding envelope cools adiabatically. When the temperature drops sufficiently to allow recombination of hydrogen the luminosity rises slowly and steadily to the secondary maximum due to the recombination radiation as well as due to the release of trapped radioactive energy of newly synthesized ^{56}Ni and its daughter ^{56}Co. The recombination front moves continuously inward until it hits the base of the envelope. The final decline is characterized by the decay of ^{56}Co. It remains to be verified whether several other SN also have a similar light curve with the first maximum and rapid decline missed by observational selection (Woosley 1991).

3. Spectrophotometry

CCD spectrophotometric observations were carried out mostly with the 1-m Zeiss reflector, and in the early phase also with the 2.3-m VBT. The dispersions employed were about 5 Å per pixel. Observations were obtained altogether on 16 nights between April 1 and May 18, 1993. Feige 34 was used as spectrophotometric standard and star B as comparison. The reductions were carried out using the RESPECT package at VBO (Prabhu & Anupama 1991).

The spectra on April 13, 14, May 17, 18 are shown in Fig. 2. These were the epochs when the best wavelength coverage could be obtained. The most prominent lines at the first epoch are, Hα, He Iλ5876 + Na I D, and several lines of Fe II ($\lambda\lambda$4568, 4924, 5018,

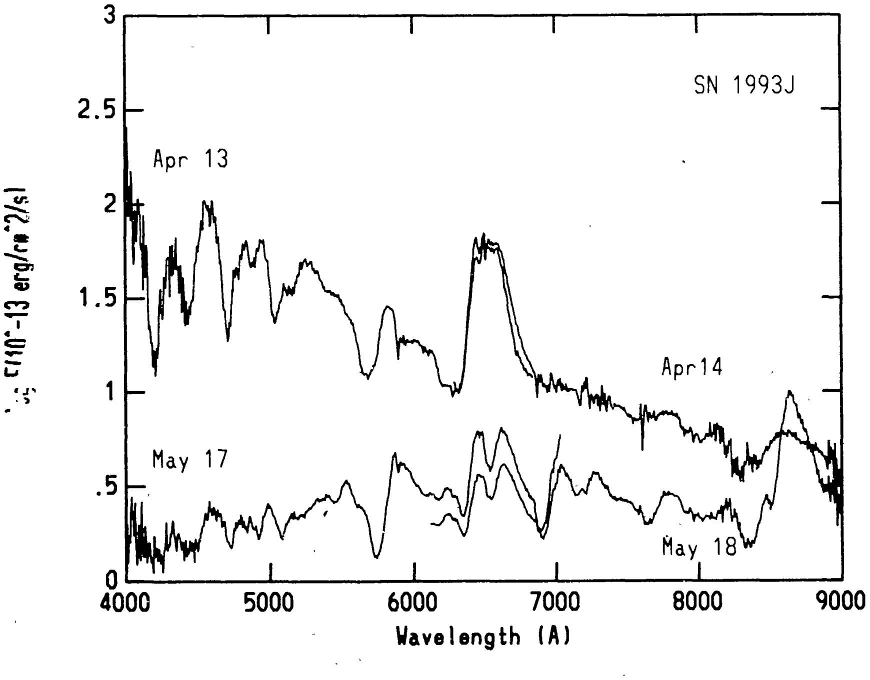

Figure 2. Spectra of SN 1993J on 1993 April 13, 14, and May 17, 18.

