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THE PECULIAR TYPE II SUPERNOVA 1993J IN M81: TRANSITION TO THE NEBULAR PHASE

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ABSTRACT

We present optical spectra of the bright, peculiar Type II supernova 1993J in M81 spanning the first 14 months of its existence, revealing its transition to the nebular phase. Unlike the case in normal Type II supernovae, during the first 2–10 months the Hα emission line gradually becomes less prominent relative to other features such as [O I] $\lambda\lambda$6300, 6364 and [Ca II] $\lambda\lambda$7291, 7324, as we had predicted based on early-time ($\tau \lesssim 2$ months) spectra. The nebular spectrum resembles those of the Type Ib/Ic supernovae 1985F and 1987M, although weak Hα emission is easily visible even at late times in SN 1993J. At $\tau = 8$ months a close similarity is found with the spectrum of SN 1987K, the only other Type II supernova known to have undergone such a metamorphosis. The emission lines are considerably broader than those of normal Type II supernovae at comparable phases, consistent with the progenitor having lost a majority of its hydrogen envelope prior to exploding. Consequently, there is now little doubt that Type Ib, and probably Type Ic, supernovae result from core collapse in stripped, massive stars; models of the chemical evolution of galaxies in which these subtypes are ascribed to exploding white dwarfs must be appropriately modified. Although all of the emission lines in spectra of SN 1993J fade roughly exponentially for a considerable time, the fading of Hα begins to slow down at $\tau \approx 8$ months, and in the interval $\tau = 10$–14 months its flux is constant, or even slightly rising in the wings of the line. This behavior, together with the box-like shape and great breadth (full width at half maximum [FWHM]$\approx$17 000 km s^{-1}) of the line profile, suggests that the Hα emission is being produced by the high-velocity outer layer of hydrogen ejecta interacting with circumstellar gas released by the progenitor prior to its explosion. A similar phenomenon has previously been seen at later phases in several Type II supernovae, most notably SN 1980K. Bumps (FWHM$\approx$1000 km s^{-1}, amplitude $\approx$20%) in the Hα profile are probably indicative of Rayleigh–Taylor instabilities in the cool gas behind the reverse shock. A very narrow component (unresolved, FWHM$\lesssim$200 km s^{-1}) of Hα at the systemic velocity of SN 1993J may instead be produced by a superposed H II region, or perhaps by recombination in a large circumstellar shell or ring that was ionized during the first few hours after outburst. In the near future the spectrum of SN 1993J should become increasingly dominated by broad Hα emission.

1. INTRODUCTION

SN 1993J, in the nearby ($d = 3.6$ Mpc; Freedman *et al.* 1994) spiral galaxy M81 (NGC 3031), was a peculiar Type II supernova (for a review, see Wheeler & Filippenko 1994). Its optical light curves were double peaked, and after the first minimum its bolometric light curve resembled that of a SN Ib (Schmidt *et al.* 1993; Richmond *et al.* 1994). The prominent Hα emission line, visible in spectra of SN 1993J during the first few weeks, became progressively weaker as absorption lines of He I (a defining characteristic of SNe Ib; Harkness & Wheeler 1990, and references therein) gradually appeared (Filippenko *et al.* 1993a, hereafter referred to as FMH; Swartz *et al.* 1993a). Data obtained at x-ray, ultraviolet, optical, and radio wavelengths suggested the presence of significant circumstellar matter, but with a density distribution unlike that of other well observed SNe II (Van Dyk *et al.* 1994, and references therein). The probable progenitor of SN 1993J had a classification of roughly K0 Ia (Filippenko 1993; Aldering *et al.* 1994), in contrast with the M-type Ia expected for most normal SNe II.

