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SN 1998A: Explosion of a Blue Supergiant

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ABSTRACT

We present spectroscopic and photometric observations of the peculiar Type II supernova (SN) 1998A. The light curves and spectra closely resemble those of SN 1987A, suggesting that the SN 1998A progenitor exploded when it was a compact blue supergiant. However, the comparison with SN 1987A also highlights some important differences: SN 1998A is brighter and the spectra show bluer continua and larger expansion velocities at all epochs. These observational properties indicate that the explosion of SN 1998A is more energetic than typical SNe II. Comparing the observational data to simulations, we deduce that the progenitor of SN 1998A was a massive star (~ 25 M$_\odot$) with a small pre–supernova radius ($\lesssim 6 \times 10^{12}$ cm). The Ba II lines, unusually strong in SN 1987A and some faint II–P events, are almost normal in the case of SN 1998A, indicating that the temperature plays a key role in determining their strength.

Key words: supernovae: general - supernovae: individual: SN 1998A, SN 1987A, SN 1909A, SN 1982F, SN 2000cb - galaxies: IC 2627 - photometry - spectroscopy

1 INTRODUCTION

The explosion of SN 1987A in Large Magellanic Cloud (LMC) led to wonder if this supernova (SN) was unique or if other similar supernovae (SNe) had been observed. A number of papers speculated on possible similarities with past events [e.g. SN 1909A (Young & Branch, 1989), SN 1982F (Van den Bergh & McClure, 1989)], but none showed an unequivocal resemblance with SN 1987A. Astronomers had to wait 11 years after SN 1987A to identify another event showing a clear observational analogy: SN 1998A (Woodings et al., 1998a; Woodings et al., 1998b).

SN 1998A was discovered with the 0.61m Perth–Lowell reflector, during the Automated Supernova Search Program of the Perth Astronomy Research Group (PARG) on 1998 January 6.77 UT (Williams et al., 1998). The position of the SN was $\alpha = 11^h09^m50^s.33$, $\delta = -23^\circ43'43''.1$ (equinox 2000.0), in the southern arm of the SBc galaxy IC 2627, 40″ West and 10″ South (Williams et al., 1998; Filippenko & Moran, 1998) from the nucleus (see Fig. 1). The discovery magnitude was R $\sim$ 17, and a prediscovery limit (m $>$ 18.5) obtained on 1997 December 18 was reported by Williams et al. (1998). Filippenko & Moran (1998) classified SN 1998A as a spectroscopically normal Type II event with strong P–Cygni features. But about 70 days after the discovery, Williams et al. (1998) noted that the luminosity of SN 1998A has increased by about 1 magnitude, reaching a broad maximum. They concluded that this photometric behaviour was analogous to that observed in SN 1987A. Later on, the PARG group published VRI photometry of SN 1998A covering until $\sim$ 160 days after discovery (Woodings et al., 1998b). Their photometry confirmed the similarity with the behaviour of SN 1987A.

The basic informations of SN 1998A and its host galaxy IC 2627 are given in Tab. 1.

We present well sampled photometry and spectroscopy of SN 1998A covering a period of more than 1 year after

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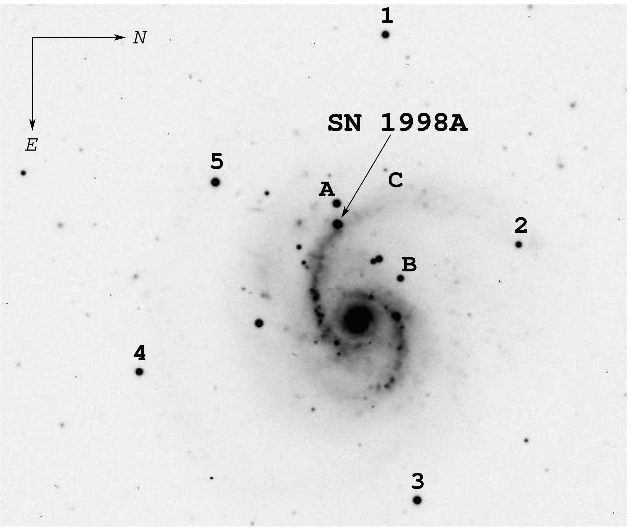

Figure 1. SN 1998A and local reference stars in the field of IC 2627 (R filter image, obtained on 1998 March 22 with the Danish 1.54m telescope equipped with DFOSC). The optical reference stars are labelled with numbers, the infrared ones with letters. East is down, North is to the right.

the explosion and obtained with several telescopes at ESO–La Silla. In Sect. 2 we present the observations and briefly describe the steps of data reduction. In Sect. 3 we present the photometric data and a comparison between the light and colour curves of SN 1998A and SN 1987A. In Sect. 4 we show the spectroscopic data, discuss the analogies with spectra of SN 1987A and compare the earliest spectrum of SN 1998A with synthetic spectra computed with the codes *SYNOW* (Fisher, 2000) and PHOENIX (Hauschildt & Baron, 1999). A discussion follows in Sect. 5, where the data of SN 1998A are compared to simulations. The implications of observational similarities between SN 1998A and SN 1987A are analysed, with particular focus on the nature of the progenitor stars. A short summary follows in Sect. 6.

2 OBSERVATIONS AND DATA REDUCTION

Our photometric and spectroscopic monitoring of SN 1998A began about 2 weeks after discovery and lasted for ∼ 400 days. All data were obtained using the ESO telescopes of La Silla (Chile), namely the Danish 1.54m + DFOSC, ESO 1.52m + B&C, Dutch 0.9m, ESO 3.6m + EFOSC2, ESO NTT + EMMI, ESO 2.2m + IRAC2b.

The data reduction was performed with standard procedures within the IRAF[3] environment, including bias, overscan, and flat–fielding corrections. At early phases the SN magnitudes were measured with a PSF–fitting technique.

[1] http://leda.univ-lyon1.fr
[2] http://nedwww.ipac.caltech.edu
[3] 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.

Table 1. Main data of SN 1998A and the host galaxy IC 2627.

SN 1998A		
α (J2000.0)	$11^h09^m50^s.33$	⊗
δ (J2000.0)	$-23°43'43''.1$	⊗
Offset SN - Gal. Nucleus	$40''$W, $10''$S	⊗, ⋄
SN Type	IIpec	⋄, ○
Discovery Date (UT)	1998 January 6.77	⊗
Discovery Julian Date	2450820.27	⊗
Assumed explosion JD	2450801	○
Discovery R Magnitude	17	⊗
IC 2627		
α (J2000.0)	$11^h09^m53^s.46$	⊙
δ (J2000.0)	$-23°43'35''.3$	⊙
Morphological Type	SBc	∇
Total B Magnitude	12.63	∇
Galactic Extinction A_B	0.519	∗
Angular Size	$2'.7 \times 2'.3$	△
v_{3K} (km s^{-1})	2428	∇
v_{vir} (km s^{-1})	1972	∇
μ (H_0=65 km s^{-1} Mpc^{-1})	32.41	∇

⊗ (Williams et al., 1998); ⋄ (Filippenko & Moran, 1998); ○ (Woodings et al., 1998a); ⊙ (Gallouet et al., 1975); ∇ LEDA[1]; ∗ (Schlegel et al., 1998); △ NED[2]

However, as the SN luminosity decreased, this method was not longer applicable. This is because of the location of the SN, near a bright H II region, in the southern arm of IC 2627. Therefore it was necessary to apply a template subtraction method. This method makes use of template images of the galaxy, which are geometrically and photometrically registered, and seeing matched to the target image. For a detailed description of the method, see e.g. Sollerman et al. (2002). As template images we used deep frames obtained on 2001 February 1 (i.e. about 3 years after the explosion) with the ESO 3.6m telescope, under excellent seeing conditions.

The SN magnitudes were computed by reference to a local sequence of 5 stars in the field of IC 2627 (see Fig. 1), which in turn were calibrated after comparison with Landolt standard stars (Landolt, 1992).

We note that our photometry of SN 1998A is systematically about 0.3 magnitudes fainter than that reported by Woodings et al. (1998b) obtained with a PSF–fitting technique. The difference may be due to the different quality of the images (e.g. the seeing and pixel sampling), and some subjectivity in the measurements. We also cannot exclude intrinsic differences in the instrumental band pass.

In addition to the optical data, we observed SN 1998A at two epochs in the H, J, K' bands with the ESO 2.2m telescope equipped with IRAC2b. The data were obtained when the SN was passing from the photospheric phase to the nebular one (∼ 100–120 days). The IR images were reduced using IRAF tasks (including flat fielding and illumination corrections, sky subtraction, image matching and stacking in order to increase the S/N ratio). The magnitudes were estimated with a PSF–fitting method. They were calibrated with respect to three stars in the SN field (Fig. 1), observed during the photometric night of 1998 March 28 and calibrated with infrared standards from the IRIS photometric

Table 2. Spectroscopic observations of SN 1998A. The phase is from the explosion epoch (JD 2450801).

