

## INTERPRETATION OF THE EARLY SPECTRA OF SN 1993J IN M81

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### ABSTRACT

We present optical spectra obtained on 1993 April 7 and April 13 of the bright supernova SN 1993J in the nearby galaxy M81. The spectra show strong hydrogen Balmer lines with pronounced P Cygni profiles, except for H $\alpha$ , which is greatly dominated by emission. In order to obtain diagnostics on the velocities, temperatures, densities, and composition of the atmosphere, we present non-local thermodynamic equilibrium (NLTE) synthetic spectrum fits to these observations. For April 7 we find a photospheric velocity of 10,000–11,000 km s<sup>-1</sup>, with a photospheric electron temperature of 7500–8000 K and a radius of 10<sup>15</sup> cm. On April 13 the photospheric velocity is about 11,000 km s<sup>-1</sup>, the photospheric temperature is about 6500 K, and the radius is  $\approx 1.6 \times 10^{15}$  cm. Most of the features of the spectra are well fitted by model atmospheres with solar composition. We find a distance for SN 1993J of  $4.0 \pm 0.5$  Mpc and the explosion epoch to be UT 1993 March  $27.5 \pm 0.5$ .

*Subject headings:* supernovae: individual (SN 1993J)

### 1. INTRODUCTION

The bright supernova in M81, SN 1993J, is a peculiar Type II supernova. The light curve showed a rapid initial rise and decline followed by a secondary maximum and a decline that is less rapid than is typical in Type II–L supernovae (Doggett & Branch 1985). The early detection of SN 1993J at radio and X-ray wavelengths suggests that the shock wave interacted with circumstellar material (Pooley & Green 1993; Van Dyk et al. 1993; Tanaka 1993). Based on later spectra and the behavior of the light curve, several authors have suggested that the progenitor was a member of a close binary system, having lost all but a few tenths of a solar mass of its hydrogen envelope to the companion (Filippenko & Matheson 1993; Nomoto et al. 1993; Podsiadlowski et al. 1993; Schmidt et al. 1993; Swartz et al. 1993; Woosley et al. 1993).

Optical spectra of SN 1993J were obtained with the Perkins 1.8 m telescope of the Ohio Wesleyan and Ohio State Universities at the Lowell Observatory on UT 1993 April 7.2 and with the Lick Observatory 3 m Shane Telescope on UT 1993 April 13.2. These spectra (Figs. 1–3) show strong hydrogen Balmer lines, confirming the classification as Type II, as well as typical Type II features due to Fe II and Ca II. Except for the broad P Cygni feature at 5600 Å and the broad emission feature at 6500 Å, the lines are relatively narrow in comparison with those of other Type II supernovae at a similar epoch. We find that the narrow lines are not due to a low photospheric velocity but rather must be formed in an atmosphere of small extension, implying very steep density profiles.

### 2. ANALYSIS

In order to provide constraints on the explosion models, it is important to analyze the supernova spectrum in detail. We use an approximate lambda iteration (or operator splitting)

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method to solve the spherically symmetric, fully relativistic radiation transport equation to all orders in  $v/c$  including the effects of relativistic Doppler shift, advection, and aberration (Hauschildt 1992a). The NLTE rate equations are solved, self-consistently, for H I, He I, Mg II, and Ca II, using an approximate lambda iteration method (Rybicki & Hummer 1991; Hauschildt 1993; Baron & Hauschildt 1993) simultaneously with the condition of radiative equilibrium in the Lagrangian frame (Hauschildt 1992b). In addition to the NLTE model atoms, the line list of Kurucz (Kurucz 1988, 1991) is used to select the 200,000 strongest lines (out of a total of 2.1 million lines) for the particular conditions being calculated, with the populations assumed to be in LTE, but accounting approximately for line scattering. We construct our model atmospheres assuming that the velocity profile is homologous,  $v \propto r$ , and that the density profile follows either a power law,  $\rho \propto v^{-N}$ , or an exponential falloff  $\rho \propto \exp(-v/v_e)$ , where  $N$  and  $v_e$  are parameters to be determined. We assume that the radius of the photosphere is given by  $R_0 = v_0 t$ , where the subscript zero denotes the photosphere. We take the explosion date to be March 27–28 and assume that the extinction to the supernova is given by  $E(B-V) = 0.1$  mag.

### 3. DISCUSSION

Our best fits were obtained with exponential density profiles and solar abundances, so we concentrate on them. For comparison, in an exponential atmosphere the equivalent power-law index at the photosphere is given by  $N = v_0/v_e$ .