Based primarily on the early-time light curves, a number of independent groups suggested that the progenitor of SN 1993J had lost a majority of its hydrogen envelope prior to exploding, largely through transfer to a bound companion (Nomoto *et al.* 1993; Podsiadlowski *et al.* 1993; Ray *et al.* 1993; Bartunov *et al.* 1994; Utrobin 1994; Woosley *et al.* 1994). Estimates of the initial mass of the progenitor are typically in the range 12–17$\mathcal{M}_\odot$ (but see Höflich *et al.* 1993 for a different opinion), with the final (pre-SN) mass being 3–5$\mathcal{M}_\odot$ (the helium core, plus a few tenths of a solar mass of hydrogen). The historical precedent of SN 1987K (Filippenko 1988b), which transformed itself from Type II at early times to Type Ib at late times, and the observed spectroscopic similarities between SN 1993J and SNe Ib, led us (FMH; see also Filippenko & Matheson 1993) to dub SN 1993J a "Type IIb" supernova (cf. Woosley *et al.* 1987; Woosley 1991). Accordingly, we predicted that after many ($\gtrsim$6) months its optical spectrum would resemble the late-time spectra of

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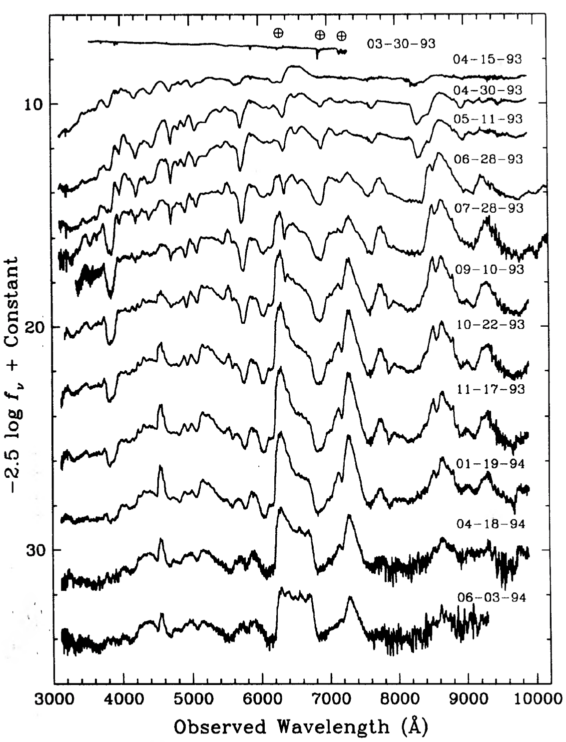

FIG. 1. A subset of the spectra of SN 1993J obtained with the Shane 3 m reflector at Lick Observatory. Telluric absorption lines were removed from all spectra except that of 1993 March 30. UT dates are indicated.

SNe Ib/Ic—dominated by strong emission lines of [O I], [Ca II], and Ca II, with Hα weak or absent.

Here we show that this was indeed the case; SN 1993J therefore supports the conclusion that SNe Ib/Ic and SNe II are physically related, having similar (massive) progenitors and explosion mechanisms. However, our latest spectra (10–14 months after the explosion) reveal a surprising new phenomenon: the strength of the Hα emission line is constant or slightly rising, while other lines continue to fade exponentially. The excess energy almost certainly comes from an interaction of the high-velocity outer envelope with circumstellar gas released by the progenitor prior to exploding.

2. THE METAMORPHOSIS

CCD spectra of SN 1993J were obtained on many nights with the Kast double spectrograph (Miller & Stone 1993) at the Cassegrain focus of the Shane 3 m reflector at Lick Observatory. Details of the observations and data reduction will be presented elsewhere; the general procedures are briefly described by FMH. Differential light losses caused by atmospheric dispersion were minimized by aligning the slit along the parallactic angle. Except in the case of the 1993 March 30 UT spectrum, telluric absorption bands were removed through division by the intrinsically almost featureless spectra of sdG stars.

A montage showing a subset of our spectra is illustrated in Fig. 1, along with the corresponding UT dates. For reference, the explosion is estimated to have occurred on 1993 March 27.5 UT (τ=0; Wheeler *et al.* 1993; Baron *et al.* 1993), and the second visual maximum was on 17 April (τ=3.0 weeks; Schmidt *et al.* 1993; Richmond *et al.* 1994; Benson *et al.* 1994). When comparing spectra in this paper, we assume that other SNe typically rise to maximum brightness roughly one month after they explode.