Date	JD	Phase (days)	Telescope+Inst.	Grism or grating	Resol. (Å)	Exp. (sec.)	Range (Å)
24/01/98	2450837.83	37	Danish1.54+DF	grs 4,5	9,10	1800+1800	3380–9790
26/01/98	2450839.75	39	ESO1.52+B&C	gt 15	9	2700	3080–10600
31/01/98	2450844.74	44	NTT+EMMI	grs 3,4	11,13	300×2+300×2	3800–10550
01/02/98	2450845.88	45	NTT+EMMI	gr 3	11	300×2	3850–8380
02/02/98	2450846.73	46	NTT+EMMI	gr 4	13	300×2	5680–10570
18/02/98	2450862.67	62	ESO1.52+B&C	gt 15	11	3600	3060–10570
22/03/98	2450894.72	94	Danish1.54+DF	gr 4	10	1800	3420–9020
27/05/98	2450960.51	160	ESO3.6+EF2	gr 12	13	1140	6070–10260
29/05/98	2450962.63	162	ESO3.6+EF2	grs 11,12	13,13	900+900	3380–10290
27/11/98	2451144.84	345	ESO3.6+EF2	gr 12	13	1800 ×2	6030–10260
08/02/99	2451217.70	417	ESO1.52+B&C	gt 15	10	2700 ×2	3090-10810

standard star list. Note that the IR local stars are different from the optical ones, because of the very small field of view of IRAC2b. The transformation from K' to K magnitudes was performed according to the conversion relations given by Wainscoat & Cowie (1992).

Also the spectra were reduced using standard IRAF tasks. In Tab. 2 the log of the spectroscopic observations is shown. The spectra were wavelength calibrated by comparison with spectra of He–Ne and He–Ar lamps and flux calibrated using spectra of standard stars (Hamuy et al., 1992; Hamuy et al., 1994; Stone & Baldwin, 1983; Baldwin & Stone, 1984) obtained during the same nights. The flux calibration of the optical spectra was checked against the photometry and, if discrepancies occurred, the spectral fluxes were scaled to match the photometric data. The agreement with photometry was finally within 5%.

3 LIGHT AND COLOUR CURVES

The photometric monitoring of SN 1998A covers a period of more than one year and, although not densely sampled, it is sufficient to describe the overall evolution of the object. The magnitudes of the local standards are reported in Tab. 3, while the optical and IR photometry is reported in Tab. 4. The B, V, R, I light curves are shown in Fig. 2. The photometric evolution of SN 1998A is very similar to that of SN 1987A. Using the light curve of SN 1987A as a template, we adjust the explosion epoch of SN 1998A to get the best match between the light curves of the two objects. We derive that SN 1998A exploded $\sim$ 19 days before discovery, close to the epoch of the prediscovery limit of Williams et al. (1998). Hereafter the phases will be relative to this epoch (JD = 2450801). We expect that, similar to SN 1987A, a decrement of the B band luminosity after shock breakout has been occurred, but unfortunately we have no direct evidence of it. The initial UV excess and the following observed dip in U and B bands observed in SN 1987A (e.g. Hamuy et al., 1988), in SN 1993J (e.g. Schmidt et al., 1993), and recently in the Type Ib/c SN 1999ex (Stritzinger et al., 2002) are probably common features in core–collapse (CC) SNe.

Later on the SN luminosity begins to rise reaching a broad maximum during which, in analogy to SN 1987A, we expect that the recombination of the hydrogen envelope

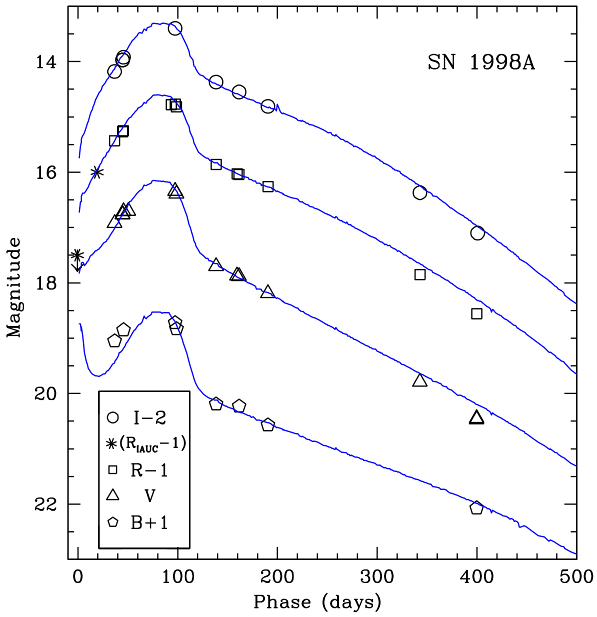

Figure 2. B, V, R, I light curves of SN 1998A. The curves of SN 1987A in the corresponding bands (solid lines) are also plotted, with an offset in magnitude (ΔB = 13.0, ΔV = 13.2, ΔR = 13.3, ΔI = 13.4) to match the points of SN 1998A. The asterisks represent the prediscovery R band limit and the discovery R band photometry from Williams et al. (1998). The temporal fit is obtained assuming that the explosion of SN 1998A occurred 19 days before discovery. The adopted explosion date (phase = 0) of SN 1987A corresponds to the epoch of the first neutrino detection JD = 2446849.82 (Bionta et al., 1987; Hirata et al., 1987).

takes place. This phase corresponds to the plateau in "normal" SNe II–P.

After that, the luminosity drops abruptly, until the main contribution to the flux comes from the radioactive decay ^{56}Co $\rightarrow$ ^{56}Fe: the nebular phase begins.

We note that at t $\sim$ 300 days past explosion, the light curve becomes steeper than in the early radioactive tail, indicating an increasing escape of trapped γ–rays and/or dust

Table 3. Magnitudes of the sequence of local stars in the field of IC 2627. The errors in brackets are the r.m.s. of the available estimates. In the U band only the measurements of 1998 May 29 are reported. The IR magnitudes of 1998 March 28 are also shown.

Star	U	B	V	R	I	J	H	K‡
1	17.96	17.71 (0.01)	16.96 (0.01)	16.50 (0.01)	16.06 (0.01)	–	–	–
2	18.97	18.54 (0.02)	17.69 (0.01)	17.20 (0.01)	16.74 (0.01)	–	–	–
3	17.26	17.07 (0.01)	16.35 (0.01)	15.90 (0.01)	15.45 (0.01)	–	–	–
4	17.79	17.61 (0.01)	16.88 (0.01)	16.41 (0.01)	15.89 (0.01)	–	–	–
5	16.66	16.65 (0.01)	16.06 (0.01)	15.67 (0.01)	15.25 (0.01)	–	–	–
A	–	–	–	–	–	15.19	14.54	14.67
B	–	–	–	–	–	16.28	15.52	15.63
C	–	–	–	–	–	17.08	15.96	15.96

‡ The K magnitudes are obtained from K' measurements using the conversion relations by Wainscoat & Cowie (1992)

Table 4. Optical and IR photometry of SN 1998A (JD +2400000).

Date	JD	U	B	V	R	I	J	H	K	Source
18/12/97	50800.5	–	–	–	$\geqslant$18.5	–	–	–	–	0
06/01/98	50820.27	–	–	–	17.0 (–)	–	–	–	–	0
24/01/98	50837.78	–	18.05 (0.10)	16.92 (0.03)	16.43 (0.04)	16.18 (0.03)	–	–	–	1
01/02/98	50845.86	–	–	16.76 (0.02)	16.27 (0.01)	15.97 (0.01)	–	–	–	5
02/02/98	50846.74	–	17.85 (0.08)	16.71 (0.04)	16.25 (0.01)	15.92 (0.06)	–	–	–	2
22/03/98	50894.70	–	–	–	15.78(0.01)	–	–	–	–	1
26/03/98	50898.5	–	17.72 (0.11)	16.34 (0.05)	15.77 (0.04)	15.40 (0.05)	–	–	–	2
27/03/98	50899.84	–	17.83 (0.17)	16.39 (0.03)	15.82 (0.06)	–	–	–	–	2
28/03/98	50900.80	–	–	–	–	–	15.17 (0.03)	14.66 (0.04)	14.52 (0.05)	4
15/04/98	50918.76	–	–	–	–	–	15.66 (0.07)	15.04 (0.06)	–	4
27/04/98	50930.63	–	–	–	–	–	15.40 (0.06)	14.94 (0.09)	14.94 (0.16)	6
06/05/98	50939.55	–	19.19 (0.28)	17.70 (0.11)	16.86 (0.08)	16.37 (0.08)	–	–	–	2
27/05/98	50960.50	–	–	17.87 (0.10)	17.03 (0.06)	–	–	–	–	3
29/05/98	50962.5	19.29 (0.30)	19.23 (0.10)	17.88 (0.05)	17.04 (0.05)	16.55 (0.05)	–	–	–	3
05/07/98	50991.5	–	19.57 (0.16)	18.19 (0.09)	17.26 (0.02)	16.81 (0.14)	–	–	–	2
26/11/98	51143.82	–	–	19.79(0.02)	18.85 (0.03)	18.37 (0.07)	–	–	–	3
21/01/99	51200.68	–	21.07 (0.32)	20.45 (0.02)	19.56 (0.03)	–	–	–	–	1
22/01/99	51201.66	–	–	–	–	19.10 (0.18)	–	–	–	1
01/02/01	51941.79	–	–	$\geqslant$23.2	$\geqslant$22.9	–	–	–	–	3

0 = IAU Circ. 6805; 1 = Danish 1.54m + DFOSC; 2 = Dutch 0.90m;
3 = ESO 3.6m + EFOSC2; 4 = ESO 2.2m + IRAC2b; 5 = ESO NTT + EMMI; 6 = IAU Circ. 7435

formation. The measurements of the slopes of the early radioactive tail (between $\sim$ 130 and 200 days) give values: $\gamma_B \approx 0.75$, $\gamma_V \approx 0.95$, $\gamma_R \approx 0.77$, $\gamma_I \approx 0.85$ mag/100^d which are slightly smaller than the slope of the radioactive decay of ^{56}Co (0.98 mag/100^d), while between 330 and 410 days are larger than expected from the ^{56}Co decay: $\gamma'_V \approx 1.18$, $\gamma'_R \approx 1.25$ and $\gamma'_I \approx 1.26$ mag/100^d. We note that the steepening in the late time light curve occurs earlier in SN 1998A than in SN 1987A.

