THE ASTROPHYSICAL JOURNAL, 415:L103–L106, 1993 October 1

THE "TYPE IIb" SUPERNOVA 1993J IN M81: A CLOSE RELATIVE OF TYPE Ib SUPERNOVAE

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Received 1993 June 4; accepted 1993 July 16

ABSTRACT

Spectra of SN 1993J at three epochs within the first 1.5 months after the explosion reveal the onset of a remarkable transformation. The prominent Hα emission line visible at early times became progressively weaker as P Cygni features of He I gradually appeared; SN 1993J is therefore a hydrogen-poor, helium-rich "Type IIb" supernova. The progenitor of SN 1993J was probably a reasonably massive star (initial mass 10–17 $M_\odot$) that transferred most, but not all, of its hydrogen envelope to a physically bound companion. We predict that many ($\gtrsim 6$) months past maximum brightness, the spectrum of SN 1993J will closely resemble the late-time spectra of Type Ib supernovae; it will be dominated by strong emission lines of [O I], [Ca II], and Ca II, with Hα very weak or absent. A similar metamorphosis has been clearly seen only in SN 1987K; however, since the development of He I lines could not be monitored, SN 1987K may have actually been Type IIc rather than Type IIb. SN 1993J demonstrates that SN 1987K was not a unique event. It strengthens the hypothesis that Type Ib and Ic supernovae are not white dwarfs undergoing thermonuclear runaway. Rather, they are triggered by core collapse in massive, evolved stars that have lost their outer envelope of hydrogen (Ib) and perhaps helium as well (Ic), often through mass transfer in close binary systems. Thus, these objects are fundamentally related to Type II supernovae.

Subject headings: binaries: close — stars: evolution — stars: mass-loss — supernovae: general — supernovae: individual (SN 1993J)

1. INTRODUCTION

SN 1993J in M81 (NGC 3031) was discovered visually by amateur astronomer F. Garcia on 1993 March 28.906 UT, and confirmed on March 28.927 at magnitude 11.4 with an unfiltered CCD image (Ripero, Garcia, & Rodriguez 1993; Kato 1993). The explosion probably occurred around March 27–28. This is the brightest supernova in the northern hemisphere since SN 1954A in NGC 4214, and the brightest overall (except SN 1987A) since SN 1972E in NGC 5253 ($\delta = -31°$). It was classified as a probable Type II by A. V. Filippenko (Filippenko et al. 1993b) and by Garnavich & Ann (1993); the first few spectra showed a nearly featureless blue continuum, with extremely weak, broad Hα and He I λ5876 lines. Unambiguous hydrogen features were reported about a week later (Wheeler et al. 1993; Wheeler & Clocchiatti 1993). The progenitor candidate, visible in prediscovery images of M81 (Perelmuter 1993), may be a Ia supergiant of approximate spectral class K0 (Filippenko 1993), although the presence of two or more stars is suggested by its colors and spatial profile (Humphreys et al. 1993; Blakeslee & Tonry 1993). Narrow emission lines of N V λ1240, He II λ4686, [Fe X] λ6374, and Hα (Andrillat 1993; Wamsteker et al. 1993; Filippenko et al. 1993a), as well as the early appearance of X-rays (Zimmermann et al. 1993; Tanaka 1993) and radio radiation (Pooley & Green 1993; Weiler et al. 1993; Van Dyk et al. 1993), provide evidence for significant circumstellar gas.

The visual light curve of SN 1993J was unlike those of normal Type II supernovae of the plateau or linear variety (Doggett & Branch 1985); it exhibited a rapid rise to a first maximum around March 30, a decline of ~1 week duration, a subsequent rise to a second maximum near April 19, and a short decline followed by an exponential tail (e.g., Schmidt et al. 1993; Richmond et al. 1993). This led a number of theorists to suggest that the progenitor of SN 1993J was a massive star with only a low-mass outer skin of helium-rich hydrogen ($M_{\rm H} \approx 0.1$–$0.5\ M_\odot$). Most of the original hydrogen envelope was lost either through winds in a single star ($M_i \approx 25$–$30\ M_\odot$; Höflich, Langer, & Duschinger 1993), or, more likely, through mass transfer in a binary system ($M_i \approx 10$–$20\ M_\odot$ for the progenitor; Nomoto et al. 1993; Podsiadlowski et al. 1993; Woosley et al. 1993; Shigeyama et al. 1994; Ray, Singh, & Sutaria 1993; Utrobin 1993). Thus, SN 1993J might be called a "Type IIb" supernova (Woosley et al. 1987; Woosley 1991); indeed, Woosley (1993) and Nomoto et al. (1993) predicted that its spectrum would evolve with time from Type II (hydrogen rich) to something resembling Type Ib (helium rich, hydrogen absent, or at least much weaker; see, for example, Harkness & Wheeler 1990, or Branch, Nomoto, & Filippenko 1991, and references therein).

