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SN 1993J in M 81: One year of observations at Asiago*

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Abstract. — The observations of SN 1993J in M 81, obtained at Asiago throughout the first year after explosion and consisting of about 80 photometric measurements and 40 spectra, are presented. The light curve has been found peculiar showing two maxima similar to SN 1987A but with a faster evolution. In the late phases, two regimes in the luminosity decline are identified, with the radioactive exponential tail setting in around day 150 and showing a rate of decline similar to that of SNIa. Although the absorption correction to be applied is still controversial, the intensity of the interstellar NaI lines indicates a moderately strong reddening which imply an absolute magnitude $M_B = -17.6$ at secondary maximum. Also the spectral evolution is peculiar with the type II signatures leaving place, a few weeks after the explosion, to those ones of type Ib, although some H emissions remain visible. High resolution profiles of forbidden OI lines reveal the presence of clumping in the ejecta.

Key words: supernovae: SN 1993J

1. Introduction

SN 1993J was discovered on March 28.9 U.T. by F. Garcia, projecting on an inner spiral arm of the nearby galaxy M 81 (Ripero 1993). The early spectra showed broad Balmer lines on a blue continuum. On this basis the supernova was classified of type II. Later on, however, with the fading of hydrogen and the appearance of helium lines the spectrum appeared more similar to that of SNIb (Filippenko et al. 1993; Swartz et al. 1993). A spectroscopic metamorphosis of this kind has been observed previously only in SN 1987K (Filippenko 1988). Also the light curve exhibited a peculiar behaviour with a first maximum attained on March 30, followed by a short decline and a new rise to a secondary maximum on April 18. This photometric behaviour, although on a much shorter time scale, was reminiscent of that of SN 1987A.

Due to the short distance, this SN has been extensively observed along the whole electromagnetic spectrum with telescopes from the ground and in orbit (see Wheeler & Filippenko 1994 for a preliminary discussion). Early optical observations have been reported by Wheeler at al. (1993) while high dispersion spectroscopy close to the first maximum has been reported by Benetti et al. (1994), Vladilo et al. (1993) and Bowen et al. (1994). A spectroscopic atlas and light curves from day 2 to day 125 has been published by Lewis et al. (1994). Additional *UBVRI* photometry in the first 120 days has been given by Richmond et al. (1994).

In this paper we present and describe the spectroscopic and photometric observations made at Asiago Observatory starting soon after the announcement of the discovery and through the first year since outburst. A detailed analysis of this data will be left to future works.

2. Observations and reductions

Photometric observations of SN 1993J have been made with the CCD camera of the 1.8 m telescope and with an experimental CCD camera at the 1.2 m reflector of the Asiago Observatory.

The calibrations of the photometric systems were obtained by observations of standard stars from the lists of Landolt (1983, 1992). When the nights were not photometric, the standard stars were used only for determining the color terms of the systems while the zero points were fixed by the local standards stars measured in the photometric nights. These last measures have been found in good agreement with the magnitudes reported in Table 1 of Lewis et al. (1994). The SN magnitude was derived using the Romafot package in MIDAS. This method has been proved to give more reliable results compared

*Based on observations collected at the Asiago Observatory, Italy to straight aperture photometry expecially when the SN fades and the contamination of the background is not negligible (cf. Turatto et al. 1993). The errors of the CCD photometry are of the order of a few hundredth of magnitudes.

A number of plates of the Asiago 67/92 Schmidt telescope were also obtained. In this case the magnitude of the SN was estimated by eye against the standard sequences around M 81 published by Brandt et al. (1972) and Sandage (1984), along with the three local standards close to the supernova and mentioned by Lewis et al. (1994). The resulting V and B magnitudes were found in fair agreement with those published by Lewis et al. (1994).

Table 1 reports our photometry and in Fig. 1 our data are compared with those from literature.

Spectroscopic observations of the supernova have been obtained both with the 1.8 m and the 1.2 m telescopes. At the 1.8 m the echelle spectrograph has first been used and the results have been published elsewhere (Benetti et al. 1994). With the same telescope the Boller & Chivens spectrograph (+CCD) has extensively been used providing spectra in the range 3500−9500 Å with resolution from 10 to 22 Å. At some epochs spectra have also been obtained at a higher resolution to study the clumpiness in Hα and in the forbidden OI lines. The flux calibration was obtained through observations of standard stars from the lists of Oke (1974) and Stone (1977). Due to maintenance of the 1.8 m, in May 1993 the SN was followed with the 1.2 m telescope equipped with a prismatic spectrograph and RCA image intensifier providing spectra in the range 4000−7000 Å with a resolution of 4 Å at Hβ. For a reliable flux calibration of these spectra, the nearby star SAO 015020 has been used as secondary spectrophotometric standard. Its flux calibration, eventually secured at the 1.8 m telescope, allowed the determination of the wavelength dependent sensitivity of the system.