The overall behaviour of the colour curves of SN 1998A (Fig. 3) is rather similar to SN 1987A, although SN 1998A is bluer, particularly at early epochs. This indicates higher temperatures for SN 1998A at comparable phases, as also confirmed by the spectra (see Sect. 4). The colour evolution of SN 1998A is also similar to that of the normal plateau SN 1999em (Hamuy et al., 2001; Leonard et al., 2002; Elmhamdi et al., 2003) (Fig. 3).

In order to compute the absolute luminosity, we assume for IC 2627 a distance modulus $\mu = 32.41$ (obtained via recession velocity corrected by Local Group infall into the Virgo cluster, with $H_0 = 65$ km s^{-1} Mpc^{-1}; see also Tab. 1). We also adopt the value of foreground Galactic extinction at the coordinates of the SN from Schlegel et al. (1998). No interstellar absorption lines are seen in the spectra of SN 1998A at the host galaxy rest wavelength. This was also found by Leonard & Filippenko (2001) who evaluated an upper limit to the equivalent width of interstellar Na ID absorption and concluded that the host–galaxy reddening was small ($E_{B-V} \leqslant 0.03$). Therefore, we also assume the host galaxy extinction to be negligible and adopt an extinction entirely due to the Galaxy ($A_{B,TOT} = 0.52$).

Guided by the resemblance of the light curve to SN 1987A (Fig. 2), we can estimate the absolute luminosity of SN 1998A at the broad peak as $M_B \sim -15.4$, $M_V \sim -16.6$, $M_R \sim -17.1$, $M_I \sim -17.4$.

In Fig. 4, the pseudo–bolometric BVRI light curve of SN 1998A is shown compared with those of SN 1987A, SN 1999em [data from Elmhamdi et al. (2003), with distance modulus obtained from Cepheids calibration by Leonard et al. (2003)] and SN 1997D (Benetti et al., 2001). We note that at late times SN 1998A is brighter than SN 1987A. From a comparison between the luminosities of SN 1998A and SN 1987A during the early radioactive tail phase, we estimate that 0.11 $M_\odot$ of ^{56}Ni have been ejected by the explosion ($M_{Ni} = 0.075$ $M_\odot$ in SN 1987A).

SN 1998A was monitored especially in the BVRI bands, but a few sparse U–band and near–IR observations allow us to compute the contribution of these bands to the total flux at the beginning of the nebular phase. We estimated that the U–band flux on 1998 May 29 (phase $\sim$ 162 days) contributes only to $\approx$ 7% of the total optical (*UBVRI*) flux, in accordance with the red colour of the SN. We used the near infrared magnitudes to estimate the IR contribution after recombination of the H envelope. The JHK flux is comparable

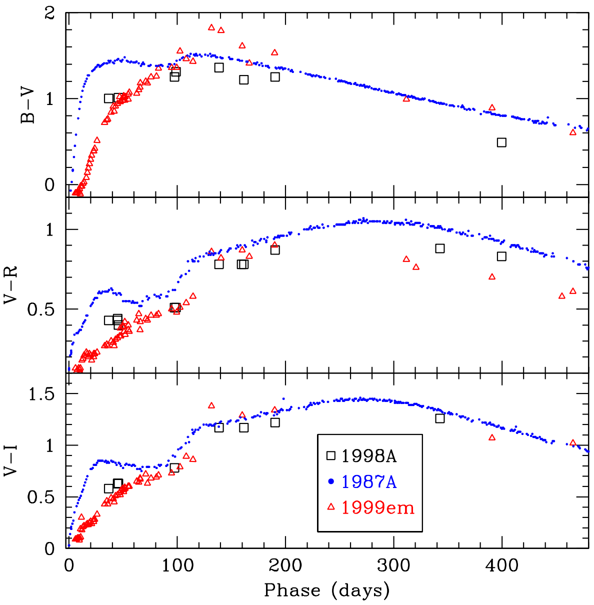

Figure 3. B–V, V–R, V–I colour curves of SN 1998A and comparison with SN 1987A and SN 1999em. The data of SN 1999em are from Hamuy et al. (2001), Leonard et al. (2002), Elmhamdi et al. (2003). For SN 1999em we assume: explosion epoch JD = 2451476 and a total extinction A_V = 0.31. As in Fig. 2, the SN 1998A data are shifted in phase by +19 days from discovery.

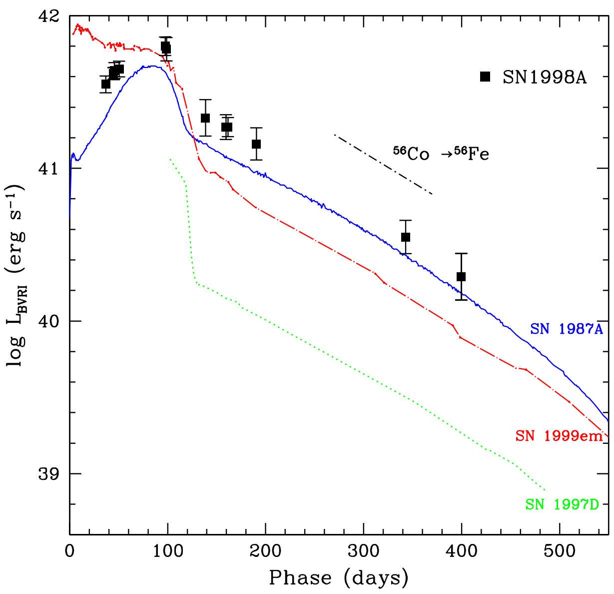

Figure 4. The integrated BVRI luminosity of SN 1998A compared with SN 1987A (Patat et al., 1994, and references therein), the SN II–P 1999em (Elmhamdi et al., 2003) and the very low–luminosity SN 1997D (Benetti et al., 2001). Errors from the distance modulus estimate have not been taken into account.

to the optical (about 75% of the BVRI flux). At comparable phases, SN 1987A showed an IR flux (but extended also to the L band) ≈ 130% of the optical one (Catchpole et al., 1987). Therefore, at least on these epochs, the contribution of IR bands to the total flux is significant.

4 SPECTROSCOPY

4.1 Spectroscopic Evolution and a Comparison with SN 1987A

Our spectroscopic data of SN 1998A cover a period of ∼ 400 days. The entire spectroscopic evolution is shown in Fig. 5. The first spectrum was obtained about 18 days after discovery (phase ∼ 37 days). It shows the photospheric broad P–Cygni lines of H I, Ca II, Na ID, Fe II, Ti II and many other metal lines typical of CC–SNe during the recombination phase. A more extensive line identification will be given in Sect. 4.2.

As already noted by Leonard & Filippenko (2001), the spectroscopic evolution of SN 1998A (in analogy with SN 1987A) is surprisingly rapid. On day ∼ 30 the spectrum already showed strong metal lines. A comparison with a spectrum of SN 1999em at phase ∼ 35 days (Leonard & Filippenko, 2001) shows that SN 1998A exhibited stronger metal features. In Fig. 6 we compare spectra of SNe 1998A, 1987A and 1999em at similar ages. It is remarkable at ∼ 40 days post–explosion (just 5 days after the comparison reported by Leonard & Filippenko) the similarity of the spectra, although the spectrum of SN 1998A was slightly more similar to that of SN 1999em than to SN 1987A.

In analogy with SN 1987A, also SN 1998A probably experienced a rapid colour evolution and a strong deficit of flux at short wavelengths, due to the rapid adiabatic cooling of the envelope and, at $\lambda \leqslant 4500$ Å, to line blanketing. The overall resemblance of the photospheric spectra of the two SNe at a comparable phase (see Fig. 6) is remarkable, but there are also a number of interesting differences. The Ba II lines of SN 1998A are similar in strength to those of SN 1999em at 40 days and much weaker than those of SN 1987A. Note also that the Bochum event detected in the spectra of SN 1987A in a phase comparable to that of our first spectra of SN 1998A (Hanuschik & Dachs, 1987), is not visible in SN 1998A at any epoch.

The temperature deduced by a blackbody fit of the continuum (see Fig. 7) is about 8200 K at ∼ 40 days. This is perhaps higher than expected given the presence of a number of metal lines and definitely higher than that of SN 1987A at the same phase. As expected, the temperature evolution measured on the plateau is slow.

The photospheric velocity estimated by the minima of Sc II 5527 Å and/or Ba II 6142 Å varies from about 4500 km s^{-1} at ∼ 40 days to 3000–3200 km s^{-1} at phase ∼ 94 days (see Fig. 8 – Top), considerably higher than that of SN 1987A at comparable phase. The velocity of the Fe II lines (multiplet 42 lines, Fig. 8 – Centre) shows the same behaviour, as well as the velocity derived from Hα (Fig. 8 – Bottom).

