THE ASTRONOMICAL JOURNAL, 120:1487–1498, 2000 September

OPTICAL SPECTROSCOPY OF SUPERNOVA 1993J DURING ITS FIRST 2500 DAYS

THOMAS MATHESON,[1] ALEXEI V. FILIPPENKO,[1] AARON J. BARTH,[2] LUIS C. HO,[3] DOUGLAS C. LEONARD,[1] MATTHEW A. BERSHADY,[4] MARC DAVIS,[1] DAVID S. FINLEY,[5] DAVID FISHER,[6,7] ROSA A. GONZÁLEZ,[8] SUZANNE L. HAWLEY,[9] DAVID C. KOO,[6] WEIDONG LI,[1] CAROL J. LONSDALE,[10] DAVID SCHLEGEL,[11] HARDING E. SMITH,[12] HYRON SPINRAD,[1] AND GREGORY D. WIRTH[13]

Received 2000 March 5; accepted 2000 June 8

ABSTRACT

We present 42 low-resolution spectra of supernova (SN) 1993J, our complete collection from the Lick and Keck observatories, from day 3 after explosion to day 2454, as well as one Keck high-dispersion spectrum from day 383. SN 1993J began as an apparent SN II, albeit an unusual one. After a few weeks, a dramatic transition took place, as prominent helium lines emerged in the spectrum. SN 1993J had metamorphosed from a SN II to a SN IIb. Nebular spectra of SN 1993J closely resemble those of SNe Ib and Ic, but with a persistent Hα line. At very late times, the Hα emission line dominated the spectrum, but with an unusual, boxlike profile. This is interpreted as an indication of circumstellar interaction.

Key words: binaries: close — stars: evolution — stars: mass loss — supernovae: general — supernovae: individual (SN 1993J)

1. INTRODUCTION

Supernova 1993J was visually discovered in the nearby galaxy M81 (NGC 3031; $d = 3.6$ Mpc; Freedman et al. 1994) by F. Garcia on 1993 March 28.906 UT (Ripero, Garcia, & Rodriguez 1993; note that all calendar dates used herein are UT). It reached a maximum brightness of $m_V = 10.8$ mag (e.g., Richmond et al. 1994), becoming the brightest supernova (SN) in the northern hemisphere since SN 1954A ($m_{pg} = 9.95$; Wild 1960; Barbon, Ciatti, & Rosino 1973). In terms of observational coverage, both in temporal consistency (almost nightly observations at early times) and in the details of individual observations (including observations with signal-to-noise ratios [S/N], spectral resolutions, and wavelength regions not typically found in studies of SNe), SN 1993J is surpassed only by SN 1987A. Early spectra showed an almost featureless blue continuum, possibly with broad, but weak, Hα and He I λ5876 lines. This led to a classification of the SN as Type II (Filippenko et al. 1993; Garnavich & Ann 1993; see Filippenko 1997 for a general discussion of SN types). Wheeler & Filippenko (1996) present a thorough review of the early work on SN 1993J.

Both the spectra and the light curve of SN 1993J quickly began to indicate that this was not a typical Type II SN. Indeed, the initially unusual light curve and the appearance of He I lines in the spectra was interpreted as evidence that SN 1993J was similar to a SN Ib, with a low-mass outer layer of hydrogen that gave the early impression of a SN II (see discussion and references below). Following Woosley et al. (1987), it was described as a "Type IIb" SN. This transformation from SN II to nearly SN Ib indicates a common mechanism (core collapse) for these two observationally defined subclasses. SN 1993J is thus one of the most significant SNe ever studied, not only for its role in linking Types II and Ib (and possibly Ic), but also because it was observed with such great detail.

In § 2 of this paper we review the study of SN 1993J; we are presenting over six years of optical spectra and it is appropriate to provide such a summary. (Wheeler & Filippenko 1996 only cover the first few months of the development of SN 1993J in their review; moreover, the interpretation to follow depends on the context of the previous observations and analyses.) We then present the collection of our spectra of SN 1993J from the Lick and Keck observatories[14] (§ 3), along with a general description of the spectra through the various phases of evolution for the SN in § 4. Detailed analysis of our spectra for individual phases is discussed elsewhere (Filippenko, Matheson, & Ho 1993, hereinafter FMH93; Filippenko, Matheson, & Barth 1994, hereinafter FMB94; Matheson et al. 2000, hereinafter Paper II).

2. PREVIOUS STUDIES OF SUPERNOVA 1993J

The evolution of the light curve of SN 1993J did not follow either of the two typical paths for SNe II. SN 1993J did not remain at a relatively constant brightness after a

[1] Department of Astronomy, University of California at Berkeley, Berkeley, CA 94720-3411.
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[3] The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101-1292.
[4] Department of Astronomy, University of Wisconsin, 475 North Charter Street, Madison, WI 53706.
[5] Eureka Scientific, Inc., 2452 Delmer Street, Suite 100, Oakland, CA 94602.
[6] University of California Observatories/Lick Observatory, Department of Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064.
[7] Current Address: Department of State, U.S. Consulate General, Ho Chi Minh City, Vietnam.
[8] Observatoire de Genève, Mailletes 51, 1290 Sauverny, Switzerland.
[9] Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195-1580.
[10] Infrared Processing and Analysis Center, California Institute of Technology 100-22, Pasadena, CA 91125.
[11] Department of Astrophysical Sciences, Peyton Hall, Princeton University, Princeton, NJ 08544.
[12] Center for Astrophysics and Space Sciences, University of California at San Diego, La Jolla, CA 92093-0424.
[13] W. M. Keck Observatory, Kamuela, HI 96743.

[14] Spectropolarimetry obtained at Lick on days 24, 34, and 45 is discussed by Tran et al. (1997) and is not duplicated here.

slight decline from maximum, as a normal Type II plateau SN would, nor did the brightness decline in the pattern of a Type II linear SN (for examples of these Type II light curves, see, e.g., Doggett & Branch 1985). Instead, SN 1993J rose quickly, then rapidly declined for $\sim$1 week, only to brighten a second time over the next two weeks. This led to another rapid decrease in brightness for $\sim$3 weeks, followed by an approximately exponential decline. For a complete discussion of the photometry of SN 1993J, see Okyudo et al. (1993), Schmidt et al. (1993), van Driel et al. (1993), Wheeler et al. (1993), Benson et al. (1994), Lewis et al. (1994), Richmond et al. (1994, 1996), Barbon et al. (1995), Doroshenko, Efimov, & Shakhovskoi (1995), and Prabhu et al. (1995).

The unusual initial behavior of the light curve rapidly led many SN modelers to conclude that SN 1993J was the result of a core-collapse explosion in a progenitor that had lost a significant fraction of its hydrogen envelope, leaving only $\sim$0.1–0.5 $M_{\odot}$ of hydrogen. The original envelope could have been lost through winds (Höflich, Langer, & Duschinger 1993) from a fairly massive star (25–30 $M_{\odot}$). Another possibility explored by Hashimoto, Iwamoto, & Nomoto (1993; see also Nomoto et al. 1993) is that SN 1993J was the result of the explosion of an asymptotic giant branch star having main-sequence mass $M_{\rm ms} \approx$ 7–10 $M_{\odot}$, with a helium-rich envelope.

A more likely solution is that the progenitor of SN 1993J was a member of a binary system and the companion had stripped away a considerable amount of hydrogen. The progenitor was observed during prior studies of M81. Aldering, Humphreys, & Richmond (1994) analyzed several sets of preexisting images and deduced that the photometry was inconsistent with a single star at the position of SN 1993J. They found that the best fit for the progenitor itself was a K0 I star with $M_{\rm bol} \approx -7.8$ mag and $V-R \approx 0.7$ mag. Cohen, Darling, & Porter (1995) derived a similar color from a 5 month series of images of M81 from 1984; there was no apparent variability.

Using the scenario of a star that had been stripped of most of its hydrogen envelope, Nomoto et al. (1993) and Shigeyama et al. (1994) found a best fit to the light curve from their model of a 4 $M_{\odot}$ helium core, although a range of 3–6 $M_{\odot}$ for the core is reasonable. The main-sequence mass of the star would have been 15 $M_{\odot}$, while the residual hydrogen envelope is less than $\sim$0.9 $M_{\odot}$. Starting with a star of initial mass of 13–16 $M_{\odot}$, Woosley et al. (1994) could reproduce the light curve from the explosion of a remaining helium core with mass 4.0 ± 0.5 $M_{\odot}$ and hydrogen envelope with mass 0.20 ± 0.05 $M_{\odot}$. A similar model by Podsiadlowski et al. (1993) had 0.2 $M_{\odot}$ of hydrogen remaining on a star of initial mass $M_{\rm i} \approx 15$ $M_{\odot}$. Ray, Singh, & Sutaria (1993) also invoked a binary system for SN 1993J with a residual hydrogen envelope mass of 0.2 $M_{\odot}$. Utrobin (1994) used an envelope mass of 0.1 $M_{\odot}$ remaining on a 3 $M_{\odot}$ helium core from an initial mass of 12 $M_{\odot}$. Bartunov et al. (1994) achieved a good fit to the light curve with a helium core mass of 3.5 $M_{\odot}$, but a larger hydrogen envelope ($M_{\rm env} \approx 0.9$ $M_{\odot}$). Later studies continued to conclude that a low-mass envelope of hydrogen on a helium core was the most likely scenario for the progenitor (Young, Baron, & Branch 1995; Utrobin 1996). Intercomparison of two methods also indicated that the results were robust (Blinnikov et al. 1998). Houck & Fransson (1996) used a nonlocal thermodynamic equilibrium (NLTE) synthetic spectrum code to fit nebular spectra and found that the Nomoto et al. (1993) models could explain the late-time spectra. They found a best fit with a 3.2 $M_{\odot}$ helium core with a 0.2–0.4 $M_{\odot}$ hydrogen envelope. Patat, Chugai, & Mazzali (1995) also used the late-time spectra, specifically the Hα line, to derive an ionized hydrogen mass of 0.05–0.2 $M_{\odot}$; this is a lower limit to the envelope mass.