Table 1. Photometry of SN 1993J from Asiago observations

Date	JD +2440000	B	V	R	I	Tel.
30/03/93	9077.50	10.8	10.75			67
10/04/93	9088.40		11.39	10.94		122
10/04/93	9088.40		11.31	10.89		122
15/04/93	9093.38		10.86	10.45		122
15/04/93	9093.38		10.85	10.47		122
16/04/93	9094.47	11.55	10.85			67
18/04/93	9096.40		10.91	10.4		122
18/04/93	9096.40			10.32		122
18/04/93	9096.50		10.75			67
19/04/93	9097.37		10.87	10.37		122
19/04/93	9097.37		10.88	10.38		122
19/04/93	9097.40	11.55	10.85			67
21/04/93	9099.33		10.98	10.44		122
21/04/93	9099.33		11.01	10.45		122
22/04/93	9100.33		11.05	10.49		122
22/04/93	9100.33		11.07	10.5		122
23/04/93	9101.46			10.64		182
23/04/93	9101.46	12.08	11.16	10.66	10.49	182
23/04/93	9101.46	12.07	11.17	10.64	10.48	182
26/04/93	9104.31		11.43	10.79		122
27/04/93	9105.33		11.51	10.86		122
18/06/93	9157.38	13.95	12.95			67
15/10/93	9275.58	15.65	15.19	14.53		182
15/10/93	9275.58	15.63	15.18	14.52		182
08/11/93	9300.44	16.25	15.36			67
17/11/93	9308.55	16.35				67
18/11/93	9310.47		15.45			67
11/12/93	9333.60			15.19		182
11/12/93	9333.60	16.31	16.01	15.22		182
15/01/94	9368.46	17.07	16.62	15.86		182
15/01/94	9368.46		16.69			182
10/02/94	9394.39	17.36	17.05	16.19	16.29	182
10/02/94	9394.39	17.33	17.02	16.19	16.25	182
12/03/94	9423.50	17.73	17.41	16.54	16.73	182
13/03/94	9424.50	17.78	17.38	16.55	16.73	182

67 = Schmidt 67/92 cm (103aO+GG13 for B and 103aD+GG14 for V)
122 = 1.2 m telescope + EEV CCD (770×1152 px)
182 = 1.8 m reflector + TK512M CCD (512×512 px)

3. The light curve

The early photometric behaviour of SN 1993J was already discussed by other authors (e.g. Lewis et al. 1994; Richmond et al. 1994). Lewis et al. (1994) estimated March 27.5 as the day of explosion and in the following this epoch will be taken as reference.

The peculiar light curve of the SN is shown in Fig. 1 in which our new observations are reported along with data from literature. The two–peak shape of the light curve is evident. Indeed we find a good resemblance of the B light curve of SN 1993J with that of SN 1987A when reducing by a factor of 4 the time axis of the latter.

After the first maximum, which is related to the emergence of the shock wave at the photosphere, the luminosity of SN 1993J decreased rapidly in all the photometric bands (in SN 1987A the early decrease was seen only in U and B). This phase lasted about one week with the luminosity decline being faster at short wavelengths ($\beta_U = 0.51$, $\beta_B = 0.35$ mag d^{-1}) than at longer ones ($\beta_V = 0.28$, $\beta_R = 0.22$, $\beta_I = 0.16$ mag d^{-1}).

In the following two weeks the energy release by ^{56}Ni–^{56}Co decay became relevant and the luminosity rose at all wavelengths until a second maximum. This second peak was narrower than in 1987A and this has been interpreted as an indication of the smaller hydrogen envelope mass in SN 1993J (e.g. 0.9 $M_\odot$, Nomoto et al. 1993, 0.4 $M_\odot$, Wheeler et al. 1993). The second peak is well defined by our V and R observations yielding, respectively, $V = 10.84$ mag at JD 2449095.4 and $R = 10.36$ mag at JD 2449096.4. These data are in good agreement with those published by Wheeler et al. (1993) and Richmond et al. (1994). Then followed a phase of rapid luminosity decline lasting about 3 weeks. Again, the decline rates were faster at the shorter wavelengths.