The spectrum at a phase ∼ 94 days shows the emergence of [Ca II] 7291–7324 Å nebular lines, that become systematically stronger in the latest spectra. In the spectrum at

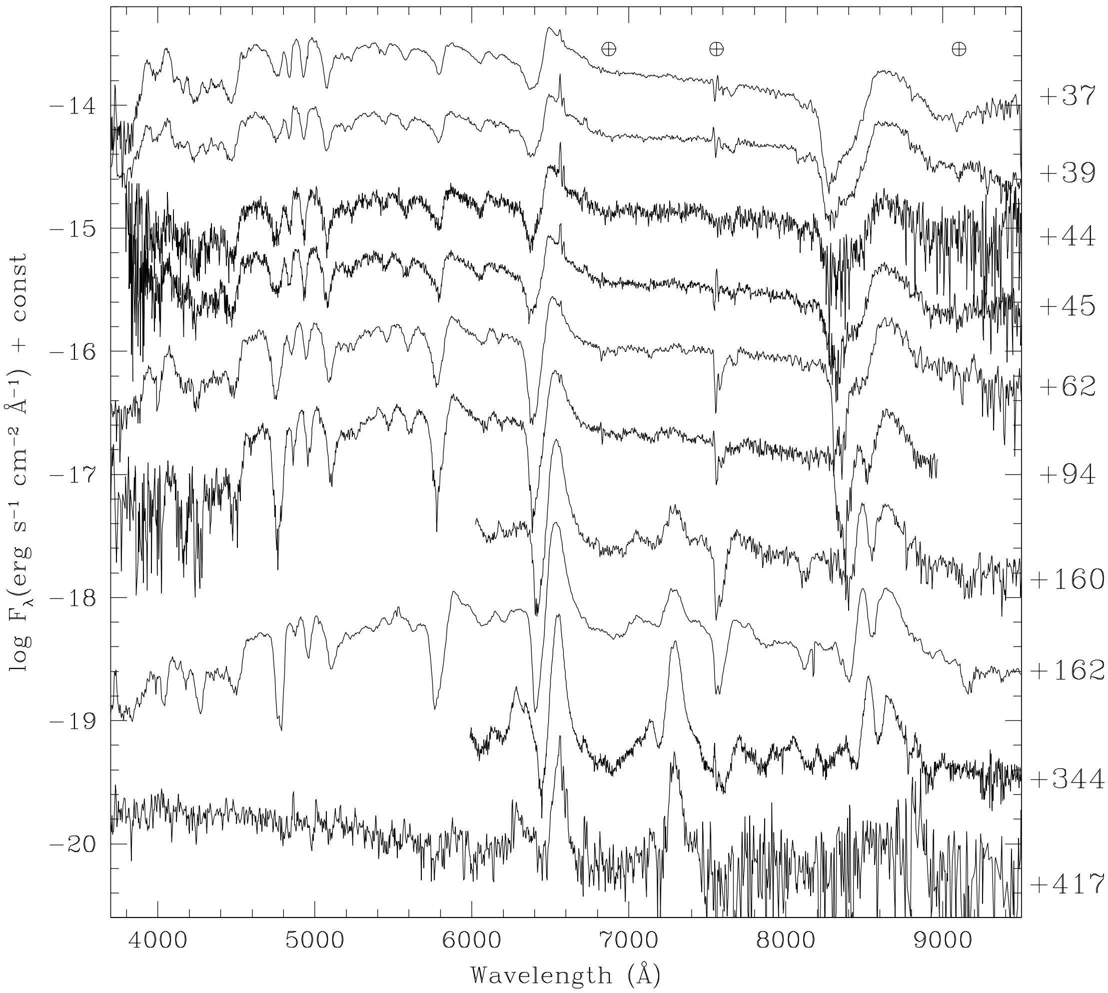

Figure 5. The spectroscopic evolution of SN 1998A from the photospheric to the nebular phase. The labels to the right indicate the days after the explosion. The spectrum at +45 days results from the combination of the spectra obtained on 1998 February 1 and 2. The contamination of an H II region is visible from the presence of narrow Hα, [N II], [S II] lines in the region 6550–6700 Å. The position of telluric bands, partially removed, is labelled by ⊕. All spectra are redshift corrected.

phase 160 days, at the same epoch of the steep luminosity drop that marks the beginning of the nebular phase, we note also a significant decrease in temperature (T $\sim$ 6200 K).

The spectrum at day 345 shows the typical nebular features of a SN II: Balmer (and possibly Paschen) lines of H, Ca II IR, [Ca II] 7291–7324 Å, [O I] 6300-6364 Å doublet, and several line blends of [Fe II], the strongest of which is the feature near 7200 Å. We tentatively identify the line at about 6150 Å as O I and the feature at 8200 Å as N I. At redder wavelengths the Paschen lines may contribute to the strength of some features: in particular, the peak at λ 10010 Å might be Paschen δ. More doubtful is the presence of [C I] lines, possibly blended with Ca II IR and [Fe II].

Our final, low S/N ratio spectrum, obtained about 420 days after the explosion, shows intense nebular features of [Ca II] and [O I]. The Ca II IR has become fainter than the [Ca II] 7291–7324 Å doublet. The observed blue pseudo–continuum is not intrinsic but probably due to background contamination by hot, young stars associated with the H II regions close in projection to SN 1998A.

Fig. 10 shows the evolution of Hα, [Ca II] and Ca II IR in the spectra of SN 1998A (corrected to the host galaxy rest frame). The narrow Hα line emitted by the underlying H II region visible in several spectra makes more evident the significant blueshift of the SN Hα emission at early–time. This effect was seen also in SN 1987A and in other SNe II, e.g. SN 1988A (Turatto et al., 1993) and SN 1999em (Elmhamdi et al., 2003). As shown in Fig. 9, the blueshift of Hα in SN 1998A is significantly stronger than that observed in SN 1987A. In SN 1987A a blueshift of the Hα emission component of about 6000 km s^{-1} was detected soon after the explosion (Menzies et al., 1987), but it decreased rapidly, dis-

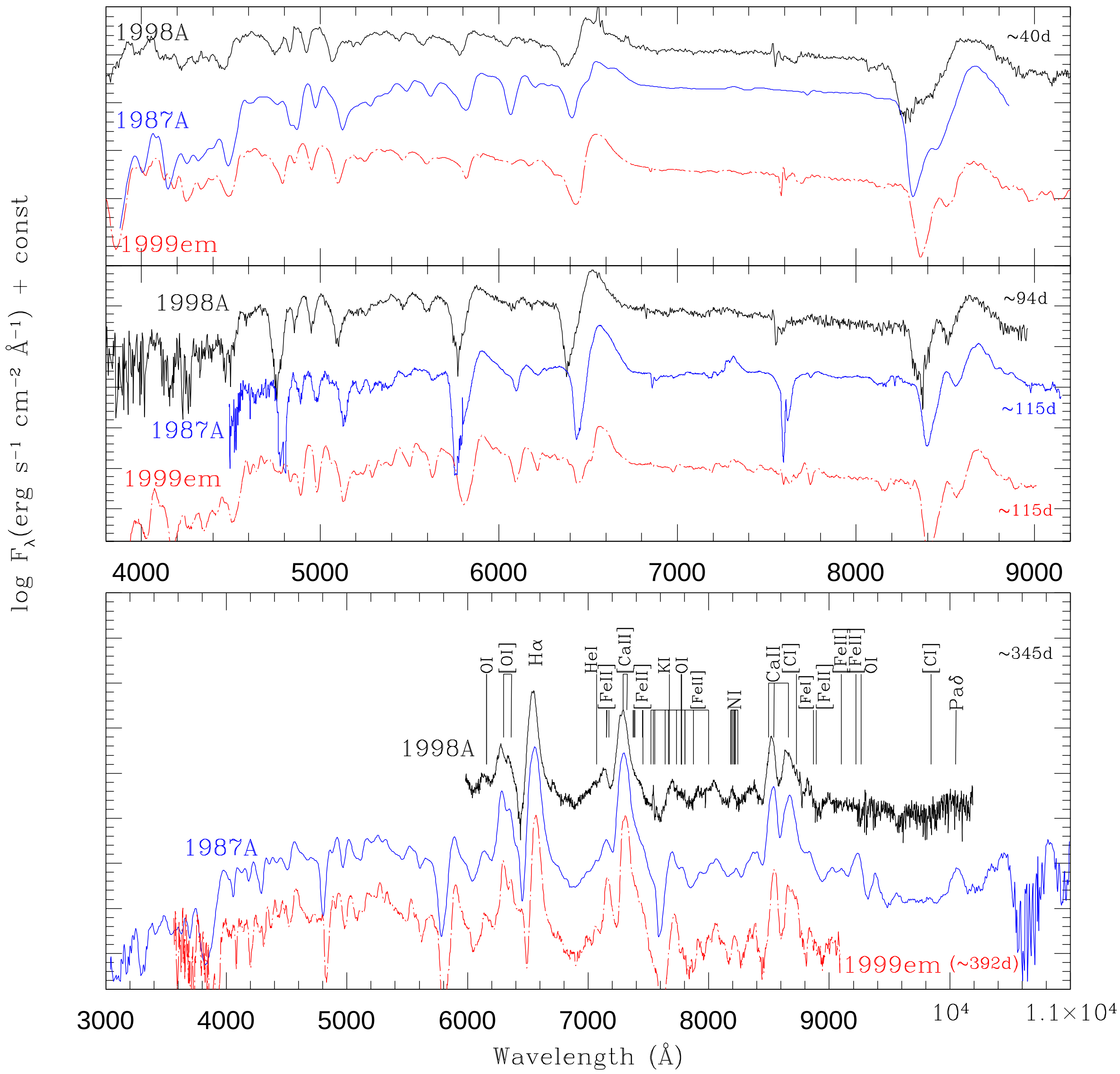

Figure 6. Spectra of SN 1998A, SN 1987A and SN 1999em at comparable phases. A strong resemblance among these spectra is evident. In the nebular spectrum of SN 1998A (taken about 1 year after the explosion) the main emission features are marked.