Woosley et al. (1987) had already considered such a possibility for core-collapse SNe, giving them a new name: SNe IIb. The low-mass outer layer of hydrogen would give the initial appearance of a SN II, but the spectrum would slowly change to one more similar to that of a SN Ib, dominated by helium lines with the hydrogen either appearing weakly or completely gone. Indeed, Nomoto et al. (1993) predicted that the spectrum of SN 1993J would show this behavior. This was first confirmed by Filippenko & Matheson (1993), followed rapidly by Schmidt et al. (1993) and Swartz et al. (1993). A complete analysis of our optical spectra covering the transformation of SN 1993J from a Type II to a Type IIb is presented by FMH93. Other studies of the early optical spectra include those of Wheeler et al. (1993), Taniguchi et al. (1993), Garnavich & Ann (1994), Ohta et al. (1994), Prabhu et al. (1995), and Metlova et al. (1995).

Jeffery et al. (1994) present an early ultraviolet (UV) spectrum of SN 1993J taken with the *Hubble Space Telescope* (*HST*) on 1993 April 15. The other core-collapse SNe that had been observed in the UV to that point were compared with SN 1993J, and there were striking differences. SN 1993J had a relatively smooth UV spectrum and was more similar to SN 1979C and SN 1980K, both of which are radio sources and thus likely to have thick circumstellar envelopes (e.g., Weiler et al. 1986). The UV spectra of SN 1987A, in contrast, showed broad absorption features. The illumination from circumstellar interaction may reduce the relative strengths of line features compared to the continuum and thus produce the featureless UV spectra of SNe 1979C, 1980K, and 1993J (Branch et al. 2000).

SN 1993J then evolved fairly rapidly into the nebular phase; our analysis of this transition is covered by FMB94. The nebular-phase spectra were similar to those of a typical SN Ib, but the hydrogen lines never faded completely. In fact, Hα began to dominate the spectrum at late times, most likely the result of circumstellar interaction. There were several other papers that considered the nebular-phase spectra (and some relatively late-time spectra). Lewis et al. (1994) present the complete La Palma archive covering days 2 through 125. Li et al. (1994) discuss the nebular-phase spectra observed from the Beijing Astronomical Observatory. Barbon et al. (1995) show the first year of observations from Asiago; the transformation of the SN from Type II to IIb is evident, as is the return of Hα at late times (by $\sim$200 days). A longer baseline ($\sim$500 days) for the spectra is found in the work of Finn et al. (1995); all the features described above are evident in their spectra, but the very late-time observations show even more clearly the presence of circumstellar interaction.

There were optical spectropolarimetric observations of SN 1993J. Trammell, Hines, & Wheeler (1993) found a continuum polarization of $P = 1.6\% \pm 0.1\%$ on day 24 (assuming 1993 March 27.5 as the explosion date; see below). Trammell et al. (1993), as well as later considerations of the same data (Höflich 1995; Höflich et al. 1996), argued that this polarization implied an overall asymmetry, but the source of this asymmetry was undetermined. The presence of SN 1993J in a binary system was implicated as a potential source for the asymmetry. With more epochs of observation (days 7, 8, 11 [V band only], 24, 30, 31, 32, 34, 45, and 48), Tran et al. (1997) also found a polarization in the continuum of $\sim 1\%$, but a different level for the interstellar polarization. Nevertheless, they also concluded that SN 1993J was asymmetric. It is interesting to note that a subsequent SN IIb, SN 1996cb, showed substantially similar polarization of its spectra (Wang et al. 2000).

The analysis of individual aspects of the spectra has yielded some interesting results. Both Wang & Hu (1994) and Spyromilio (1994) found evidence for clumpy ejecta with blueshifted emission lines. Houck & Fransson (1996) argue that the lines are not actually blueshifted, but that contamination from other lines appears to shift them. Nonetheless, the lines do show substructure that indicates clumpy ejecta. The discussion of the clumpy nature of the ejecta based on analysis of our spectra is presented in Paper II.

Models of the early spectra could reproduce their overall shape, but the line strengths were problematic. Baron et al. (1993) found a photospheric temperature of ~ 8000 K for day 10, but the predicted hydrogen and helium lines were too weak, possibly indicating unusual abundances or nonthermal effects. A later analysis including the *HST* UV spectrum was fit well by including enhanced helium abundance and NLTE effects (Baron, Hauschildt, & Branch 1994). Jeffery et al. (1994) also had difficulties fitting line strengths for transitions that are susceptible to NLTE effects. Clocchiatti et al. (1995) studied the early spectra to follow the evolution of color temperature and to calculate a distance to M81 (~ 3.5 Mpc) using the expanding photosphere method (e.g., Eastman, Schmidt, & Kirshner 1996). The NLTE treatment of calcium is explored by Zhang & Wang (1996), who found a best fit with a reduced calcium abundance.

SN 1993J was also observed quite thoroughly at other wavelengths (see Wheeler & Filippenko 1996 for a summary of early results). Pooley & Green (1993) presented a light curve at 2 cm obtained with the Ryle Telescope. These data were merged by Van Dyk et al. (1994) with the VLA data, which included not only observations at 2 cm, but also at 1.3 cm, 3.6 cm, 6 cm, and 20 cm. Interpreting the data within the context of standard theories of radio emission from SNe (e.g., Chevalier 1982, 1984; Weiler et al. 1986; Weiler, Panagia, & Sramek 1990), Van Dyk et al. (1994) concluded that the radio absorbing material around the SN is inhomogeneous and that the circumstellar density profile is flatter than that expected for a constant mass-loss rate, constant-velocity wind. The flatter profile could be the result of decreasing mass-loss rate or increasing wind velocity. SN 1993J was also observed using very long baseline interferometry (VLBI). Early studies indicated either a disklike structure or an optically thick shell (Marcaide et al. 1994), and other observations found SN 1993J to be circularly symmetric and expanding linearly (Bartel et al. 1994). Later measurements found a spherically symmetric shell (Marcaide et al. 1995). After years of observation using VLBI, Marcaide et al. (1997) still observed a symmetric shell, but the SN expansion had apparently begun to decelerate. With an even longer baseline, Bartel et al. (2000) also found that the expansion had begun to decelerate, as well as revealing some structure in the ejecta. As these studies probe different regions than the polarimetric observations described above, the spherical symmetry revealed by the VLBI images is not inconsistent with the asymmetry deduced from polarimetry.

Soft X-rays were detected from SN 1993J six days after the explosion by *ROSAT* (Zimmerman et al. 1994) and two days later by *ASCA* (Kohmura et al. 1994). Both observatories followed the SN for several months, recording a gradual decrease in X-ray flux as well as a softening of the energy spectrum. The *Compton Gamma-Ray Observatory* detected SN 1993J with OSSE, and hard X-rays (>50 keV) were observed on at least two epochs (Leising et al. 1994). All three of these groups, as well as Suzuki & Nomoto (1995) and Fransson, Lundqvist, & Chevalier (1996), interpreted these observations as indications of circumstellar interaction, with the X-rays coming from either the shocked wind material or the reverse-shocked SN ejecta. Both Patat et al. (1995) and Houck & Fransson (1996) concluded that the late-time optical spectra could only be powered by a circumstellar interaction; radioactive decay alone was not enough.

Although SN 1993J has provided the best observational evidence for the transformation of a SN from one type to another, there have been other examples. The early spectra of SN 1987K showed hydrogen lines, but the late-time spectra more closely resembled those of SNe Ib (Filippenko 1988). The transition itself was not observed, occurring while SN 1987K was in conjunction with the Sun. SN 1996cb underwent a very similar metamorphosis from SN II to SN Ib; Qiu et al. (1999) present a complete spectroscopic record of the transformation. In addition, there were some suggestions of hydrogen in spectra of the Type Ic SN 1987M (Jeffery et al. 1991; Filippenko 1992) and the SN Ic 1991A (and perhaps SN Ic 1990aa; Filippenko 1992). SN 1993J is clearly a significant object in the study of SNe. By providing a link between SNe II and SNe Ib, it has strengthened the argument that SNe Ib (and, by extension, SNe Ic) are also core-collapse events.