From about May 10 (about 40 days past explosion) a roughly exponential tail settled in. Even if the data are

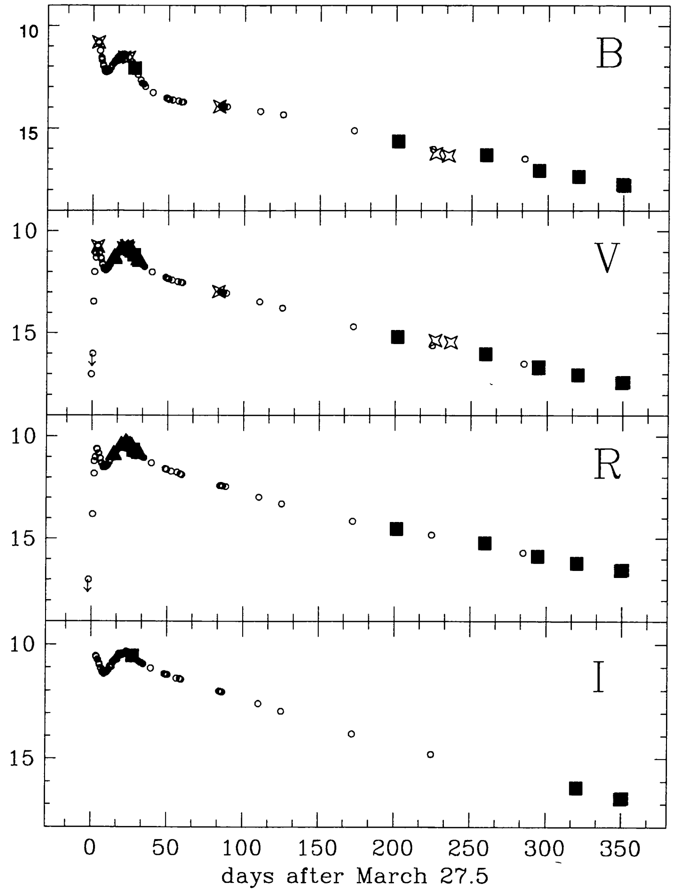

Fig. 1. The light curves of SN 1993J in B, V, R, I. Circles are data from the literature (mainly from IAU Circulars and from the Supernova Data Archive of RGO), stars from the Schmidt 67/92 cm, squares from the 1.8 m and triangles from the 1.2 m telescope

scanty there is an indication of two different regimes in the late luminosity decline. As shown in Table 2, in the range 45−150 days, the rates in the various bands are different and, contrary to the earlier phases, the shorter wavelengths are, in average, fading slower than the redder ones. Clearly this reflects a significant spectral evolution in this phase range (see next section). Instead, between 150 and 350 days the slopes in the various bands are similar, suggesting the onset of the radioactive decay tail. We note that also in normal type II SNe this tail sets in at about the same phase (Barbon et al. 1984; Turatto et al. 1990) and, in analogy to what found for 1987A, also for this SN the V decline rate turns out to be very similar to the $UBVRI$ bolometric luminosity decline (Lewis et al. 1994).

Because of the peculiar spectroscopic evolution, it was expected that the late light curve of SN 1993J resembled that of SNIb. Nomoto et al. (1993) noted a close resemblance of the secondary maximum with the light curve of 1983N and Richmond et al. (1994) detected similarities

Table 2. Luminosity decline rates of SN 1993J (mag 100 d^{-1})

	45–150 d	150–350 d
B	0.95	1.40
V	1.90	1.56
R	2.21	1.38
I	2.07	1.57

also at late phases. However their comparison was limited to the first 2 months past maximum.

The available observations of the late light curves of SNIb are still very scanty. The late decline rates of the two SNIb 1984L and 1985F were examined in Turatto et al. (1990). New observations are now available for the late light curves of other SNIb, e.g. SN 1990I (ESO KP on SNe in preparation). It appears that, contrary both to SNIa and to SNII having homogeneous photometric evolution after 150 days, SNIb exhibit individual behaviours. Some have decline rates not dissimilar to SNII (about 1 mag 100 d^{-1}) while others, in particular SN 1990I, show a much steeper decline (about 2 mag 100 d^{-1}). SN 1993J, having the declines rates listed in Table 2, has an intermediate behaviour which, somehow unexpected, resembles that of SNIa (1.5 mag 100 d^{-1}).