appearing about 20 days after the explosion. Chugai (1988a) explained this initial blueshift of the Hα peak as due to diffuse reflection of resonance photons emitted inward toward the photosphere. In SN 1998A the blueshift is detectable until $\sim$ 1 year after the explosion and thus is more difficult to explain with this mechanism. Other very late spectra of CC–SNe show evidence of blueshifted emission peaks (e.g. SN 1993J, Matheson et al., 2000).

In fact, SN 1987A showed an increase of the blueshift of Hα and other forbidden lines at very late–time (phase $\geqslant$ 580 days). This occurred in coincidence with the deviation of the light curves from the radioactive decay of ^{56}Co that possibly indicates dust formation (Kozasa et al., 1991). No clear evidence of dust formation is visible in the late optical spectra of SN 1998A. In particular there is no evidence of blueshift of the [O I] 6300-6364 Å emission (e.g. SN 1999em, Elmhamdi et al., 2002).

Also interesting is the evolution of the Ca II IR triplet. In the early spectra only the broad Ca II λ8662 line is detected. At the end of recombination also the line at 8542 Å appears, and then becomes prominent in the nebular spectra. The emission line at 8542 Å is narrower ($FWHM \sim$ 1700 km s^{-1}) than that at 8662 Å ($FWHM \sim$ 2750 km s^{-1}) and the [Ca II] doublet $\lambda\lambda$7291–7324 ($FWHM \sim$ 3100 km s^{-1}). Swartz et al. (1989) suggest that the relatively narrow width of the 8542 Å line observed in the nebular spectra of SN 1987A may have been caused by a partial absorption by the line at 8662 Å. Indeed, the first line of the triplet (λ8498) is not visible at any epoch in the spectra of SN 1998A, due to the absorption of the two redder lines of

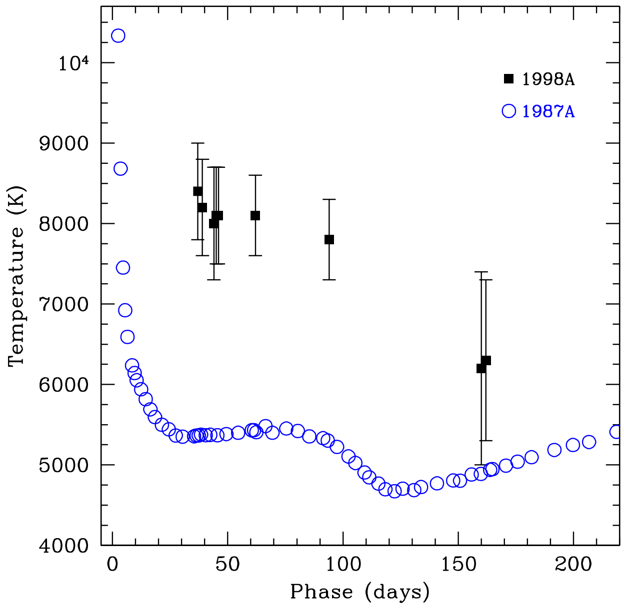

Figure 7. Evolution of the temperature from the blackbody fit of the continuum and comparison with SN 1987A. The data of SN 1987A are from Phillips et al. (1988).

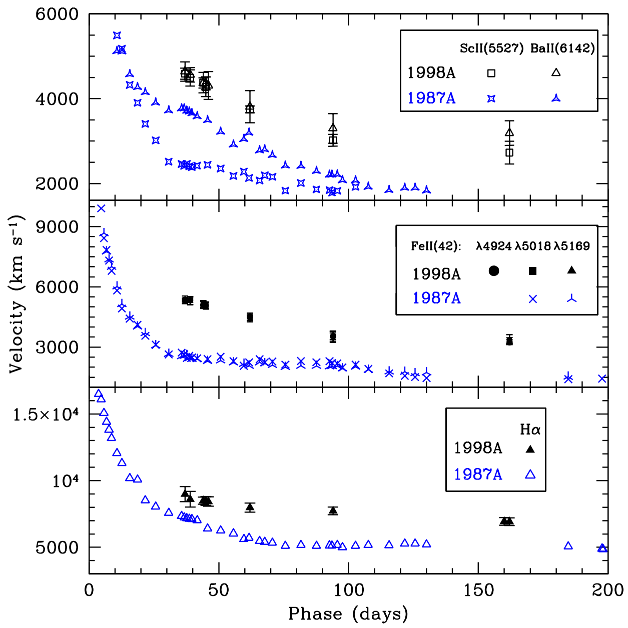

Figure 8. Comparison between the expansion velocities of SN 1998A and SN 1987A. The velocities are derived from the minima of Ba II λ6142 and Sc II λ5527 (**Top**); Fe II multiplet 42 $\lambda\lambda\lambda$ 4924, 5018, 5169 (**Centre**); Hα (**Bottom**). Again the data of SN 1987A are from Phillips et al. (1988).

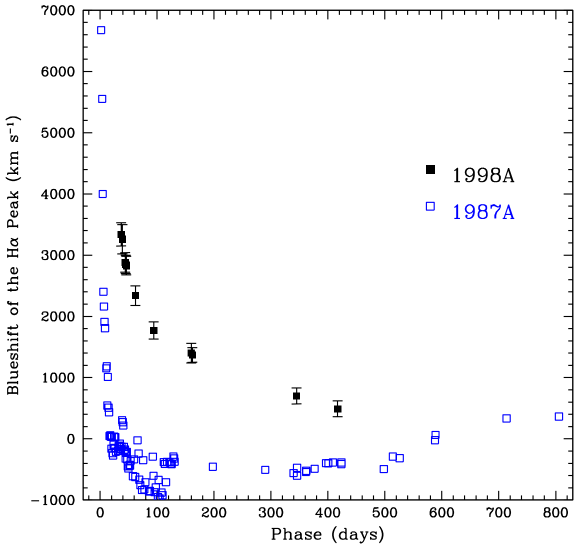

Figure 9. Comparison between SN 1998A (filled symbols) and SN 1987A (empty symbols): blueshift of the Hα emission peak with respect to the rest wavelength. The data for SN 1987A are taken from Phillips et al. (1988) and Phillips et al. (1990).

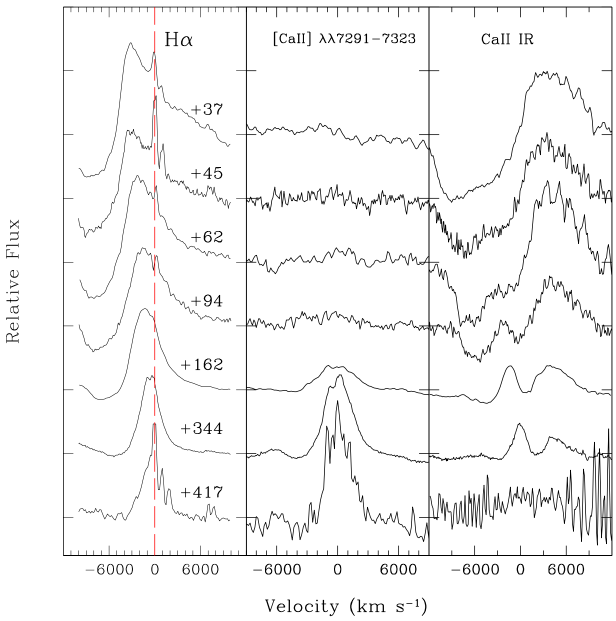

Figure 10. Evolution of the profile of some spectral lines of SN 1998A. All spectra have been normalised to the peak of the broad Hα.

the Ca II IR triplet (Li & McCray, 1993). This may also explain the absence of the O I λ8446 line.

In the next Section we will show that the broad profile of the whole Ca II IR triplet can be reproduced without invoking blends with other lines, but simply with a larger expansion velocity of Ca–rich ejecta (see model on Sect. 4.2 and Fig. 12, Left–Bottom panel).