3. OBSERVATIONS AND REDUCTIONS

3.1. *Low-Dispersion Spectra*

Low-dispersion spectra of SN 1993J were obtained with the Kast double spectrograph (Miller & Stone 1993) at the Cassegrain focus of the Shane 3 m reflector at Lick Observatory and with the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) at the Cassegrain focus of the Keck 10 m telescopes (both Keck I and Keck II were used). The Kast spectrograph has Reticon 400×1200 pixel CCDs in both cameras, while LRIS has a single Tektronix 2048×2048 pixel CCD. The spatial scale for the Kast CCD was $0\farcs8$ per pixel; the LRIS CCD was binned in the spatial direction, yielding $0\farcs43$ per pixel. At Lick, the slit width was generally $2''$, but $8''$ observations were also taken on potentially photometric nights to provide an absolute flux scale; the $2''$ data were scaled to the flux level of the $8''$ observation. The $8''$ observations were done only when SN 1993J was reasonably bright (until about day 200). The LRIS slit width was typically $1''$, but $0\farcs7$ widths were also used when conditions allowed or when attempting to obtain better spectral resolution. Various gratings and grisms were utilized, yielding resolutions (full width at half maximum, FWHM) ranging from 2.5 to 15 Å. Details of the exposures are given in Table 1. Most of the spectra were taken with the slit oriented at, or near (within 10°), the parallactic angle

TABLE 1

JOURNAL OF OBSERVATIONS

Day[a]	UT Date	Tel.[b]	Range[c] (angstroms)	Res.[d] (angstroms)	P.A.[e] (deg)	Opt. P.A.[f] (deg)	Air Mass[g]	Flux Std.[h]	Ph.[i]	Seeing[j] (arcsec)	Slit (arcsec)	Exp.[k] (s)	Observer(s)
3	1993 Mar 30	L	3560–7300	6	137	136	1.2	F34	N	1.5	2	180	MD, DS
16	1993 Apr 12	L	3340–7460	6	25	20–24	1.2	F34/HD84	N,S	2.0	2	100–300	DSF
17	1993 Apr 13	L	3120–10300	6–15	152–188	151–192	1.2	F34/HD84	P,S	1.2	2	50–300	AVF, TM
18	1993 Apr 14	L	3120–10300	6–15	132–156	133–159	1.2	F34/HD84	P,S	1.5	2	40–300	AVF, TM
19	1993 Apr 15	L	3120–10300	6–15	111–188	114–194	1.2	F34/BD26	P,S	2.0	2	80–800	AVF, TM
32	1993 Apr 28	L	3200–7380	3–6	177	177	1.2	F34/BD26	Y	1.5	2	300	SLH
33	1993 Apr 29	L	3200–7380	3–6	177	178	1.2	F34/BD26	Y	1.5	2	300	SLH
34	1993 Apr 30	L	3120–9900	6–7	89	87–95	1.5	F34/BD26	Y,S	1.5	2	50–400	AVF, LCH
45	1993 May 11	L	3120–9900	6–7	117–130	118–132	1.2	F34/BD26	N,S	3.5	2	100–900	AVF, TM
51	1993 May 17	L	4221–5580	3	145	147	1.2	F34	Y	2.0	2	300–600	DF
56	1993 May 22	L	3250–10400	6–15	135	127	1.3	F34	P,S	2.5	2	200	HS, RAG
83	1993 Jun 18	L	3220–10400	6–15	90	98	1.5	BD28/BD26	N	2.0	2	300	HES, CJL
89	1993 Jun 24	L	3340–8050	6–7	90	98	1.5	F56	N	2.0	2	60–300	RHB, RLW
91	1993 Jun 26	L	3480–8150	6–7	90	93	1.5	F34	N	2.0	2	300	MAB, DCK, GDW
93	1993 Jun 28	L	3110–10400	6–15	84	82–86	1.6	F34/BD26	P,S	2.0	1.8	200–400	AVF, TM
109...	1993 Jul 14	L	3110–10400	6–15	18	5–14	3.5	F34/BD26/HD19	Y,S	3.5	2	200–600	AVF, TM, AJB
123...	1993 Jul 28	L	3350–10350	6–15	72–147	149–155	2.9	BD28/BD26	Y,S	2.0	2	50–400	AVF, TM, AJB
139...	1993 Aug 13	L	3160–9880	6–7	153–158	149–160	3.0	BD28/BD26	Y,S	2.5	2	100–600	AVF, TM
167...	1993 Sep 10	L	3180–9910	6–7	118–130	116–131	2.2	BD28/BD26	Y,S	1.5	2	150–900	AVF, TM
182...	1993 Sep 25	L	3120–9920	6–7	91–95	89–95	1.5	F34/HD19	Y,S	2.5	2	500–600	AVF, TM
209...	1993 Oct 22	L	3130–9910	6–7	75–85	75–87	1.4	F34/HD84	N,S	1.0	2	100–900	AVF, TM
226...	1993 Nov 08	L	3120–9920	6–7	213–223	212–225	1.2	BD28/BD17	N	1.5	2	600–900	AVF, TM
235...	1993 Nov 17	L	3120–10300	6–15	61–81	62–83	1.4	F34/BD17	N	1.0	2	900–1500	AVF, TM
266...	1993 Dec 18	L	3120–9910	6–7	218–252	219–268	1.3	F34/BD17	N	2.0	2	1200–1800	AVF, LCH
286...	1994 Jan 07	L	3260–9900	6–7	138–155	139–157	1.2	F34/BD17/BD26	N	1.5	2	900–1800	AVF, TM
298...	1994 Jan 19	L	3120–9910	6–7	214–233	216–234	1.2	F34/BD17/BD26	N	1.0	2	1200–1800	AVF, TM
315...	1994 Feb 05	L	3120–9920	6–7	90–116	91–117	1.4	F34/HD19	N	1.5	2	900–1800	AVF
355...	1994 Mar 17	L	3120–8020	6–7	118–144	111–144	1.2	F34/BD26	N	2.0	2	750–1800	AVF, TM, AJB

TABLE 1—*Continued*

Day[a]	UT Date	Tel.[b]	Range[c] (angstroms)	Res.[d] (angstroms)	P.A.[e] (deg)	Opt. P.A.[f] (deg)	Air Mass[g]	Flux Std.[h]	Ph.[i]	Seeing[j] (arcsec)	Slit (arcsec)	Exp.[k] (s)	Observer(s)
387	1994 Apr 18	L	3120–9900	6–7	277–299	278–299	1.3	F34/HD84	N	1.5	2	1800–2700	AVF, LCH
433	1994 Jun 03	L	3120–12000	6–15	81–95	81–93	1.5	F34/HD84	N	2.0	2	1200–1500	AVF, TM, AJB
473	1994 Jul 13	L	3120–11400	6–15	17	−3.5–11	3.4	BD28/BD17	P	2.0	2	1800	AVF
523	1994 Sep 01	L	3120–8030	6–7	136–169	134–165	3.0	BD28/BD26	Y	4.0	2	1800	AVF, TM, AJB
525	1994 Sep 03	L	3120–8030	6	126–134	125–133	2.3	BD28/BD26	Y	2.5	2	1800	AVF, TM, AJB
553	1994 Oct 01	L	3120–8040	6–7	129	116–126	1.2	BD28/BD26	Y	1.5	2	1800	TM, LCH
670	1995 Jan 26	K-I	3880–8800	2.5–9	180	170–188	1.5	BD26	Y	1.3	1	300–450	AVF, LCH
			5628–6939	2.5	180	182	1.5	BD26	Y	1.3	0.7	900	AVF, LCH
881	1995 Aug 25	L	4260–7010	7	197	132	2.4	BD26	Y	2.0	4	300–1800	AVF, DCL
976	1995 Nov 28	K-I	3930–8970	9	47	47	1.7	BD17	N	1.3	1	300–600	AVF, AJB
			5784–7092	2.5	47	39	1.7	HD84	N	1.3	0.7	600	AVF, AJB
1766...	1998 Jan 26	K-II	3920–8950	5–8	150	149–155	1.6	BD26	Y	1.0	1	300–900	AVF, DCL
2028...	1998 Oct 15	L	3300–10200	6–15	250	253	1.4	F34/HD84	N	2.5	2	1800	AVF, DCL
2069...	1998 Nov 25	L	3340–10200	6–15	68	52	1.3	BD28/BD17	N	2.5	2	2700	AVF, TM
2115...	1999 Jan 10	L	3350–10300	6–15	180	175	1.2	BD28/BD17	N	1.5	2	1800	AVF, TM, WL
2176...	1999 Mar 12	L	3280–10500	6–15	186	157	1.2	F34/HD19	N	2.0	2	1800	AVF, TM, WL
2454...	1999 Dec 15	K-II	3900–8900	9	205	207	1.6	BD17	Y	1.1	1	600	AVF

NOTE.—For each day, multiple observations are combined into a one-line summary. For days 670 and 976, the exposures with different slit widths are listed separately.

[a] Days since estimated date of explosion, 1993 March 27 UT (JD 2,449,074). Note that the data from days 523 and 525 are combined into one spectrum in the figures.

[b] L = Lick 3 m/Kast Double Spectrograph; K-I = Keck I 10 m/Low Resolution Imaging Spectrometer (LRIS); K-II = Keck II 10 m/LRIS.

[c] Observed wavelength range of spectrum. In some cases, the extreme ends are very noisy, and are not shown in the figures.

[d] Approximate spectral resolution (full width at half maximum intensity).

[e] Position angle of the spectrograph slit. Most observations taken within 10° of the parallactic angle (Filippenko 1982). On day 123, difficult conditions arising from observing under the pole with an equatorially mounted telescope required constant rotation of the slit to observe the supernova; the orientation was within 10° of the parallactic angle for the duration of the observation. For day 881, a specific position angle (197) going through a nearby star was used to ensure that SN 1993J was in the slit. On days 83 and 89, the position angle used to observe the standard stars was significantly different from the optimal parallactic angle, but the air mass of the observations was low.

[f] Optimal parallactic angle over the course of the exposures.

[g] Average air mass of observations.

[h] The standard stars are as follows: F34 = Feige 34, F56 = Feige 56, BD28 = BD+28°4211—Stone (1977), Massey & Gronwall (1990); HD19 = HD 19445, HD84 = HD 84937, BD26 = BD+26°2606, BD17 = BD+17°4711—Oke & Gunn (1983).