The rate of luminosity decline in the exponential tail is equal to the radioactive decay rate if the γ-ray trapping is complete as it is true in normal SNII within 2 years from outburst. Faster decline rates indicate a decreasing efficiency of the trapping. Considering that SN 1993J is thought to be the outcome of the core collapse of a H–deprived massive star, whereas SNIa derive from the explosion of small mass stars, it is surprising that the fraction of γ-ray escaping from the ejecta is similar in the two cases. This may be related to the small amount of mass ejected in SN 1993J.

The estimate of the absolute magnitude of this nearby supernova is hampered by the still uncertain correction due to absorption. $E(B-V)$ estimates in the literature range from 0.08 up to 0.4 mag, depending on which calibrator one is trusting (Benetti et al. 1994; Richmond et al. 1994). At this regard, it is interesting to note that applying the empirical relation between reddening and equivalent width of the interstellar NaI lines given by Barbon et al. (1990), and assuming for the latter the average value measured in our spectra, EW(NaID)= 1.3 ± 0.2 Å, we find $E(B-V) = 0.3$ mag, thus supporting the presence of a relatively large extinction. With B= 11.39 at secondary peak, adopting the Cepheids based distance modulus $\mu = 27.8$ mag to M 81 (Freedman et al. 1994), SN 1993J should have brightened up to $M_B = -17.6$ mag, a value similar to that of other type Ib supernovae.