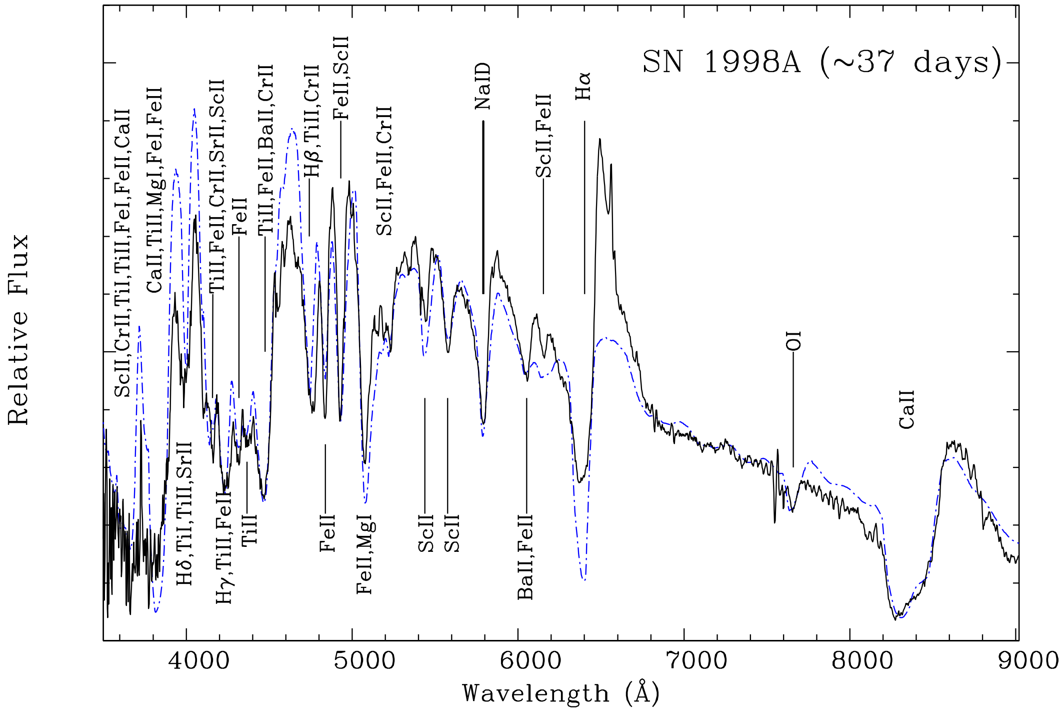

Figure 11. Comparison of the observed spectrum of SN 1998A at day 37 (solid line) with the *SYNOW* synthetic spectrum (dash–dotted line). The synthetic spectrum was obtained assuming T_{bb} = 8400 K, v_{ph}=5400 km s^{-1} and adjusting the opacity from 13 different ions.

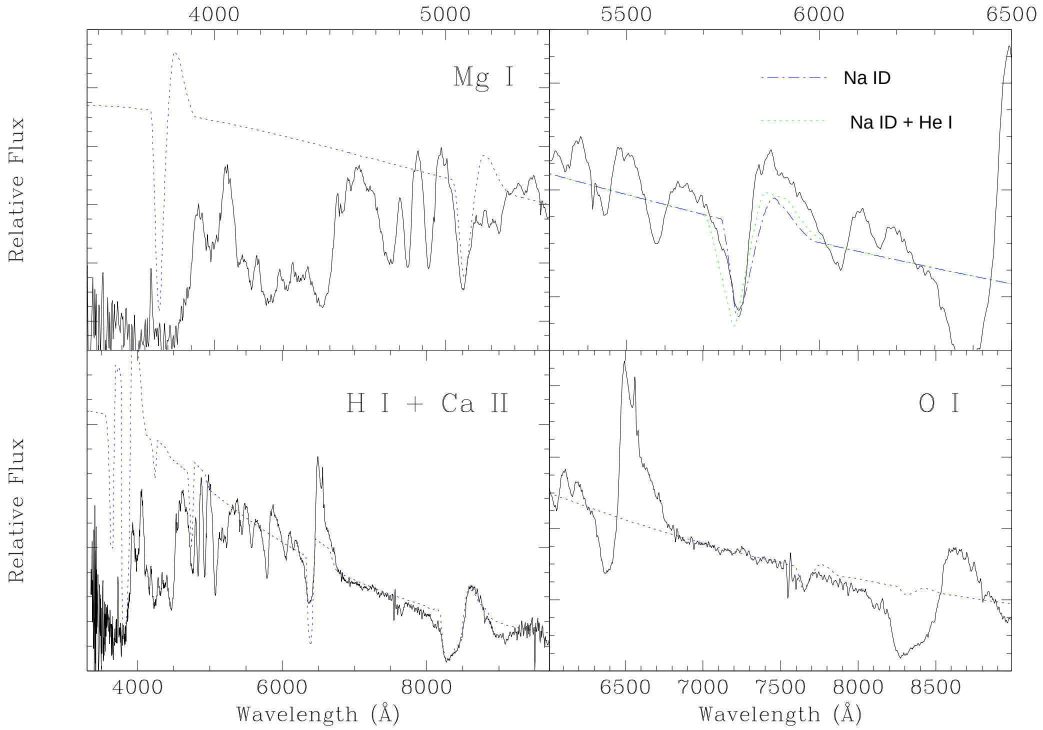

Figure 12. Same as Fig. 11, but considering only contribution of Mg I, Na ID (& NaID + He I), H I + Ca II, O I in the *SYNOW* synthetic spectrum.

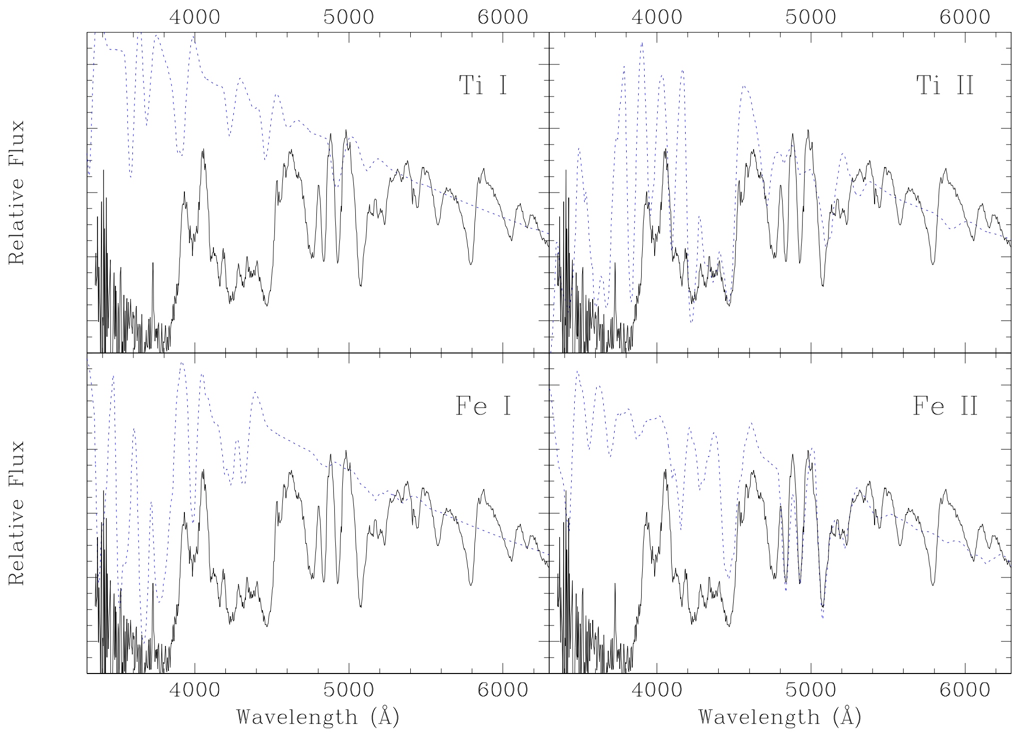

Figure 13. Same as Fig. 11, but considering only contribution of Ti I, Ti II, Fe I, Fe II in the *SYNOW* synthetic spectrum.

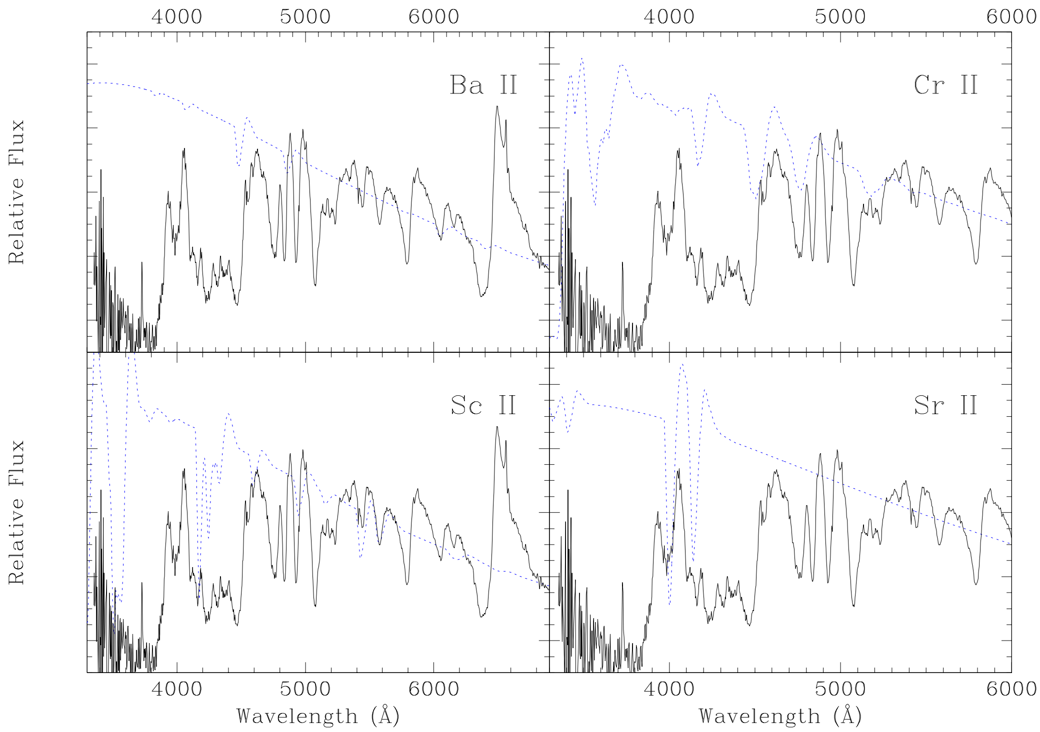

Figure 14. Like Fig. 11, but considering only contributions of Ba II, Cr II, Sc II, Sr II in the *SYNOW* synthetic spectrum.