This prediction was confirmed spectroscopically by Filippenko & Matheson (1993). An independent confirmation was made by Wheeler (1993) and collaborators (Swartz et al. 1993a) shortly thereafter. Here we show a few representative spectra of SN 1993J, illustrating its transformation from a relatively normal Type II to an unambiguous Type IIb having progressively stronger helium lines and weaker hydrogen lines. We conclude that the hydrogen and helium features will eventually disappear, making the late-time spectrum ($t \gtrsim 6$ months past maximum) closely resemble those of Type Ib supernovae. Our full data set, together with analysis and interpretation, will be published elsewhere. Previously, the only other supernova known to have clearly experienced a spectroscopic metamorphosis from Type II at early times to Type Ib (or Ic) at late times is SN 1987K (Filippenko 1988). SN 1987K and SN1993J provide additional evidence in support of the hypothesis that Types Ib and Ic supernovae are driven by core collapse in

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massive stars, rather than by deflagrations or detonations of white dwarfs.

2. OBSERVATIONS

Spectra of SN 1993J were obtained on 1993 April 15, 30, and May 11 UT with the Kast double spectrograph (Miller & Stone 1993) at the Cassegrain focus of the Shane 3 m reflector at Lick Observatory. Reticon 400 × 1200 pixel CCDs were used in both cameras. A long, narrow (2″) slit was oriented along the parallactic angle to minimize differential light losses produced by atmospheric dispersion. To check the relative and (on photometric nights) absolute flux calibration, spectra were also obtained with a wide (8″) slit; in all cases the continuum shape was found to closely match that of the narrow-slit spectra. Several different grating and grism settings were required to cover the entire accessible wavelength range (3100–9900 Å) with a resolution of ~5 Å.

Standard procedures were followed when calibrating the spectra (e.g., Filippenko & Sargent 1988). The background sky was subtracted from regions adjacent to SN 1993J. Wavelengths were determined by fitting polynomials to a set of He-Hg-Cd-Ne-Ar comparison lines. Excellent relative spectrophotometry was obtained through the use of the sdO comparison star Feige 34 (Massey et al. 1988) in the range 3100–5200 Å and the sdG comparison stars HD 84937 and BD +26°2606 (Oke & Gunn 1983) in the range 4300–9900 Å. Particular care was taken to remove telluric absorption bands in the red and near-infrared regions through division by the intrinsically almost featureless spectra of the above sdG stars (Wade & Horne 1988).

3. RESULTS

Our spectra of SN 1993J are shown in the middle part of Figure 1. They correspond to roughly 0.5 week prior to second visual maximum (April 15), 1.5 weeks after second maximum (April 30), and 3 weeks after second maximum (May 11). In the first spectrum, Hα exhibits a clear P Cygni profile, but with the emission (which has a peculiar flat-topped shape) much stronger than the absorption (possibly contaminated by another emission line). Hβ and Hγ are primarily in absorption, although the emission component of the former coincides with Fe II lines.

All of the absorption lines are stronger in the second spectrum, and the continuum is significantly redder. Of particular interest is the "double-peaked" appearance of the Hα emission line. This was first noted by Jannuzi et al. (1993), and it was confirmed by Porter et al. (1993) and by Hu, Wang, & Jiang (1993). The third spectrum, however, reveals the true nature of the feature: it is actually a blend of Hα and the P Cygni profile of He I λ6678 (Filippenko & Matheson 1993). Instead of increasing in contrast, as in normal Type II supernovae, the Hα emission line is gradually becoming less pronounced, and it is also being eroded by He I λ6678. This interpretation is supported by the presence of other He I lines, including He I λ7281 (weak), λ7065 (strong), λ5876 (possibly blended with Na I D), λ5015 (blended with Fe II), perhaps λ4921 (blended with Hβ emission and Fe II), and λ4471 (blended with Hγ emission). Indeed, SN 1993J is beginning to resemble Type Ib supernovae, which are characterized by the absence of hydrogen and the presence of strong He I lines in their early-time spectra—especially ~1 month past maximum brightness. A direct comparison can be made with the spectrum of SN Ib 1984L (from Harkness et al. 1987) obtained 3 weeks after maximum.