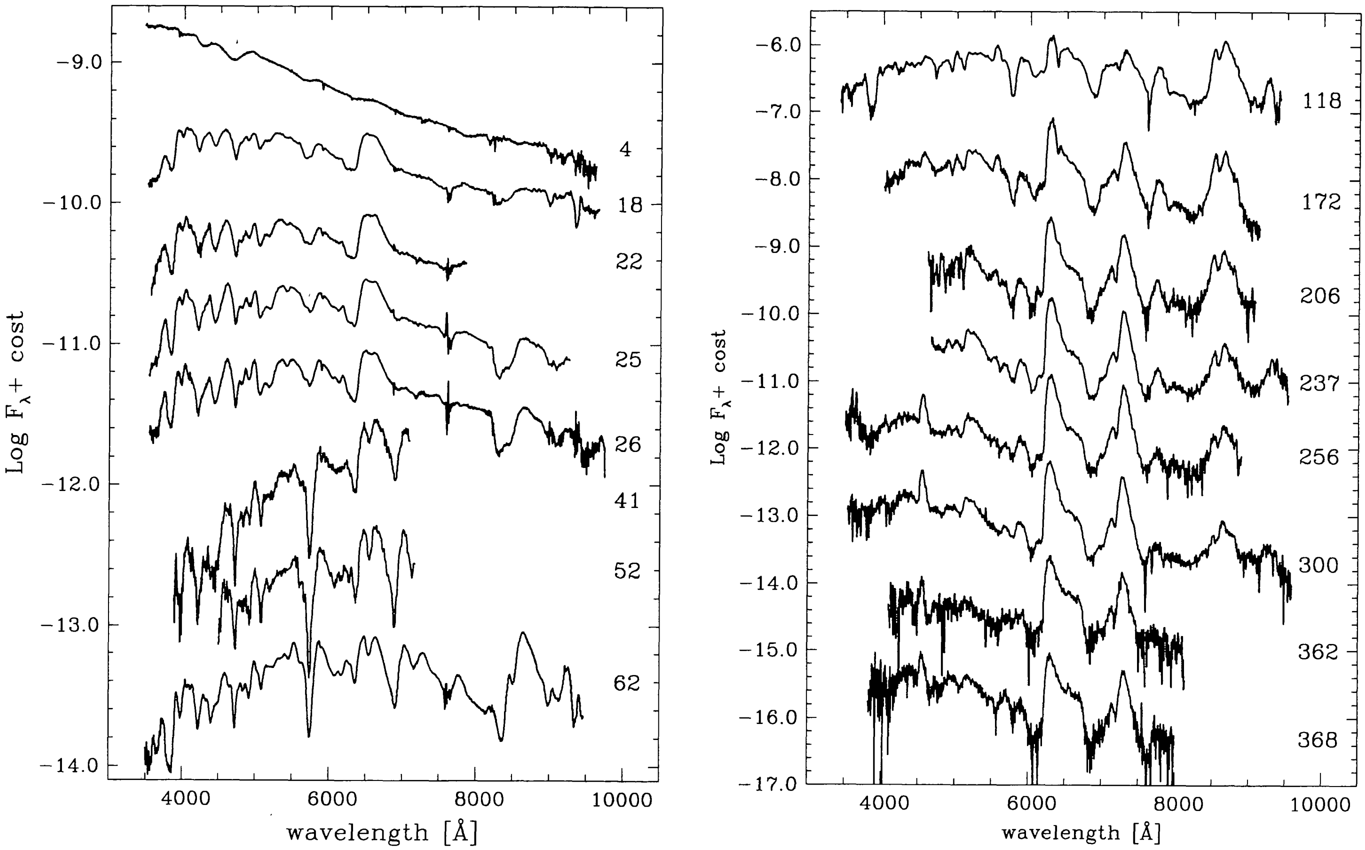

Fig. 2. Spectral evolution of SN 1993J in the first year past explosion. Fλ units are erg cm^{-2} s^{-1} Å^{-1}. Constant added to the spectra are as follow: left panel: 4d +3.7, 18d +3.2, 22d +2.7, 25d +2.1, 26d +1.7, 41d +0.9, 52d +0.9, 62d 0; right panel; 118d +7.7, 172d +6.7, 206d +5.7, 237d +4.2, 256d +3.3, 300d +1.3, 362d +1.2, 368d 0

4. Spectroscopic evolution

We have monitored spectroscopically SN 1993J starting a few days after explosion and up to one year. In Table 3 we give the log of the observations and in Fig. 2 the evolution of the spectrum is presented.

On our first available spectrum, taken on day 4, only a few features are visible superimposed on a blue continuum with a black body temperature between 12000 K and 18000 K depending on the adopted extinction correction. On the spectrum are visible the signatures of the interstellar gas, i.e. the NaID and the H and K CaII lines.

While Hα shows a very broad and almost purely emission profile, the other features, identified with Hβ, Hγ (blended with HeI λ4471) and HeI λ5876, present a clear P-Cygni profile. The expansion velocity, derived from the minimum of the absorption through of the Hβ line, is 10500 km s^{-1}, while that deduced for the HeI λ5876 is 8300 km s^{-1}. It is worthwhile to note that the broadness of the features, the steepness of the continuum and the likely presence of blending with lines from other species make the measures quite uncertain and this fact might explain part of the discrepancies with the HeI velocity estimated by Wheeler et al. (1993) at the same epoch.

In the following three weeks the SN develops strong features of which the strongest is the P-Cygni profile of Hα. Both the emission and absorption component of this line have a flat profile indicating the presence of an expanding, geometrically thin H shell. Moreover the absorption/emission intensity ratio for this line is clearly lower than that of all the other observed features and this may give some indications of the structure of the outer layer. Among others, the following lines can be identified: HeI λ5876 (blended with NaI λ5892) , HeI λ5015 (probably blended with FeII λ5018), Hβ and Hγ (blended with the HeI λ4471 line). S-process element lines (i.e. ScII, SrII and BaII), which were strong in SN 1987A at this phase (Mazzali et al. 1992), are in SN 1993J much fainter.

The simultaneous presence of strong H and HeI lines makes difficult the measurements of the line parameters. In Table 4 we list the wavelengths, in the observer's frame, of the P-Cygni absorptions of the more readable lines and their velocity evolution is displayed in Fig. 3. The higher values of the Hα velocity, if compared to that of SN 1987A, are probably due to the less amount of material ejected by SN 1993J.