The first spectrum (30 March; $\tau\approx$3 days) is nearly featureless, although there are some narrow emission lines from circumstellar gas and several interstellar absorption lines (Filippenko *et al.* 1993b). As discussed by FMH, the second spectrum (15 April; τ=2.7 weeks) exhibits Hα with a P Cygni profile of somewhat unusual appearance. The third (30 April; τ=4.9 weeks) and fourth (11 May; τ=6.4 weeks) spectra reveal the presence of He I lines, most notably λ6678 and λ7065 (since He I λ 5876 is heavily contaminated by Na I D), prompting the "Type IIb" classification.

The He I lines grow less distinct in the fifth (28 June; τ=3.1 months) spectrum, and are essentially absent in the sixth (28 July; τ=4.0 months) spectrum. Instead, emission lines of [O I] λ5577, [O I] $\lambda\lambda$6300, 6364, [Ca II] $\lambda\lambda$7291, 7324, O I λ7774, and the Ca II near-infrared triplet are easily visible, making SN 1993J resemble a dense nebula quite early in its evolution. These lines must have emerged during the sizable gap (12 May through 27 June) in our coverage; Benetti & Barbon (1993), in fact, note the presence of nebular lines in a spectrum obtained on 29 May, at τ=2.1 months. It is possible that [O I] λ5577 appears on 30 April (τ=1.1 month); a bump can be seen at the correct location. However, as noted previously by Filippenko *et al.* (1990, hereafter referred to as FPS) in their study of the SN Ic 1987M, spectral synthesis is necessary to confirm this identification. Similarly, the Hα absorption component in the 11 May spectrum could be contaminated by [O I] $\lambda\lambda$6300, 6364 emission. The intensity ratio [O I] λ6300/[O I] λ6364 is closer to 1/1 than to 3/1 (the ratio of statistical weights) at early times, indicating that the electron density is high, and this is supported by the large relative strength of [O I] λ5577. Detailed analysis of the intensity ratios would be useful (Spyromilio & Pinto 1991), but the situation is more complicated than in SN 1987A because the SN 1993J lines are much broader.

Most of the emission lines become progressively stronger compared with other features in the seventh (10 September; τ=5.5 months), eighth (22 October; τ=6.9 months), ninth (17 November; τ=7.7 months), and tenth (19 January 1994; τ=9.8 months) spectra, although [O I] λ5577 fades due to the steadily decreasing density. Mg I] λ4571 appears in the 10 September spectrum (possibly earlier, but spectral synthesis is needed to verify this), and its relative strength increases for several months. This feature is substantially narrower (full width at half maximum [FWHM] $\approx$4300 km s^{-1}) than other emission lines. Despite being a dominant component through 22 October, the Ca II near-IR triplet subsequently exhibits a rapid decline, probably because of the decreasing flux of near-ultraviolet photons available to pump the Ca II H+K doublet (whose upper level is the source of the triplet). O I λ7774 emission fades during this interval as well. The

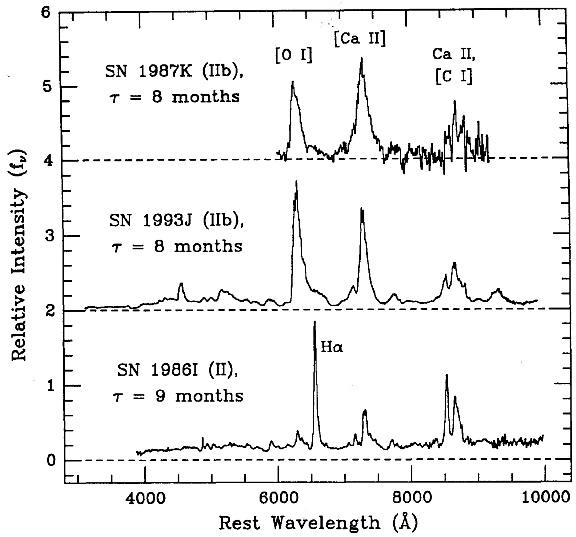

FIG. 2. Comparisons of the nebular spectra of SN 1993J with SN 1987M (τ=5 months, top) and with SN 1985F (τ=10 months, bottom). SN 1993J exhibits weak, broad Hα emission, but otherwise appears very similar to SNe Ib/Ic at late times. The redshift of the host galaxy has been removed in each case.