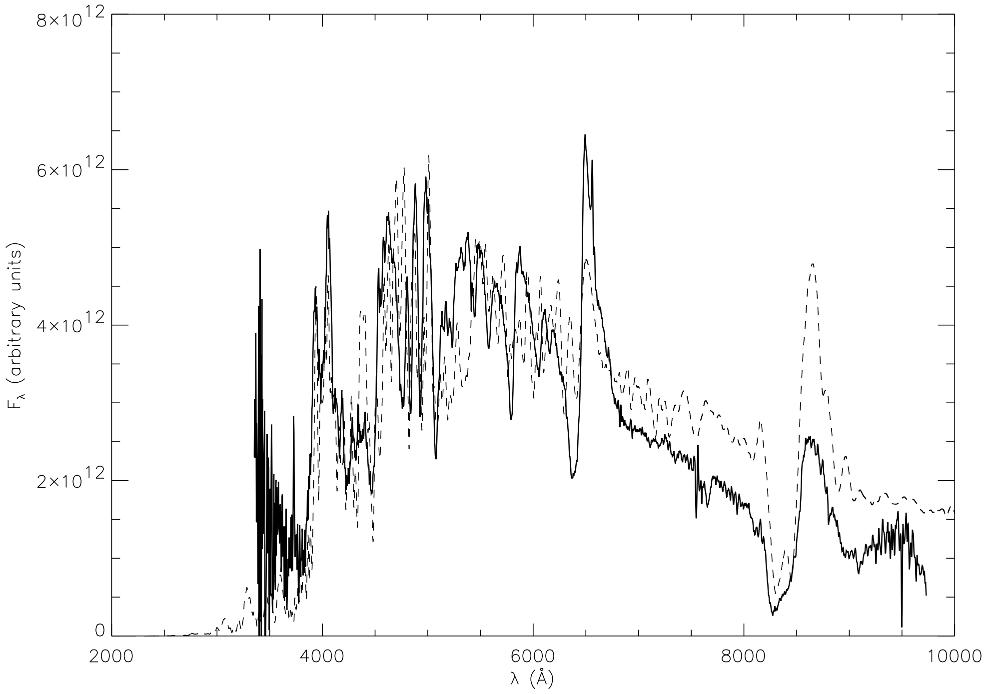

Figure 15. Comparison between the observed spectrum at day 37 and the `PHOENIX` synthetic spectrum at day 38 after explosion. The solid line is the observed spectrum, while the dashed line is the synthetic one.

4.2 Line Identifications: a *SYNOW* Photospheric Synthetic Spectrum

In order to attempt a complete line identification, we have used the simple, parameterized code *SYNOW* (Fisher, 2000) to calculate a synthetic photospheric spectrum to be compared with our observed spectrum at phase $\sim$ 37 days. Because of the rapid spectroscopic evolution of SN 1998A, the observed spectrum already shows the main P–Cygni permitted lines of metals. The simple assumptions on which the code is based are: spherical symmetry, homologous expansion, sharp photosphere and line formation coming from resonant scattering. Optical depths for the lines are calculated in the Sobolev approximation, and free parameters are: the continuum blackbody temperature (T_{bb}), the excitation temperature (T_{exc}) of each ion, the velocity at the photosphere (v_{ph}), and the optical depths (τ) of reference lines for each ion (Hatano et al., 1999). The relative line intensities of an ion are adjusted by assuming LTE (Jeffery & Branch, 1990). To fit the absorption line profiles, we assume that the radial dependence of the optical depths goes as a power–law function of index n = 6. In Fig. 11 the observed spectrum at day 37 (corrected for a redshift z = 0.0072 and for a reddening E_{B-V} = 0.12) is compared with the synthetic spectrum obtained with parameters T_{bb} = 8400 K, v_{ph} = 5400 km s^{-1}. The ions included in the synthetic spectrum are H I, Ca II, Na I, Fe II, Ti II, Sc II, Ba II, Sr II, Cr II, Mg I, Fe I, Ti I, O I. Only the lines of H I and Ca II are detached from the photosphere, respectively at 7500 and 6300 km s^{-1}. We assume that T_{exc} for each ion is close to 5000 K for neutral species and 10000 K for once ionized atoms as suggested by Hatano et al. (1999). We adopt a T_{bb} that is unusually high for a spectrum showing such well developed permitted metal lines. Moreover, in order to improve the quality of the fit, we also assume large optical depths (log $\tau \approx 2.5$) for the Ti II lines.

The fit of the observed spectrum on day 37 is rather good (Fig. 11), with the usual exception of the Hα emission for which collisional excitation and other non–LTE effects are expected to be important. Detail of the contribution of each species is shown in Figs. 12–14. The fit of Na ID is relatively poor; we tried to improve the result using a small contribution of He I λ 5876, and the comparison between the two different choices is shown in Fig. 12. Significant contribution of He I is expected to be important during the photospheric phase only shortly after the explosion. However, the high value of T_{bb} may indicate high γ–ray deposition which could enhance the He I λ5876 line. In SN 1987A the He I line was visible only up to 3 days after the explosion and a few days later Na ID began to emerge (see e.g. the sequence of early spectra in Hanuschilk & Dachs, 1988; Phillips et al., 1988; Tyson & Boeshaar, 1987; Menzies et al., 1987), although in SN 1998A, because of the higher temperatures (or higher γ–ray deposition), the situation could be different.

The line–blanketing below $\sim$ 5100 Å mainly derives from the strength of a number of Fe II and Ti II multiplets. To improve the quality of the fit in the bluest region of the spectrum, strong contributions from Ca II H & K, Sc II, Sr II and Cr II are needed. Also the presence of neutral species (e.g. Ti I and Fe I) at the photospheric velocity, allows to improve the quality of the fit in the line blanketed region. We stress that lines of neutral ions are expected to be produced in external regions (if at all), with velocities larger than v_{ph}. The absorption feature at $\lambda \sim$ 7700 Å is reproduced by O I and the P–Cygni profile of the strong Ca II IR triplet is well fitted by the synthetic spectrum.

4.3 A PHOENIX Model

In order to obtain some physical insight with respect to the blue colour of SN 1998A, we calculated a synthetic spectrum using a hydrodynamical model of SN 1987A (Blinnikov et al., 2000) and the generalised stellar atmosphere code PHOENIX (Hauschildt & Baron, 1999). Our procedure was the same as that described in Mitchell et al. (2001; 2002). Fig. 15 shows the resulting synthetic spectrum compared to the observed spectrum of SN 1998A at day 37. Considering that we have not adjusted any parameters, the fit is reasonable. The synthetic Balmer lines are too weak and the Ca IR triplet is too strong, but most of the features match the observed ones. However, in general, the synthetic lines are too narrow, again indicating that SN 1998A is likely more energetic than SN 1987A. We stress that the "photospheric temperature", i.e. the electron temperature at the point in the model where the electron scattering optical depth is one, is about 6000 K, just as expected for SNe II–P at this epoch (Popov, 1992). The blue colour of the synthetic spectrum comes from the effects of increased γ–ray heating (see Mitchell et al., 2001). In fact, higher γ–ray heating is likely required in order to reproduce the strength of the synthetic Hα feature, to reduce the flux in the red the strength of the Ca IR triplet. All this confirms that SN 1998A ejected more ^{56}Ni than SN 1987A.