[i] Estimation of the photometric conditions for the night: N = not photometric, P = possibly photometric, Y = photometric, S = 2″ slit width observations scaled to 8″ slit width observations.

[j] Seeing is estimated from the data and observers' records.

[k] The range of exposure times for the various observations. In some cases, multiple exposures were taken so the actual time of integration at any given wavelength may be 3–4 times the longest exposure time listed.

(Filippenko 1982), but exceptions are noted in Table 1. We follow Lewis et al. (1994) in adopting 1993 March 27.5 (JD 2,449,074) as the date of explosion.

Standard CCD processing and spectrum extraction were accomplished with VISTA (Terndrup, Lauer, & Stover 1984) through day 553 and IRAF[15] for day 670 and thereafter (day 56 was also processed using IRAF). Optimal extraction was used for the IRAF reductions (Horne 1986). The wavelength scale was established using low-order polynomial fits to calibration lamps of He-Hg-Cd-Ne-Ar (Lick) or He-Ne-Kr-Ar (Keck). The typical root mean square (rms) deviation for the wavelength solution was 0.1–0.5 Å, depending on the resolution for the particular exposure. Final adjustments to the wavelength scale were obtained by using the background sky regions to provide an absolute scale. We employed our own routines to flux calibrate the data; comparison stars are listed in Table 1. Particular care was taken to remove telluric absorption features through division by an intrinsically featureless spectrum, where possible (Wade & Horne 1988; see also Paper II). The flux standard was routinely employed for this purpose.

As most of the spectra were observed with the position angle oriented along or near the parallactic angle, the relative spectrophotometry is quite good. For the nights during which an 8″ slit width exposure was taken to provide an absolute flux scale, we checked our fluxes against the *BVRI* photometry of Richmond et al. (1996). Days 16, 45, and 209 were not photometric. Days 17, 18, 19, 34, 56, and 93 all agreed quite well with the photometry (within $\sim 5\%$ in *B* and *V*, slightly larger deviations in *R* and *I*, probably due to the differences between the observed passband and the assumed passband used to calculate fluxes from the spectra). The flux of the day 109 spectrum has large deviations from the broadband photometry ($\sim 20\%$). That night was our first attempt to observe SN 1993J "under the pole" with the equatorially mounted Shane 3 m telescope, and we attribute the fluxing errors to the difficulties arising from this complication to the observing program. Subsequent uses of the telescope "under the pole" were more successful, and days 123 and 139 are in fairly good agreement with the photometry, although they do differ in *B*. This may be the result of difficulties aligning the slit along the parallactic angle for these observations. Day 167 agrees with the photometry to within $\sim 10\%$, but day 182 shows much larger differences. The spectrum had become almost completely nebular by this stage, so the effects of strong emission lines falling near the edges of passbands may explain the discrepancies. For all of the other spectra, we had no absolute calibrators.

3.2. *High-Dispersion Spectrum*

A single high-dispersion spectrum was obtained on 1994 April 14 UT (day 383) with the HIRES echelle spectrometer (Vogt 1992, 1994) on the Keck I 10 m telescope. The HIRES detector is a Tektronix 2048 × 2048 pixel CCD. The setup for these observations encompassed the range 4240–6720 Å in 31 spectral orders. Beyond ~ 5100 Å, small gaps in the wavelength coverage appear because the CCD was too small to span the progressively wider orders. A KV408 order-blocking filter was used to eliminate second-order blue light. The "C5" slit decker (1″.15 × 7″) was utilized to prevent overlapping orders and to ensure adequate sky background, yielding a spectral resolution of $R = 38{,}000$. The HIRES chip was binned in the spatial direction, with 0″.41 per pixel. There were three exposures of SN 1993J, two with integration times of 2700 s and one with an integration time of 1800 s. The seeing was $\sim 1''.2$ and the night was photometric. At the time, HIRES had neither an image rotator nor an atmospheric dispersion compensator, so differential light losses may affect the spectrum; the position angle of the slit was not at the parallactic angle (Filippenko 1982). For all three observations, SN 1993J was at an air mass of ~ 1.5, so the effects are small, especially redward of 4500 Å.

Once again, IRAF was used for standard CCD processing and spectrum extraction. We extracted one-dimensional spectra by summing the five pixels centered on a polynomial fit to the centroid of the light distribution along the dispersion, yielding an effective aperture of 1″.15 × 2″.05. A third-order fit to the thorium-argon comparison lamp spectra provided a wavelength solution with a dispersion of ~ 0.003 Å. No attempt was made to flux calibrate the data. The sdG star HD 84937 (Oke & Gunn 1983) was observed for use in the identification and removal of telluric lines. In order to preserve the large-scale shape of the lines, several different attempts were made using the observed spectrum of HD 84937 and featureless regions of the spectrum of SN 1994I (see Ho & Filippenko 1995 for a discussion of the SN 1994I spectrum observed on this night). The corrections to the continuum shape made with SN 1994I provided the best representation when compared with low-dispersion spectra taken on approximately the same date. Residual errors remain in the overall shape of individual orders, but the small-scale structure is reproduced accurately.

4. RESULTS AND DISCUSSION

4.1. *Days 3 to 34*

Spectra from days 3 to 34 are shown in Figure 1. The first spectrum obtained at Lick Observatory was taken on 1993 March 30, day 3. It shows a blue, nearly featureless continuum. There are some broad undulations that may be incipient P-Cygni features of Hα and He I λ5876, but the presence of reduction artifacts makes interpretation problematic. Clocchiatti et al. (1995) found a best-fit blackbody curve for this spectrum that indicated a temperature of $\sim 30{,}000$ K, along with $A_V \approx 0.7$ mag. The day 3 spectrum also contained narrow (unresolved) emission features of He II λ4686, [Fe X] λ6374, and Hα. Benetti et al. (1994) also observed [Fe XIV] λ5303. In addition, there are narrow absorption components of Ca II H and K and Na I D. The observed wavelengths of the narrow emission features allowed us to derive a relative heliocentric velocity for the SN of -140 km s^{-1}, well in agreement with other results (e.g., Vladilo et al. 1993, -135 km s^{-1}). All spectra presented herein have had this velocity removed. More detailed studies using high-resolution spectrographs that discuss the narrow lines in the spectra of SN 1993J include those of Benetti et al. (1994), Vladilo et al. (1993, 1994), and Bowen et al. (1994).

As the SN cools, line structure begins to appear in the spectra. By days 16 through 19, SN 1993J resembles a rela-

[15] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

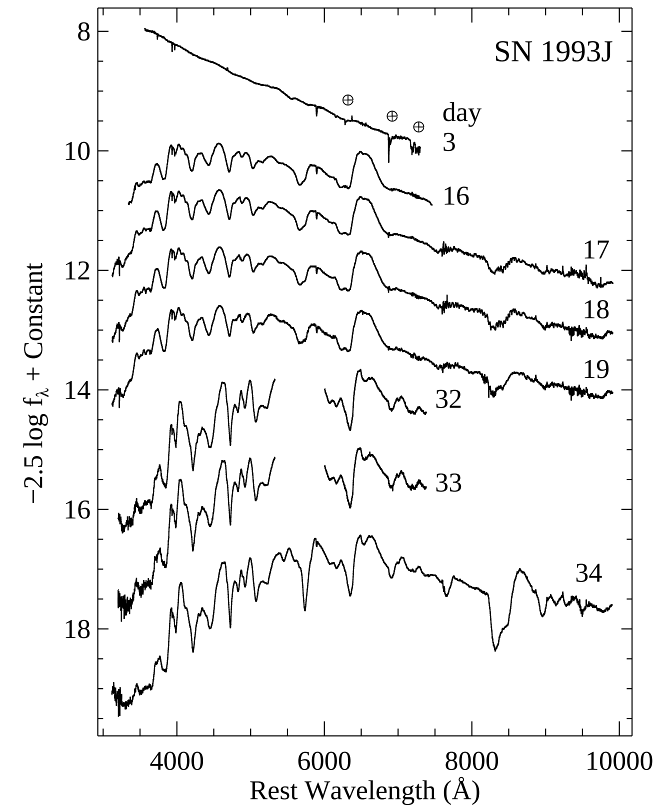

FIG. 1.—Spectra of SN 1993J from days 3 to 34, assuming explosion on 1993 March 27.5 (JD 2,449,074). The flux units are $-2.5 \log f_\lambda - 21.10$, following the definition of space telescope (ST) magnitudes (e.g., Koorneef et al. 1986). ST magnitudes are analogous to AB magnitudes ($-2.5 \log f_\nu - 48.60$; Oke & Gunn 1983), with the zero point yielding monochromatic magnitudes for Vega in the Johnson V passband of ~ 0. The following constants have been added to the individual spectra (*top to bottom*): +1.7, −0.5, 0.0, 1.0, 2.0, 2.3, 3.5, and 5.3. Telluric absorption features are indicated for the day 3 spectrum, from which they could not be properly removed. In this and all subsequent figures the systemic heliocentric velocity of -140 km s^{-1} has been removed.