Table 3. Journal of the spectroscopic observations

JD +2440000	phase [days]	telescope instrument	range [Å]	R [Å]
9078.35	4	1.8+B&C/300	3500-9500	11
9078.57	4	1.8+B&C/1200	3600-4100	2.5
9079.35	5	1.8+B&C/150	3500-7500	22
9084.55	10	1.2+A/VI	4000-7000	4
9092.63	18	1.8+B&C/150	3500-9500	22
9093.44	19	1.8+B&C/150	3500-9000	22
9096.44	22	1.8+B&C/150	3500-8000	22
9098.37	24	1.8+B&C/150	3500-9000	22
9098.53	24	1.8+B&C/150	3500-9000	22
9099.39	25	1.8+B&C/150	3500-9000	22
9099.52	25	1.8+B&C/1200	6000-7000	2.5
9100.37	26	1.8+B&C/300	3500-9500	11
9100.53	26	1.8+B&C/300	3500-9500	11
9111.54	37	1.2+A/VI	4000-7000	4
9115.40	41	1.2+A/VI	4000-7000	4
9121.43	47	1.2+A/VI	4000-7000	4
9124.43	50	1.2+A/VI	4000-7500	4
9126.59	52	1.2+A/VI	4000-7300	4
9128.38	54	1.2+A/VI	4000-7300	4
9131.41	57	1.2+A/VI	4000-7300	4
9133.45	59	1.2+A/VI	4000-7300	4
9136.39	62	1.8+B&C/150	3500-9500	22
9136.53	62	1.8+B&C/600	6000-7100	6
9142.51	68	1.8+B&C/150	4500-9000	22
9163.45	89	1.8+B&C/300	3500-9500	11
9177.40	103	1.2+A/VI	4000-7000	4
9191.38	117	1.8+B&C/300	3500-9500	11
9192.39	118	1.8+B&C/300	3500-9500	11
9246.36	172	1.8+B&C/150	4000-9000	22
9246.49	172	1.8+B&C/1200	5250-5850	2.5
9247.51	173	1.8+B&C/150	4000-9000	22
9247.58	173	1.8+B&C/1200	5900-6500	2.5
9280.41	206	1.8+B&C/150	4000-9000	22
9311.43	237	1.8+B&C/150	4500-9500	22
9330.47	256	1.8+B&C/150	4000-9000	22
9374.40	300	1.8+B&C/150	4000-9000	22
9374.66	300	1.8+B&C/600	6100-7200	6
9404.64	330	1.8+B&C/150	4000-9000	22
9436.63	362	1.8+B&C/150	4000-9000	22
9442.46	368	1.8+B&C/300	3500-9500	11

N.B. The quoted resolution R for the 1.2 m A/VI spectra refers to Hβ.

A spectrum taken in this wavelength region on day 25 with an higher resolution (2.5 Å FWHM) shows the presence of sub–structures on top of the Hα (Fig. 4).

After one month, the emission profile of the Hα line displayed a gradual change from a flat-topped shape into a two-peak line profile indicating the emergence of a strong HeI λ6678 emission on the red wing of the decreasing Hα emission (as reported also by Filippenko et al. 1993). This is a clear departure to what normally seen in type II SNe in which the equivalent width of the Hα is steadily increasing.

In the spectrum of day 62 several forbidden lines become visible, in particular [OI] λ5577 [OI] $\lambda\lambda$6300−6364 and CaII] $\lambda\lambda$7291,7323, indicating the onset of the nebular phase. Also present are Hα and HeI λ6678 at

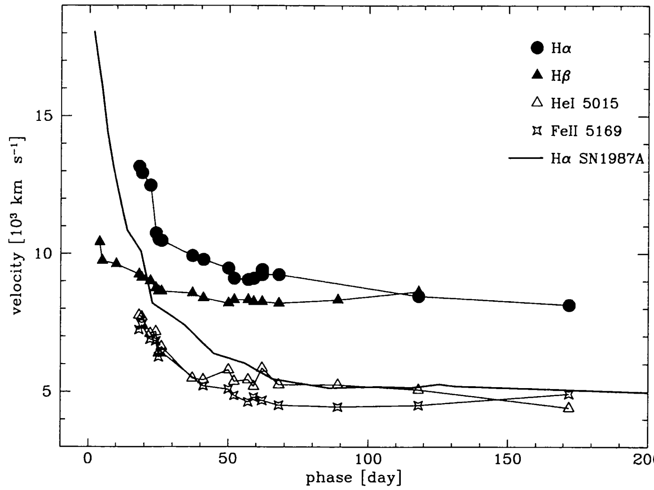

Fig. 3. Photospheric velocity evolution of SN 1993J as deduced from the positions of the minima of the P-Cygni profiles. For comparison, the Hα evolution of SN 1987A (Phillips et al. 1988, 1990) is reported