From the blueshifts of the weak Fe II lines  $\lambda\lambda$  5018 and 4924, we obtain a photospheric velocity of  $v_0 = 10,000$ – $11,000$  km s<sup>-1</sup>. From our models, the photospheric temperature is well determined to be  $T_0 = 7500$ – $8000$  K. Figure 1 shows our synthetic spectrum with  $v_0 = 10,500$  km s<sup>-1</sup>,  $R_0 = 10^{15}$  cm,  $T_0 = 7500$  K, and  $v_e = 450$  km s<sup>-1</sup>. The spectrum is also well fitted with the same parameters but a power-law profile with  $N = 25$ . The quality of the fit is lost when  $v_e$  is reduced to 200 km s<sup>-1</sup>. Increasing the velocity  $v_0$  to 12,000 km s<sup>-1</sup> with  $v_e$  reduced to 300 km s<sup>-1</sup> clearly produces too large a blueshift at the photosphere, but provides a reasonable fit to the line widths. Higher

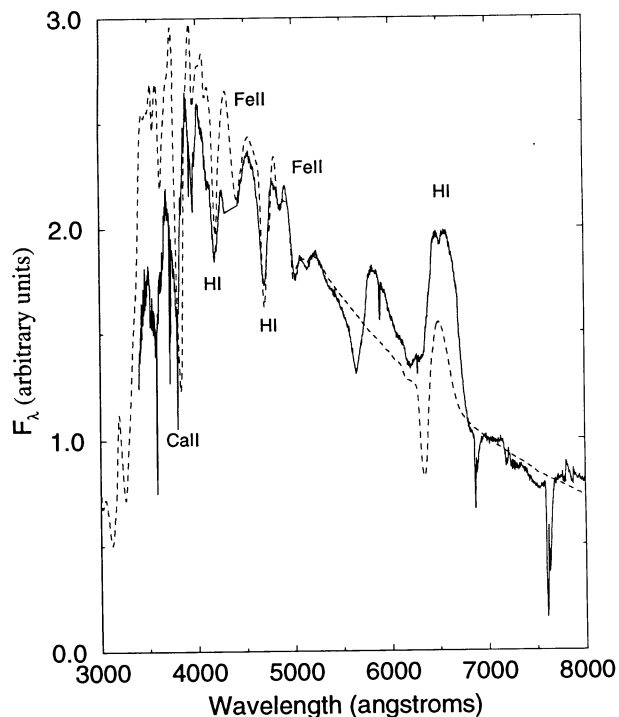


FIG. 1.—Synthetic spectrum (*dashed line*) compared with observed spectrum (*solid line*) of SN 1993J on 1993 April 7. The parameters are  $v_0 = 10,500$  km s $^{-1}$ ,  $R_0 = 10^{15}$  cm,  $T_0 = 7500$  K, and  $v_e = 450$  km s $^{-1}$ . The absorption lines near 6860 and 7600 Å are telluric. A small section of the spectrum is missing near 4300 Å. Note that the flux is plotted on a *linear* scale.

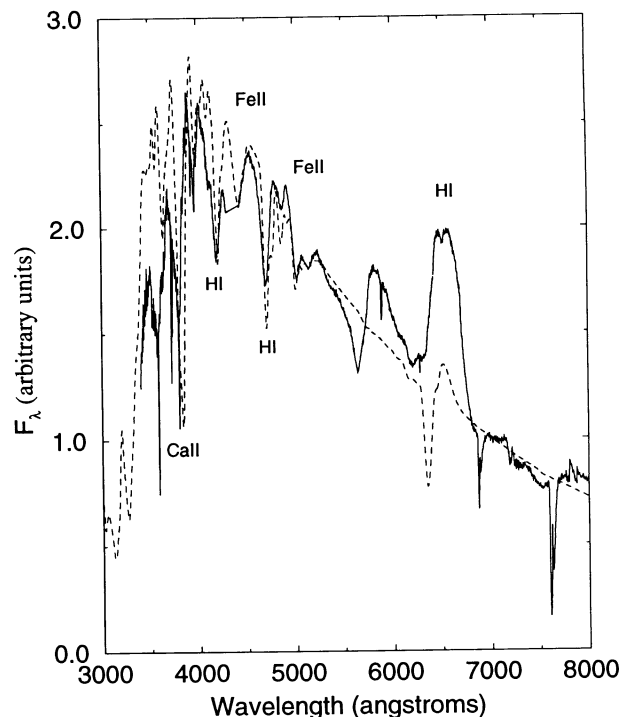


FIG. 2.—Synthetic spectrum (*dashed line*) compared with observed spectrum (*solid line*) of SN 1993J on 1993 April 7. The photospheric temperature is  $T_0 = 8000$  K, and the other parameters are as in Fig. 1.

velocities would produce significantly wider lines than are observed. Figure 2 shows that a good fit can also be found with the same parameters as used in Figure 1, but with the effective temperature increased to  $T_0 = 8000$  K. The quality of the fit is significantly reduced when we lower the effective temperature to  $T_0 = 7000$  K.

Figure 3 displays the April 13 spectrum and a fit using a synthetic spectrum with  $v_0 = 11,000$  km s $^{-1}$ ,  $R_0 = 1.6 \times 10^{15}$  cm,  $T_0 = 6500$  K, and  $v_e = 450$  km s $^{-1}$ . The photospheric velocity has remained nearly constant in time since April 7, which is consistent with the steep density profiles we find. The photospheric temperature has dropped to  $T_0 = 6500$  K. Decreasing  $v_e$  to 300 km s $^{-1}$  also produces a reasonably good fit; however, the Ca II H+K 3950 Å resonance lines become far too strong. Increasing  $v_e$  to 600 km s $^{-1}$  results in a poorer fit. It would seem the density profiles are reasonably well constrained. Raising the temperature to  $T_0 = 7000$  K results in far too much flux below 4000 Å.