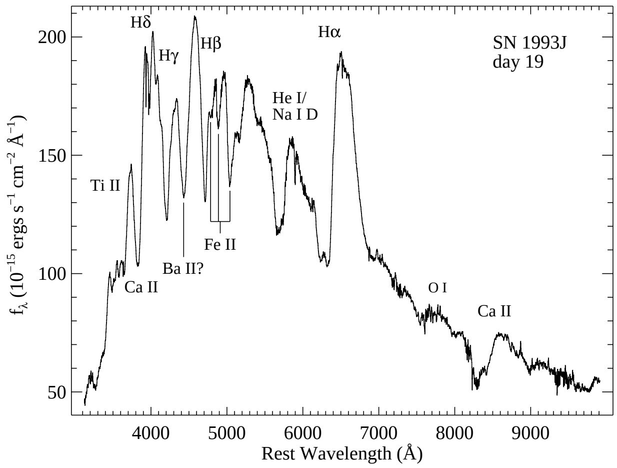

FIG. 2.—Spectrum of SN 1993J from day 19 (1993 April 15) with line identifications. The flux-density scale is linear and has been scaled to match the V-band photometry of Richmond et al. (1996). The identification of the line at $\sim$4430 Å is uncertain, but it may be Ba II λ4554 (see, e.g., Williams 1987; Turatto et al. 1998; Fassia et al. 1998).

tively typical SN II, although some details of the lines are slightly unusual. The emission component of the Hα P-Cygni line has a flat top. Figure 2 shows the day 19 spectrum on a linear flux-density scale with some line identifications. Overall, this spectrum is very much like that of most SNe II. The spectra from days 32 through 34 start to show that SN 1993J is not a typical SN II. A broad notch develops in the Hα profile, and the emission component begins to split in two. In addition, the profile associated with He I λ5876 and Na I D strengthens, especially in the absorption component. As described above, this is interpreted as the onset of a phase wherein the He I lines grow in prominence, with the notch in Hα being the P-Cygni profile of He I λ6678. Note that the narrow feature seen in the Hα emission profile of earlier spectra at the wavelength of the helium notch is most likely telluric absorption (see Paper II for details). Another indication of helium is the P-Cygni profile of He I λ7065 that also appears on day 32 in our spectra. Other He I lines are blended with other lines or are weak, and so are less convincing than λ6678 and λ7065.

The notch in Hα is not obvious in the day 22 spectra of Barbon et al. (1995) or Lewis et al. (1994), or in the day 23 spectrum of Prabhu et al. (1995). It does appear in the day 25 spectra of Prabhu et al. (1995) and Barbon et al. (1995); they also have a day 26 spectrum with the notch. The notch is clearly present in the day 27 spectrum of Finn et al. (1995). (Note that the day 26 spectrum of Lewis et al. 1994 appears to have some reduction and/or observation errors; it is very different from the spectra of the other groups at similar times, including their own from day 22.)

4.2. *Days 45 to 109*

The helium features continue to strengthen and the metamorphosis of SN 1993J from a Type II to IIb becomes readily apparent in days 45 through 109, shown in Figure 3. The day 45 spectrum (Fig. 4) exhibits almost the entire He I series of lines. The most obvious lines remain He I λ5876, λ6678, and λ7065, although λ5876 is probably contaminated by Na I D. Other He I lines are also blended with other features, including λ7281 (contaminated by [Ca II] $\lambda\lambda$7291, 7324), λ5015 (blended with Fe II λ5018), λ4921 (affected by Hβ and Fe II λ4924), and λ4471 (blended with Hγ).

By day 89, the helium lines begin to weaken in comparison with the rest of the spectrum, and they are effectively gone by day 109, although a strong absorption due to He I λ5876 and Na I D remains. This is similar to the late-time behavior of a typical SN Ib (e.g., Gaskell et al. 1986; Branch, Nomoto, & Filippenko 1991). Although not quite at the fully nebular phase, some nebular lines begin to appear at these times, including Mg I] λ4571, [O I] $\lambda\lambda$6300, 6364, and [Ca II] $\lambda\lambda$7291, 7324.

4.3. *Days 123 to 266*

The spectra from days 123 through 226 (Fig. 5) show fairly little evolution. The nebular lines strengthen relative to the continuum over time, resulting in an almost purely emission-line spectrum. The most dramatic aspect of these spectra is the continuing weakness of Hα. Qualitatively following the relative strength of [O I] $\lambda\lambda$6300, 6364 and Hα over these days shows the oxygen lines evolving to dominate the hydrogen strength. (Blending of the lines makes a quantitative ratio of these features very difficult.) The spectrum from day 182 is shown in Figure 6 with some line identifications. Aside from the weak Hα, this could easily be the nebular spectrum of a SN Ib or SN Ic.

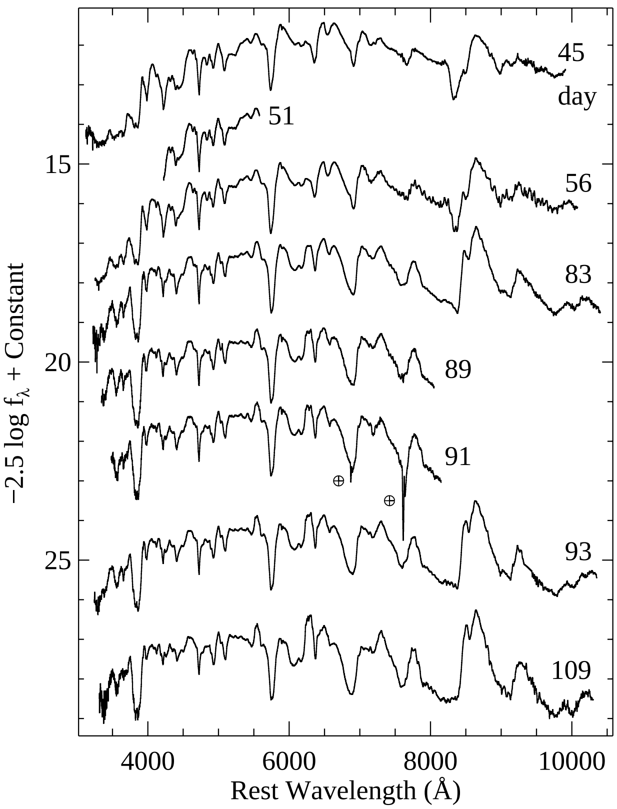

FIG. 3.—Spectra of SN 1993J from days 45 to 109, with date of explosion and flux units as in Fig. 1. The following constants have been added to the individual spectra (*top to bottom*): 0.0, 1.5, 3.0, 4.5, 6.5, 8.3, 11.3, and 13.5. Telluric absorption features are indicated for the day 91 spectrum, from which they could not be properly removed.

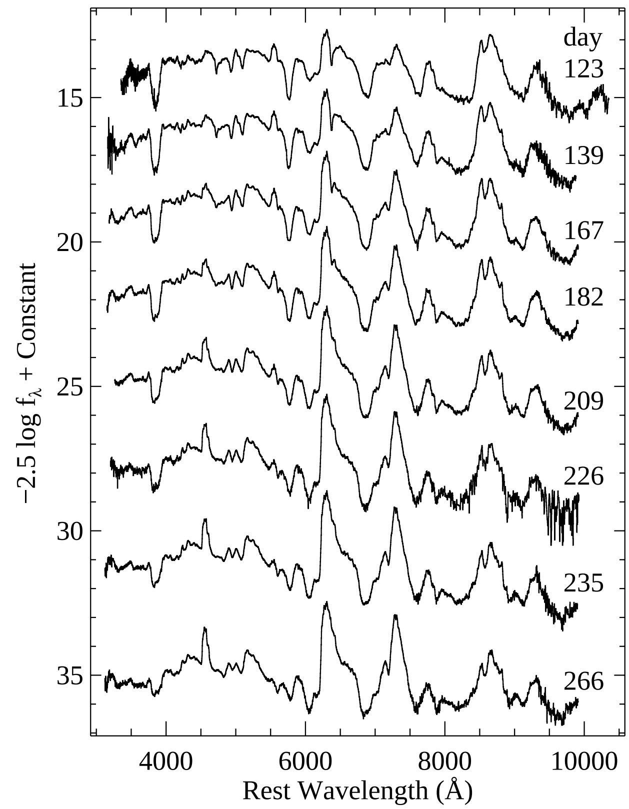

FIG. 5.—Spectra of SN 1993J from days 123 to 226, with date of explosion and flux units as in Fig. 1. The following constants have been added to the individual spectra (*top to bottom*): 0.0, 2.0, 4.0, 6.5, 9.0, 11.0, 15.0, and 19.0. Noisy spectra have been clipped for clarity.

4.4. *Days 286 to 553*

The nebular lines begin to fade away during days 286 through 553 (Fig. 7). The most prominent lines in the spectra on day 286—Mg I] λ4571, [O I] $\lambda\lambda$6300, 6364, [Ca II] $\lambda\lambda$7291, 7324, and the Ca II near-IR triplet—are virtually gone by days 473 and 523. The Hα line, though, remains at a fairly constant strength as the [O I] doublet decreases (see Fig. 4 of FMB94). Hα is comparable to [O I] $\lambda\lambda$6300, 6364 in strength by days 387 and 433, and the oxygen line is reduced to a small feature on the blue shoulder of the Hα line by day 553.