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the last two blended with Hβ; λ5169 blended with Mg I λ5183; 5276, 5284, 5317, 5363 blended with each other). At the later epoch, the Hα line showed distinctly double structure. The emergence of He I λ7065 and strengthening of He I λ5876 imply that the structure in Hα is due to the superposition of the P-Cygni profile of He I λ6678. The features near $\lambda\lambda$4925, 5015 should hence be identified with He I rather than Fe II at this stage. The lines O I λ7774 as well as Ca II infrared triplet are much stronger at the later phase. The emission at λ5535 is very likely due to [O I] λ5577. This transition has a higher value of critical density and is generally present at relatively higher density diffuse matter. The blue shift of the centre of this line is suggestive of asymmetries in the envelope. The absorptions due to Ba II λ6141 and Sc II λ6245 are evident clearly on May 17 at $\lambda\lambda$6078, 6170. These dips can be traced back with some difficulty till April 19. The s-process elements like Ba and Sc are expected in the helium layer and not in the H + He envelope. Their strength in the spectra of SN 1987A indicated mixing of the envelope matter with inner layers (see Dopita 1988). The emergence of these lines in SN 1993J during the phase when lines of helium strengthened imply that there was no extensive mixing.

4. Spectroscopic distance to the supernova

The temperature and angular radius of the photosphere can be estimated from a black-body fit to the observed magnitudes (e.g. Ray, Singh & Sutaria 1993) or by comparing the colours with a supergiant (Ashoka *et al.* 1987). The absorption velocities due to lines formed near the photosphere give us the rate of change of photospheric radius in absolute units. A comparison of the spectroscopically determined radius with the observed angular radius gives us an estimate of the distance to the supernova.

Two sources of systematic error in such an estimate are known (Schmidt-Kaler 1991). First, the geometry of the photosphere need not be spherical as assumed. Spectropolarimetry of SN 1993J by Trammell, Hines & Wheeler (1993) is indicative of departure from spherical symmetry though both prolate and oblate models can explain the asymmetry. Depending on whether the actual geometry is prolate or oblate, Schmidt-Kaler (1991) had estimated in the case of SN 1987A that the derived distance needs to be multiplied by 1.05 or 0.95. The continuum polarization is higher for SN 1993J compared to SN 1987A and hence the correction factor would probably depart from unity by a larger amount.

Secondly the photosphere may not behave as a blackbody. The model calculations for SN 1987A indicated that the photosphere was grey and a correction factor of 0.95 needed to be applied to the derived distance during the secondary maximum (Schmidt-Kaler 1991). A similar correction factor may be applicable in the case of SN 1993J during the secondary maximum.

The velocities of absorption dips yield expansion velocities of the envelope. The velocities derived from different lines in SN 1993J show a similar trend as observed in SN 1987A (Ashoka *et al.* 1987). The Hα yields the highest velocity indicating that it is formed well above the photosphere. The weak lines like Fe II $\lambda\lambda$4568, 4924, 5018, 5176, 5300 yield the lowest velocities and are probably formed close to the photosphere. The velocities decrease as the photosphere recedes with respect to the matter. The decrease is sharp in the case of the weakest lines particularly after April 23 when the photosphere has probably reached the bottom of the H + He envelope. We will use velocities derived from the weak lines till April 23 as indicative of photospheric velocities.

Counting time from March 28, the probable date of explosion, the observed velocities of Fe II lines between days 11 and 26 can be approximated by the parabola

$$V_{\exp}(t_d) = 9260 - 4.668t_d^2,$$

where $V_{\exp}$ is in km s^{-1} and t_d is time since explosion in days. The angular radius of the photosphere should then vary as

$$\theta = \theta_0 + D^{-1} \int V_{\exp}(t)\mathrm{d}t.$$

Using the estimates of angular size based on *UBVRIJHK* photometry (Ray, Singh & Sutaria 1993), we obtain from a least-squares fit to the above equation, a distance of 4.2 ± 0.2 Mpc to the supernova. The best current estimate of the distance to M 81 is 3.6 ± 0.3 based on the photometry of Cepheids using the Hubble Space Telescope (Freedman *et al.* 1993). A correction factor of 0.9 for possible oblateness and 0.95 for grey atmosphere would make the two distances agree exactly.

The accuracy of the expanding photosphere method does not depend on the distance at all. Hence, we conclude that even ignoring the effect of asymmetric explosion and grey atmosphere, it is possible to estimate distances to supernovae to an accuracy of 15–20%.

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