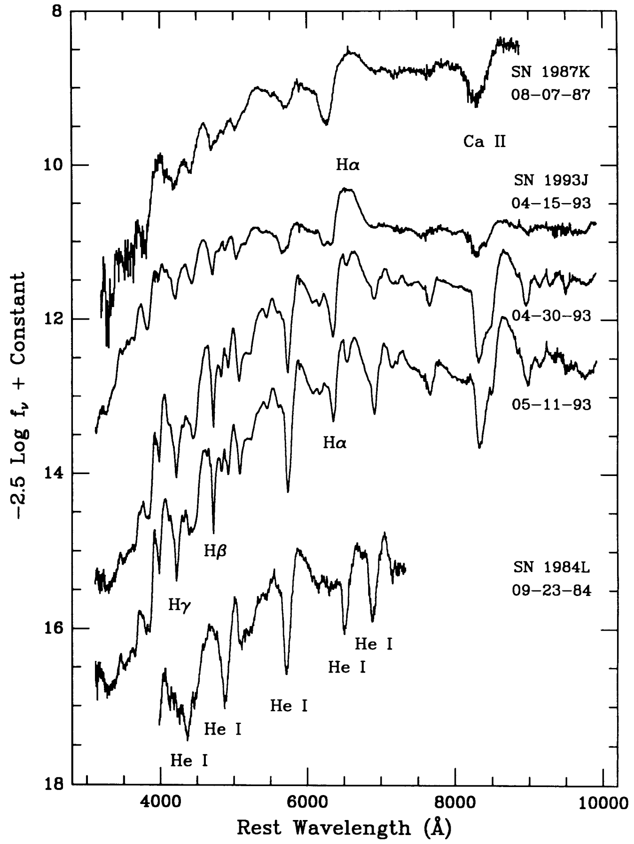

FIG. 1.—Spectra of SN 1987K (*top*) about 1 week past maximum (from Filippenko 1988), SN 1993J (*middle*) about (−0.5, 1.5, and 3) weeks past second maximum, and SN 1984L (*bottom*) ~3 weeks past maximum (from Harkness et al. 1987). All dates are UT. The effective units of the ordinate are magnitudes ($-2.5 \log f_\nu$ + constant; Oke & Gunn 1983). The heliocentric redshift of the host galaxy has been removed in each case. No reddening corrections have been applied. SN 1984L is a classic Type Ib supernova, defined by the absence of hydrogen and the presence of He I lines. Note the emergence of He I absorption lines in the April 30 spectrum of SN 1993J, and their increased strength in the May 11 spectrum, while Hα emission gradually decreases in prominence. These are the defining characteristics of the Type IIb subclass. SN 1987K is also a Type IIb (or perhaps IIc) supernova; see Filippenko (1988).

(According to the light curves in Nomoto et al. 1993, it is appropriate to compare SN 1993J three weeks past *second* maximum with Type Ib supernovae 3 weeks past maximum.) A spectrum of SN 1993J obtained on May 17 by Schmidt et al. (1993) shows even stronger He I lines. The blueshift of the He I absorption minima in the May 11 spectrum ranges from 5500 to 7300 km s^{-1}, significantly less than that of Hα (9800 km s^{-1}) and the other Balmer lines (8500 km s^{-1}); hence, the He layer is generally distinct from, and interior to, the hydrogen envelope.

Based on the May 11 data, and on the known late-time spectra of Type Ib supernovae (e.g., Gaskell et al. 1986; Branch et al. 1991), Filippenko & Matheson (1993) predicted that the late-time spectrum of SN 1993J will be dominated by strong, broad [O I], [Ca II], and Ca II emission lines, with hydrogen and helium lines very weak or absent. The evolution may resemble that of SN 1987M (Filippenko, Porter, & Sargent 1990), except that prominent helium lines were never present in this Type Ic supernova. The above features were already beginning to appear in a spectrum obtained on May 29 by Benetti & Barbon (1993), and our own observations show that they had become quite prominent by June 28. We have no compelling reason to doubt that they will continue to grow.