The day 387 spectrum is shown in Figure 8. Note the development of the box-like Hα profile in comparison with day 182 (Fig. 6). The presence of the boxlike profile for Hα on day 553, as well as for other lines (He I λ5876 and Na I D, possibly [O III] λ4363 and [O III] $\lambda\lambda$4959, 5007), indicates that a new emission phase has begun for SN

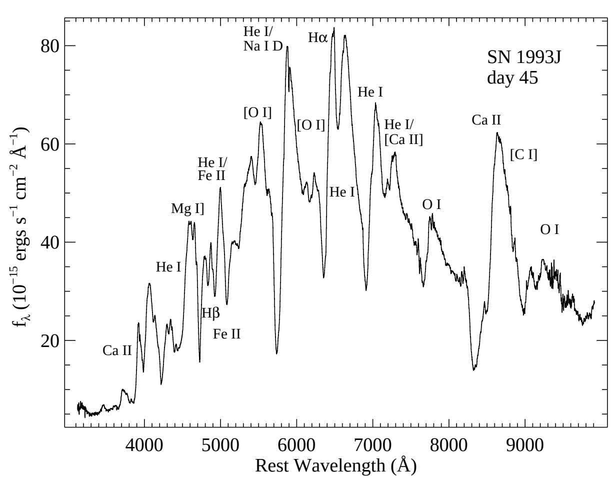

FIG. 4.—Spectrum of SN 1993J from day 45 (1993 May 11) with line identifications. The flux-density scale is linear and has been scaled to match the *V*-band photometry of Richmond et al. (1996).

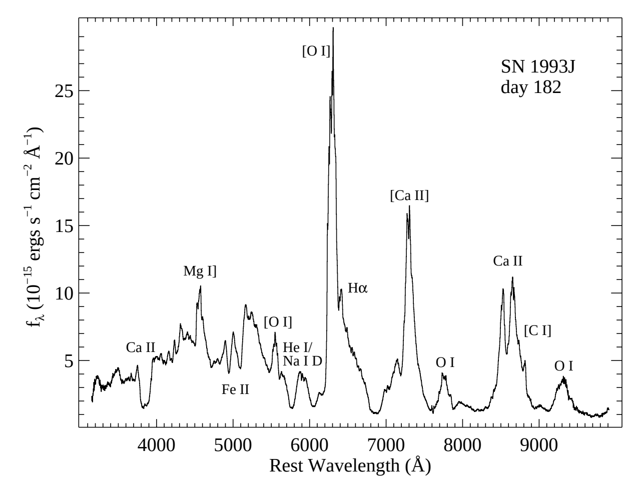

FIG. 6.—Spectrum of SN 1993J from day 182 (1993 September 25) with line identifications. The flux-density scale is linear and has been scaled to match the *V*-band photometry of Richmond et al. (1996).

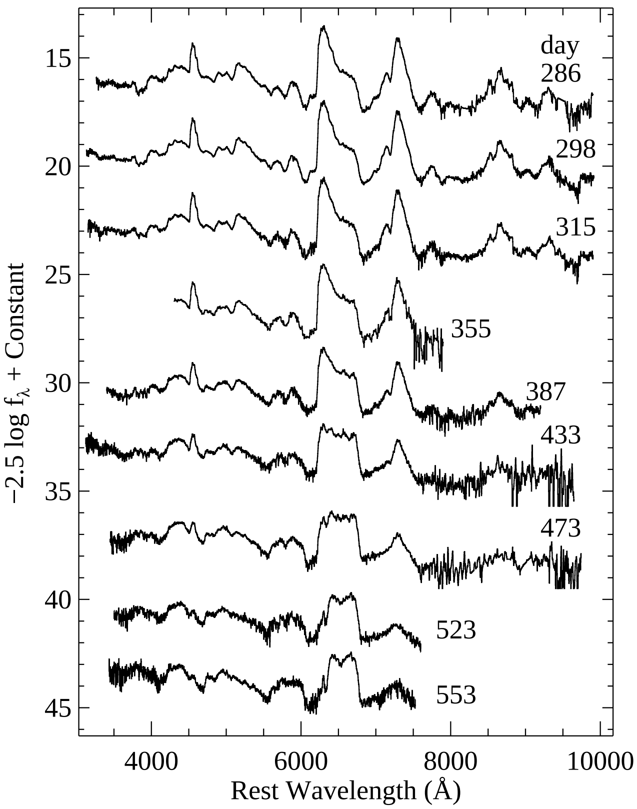

FIG. 7.—Spectra of SN 1993J from days 286 to 553, with date of explosion and flux units as in Fig. 1. The following constants have been added to the individual spectra (*top to bottom*): 0.0, 2.5, 5.5, 7.5, 12.5, 15.5, 19.0, 22.0, and 25.0. Noisy spectra have been clipped for clarity.

1993J—one dominated by the effects of circumstellar interaction. This profile for Hα is discernible as early as day 298, perhaps even day 226, but it does not dominate the emission until day 473 and beyond. These emission profiles imply a roughly spherical distribution for the source material, probably a geometrically thin shell, similar to that discussed above in the context of late-time radio observations. The nature of the spectra is very similar to that described by Chevalier & Fransson (1994). Another interesting aspect of the day 387 spectrum (and earlier spectra) is the presence of small-scale features in some of the emission lines. They are even more evident in Figure 9, wherein the region of the spectrum containing [O I] $\lambda\lambda$6300 6364 and Hα is shown in greater detail, along with the HIRES spectrum obtained four days earlier. A full exploration of the clumps exhibited in the spectra of SN 1993J is presented in Paper II.

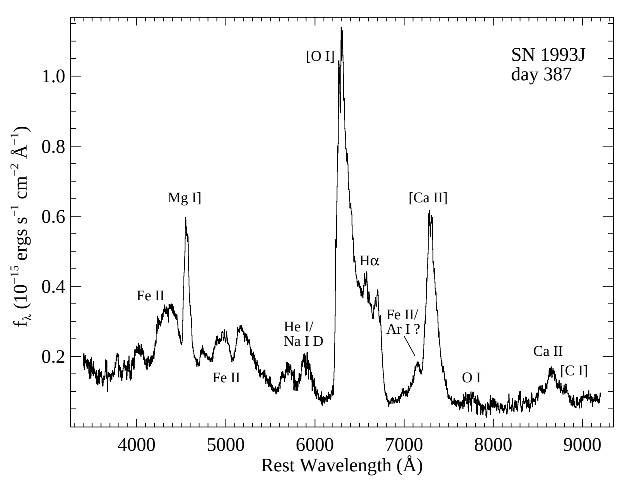

FIG. 8.—Spectrum of SN 1993J from day 387 (1994 April 18) with line identifications. The flux-density scale is linear and has been scaled to match the *V*-band photometry of Richmond et al. (1996).

4.5. *Days 670 to 2454*

Circumstellar interaction continues to dominate the spectra of SN 1993J up to the most recent observations. Spectra from days 670 through 2454 are shown in Figure 10. The box-like profiles are especially obvious in the day 976 spectrum (Fig. 11). While these profiles are present earlier, the high S/N ratio of this spectrum allows one to see clearly the "double-box" created by the overlapping lines of He I λ5876 and Na I D.

One striking change that occurs during this period is highlighted by the spectra from day 976 (Fig. 11) and day 1766 (Fig. 12). There appear to be narrower emission features on top of the boxy profiles for [O III] $\lambda\lambda$4959, 5007 and [O II] $\lambda\lambda$7319, 7330 on day 1766 that are not obvious in the day 976 spectrum. Unfortunately, there is a large gap in the coverage at this point, so it is not known when these features appeared. They do show up at the same relative velocity in each profile (including the [O I] $\lambda\lambda$6300, 6364 doublet), indicating that they are related to the underlying oxygen lines. We interpret these features as the blue and red peaks of a double-horned profile due to a somewhat flattened, perhaps even disk-like emission source, with the red peak attenuated by absorption (see Paper II for details). They are superposed on the box-like profile from a roughly spherically distributed source. This is especially intriguing in light of the polarization measurements done at early times (Trammell et al. 1993; Tran et al. 1997).

With the knowledge of the day 1766 spectrum, the incipient beginnings of these features are discernible in the day 976 spectrum. In fact, the day 976 spectrum shows the weak, narrow remnant of the once prominent [O I] λ6300 line still

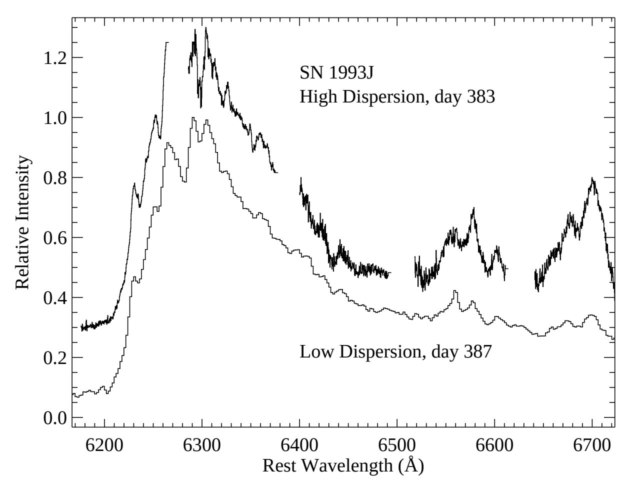

FIG. 9.—Low-resolution spectrum of SN 1993J on day 387 compared with a high-resolution spectrum on day 383 (1994 April 14). The high-resolution spectrum has been binned to 0.25 Å pixel^{-1} for clarity. The global shape of each order of the high-resolution spectrum is not necessarily accurate. The substructure seen in the low-dispersion spectrum is reflected in the high-dispersion spectrum, and there is no apparent structure hidden by the lower resolution of the low-dispersion spectrum.