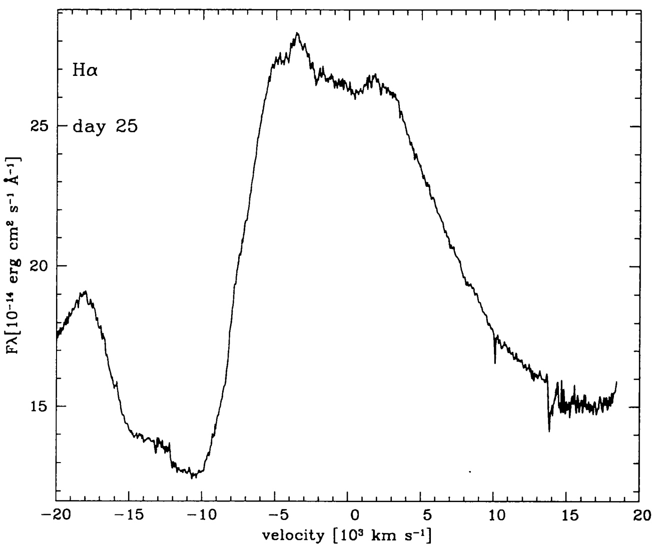

Fig. 4. The velocity profile of Hα on day 25

almost the same strength, HeI λ7065, OI λ7773 and OI $\lambda\lambda$9261,9263,9266. CaII $\lambda\lambda$8498,8542,8662 is the more pronounced feature in the red whereas MgI] λ4571 and a number of blended HeI, FeII and other Balmer lines of H contribute to the blue luminosity. The overall appearance of the spectrum is now reminiscent of that of a Type Ib supernova at late phases. This spectrum, along with some proposed identifications, is shown in Fig. 5.

On day 118 the spectrum is dominated by the [OI] $\lambda\lambda$6300,6364 and the CaII IR triplet. Hα and Hβ are still present while the HeI lines are weakening. The structure of the complex of Hα and [OI] doublet is complicated by the presence of sub–components, visible also in the [OI] λ5577 line, and confirms the onset of the ejecta

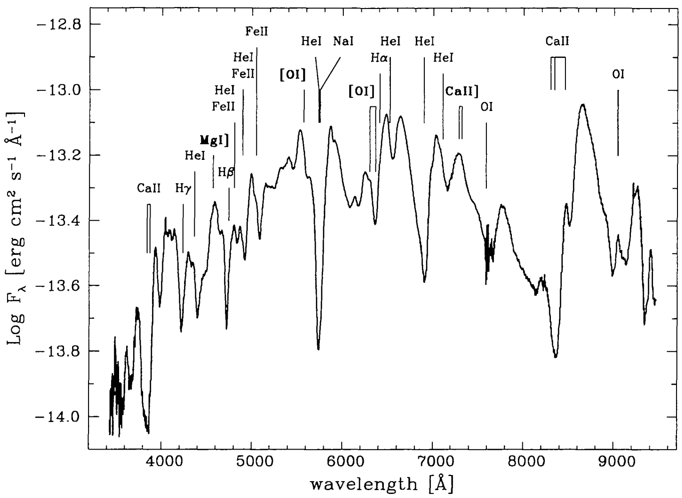

Fig. 5. The line identifications on the spectrum of day 62. Vertical bars mark the expected positions of the absorptions of the P-Cygni profiles blueshifted by 7000 km s^{-1}. The markers of the forbidden lines are at the expected restframe positions

clumping pointed out by Spyromilio (1994). The clumping is better seen in the spectrum taken on day 172 in the [OI] doublet spectral region, with a resolution of 2.5 Å and a S/N ratio of about 30 and shown in Fig. 6. Several attempts to reproduce the profile of the [OI] doublet by using the [OI] λ5577 line as a template have given no satisfactory results. This may be an indication that the single clumps present different physical conditions. At this phase no more HeI lines are clearly detectable.