centroids of all emission lines are blueshifted by various amounts (typically $\sim$1000 km s^{-1}; see, also, Wang *et al.* 1993; Clocchiatti *et al.* 1993), a consequence of viewing primarily the near side of the optically thick ejecta. Moreover, despite being difficult to discern in Fig. 1, the emission lines (especially [O I]) exhibit long-lived fine structure resembling that seen in SN 1985F (Filippenko & Sargent 1989) and SN 1987A (Stathakis *et al.* 1991), indicating that clumps have formed in the ejecta. Using the technique of Chugai (1994), we derive an approximate mass of $0.6\mathscr{M}_\odot$ for the clumpy oxygen in SN 1993J. The structure in the emission-line profiles will be discussed more fully in a separate paper, but the reader is also referred to Wang & Hu (1994) and Spyromilio (1994).

Relative to a majority of the forbidden lines and the Ca II near-IR triplet, Hα emission and absorption both fade with time from 1993 June through November. Indeed, by 10 September the Hα absorption line is only a small notch in the wing of the [O I] $\lambda\lambda$6300, 6364 blend. Hα emission persists as a broad (FWHM $\approx$14 000 km s^{-1}), box-like extension redward of the [O I] blend, but it is weak compared with the [O I] and [Ca II] lines, and much weaker than in normal SNe II at late times. This is illustrated in Fig. 2, which compares the 17 November spectrum of SN 1993J with a spectrum of the SN II-P 1986I (from Filippenko 1988a) at a similar phase. It is obvious that SN 1993J now bears a much closer resemblance to the "Type IIb" SN 1987K than to SN 1986I. Note, in retrospect, that SN 1987K also exhibits weak Hα emission at late times; this was not easily discernible in the spectra published by Filippenko (1988b) because the narrow emission lines (from a superposed H II region) and the underlying stellar continuum had not been removed.

Figure 2 shows that the emission lines of SNe 1987K and

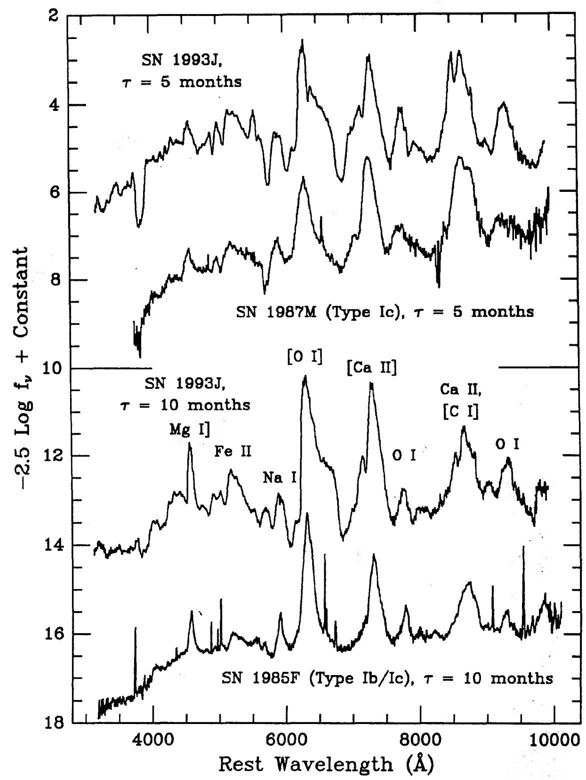

FIG. 3. The nebular spectra of SNe 1987K, 1993J, and 1986I are shown after scaling the fluxes by arbitrary factors. The underlying stellar continuum and the superposed H II region in the 1988 February spectrum of SN 1987K published by Filippenko (1988b) have been subtracted. The redshift of the host galaxy has been removed in each case.

1993J are broader than those of SN 1986I at comparable phases. For example, the FWHM of the [Ca II] $\lambda\lambda$7291, 7324 blend in SNe 1987K, 1993J, and 1986I are approximately 7500, 4600, and 2600 km s^{-1}, respectively. This reinforces our belief that the progenitors of SNe 1987K and 1993J were less massive than that of SN 1986I: for a given explosion kinetic energy, a low-mass star has higher expansion velocities than a high-mass star. Moreover, if the hydrogen envelopes of SNe 1987K and 1993J were depleted relative to that of SN 1986I, their inner ejecta would experience less deceleration. Since SN 1993J has slightly narrower emission lines than SN 1987K, its progenitor may have been somewhat more massive than that of SN 1987K, perhaps because of less extensive mass loss; on the other hand, such slight differences could easily be due to unequal kinetic energies.