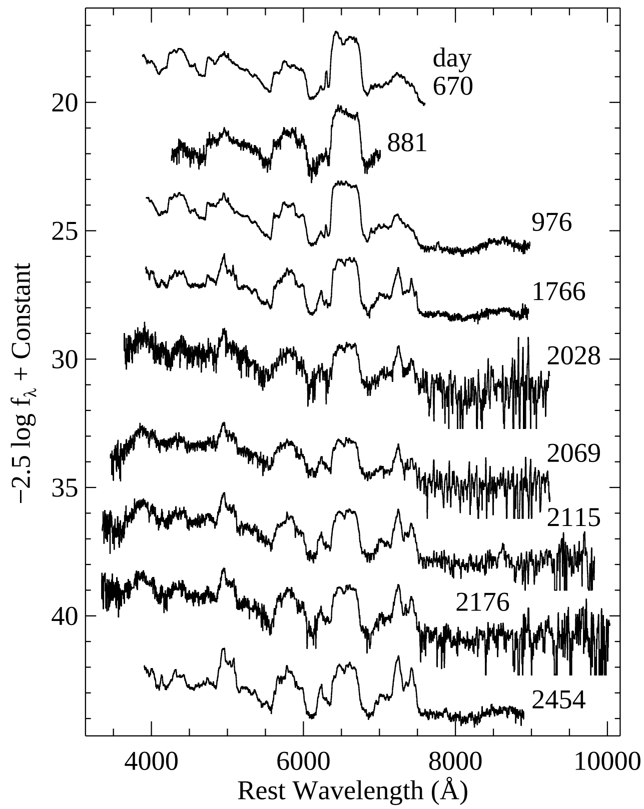

FIG. 10.—Spectra of SN 1993J from days 670 to 2454, with date of explosion and flux units as in Fig. 1. The following constants have been added to the individual spectra (*top to bottom*): 0.0, 3.5, 6.5, 7.5, 10.5, 15.0, 17.5, 20.0, and 22.5. Noisy spectra have been clipped for clarity.

present, but fading in comparison with the blue component of the two-horned profile of [O I]. These features persist, being strongly evident in the day 2454 spectrum (Fig. 13).

The only other significant change in the later spectra is the strengthening of [O III] $\lambda\lambda$4959, 5007 relative to [O III] λ4363, indicating a drop in the density of the oxygen-emitting regions. The [O I] $\lambda\lambda$6300, 6364 doublet begins to grow again relative to Hα. These changes are especially clear when comparing the day 2454 spectrum (Fig. 13) with the day 976 spectrum (Fig. 11). Note that there is very little change between days 2176 and 2454 (see Fig. 10). The overall spectra exhibit almost solely the emission from circumstellar interaction. The line-intensity ratios are generally similar to the predictions of Chevalier & Fransson (1994), although some differ. Details of this analysis of the late-time spectral lines is presented in Paper II.

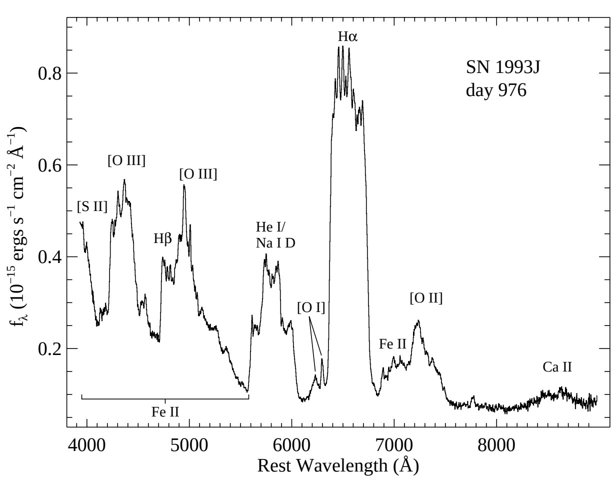

FIG. 11.—Spectrum of SN 1993J from day 976 (1995 November 28) with line identifications. The flux-density scale is linear.

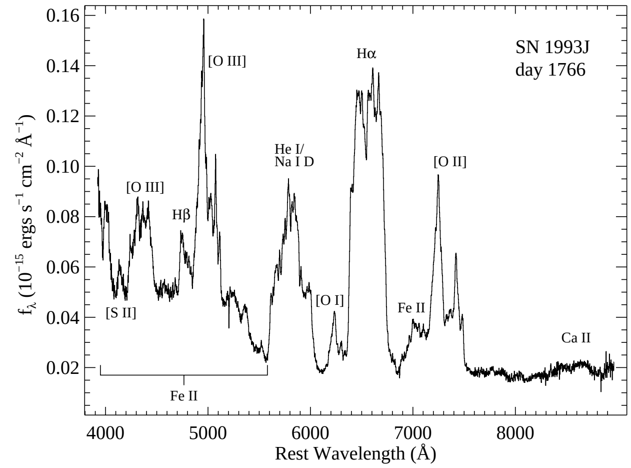

FIG. 12.—Spectrum of SN 1993J from day 1766 (1998 January 26) with line identifications. The flux-density scale is linear.

5. CONCLUSIONS

We have presented the complete existing collection of low-dispersion spectra of SN 1993J obtained at Lick and Keck observatories, as well as one high-dispersion spectrum from Keck. These 42 low-dispersion spectra, representing coverage from day 3 after explosion to day 2454, document thoroughly the distinctive characteristics of SN 1993J. The early spectra show a slightly unusual Type II event, followed by the appearance of strong helium absorption lines. After SN 1993J underwent this metamorphosis from Type II to IIb, the nebular phase developed rapidly, appearing as a typical late-time SN Ib or SN Ic, but with a weak residual Hα line. As the nebular lines weakened, new line profiles emerged with box-like shapes implying circumstellar inter-

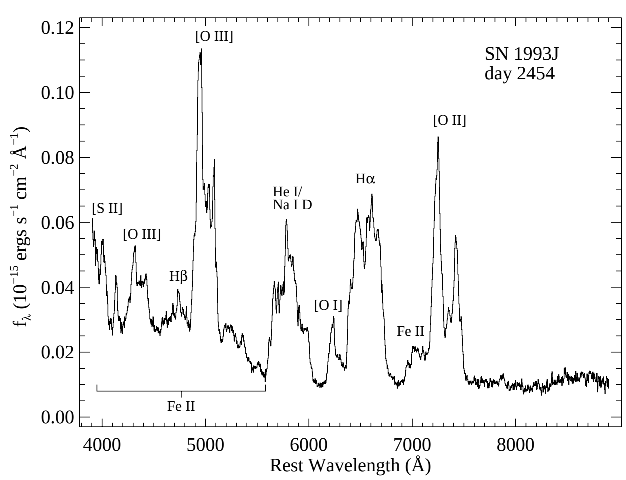

FIG. 13.—Spectrum of SN 1993J from day 2454 (1999 December 15) with line identifications. The flux-density scale is linear. There is some second-order contamination of the spectrum beyond ~7600 Å, although it is not significant; as Fig. 10 shows, there is little structure in this region of the spectrum on earlier days.

action with a spherical shell-like distribution. At even later times, double-horned profiles appeared on top of the box profiles, indicating the presence of a somewhat flattened or disk-like morphology along with the shell. As SN 1993J appears to be fading slowly (see Paper II), we plan to continue monitoring it spectroscopically for years to come. The metamorphosis in our spectra was discussed by FMH93, while the nebular spectra were analyzed by FMB94. Our study of the detailed line structure at relatively early times and the circumstellar interaction phase is presented in Paper II.

This research was supported by NSF grants AST 91-15174 and AST 94-17213 to A.V. F. We are grateful to the staffs of the Lick and Keck observatories for help with the observations; we are especially thankful to the Lick staff for their heroic efforts in reconfiguring the hardware and software of the equatorial Shane 3 m telescope to allow us to observe "under the pole" during the summer months of 1993 and 1994. William and Marina Kast provided a generous gift that led to the construction of the double spectrograph on the 3 m telescope that was used for most of the observations reported here. The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA. The observatory was made possible by the generous financial support of the W. M. Keck Foundation. Robert H. Becker and Richard L. White graciously provided the 1993 June 24 (day 89) spectrum. We thank Alison Coil, Ryan Chornock, Isobel Hook, Chien Peng, Saul Perlmutter, Adam Riess, Hien Tran, and Schuyler Van Dyk for assistance with some of the observations and reductions.