5 DISCUSSION

The observations show that, in spite of the similar evolution of the light curves and spectra, SN 1998A and SN 1987A have a number of different properties. SN 1998A has a higher luminosity at all epochs, likely due to the ejection of a larger amount of ^{56}Ni. It has also higher colour temperatures, and higher expansion velocities, suggesting a more energetic explosion than that of SN 1987A. The low luminosity at early phases and the presence of a broad peak indicate that SN 1998A exploded when the progenitor star was in the blue supergiant stage. In order to obtain an approximate estimate of the explosion parameters and gather some information on the nature of the progenitor star, we have compared the data of SN 1998A with the output of the semi–analytic code developed by Zampieri et al. (2003). The model incorporates all the main sources of energy powering a CC–SN and calculates the evolution of the expanding envelope from the photospheric phase up to the late nebular phase (with the exception of shock breakout which is not included). It assumes idealised initial conditions that provide an approximate description of the ejected material as derived from hydrodynamical calculations. The parameters of the ejected envelope are estimated performing a simultaneous comparison of the observed and computed light curve, photospheric gas velocity and continuum temperature. The results of the fit for SN 1998A are shown in Fig. 16, where we assume that the explosion epoch occurred $\sim$ 19 days before discovery. The main parameters of the post–shock, ejected envelope are listed in Table 5. The fraction of the initial energy that goes into kinetic energy f_0 and the gas opacity κ are input physical constants. In this calculation

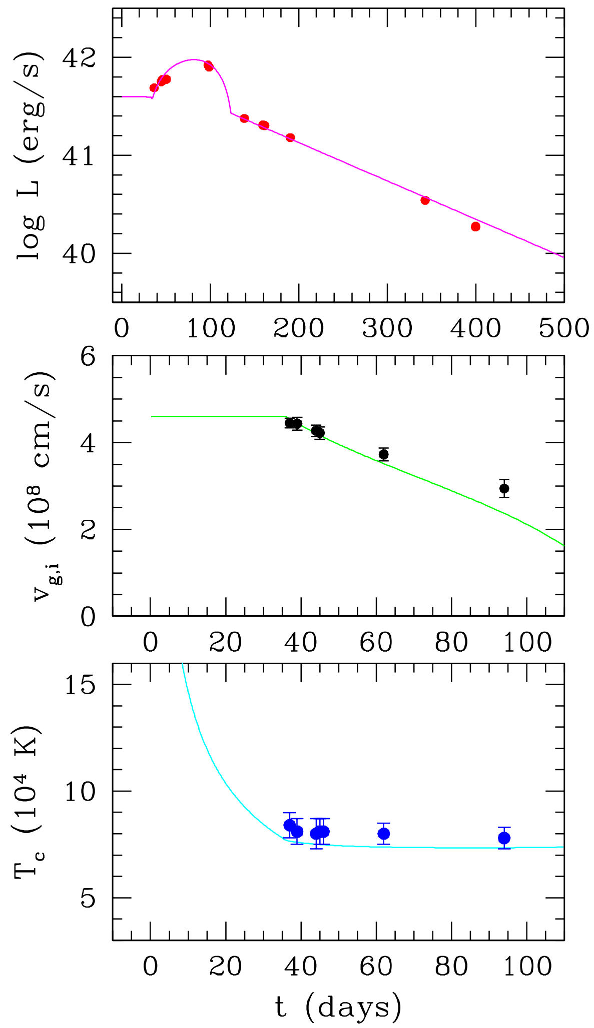

Figure 16. Evolution of the luminosity (**Top**), expansion velocity (**Centre**) and continuum temperature (**Bottom**) as functions of time: comparison between the model (solid lines) and the observations (filled circles).

we adopt $f_0 = 0.5$ (initial equipartition between thermal and kinetic energies) and $\kappa = 0.2$ cm^2 g^{-1} (appropriate for an envelope comprised of He and iron–group elements). The colour correction factor $f_c = T_c/T_{eff}$ measures the deviation of the continuum radiation temperature T_c from the blackbody effective temperature T_{eff}. The value of f_c required to fit the data of SN 1998A lies in the high end tail of the typical range for SN II (see e.g. Eastman, Schmidt & Kirshner, 1996). This is probably the consequence of the different physical conditions at the photosphere of SN 1998A.

Despite the similarity in the photometric evolution, a comparison of the inferred parameters of SN 1998A with those of SN 1987A (also reported in Table 5) shows that there are significant differences between the ejecta of these two SNe. In fact, although the initial radius is small in both objects ($\sim 5 \times 10^{12}$ cm), the ejected mass is different (18 M$_\odot$ in SN 1987A, 22 M$_\odot$ in SN 1998A) and the total energy a few times larger in SN 1998A (5–6 $\times$ 10^{51} erg). This is

Table 5. Parameters of SN 1987A and SN 1998A from the semi-analytic model.

SN	R_0 (10^{12} cm)	M_{ej} ($M_\odot$)	M_{Ni} ($M_\odot$)	V_0 (10^8 cm s^{-1})	E (10^{51} erg)	f_0	κ (cm^2 g^{-1})	$t_{rec,0}$ (days)	T_{eff} (K)	f_c
1987A	$\lesssim 5$	18	0.075	2.7	1.6	0.5	0.2	25	4800	1.1
1998A	$\lesssim 6$	22	0.11	4.6	5.6	0.5	0.2	36	4500	1.6

R_0 is the initial radius of the ejected envelope at the onset of expansion
M_{ej} is the ejected envelope mass
M_{Ni} is the ejected ^{56}Ni mass
V_0 is the velocity of the envelope at the outer shell (i.e. at R_0)
E is the initial thermal+kinetic energy of the ejecta
f_0 is the fraction of the initial energy that goes into kinetic energy
κ is the gas opacity
$t_{rec,0}$ is the time when the envelope starts to recombine
T_{eff} is the effective temperature during recombination
$f_c = T_c/T_{eff}$ is the colour correction factor

shown by the higher expansion velocity and continuum temperature. The large inferred envelope mass and total energy of SN 1998A places it in the upper end of the correlations among the parameters of the ejecta of SN II recently reported by Hamuy (2003), Pastorello (2003) and Zampieri et al. (in preparation). This suggests that the properties of the SN II ejecta vary continuously also in 1987A-like events. The large ejected mass of SN 1998A implies a fairly massive progenitor, that may form more easily in a low metallicity environment.

One of the most intriguing properties of SN 1998A is that Ba II lines are fainter than those of SN 1987A and nearly equal to the typical strength in a normal Type II event [e.g. SN 1988A (Turatto et al., 1993) and SN 1996W (Pastorello, 2003)]. Mazzali & Chugai (1995) suggest two possibilities to explain the difference in strength of the Ba II lines: an intrinsic difference in the abundance of Ba in the ejecta and different physical conditions. Although it is impossible to exclude local overproduction of Ba (e.g. a scenario involving binary systems or stellar mergers, or higher degree of mixing in the envelope of the Ba synthesised via s–process in the He core), the s–process nucleosynthesis in Type II progenitors cannot explain a Ba overabundance in the envelope larger than 40%. This is well below than deduced from the strength of the Ba II lines in SN 1987A (a factor 20; Utrobin & Chugai, 2002). Therefore, the different physical conditions at the photosphere are likely to play a crucial role in determining the appearance or disappearance of strong Ba lines. In particular, a lower temperature caused by a smaller γ–ray heating may be a key ingredient. If in the atmosphere of most SNe II–P barium is present as Ba III due to non–thermal ionization by γ–rays, the observed spectra will show "normal" strength of the Ba II lines. On the contrary, in SN 1987A (but also in SN 1997D and similar events, Turatto et al., 1998; Pastorello et al., 2004) lower amounts of ^{56}Ni ejection produce less non–thermal ionization and increase the abundance of Ba II ions (Chugai, 1988b). In addition, we note that the almost normal strength of the Ba II lines in the spectra of SN 1998A suggests that these lines are probably not sensitive to the initial radius.

Another observational property of SN 1998A is the low intrinsic polarization at early phases (Leonard & Filippenko, 2001): this indicates relatively low asphericity of the emitting region, supporting the general scenario that core–collapse events which retain hydrogen envelopes at the epoch of explosion are not significantly aspherical during the early photospheric phase (Leonard & Filippenko, 2001).

The differences between the progenitor properties of SN 1998A and SN 1987A suggest that stars with different masses can explode in the blue supergiant stage. In particular, the discovery of a few SNe II with light curves similar in shape to SNe 1987A and 1998A [SN 1909A (Sandage & Tammann, 1974; Young & Branch, 1989), SN 1982F (Yamagata & Iye, 1982; Tsvetkov, 1984; Tsvetkov, 1988), SN 1998bt (Germany, 1998) and SN 2000cb (Hamuy, 2001)], but showing a significant spread in the magnitudes at maximum, is an indication that these objects are moderately common, even if less frequent than predicted by previous works (e.g. Schmitz & Gaskell, 1988). In analogy to more typical SNe II–P (Hamuy, 2001; Hamuy, 2003; Pastorello, 2003), 1987A–like events are therefore expected to cover a wide range of physical properties.

6 CONCLUSIONS

In this paper we have presented the spectroscopic and photometric data of the peculiar SN 1998A, which shows clear observational analogies with SN 1987A. However, despite the spectro–photometric similarities, the physical parameters characterising both SN 1987A and SN 1998A, and their progenitors, are different.

Optical photometry indicates that the progenitor of SN 1998A was a compact blue supergiant and that the progenitor star mass was ~ 25 M$_\odot$.

The high line velocities in SN 1998A indicate that the explosion energy is larger than that of SN 1987A: the total initial energy of the ejecta soon after the explosion is about 4 times higher than in SN 1987A.

The luminosity of SN 1998A exceeds that of SN 1987A at all epochs. In particular, the luminosity of the radioactive tail indicates that the amount of ^{56}Ni ejected by the explosion of SN 1998A is about 0.11 M$_\odot$ (as compared to 0.075 M$_\odot$ in SN 1987A).

In SN 1998A the Ba II P–Cygni lines are fainter than those observed in SN 1987A and in several other faint CC–SNe (Pastorello et al., 2004), suggesting that a relation exists between the strength of the Ba II lines and the ejected ^{56}Ni mass.

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