Confirmation of the prediction that nebular spectra of SN 1993J at $t\approx6$ months would resemble those of SNe Ib/Ic is most clearly demonstrated in Fig. 3, which compares SN 1993J with SN Ic 1987M (from FPS) and with SN Ib (possibly Ic) 1985F (from Filippenko & Sargent 1986). The unambiguous presence of weak Hα emission in the high-quality spectrum distinguishes SN 1993J from the other two SNe, but otherwise their characteristics are quite similar; thus, SN 1993J "metamorphosed" into an object nearly identical to SNe Ib/Ic, as did SN 1987K.[2] These data provide strong support for the hypothesis that the progenitor of SN 1993J was a helium star with a low-mass envelope of hydrogen. They demonstrate that the "transition" (Type IIb) object SN 1987K was not unique, and solidify the physical connection between Type Ib/Ic and II supernovae. However, given the lasting presence of weak Hα emission in SNe 1987K and 1993J, and the fact that "Type IIb" is not a strictly empirical term but has overtones of interpretation (e.g., Woosley *et al.* 1994, and references therein), perhaps it would be more appropriate to simply call these transition objects "peculiar SNe II" rather than "SNe IIb." This is particularly true for SN 1993J; as will be shown in the next section, Hα actually becomes the dominant emission line at very late times.

3. COLLISION WITH THE CIRCUMSTELLAR GAS

In the nebular spectra obtained through 1993 November 17 (τ=7.7 months), the intensity ratio of Hα to the adjacent [O I] $\lambda\lambda$6300, 6364 blend gradually decreases with time. (A crude, but simple, quantitative measure of this may be obtained by assigning the integrated flux blueward of 6300 Å to [O I], and the integrated flux redward of 6560 Å to Hα; these regions are relatively uncontaminated by neighboring lines [Chevalier & Fransson 1994].) During the subsequent two months, however, the ratio remains nearly constant, perhaps even increasing very slightly in the 1994 January 19 spectrum (τ=9.8 months). An obvious increase in the relative strength of Hα is visible in the 1994 February 5 through June 3 spectra (τ=10.3–14.2 months; Fig. 1); in fact, by 1994 June 3 the Hα integrated flux is considerably larger than that of [O I], as was independently noted by Clocchiatti & Wheeler (1994).[3] Figure 4 demonstrates that the flux of [O I] (and other forbidden lines; see Fig. 1) rapidly drops during this interval, since heating by radioactive decay of ^{56}Co is decreasing exponentially, while the flux of Hα remains nearly constant. Indeed, the red wing of the Hα emission is actually getting brighter, and the same might be true of the blue wing (which is still blended with [O I]).

The energy being radiated by Hα at these late phases is almost certainly produced primarily by the interaction of the high-velocity ejecta of SN 1993J with dense circumstellar gas. As reviewed by Chevalier (1990; see Chevalier & Fransson 1994 for additional details), an outward moving forward shock is initiated in the circumstellar gas, while an inward moving reverse shock travels through the supernova ejecta. The reverse shock heats the hydrogen-rich outermost ejecta to $T \approx 10^7$ K ($n \approx 10^9$ cm^{-3}); the resulting soft x-rays ionize the ejecta downstream and the cool, dense gas ($T \approx 10^4$ K, $n \approx 10^{12}$ cm^{-3}) behind the reverse shock. Hα is subsequently produced through recombination, and its luminosity is predicted by Fransson *et al.* (1994) to be nearly constant with time. For the case of SN 1993J, the x-ray luminosity should be $\sim 10^{41}$ erg s^{-1} if the circumstellar gas density decreases as r^{-2}; the corresponding Hα luminosity (Chevalier & Fransson 1994) is 4.4×10^{38} erg s^{-1}, in perfect agreement with the observed value on 1994 June 3. [The Hα flux was assumed to be twice the value measured in the interval 6560–6820 Å. It was corrected for extinction using $E(B-V)=0.2$ mag, an average of the reddenings derived by Richmond *et al.* 1994.] In the more realistic case of circumstellar gas density decreasing as $r^{-1.7}$ (Van Dyk *et al.* 1994; Fransson *et al.* 1994), the x-ray and Hα luminosities are a factor of 4 higher, but the agreement with observations can still be considered satisfactory in light of the simplifying assumptions. Indeed, one positive aspect of the $r^{-1.7}$ density profile is that the Hα luminosity should slowly increase with time, as may be evident in Fig. 4. Note that the wings of the line appear to be rising more rapidly than the center, suggesting that the ejecta may have a somewhat flattened rather than spherical distribution.