The density profiles are extremely steep, with an equivalent power-law index  $N \geq 20$ , especially in comparison with SN 1987A, which had a power-law index  $N = 4$  at the same epoch (Jeffery & Branch 1990). There is no way to obtain the narrow lines in the blue and have significant material at high velocity; thus more extended atmospheres are ruled out. This steep density profile may be indicative of a low-mass extended progenitor, or it may be due to material piling up behind a circumstellar shell. In none of our fits were we able to produce the nearly pure emission that is seen in H $\alpha$ . Since the supernova shows evidence of early circumstellar interaction, and H $\alpha$  formation extends far above the photosphere, it may be that the nearly pure emission profile of H $\alpha$  is due to altered level popu-

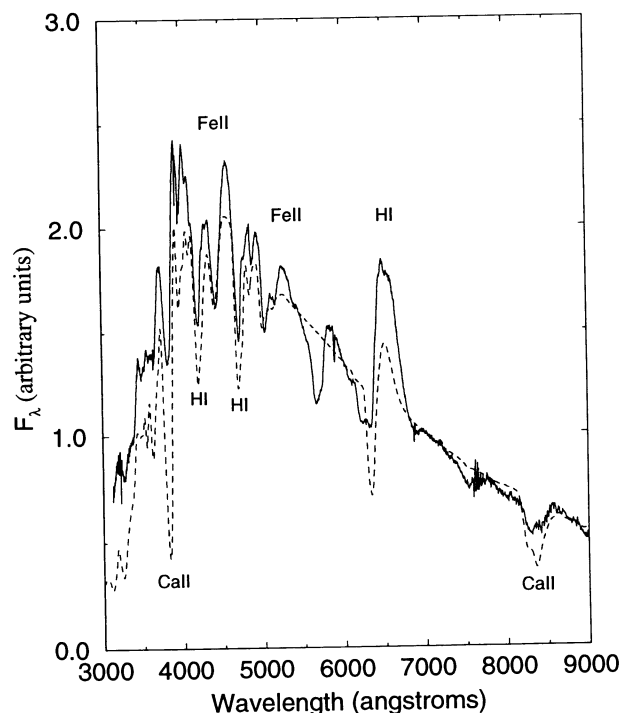


FIG. 3.—Synthetic spectrum (*dashed line*) compared with observed spectrum (*solid line*) of SN 1993J on 1993 April 13. The parameters are  $v_0 = 11,000$  km s $^{-1}$ ,  $R_0 = 1.6 \times 10^{15}$  cm,  $T_0 = 6500$  K, and  $v_e = 450$  km s $^{-1}$ .

lations produced by the radiation impinging on the outer parts of the atmosphere from the circumstellar interaction region. It could also be due to a density structure different from the ones we have used. Although the density profile must be extremely steep around the photosphere in order to fit the observed narrow lines, a flatter density external to the steeply falling profile near the photosphere as seen in the calculations of Shigeyama (Shigeyama 1993) might be able to produce the  $H\alpha$  emission. The velocity structure may also be non-homologous in the outer atmosphere due to circumstellar interaction.

We fail to find a broad feature around 5600 Å that must be the He 5876 Å line and/or the Na I D doublet. With solar composition we predict insignificant helium lines, although nonthermal excitation, either from hard radiation produced by the circumstellar interaction or from Comptonized gamma rays released in the decay of  $^{56}\text{Ni}$ , could produce the helium feature, but it is likely to produce other helium lines as well. We treat sodium only in LTE, but it might be possible for NLTE effects to produce the sodium feature. In later spectra, after about April 26, the  $H\alpha$  emission feature is split by an absorption due to the He 6677 Å line. It may be that at these early times the “ $H\alpha$ ” feature is a blend of  $H\alpha$  and the He 6677 Å line, and the 5600 Å feature a blend of the Na D and He 5876 Å lines.

Reduced hydrogen abundance models do produce helium at roughly the right place, but it is not strong enough. The strength of the hydrogen lines is relatively insensitive to decreasing the hydrogen abundances by as much as a factor of

100, so at present we cannot determine whether the photosphere has receded into the helium-rich layer where some hydrogen has been mixed. We will study nonthermally excited helium in future work.

Since our models predict the absolute emitted flux as well as the shape of the spectrum, by comparing synthetic photometry with observations for these and other spectra we obtain the distance modulus to the supernova,  $(m - M)_0 = 28.0 \pm 0.3$  ( $D = 4.0 \pm 0.5$  Mpc). This distance is slightly larger than, but consistent with, the Cepheid distance  $(m/M)_0 = 27.8 \pm 0.2$  ( $D = 3.6 \pm 0.3$  Mpc) (Freedman et al. 1993; Freedman & Madore 1988). We find that our distance is most consistent with an explosion date of UT 1993 March  $27.5 \pm 0.5$ . Of course, our distance is dependent on the assumed extinction, the assumption of spherical symmetry, and whatever changes are required to fit the  $H\alpha$  and 5600 Å features.

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