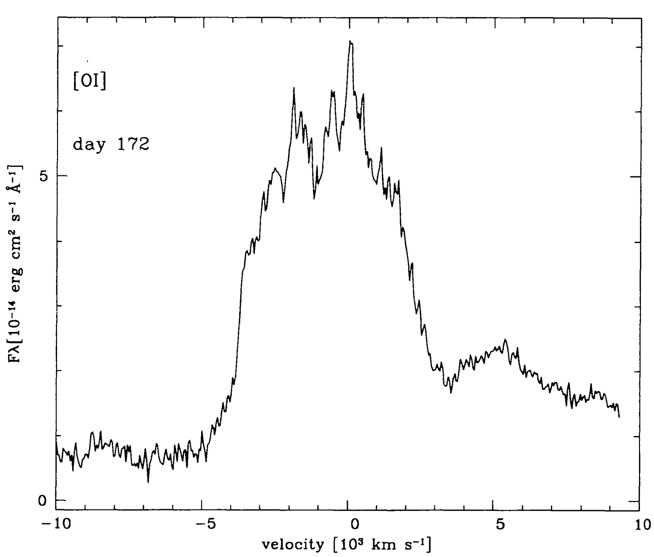

Fig. 6. The velocity profile of [OI] $\lambda\lambda$6300,6364 on day 172

Starting with day 206 the spectra are dominated by the lines of CaII], [OI] and the CaII infrared triplet. Hα is still present as a very broad feature in the red wing of the [OI] $\lambda\lambda$6300,6364 whereas, in the blue, the MgI] λ4571 line increases in strength with time. These features are present up to the last spectrum taken one year after explosion. At this late epoch the spectrum is similar to that of a typical SNIb (Gaskell et al. 1986) but for the presence of the Hα emission line with a flat-topped profile which likely indicates the existence of a thin shell of ionized H, expanding with an edge velocity of about 11000 km s^{-1}(Patat et al. 1995).

5. Concluding remarks

Both the photometric and the spectroscopic behaviour of SN 1993J proved to be unusual. The double peak in the light curve normally not seen in the type II SNe, but observed in SN 1987A though with a slower evolution, has been explained by the small mass (0.4−0.9 $M_\odot$) of the ejected hydrogen envelope.

The H lines and the blue continuum observed in the first spectra of this supernova led to a type II classification. However, the peculiar profile of the Hα line starting from day 20 and the definite appearance of strong He emissions revealed that this SN was an odd object (some He lines might also have been present at very early epochs). This was confirmed by the later evolution of the supernova spectrum which appeared less and less similar to a type II event. In addition to those of He, also lines of Ca and O increased in prominence suggesting that SN 1993J was experiencing a transformation into a type Ib event. Similar behaviour was also seen in SN 1987K (Filippenko et al. 1988). Most likely these two objects provide the missing link between type II and Ib supernovae which both are thought to occur from core collapse explosions. Among the objects of this class, the mass of the H-envelope may play a key role in the photometric and spectral evolution. Finally, the complex structures seen in some lines profiles and explained by clumping in the ejecta, should help toward a more realistic modelling of a supernova explosion.

The spectroscopic data presented in this paper are available in digital form upon request by addressing to the authors (SPAN· astrpd::author, INTERNET author@astrpd.pd.astro.it).

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Table 4. Measured wavelengths of the P-Cygni absorption features in the spectra of SN 1993J

Phase days	HeI 7283	HeI 7065	HeI 6678	Hα	HeI+NaI 5876 5892	FeII 5169	HeI+FeII 5015 5018	HeI+FeII 4921 4925	Hβ	HeI 4471	Hγ
4					5712				4690	4286*	
5									4701		
10					5658				4703		
18				6272	5675	5042	4883		4709	4431	
19				6277	5690	5039	4884		4711	4430	4207
22				6287	5706	5048	4894	4785	4713	4430	4204:
24	7178?		6524:	6325	5725	5049	4893	4792:	4717	4439	4214
25			6576	6330	5733	5059	4906	4802:	4719	4445	4211
26	7175		6566	6331	5729	5056	4902	4795:	4719	4440	4210
37		6882	6523	6343:	5736		4921:	4828	4720	4429	4216
41		6844:	6540	6346	5732	5077	4922	4833	4723		4219
50	7174	6904	6551	6353	5741	5079:	4916	4834	4726		4226
52	7132	6892	6551	6361	5737	5083	4923	4831	4724	4395	4237:
57	7123	6893	6561	6362	5741	5087	4922	4835	4724	4397	4225
59	7125	6893	6558	6361:	5741	5084:	4926	4843:	4725	4397	4218:
62	7161	6904	6549	6358	5743	5086	4915	4837	4725	4402	4226
68	7171:	6907	6553	6358	5747	5089	4925		4726		
89						5090	4925		4724	4410:	4222:
118	7209?	6878?		6375:	5757	5089	4928		4719		
172				6382:	5764:	5082	4939		4711		

N.B. "?" uncertain identification; ":" uncertain measurement; "*" blend of HeI and Hγ