The large velocity width (FWHM$\approx$17 000 km s^{-1}, full

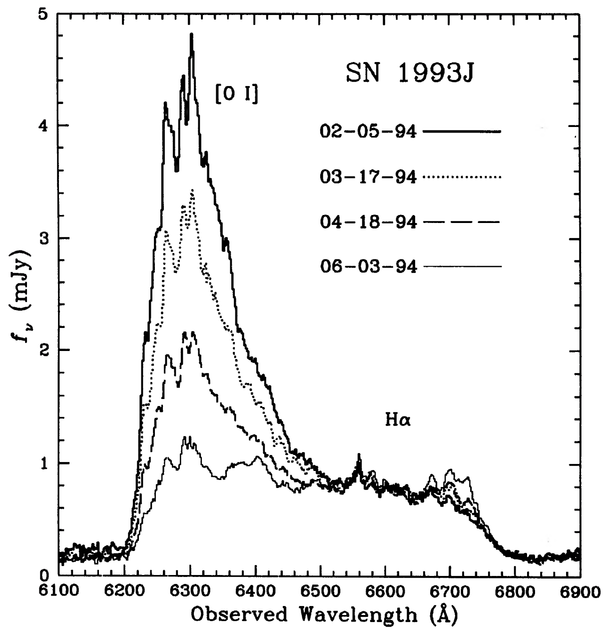

FIG. 4. Late-time spectra of SN 1993J illustrate the rapidly declining flux of the [O I] $\lambda\lambda$6300, 6364 blend and the relatively constant flux of the broad Hα emission line. Note the slight increase in the flux of the red (and possibly blue) edge of the flat Hα profile in the 1994 June spectrum, as well as that of the narrow Hα component at 6560 Å.

[2]In Fig. 3, note that very faint Hα emission may be visible in SN 1987M, and possibly even in SN 1985F. Filippenko (1988b; see also FPS) mention that the early-time spectrum of SN 1987M shows a weak feature due to Hα, and this is corroborated by spectral fits done by Jeffery *et al.* (1991), suggesting that the progenitor of SN 1987M was a helium star with a low-mass envelope of hydrogen. According to the calculations of Swartz *et al.* (1993b), on the other hand, SN 1987M had no hydrogen and was deficient in helium relative to SNe Ib. A detailed understanding of the progenitors of SNe Ic will not be possible until we definitively settle the question of whether hydrogen is present or absent in these objects.

[3]However, we disagree with the statement made by Clocchiatti & Wheeler (1994) that "the presence of Hα at late times is a distinctive feature that differentiates SN 1993J from the prior transition event SN 1987K." Figure 3 shows that at τ=8 months, weak Hα emission is actually present in SN 1987K at a relative intensity similar to that in SN 1993J. No spectra of SN 1987K were obtained at very late times (τ=12–14 months), precluding comparisons with the corresponding spectra of SN 1993J.

width near zero intensity [FWZI]≈23 000 km s^{-1}) and flat-topped profile of the Hα line are naturally explained by the interaction hypothesis. Note that each of the components in the [O I] λλ6300, 6364 blend has a much smaller width (FWHM≈6500 km s^{-1}); this doublet is emitted primarily in an oxygen-rich layer deep within the ejecta of SN 1993J. The Hα profile does not have a perfectly box-like shape, with vertical sides (FWHM=FWZI), because the shell of line-emitting gas has an appreciable thickness, and the expansion velocity depends on radius.