4. DISCUSSION

Prior to SN 1993J, the only supernova known to have gone through a *clear* spectroscopic metamorphosis from Type II at early times (1–2 weeks past maximum) to Type Ib or Ic at late times ($\gtrsim 6$ months past maximum) is SN 1987K (Filippenko 1988). SN 1993J, which will surely become the most extensively observed supernova apart from SN 1987A, gives us an opportunity to study this phenomenon in detail. It also suggests that this behavior is not rare, and is more important than has generally been assumed.

The spectrum of SN 1987K (1987 August 7) obtained roughly 1 week past maximum brightness is shown at the top of Figure 1. It generally resembles the April 15 spectrum of SN 1993J, but the continuum of SN 1993J is bluer. The Hα profile of SN 1987K has a more classic P Cygni shape than that of SN 1993J, and in both cases it is not as prominent as in most Type II plateau supernovae. The Ca II near-infrared triplet is visible in both objects. Unfortunately, it was not possible to monitor the spectral development of SN 1987K for a long time interval after maximum brightness, due to the object's proximity to the Sun. In retrospect, it appears as though the August 12 spectrum published by Filippenko (1988) exhibits weak P Cygni lines of He I λ6678 (the dip and bump redward of the narrow nebular lines), He I λ7065, and He I λ7281; thus, SN 1987K is probably a Tybe IIb supernova (i.e., a SN Ib, but with weak hydrogen). However, it remains possible that the helium lines were never very strong in SN 1987K— in which case it more closely resembles a Type Ic supernova (Wheeler et al. 1987) and could therefore be designated "Type IIc." The distinction between Types Ib and Ic supernovae was not well recognized at the time SN 1987K was being analyzed, and the existence of two distinct subclasses (rather than a continuum of He I line strengths) is still not completely certain; nevertheless, it would be useful to know in detail the spectral evolution of SN 1987K.

The theoretical predictions (§ 1) that SN 1993J had only a low-mass outer layer of hydrogen were based on the observed light curve. By contrast, Filippenko (1988) drew the same conclusion for SN 1987K almost entirely from inspection of spectra, since the light curve was poorly sampled. He noted that the two most likely types of progenitors are very massive stars (20–25 $M_\odot$) that lost their envelopes through winds, or massive stars (8–20 $M_\odot$) that transferred substantial gas to binary companions. In the case of SN 1993J, the binary scenario is most plausible (Filippenko & Matheson 1993, and other references mentioned in § 1); the short duration of the second maximum implies that the helium core had a small mass, and the observed luminosity of the progenitor is probably too low for consistency with a single very massive star.[2] Moreover, there is only a small a priori probability that a very massive star near the end of its life will retain a few tenths of a solar mass of hydrogen, rather than several solar masses or none at all.

Podsiadlowski, Joss, & Hsu (1992) extensively discuss the possibility that mass transfer in binary systems could lead to a new observable subclass of Type II supernovae; they refer to these objects as Type II [stripped]. Here we adopt the notation of Woosley et al. (1987), Type IIb, since it is linked more directly to the observations. Note that not *all* of the lost mass was transferred to the companion; some was expelled to form the detected circumstellar wind, unless that wind was instead produced by the companion.

SN 1993J has interesting implications for the physical nature of Types Ib and Ic supernovae. As already pointed out by Filippenko (1988), the existence of Type IIb supernovae suggests that Type Ib supernovae (and probably Type Ic supernovae) are closely related to Type II supernovae, with core collapse being the explosion mechanism; they are not white dwarfs undergoing some sort of slow deflagration, such as that discussed by Woosley (1990). The cause of the observed differences between Types Ib and Ic supernovae, however, is less obvious. Harkness et al. (1987; see also Swartz et al. 1993b) postulate that Type Ic supernovae are very massive stars that have lost (through winds or mass transfer) their hydrogen *and* helium layers, while Type Ib supernovae have lost only their hydrogen. Unless some hydrogen is deposited back on the progenitor shortly prior to core collapse, we would *not* expect to find Type Ic supernovae with weak Hα in their early-time spectra (i.e., Type IIc supernovae)—yet several possible examples are illustrated by Filippenko (1992), and spectral synthesis by Jeffery et al. (1991) provides supporting evidence for SN Ic 1987M. On the other hand, Swartz et al. (1993b) use more extensive calculations to dispute the Hα identification in SN 1987M; thus there is no completely convincing evidence for hydrogen in the early-time spectra of Type Ic supernovae, if we assume that SN 1987K was indeed a SN IIb like SN 1993J. The Harkness et al. (1987) hypothesis (H layers removed in Type Ib supernovae, H and He layers removed in Type Ic supernovae) remains feasible.