REFERENCES

Aldering, G., Humphreys, R. M., & Richmond, M. 1994, AJ, 107, 662
Barbon, R., Benetti, S., Cappellaro, E., Patat, F., Turatto, M., & Iijima, T. 1995, A&AS, 110, 513
Barbon, R., Ciatti, F., & Rosino, L. 1973, A&A, 25, 241
Baron, E., Hauschildt, P. H., & Branch, D. 1994, ApJ, 426, 334
Baron, E., Hauschildt, P. H., Branch, D., Wagner, R. M., Austin, S. J., Filippenko, A. V., & Matheson, T. 1993, ApJ, 416, L21
Bartel, N., et al. 2000, Science, 287, 112
———. 1994, Nature, 368, 610
Bartunov, O. S., Blinnikov, S. I., Pavlyuk, N. N., & Tsvetkov, D. Yu. 1994, A&A, 281, L53
Benetti, S., Patat, F., Turatto, M., Contarini, G., Gratton, R., & Cappellaro, E. 1994, A&A, 285, L13
Benson, P. J., et al. 1994, AJ, 107, 1453
Blinnikov, S. I., Eastman, R., Bartunov, O. S., Popolitov, V. A., & Woosley, S. E. 1998, ApJ, 496, 454
Branch, D., Jeffery, D. J., Blaylock, M., & Hatano, K. 2000, PASP, 112, 217
Branch, D., Nomoto, K., & Filippenko, A. V. 1991, Comm. Ap., 15, 221
Bowen, D. V., Roth, K. C., Blades, J. C., & Meyer, D. M. 1994, ApJ, 420, L71
Chevalier, R. A. 1982, ApJ, 259, 302
———. 1984, ApJ, 285, L63
Chevalier, R. A., & Fransson, C. 1994, ApJ, 420, 268
Clocchiatti, A., Wheeler, J. C., Barker, E. S., Filippenko, A. V., Matheson, T., & Liebert, J. W. 1995, ApJ, 446, 167
Cohen, J. G., Darling, J., & Porter, A. 1995, AJ, 110, 308
Doggett, J. B., & Branch, D. 1985, AJ, 90, 2303
Doroshenko, V. T., Efimov, Yu. S., & Shakhovskoi, N. M. 1995, Astron. Lett., 21, 513
Eastman, R. G., Schmidt, B. P., & Kirshner, R. 1996, ApJ, 466, 911
Fassia, A., Meikle, W. P. S., Geballe, T. R., Walton, N. A., Pollacco, D. L., Rutten, R. G. M., & Tinney, C. 1998, MNRAS, 299, 150
Filippenko, A. V. 1982, PASP, 94, 715
———. 1988, AJ, 96, 1941
———. 1992, ApJ, 384, L37
———. 1997, ARA&A, 35, 309
Filippenko, A. V., & Matheson, T. 1993, IAU Circ. 5787
Filippenko, A. V., Matheson, T., & Barth, A. J. 1994, AJ, 108, 2220 (FMB94)
Filippenko, A. V., Matheson, T., & Ho, L. C. 1993, ApJ, 415, L103 (FMH93)
Filippenko, A. V., Treffers, R. R., Paik, Y., Davis, M., & Schlegel, D. 1993, IAU Circ. 5731
Finn, R. A., Fesen, R. A., Darling, G. W., Thorstensen, J. R., & Worthey, G. S. 1995, AJ, 110, 300
Fransson, C., Lundqvist, P., & Chevalier, R. A. 1996, ApJ, 461, 993
Freedman, W. L., et al. 1994, ApJ, 427, 628
Garnavich, P., & Ann, H. B. 1993, IAU Circ. 5731 (erratum 5733 [1993])
———. 1994, AJ, 108, 1002
Gaskell, C. M., Cappellaro, E., Dinerstein, H. L., Garnett, D. R., Harkness, R., P., & Wheeler, J. C. 1986, ApJ, 306, L77
Hashimoto, M., Iwamoto, K., & Nomoto, K. 1993, ApJ, 414, L105
Ho, L. C., & Filippenko, A. V. 1995, ApJ, 444, 165 (erratum 463, 818 [1996])
Höflich, P. 1995, ApJ, 440, 821
Höflich, P., Langer, N., & Duschinger, M. 1993, A&A, 275, L29
Höflich, P., Wheeler, J. C., Hines, D. C., & Trammell, S. R. 1996, ApJ, 459, 307
Horne, K. 1986, PASP, 98, 609
Houck, J. C., & Fransson, C. 1996, ApJ, 456, 811
Jeffery, D. J., Branch, D., Filippenko, A. V., & Nomoto, K. 1991, ApJ, 377, L89
Jeffery, D. J., et al. 1994, ApJ, 421, L27
Kohmura, Y., et al. 1994, PASJ, 46, L157
Koorneef, J., Bohlin, R., Buser, R., Horne, K., & Turnshek, D. 1986, in Highlights of Astronomy, vol. 7, ed. J. P. Swings (Dordrecht: Reidel), 833
Leising, M. D., et al. 1994, ApJ, 431, L95
Lewis, J. R., et al. 1994, MNRAS, 266, L27
Li, A., Hu, J., Wang, L., Jiang, X., & Li, H. 1994, Ap&SS, 211, 323
Marcaide, J. M., et al. 1994, ApJ, 424, L25
———. 1995, Nature, 373, 44
———. 1997, ApJ, 486, L31
Massey, P., & Gronwall, C. 1990, ApJ, 358, 344
Matheson, T., Filippenko, A. V., Ho, L. C., Barth, A. J., & Leonard, D. C. 2000, AJ, 120, 1499 (Paper II)
Metlova, N. V., Tsvetkov, D. Yu., Shugarov, S. Yu., Esipov, V. F., & Pavlyuk, N. N. 1995, Astron. Lett., 21, 598
Miller, J. S., & Stone, R. P. S. 1993, Lick Obs. Tech. Rep., No. 66
Nomoto, K., Suzuki, T., Shigeyama, T., Kumagai, S., Yamaoka, H., & Saio, H. 1993, Nature, 364, 507
Ohta, K., Maemura, H., Ishigaki, T., Aoki, K., & Ohtani, H. 1994, PASJ, 46, 117
Oke, J. B., et al. 1995, PASP, 107, 375
Oke, J. B., & Gunn J. E. 1983, ApJ, 266, 713
Okyudo, M., Kato, T., Ishida, T., Tokimasa, N., & Yamaoka, H. 1993, PASJ, 45, L63
Patat, F., Chugai, H., & Mazzali, P. A. 1995, A&A, 299, 715
Podsiadlowski, Ph., Hsu, J. J. L., Joss, P. C., & Ross, R. R. 1993, Nature, 364, 509
Pooley, G. G., & Green, D. A. 1993, MNRAS, 264, L17
Prabhu, T. P., et al. 1995, A&A, 295, 403
Qiu, Y., Li, W., Qiao, Q., & Hu, J. 1999, AJ, 117, 736
Ray, A., Singh, K. P., & Sutaria, F. K. 1993, J. Astrophys. Astron., 14, 53
Richmond, M. W., Treffers, R. R., Filippenko, A. V., Paik, Y., Leibundgut, B., Schulman, E., & Cox, C. V. 1994, AJ, 107, 1022
Richmond, M. W., Treffers, R. R., Filippenko, A. V., & Paik, Y. 1996, AJ, 112, 732
Ripero, J., Garcia, F., & Rodriguez, D. 1993, IAU Circ. 5731
Schmidt, B. P., et al. 1993, Nature, 364, 600
Shigeyama, T., Suzuki, T., Kumagai, S., Nomoto, K., Saio, H., & Yamaoka, H. 1994, ApJ, 420, 341
Spyromilio, J. 1994, MNRAS, 266, L61
Stone, R. P. S. 1977, ApJ, 218, 767
Suzuki, T., & Nomoto, K. 1995, ApJ, 455, 658
Swartz, D. A., Clocchiatti, A., Benjamin, R., Lester, D. F., & Wheeler, J. C. 1993, Nature, 365, 232
Taniguchi, Y., Murayama, T., Sato, Y., Yadoumaru, Y., Ohyama, Y., Kosugi, G., Yoshida, M., & Kurakami, T. 1993, PASJ, 45, L43
Terndrup, D. M., Lauer, T. R., & Stover, R. 1984, Lick Obs. Tech. Rep., No. 33
Trammell, S. R., Hines, D. C., & Wheeler, J. C. 1993, ApJ, 414, L21
Tran, H. D., Filippenko, A. V., Schmidt, G. D., Bjorkman, K. S., Jannuzi, B. T., & Smith, P. S. 1997, PASP, 109, 489
Turatto, M., et al. 1998, ApJ, 498, L129
Utrobin, V. 1994, A&A, 281, L89
———. 1996, A&A, 306, 219
van Driel, W., et al. 1993, PASJ, 45, L59
Van Dyk, S. D., Weiler, K. W., Sramek, R. A., Rupen, M. P., & Panagia, N. 1994, ApJ, 432, L115
Vladilo, G., Centurión, M., de Boer, K. S., King, D. L., Lipman, K., Stegert, J. S. W., Unger, S. W., & Walton, N. A. 1993, A&A, 280, L11
———. 1994, A&A, 291, 425
Vogt, S. S. 1992, in Proc. ESO Workshop 40, High Resolution Spectroscopy with the VLT, ed. M.-H. Ulrich (Garching: ESO), 223
———. 1994, UCO/Lick Obs. Tech. Rep. No. 76
Wade, R. A., & Horne, K. D. 1988, ApJ, 324, 411

Wang, L., Howell, D. A., Höflich, P., & Wheeler, J. C. 2000, ApJ, submitted (astro-ph/9912033)
Wang, L., & Hu, J. 1994, Nature, 369, 380
Weiler, K. W., Panagia, N., & Sramek, R. A. 1990, ApJ, 364, 611
Weiler, K. W., Sramek, R. A., Panagia, N., van der Hulst, J. M., & Salvati, M. 1986, ApJ, 301, 790
Wheeler, J. C., et al. 1993, ApJ, 417, L71
Wheeler, J. C., & Filippenko, A. V. 1996, in Supernovae and Supernova Remnants, ed. R. A. McCray & Z. Wang (Cambridge: Cambridge University Press), 241
Wild, P. 1960, PASP, 72, 97
Williams, R. 1987, ApJ, 320, L117
Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. A. 1994, ApJ, 429, 300
Woosley, S. E., Pinto, P. A., Martin, P. G., & Weaver, T. A. 1987, ApJ, 318, 664
Young, T. R., Baron, E., & Branch, D. 1995, ApJ, 449, L51
Zhang, Q., & Wang, Z. R. 1996, A&A, 307, 166
Zimmerman, H.-U., et al. 1994, Nature, 367, 621