Figure 4 shows that the flat top of the Hα profile has a bumpy appearance, with a peak-to-valley amplitude of ~20% and velocity width of ~1000 km s^{-1}. The likely origin of these moderately broad bumps is Rayleigh–Taylor instabilities in the cool, dense shell of gas behind the reverse shock (Chevalier *et al.* 1992), especially if the shock is radiative (Blondin & Chevalier 1994) as suggested by Fransson *et al.* (1994). Interaction of the ejecta with dense clumps in the wind, whose presence is inferred from radio observations (Van Dyk *et al.* 1994), might also contribute to the bump observed at the rest wavelength of Hα; this process (Chugai & Danziger 1994) has been invoked to explain the strong, relatively broad (FWHM≈1000 km s^{-1}) Hα emission line which dominates the late-time spectra of some peculiar SNe II such as SN 1988Z (Filippenko 1991; Stathakis & Sadler 1991).

In general terms, the spectrum of SN 1993J is beginning to resemble that of SN 1980K (Fesen & Matonick 1994), whose late-time emission is very likely to be dominated by interaction of the ejecta with circumstellar gas. The luminosity of the Hα line in SN 1980K has been nearly constant during the past several years, and the linewidth is smaller than that of SN 1993J, in agreement with the model of Chevalier & Fransson (1994; see, also, Chugai 1992). Another well observed SN II exhibiting similar behavior is SN 1979C (Fesen & Matonick 1993). We expect that the spectrum of SN 1993J will more closely resemble the current spectra of SNe 1979C and 1980K as SN 1993J continues to age.

Finally, it is worth noting that our last few spectra of SN 1993J exhibit a weak, unresolved (FWHM ≲200 km s^{-1}) component of Hα emission at 6560 Å, exactly the systemic velocity (as defined by the wavelengths of narrow circumstellar emission lines in the early-time spectrum; see Filippenko *et al.* 1993b). The origin of this line might be recombination in a large shell or ring of circumstellar gas that was ionized by ultraviolet radiation emitted by the hot surface of the progenitor star at the time of shock breakout. If so, its strength should continue to grow as we see a progressively larger fraction of the ionized gas, as was the case with the narrow emission lines in spectra of SN 1987A (e.g., Fransson *et al.* 1989). Preliminary analysis of our full set of spectra, however, suggests that this is not the case; the line may instead be produced by a faint superposed H II region.

4. SUMMARY

Optical spectra of the peculiar Type II SN 1993J obtained at Lick Observatory over the first 14 months after outburst reveal a rapid transition to the nebular phase: strong forbidden lines of [O I] and [Ca II] are visible by τ=3 months. The presence of He I absorption lines at τ=1–3 months, together with a decline in the relative strength of Hα, supports early conjectures (based on light curves) that the progenitor was an initially massive star which lost most of its hydrogen envelope prior to exploding via core collapse.

By an age of 5–10 months, the spectrum of SN 1993J bears a striking resemblance to the late-time spectra of Type Ib/Ic supernovae, confirming the prediction of Filippenko *et al.* (1993); the main difference is that SN 1993J continues to show weak Hα emission. In retrospect, faint Hα emission is also visible in the τ≈8 months spectrum of SN 1987K, the only other unambiguous example of a Type II supernova exhibiting this behavior. At a given phase, SNe Ib and Ic exhibit broader nebular emission lines than SNe 1987K and 1993J, which in turn have broader lines than normal SNe II-P. It is now highly likely that SNe Ib/Ic and SNe II have similar massive progenitors, except that the former have lost their outer envelope of hydrogen through mass transfer or winds; in all cases the explosion mechanism is core collapse rather than thermonuclear runaway in a white dwarf.

At τ≈10 months the Hα emission line in SN 1993J stops fading, in contrast to other lines, and by τ≈14 months its flux dominates that of the adjacent [O I] λλ6300, 6364 blend. The excess Hα emission is almost certainly produced by the high-velocity outer layer of hydrogen ejecta interacting with dense circumstellar gas. Consistent with this hypothesis, the Hα profile is very broad (FWHM≈17 000 km s^{-1}) and has a flat top, with prominent bumps that are probably indicative of Rayleigh–Taylor instabilities. The broad Hα line should continue to dominate the spectrum as SN 1993J ages, although we expect that its width will gradually decrease. An unresolved (FWHM ≲200 km s^{-1}) component of Hα emission, possibly from a large circumstellar shell or ring but more likely from a superposed H II region, is visible in our last few spectra (τ=12–14 months).

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