Alternatively, Shigeyama et al. (1990) and Hachisu et al. (1991) suggest that the progenitors of both Types Ib and Ic supernovae are in binary systems and retain their helium envelopes; different degrees of mixing of the ^{56}Ni into the outer regions are used to explain the potentially real differences in observed light curves of Types Ib and Ic supernovae (Nomoto, Filippenko, & Shigeyama 1990). The presence of weak Hα emission in the early-time spectra of some Type Ic supernovae (i.e., Type IIc supernovae) is consistent with this hypothesis, since a hydrogen skin may occasionally remain on the helium envelope. On the other hand, as pointed out by Nomoto et al. (1990; see also Baron 1992), a major difficulty is the *absence* of He I lines in the photospheric spectra of Type Ic supernovae; if anything, Type Ic supernovae should have stronger He I lines than Type Ib supernovae since the former undergo more ^{56}Ni mixing than the latter (Shigeyama et al. 1990; Hachisu et al. 1991) and the He I levels are excited by nonthermal electrons. The natural conclusion is that Type Ic supernovae *do not* have a helium layer, as in Harkness et al. (1987) and Swartz et al. (1993b). If Type IIc supernovae really do exist, and the Harkness et al. (1987) scenario is incorrect, the early-time spectroscopic distinctions between Types Ib and Ic supernovae remain an unsolved puzzle. Perhaps the ^{56}Ni is actually mixed less in Type Ic than in Type Ib supernovae.

In any case, intensive study of the Type IIb SN 1993J,

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[2] Information concerning the site of SN 1993J, reported by many authors in the IAU Circulars, leads us to conclude that the progenitor is contaminated by an unassociated blue star less than 1″ away. Using a plausible decomposition similar to some of those circulated by Humphreys (1993), we subtract the contribution of the blue star and find that the bolometric luminosity of the remainder (SN 1993J progenitor plus any companion) is roughly $(2.5–4) \times 10^{38}$ ergs s^{-1} for assumed visual extinctions of 0–1 mag. Thus, the progenitor's mass is $\lesssim 17\ M_\odot$ if it is a single star (according to the solar abundance evolutionary models of Schaller et al. 1992), and perhaps $\lesssim 13\ M_\odot$ if in a binary system.

together with a search for more objects of this subclass (also Type IIc supernovae), should reveal much about the evolution of massive stars, both single and binary. A particularly exciting opportunity with SN 1993J is the possibility of quantifying the effect of a close physical companion (a few AU away). If the progenitor of SN 1993J began its life as a 10–17 $M_{\odot}$ star and really did lose all but $\sim$3–5 $M_{\odot}$ (the He core) primarily through mass transfer to its companion, the companion is now a luminous object that will reappear when the supernova becomes sufficiently faint, with optically thin ejecta (2–3 yr after the explosion). Since the system probably remained bound (as already mentioned by Podsiadlowski et al. 1993), it may be possible to measure the mass function by careful time-resolved spectroscopy of the companion. Also, late-time spectra of SN 1993J could reveal low-velocity hydrogen that was stripped off the companion by the supernova ejecta (Chugai 1986; Livne, Tuchman, & Wheeler 1992). The system should eventually become an X-ray binary, when the companion fills its Roche lobe and mass transfer to the neutron star commences.

This research was supported by NSF grants AST 89-57063 and AST 91-15174 (A. S. F.), by NSF Cooperative Agreement AST 88-09616 (Center for Particle Astrophysics), and by an NSF Graduate Fellowship (T. M.). William and Marina Kast provided a generous gift that led to the construction of the double spectrograph on the 3 m Shane reflector at Lick Observatory. Robert Harkness kindly sent the digital spectrum of SN 1984L shown in Figure 1. We have enjoyed stimulating discussions with Stan Woosley and the referee, Craig Wheeler.

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