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The supernova 1998S in NGC 3877: Another supernova with Wolf-Rayet star features in pre-maximum spectrum

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Abstract. We present the BVR photometry and the spectra of SN 1998S taken about four months after discovery, beginning a week and 6 days before maximum brightness respectively. The light curves show a steep and linear decline, which are consistent with those of SN 1979C and are typical of a SN II-L. An absolute magnitude at maximum $M_B^0 \leq -18.7$ is derived, which is more than 2 mag brighter than the regular SNII and indicates this SN is a member of the rare class of Bright SNII. The $B-V$ color evolution at early epoch is also typical of linear SN II with a maximum $(B-V)$ value of +1.35, similar to the typical Type II-L SN 1980K.

The spectral evolution is typical for SN II-L, very similar to that of the SN 1979C. They, however, showed some differences. The spectrum before maximum showed high-ionization N III and He II emission lines superposed on a strong blue continuum. Around the maximum light the high-ionization emission lines disappeared, leaving weak H I, He I emission lines, which are similar to those of SN 1983K. The extraordinary feature on the post-maximum spectra is the narrow emission P Cygni profile superposed on a much broader P Cygni structure in all five Balmer lines, Hα to Hϵ. Such feature is reminiscent of the post-maximum spectra of SN 1984E.

Rapid spectral and photometric evolution, together with the presence of obvious P Cygni profile, suggests that SN 1998S is more consistent with the nature of a type II-L supernova than that of a IIn supernova, although narrow lines are present on the premaximum spectrum.

Key words: supernovae: general — supernovae: individual (SN 1998S)

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1. Introduction

The supernova 1998S in NGC 3877 was discovered by Zhou Wan at Beijing Astronomical Observatory (BAO) on 1998 March 3 UT (Li & Li 1998). It is located at R.A. $= 11^{\rm h}46^{\rm m}06^{\rm s}$, $\delta = +47°29'0$ (equinox 2000.0), which is 16″ west and 46″ south of the nucleus of NGC 3877. CCD images taken on Feb. 23.7 showed no star at the position of SN 1998S. As the object is embedded in the galaxy, the BAO magnitude was obtained from a subtracted image.

Spectra obtained by Filippenko & Moran (1998a) showed that the supernova was a type-II supernova due to the presence of broad Hα emission superposed on a featureless continuum. Further observation (Filippenko & Moran 1998b) indicated that the object was not a typical supernova, and suggested that the supernova belonged to the type IIn based on the presence of the narrow Hα emission component. More recently, Leonard et al. (1999) presented optical spectropolarimetry and spectra of the supernova and found that the SN exhibits a high degree of linear polarization, implying significant asphericity for its continuum-scattering environment.

Type II supernovae are defined by the presence of hydrogen. They can be divided photometrically into II-P and II-L (Barbon et al. 1979). The II-P light curves show an essentially constant-light phase from approximately 30 to 80 days post-maximum, while the II-L light curves decay quite linearly, at a rate of about 0.05 mag day^{-1} in the B band from the maximum to about 100 days past maximum. Schlegel (1996) suggested that the spectroscopic differences between these two subtypes were that the early spectra of SNe II-L lacked a strong P Cygni at Hα line. In addition to the two well-known photometric subclass of SNII, Schlegel (1990) defined a new subclass of type IIn, distinguished by relatively narrow emission lines with little or no P Cygni absorption component and slowly declining light curves. The typical spectrum of a type IIn supernova is a narrow component superposed on a broad component. The centroid of the base is blueshifted with respect to the systemic velocity (Filippenko 1989). The evolution of the IIn spectrum is slow, with the overall appearance remaining approximately constant for $50 - 100$ days.

In this paper, we present the spectral and photometric evolution of SN 1998S through the first four months after discovery based on BAO observations. The pre-maximum spectrum was dominated by the Wolf-Rayet star lines, while the post maximum spectrum was dominated by double P Cygni profile at Hα to Hε. Possible interpretations of these features are discussed.

2. Observations and results

2.1. Photometry

The photometric data of SN 1998S were obtained on a total of 32 nights between 1998 March 5 and 1998 July 2 with a 0.6 m telescope at Xinglong Station of the BAO. The CCD camera attached at the prime focus is a Texas Instruments TI-215, which has 1024×1024 pixels and a field of view of $16.'8 \times 16.'8$. The broadband filters used for the photometry of SN 1998S are B and V and Cousins' R_c. Since there is no guider on the 0.6 m telescope, the exposure time could not exceed 300 s. We primarily used exposures of 120 s when the SN was around maximum and 300 s when it dimmed. The data were reduced using the IRAF package. The photometry for 1998S in B, V and R bands is listed in Table 1, and plotted in Fig. 1, together with the photometry reported in the IAU circulars (Nakamura et al. 1998; Garnavich et al. 1998; Garnavich et al. 1998b). The solid lines are schematic light curves of SN 1979C in the B and V systems, a typical SN II-L in NGC 4321 (Barbon et al. 1982).

SN 1998S was rising when we began to do photometry on 1998 March 5. B rose quickly (-0.19 mag day^{-1}) from March 5 to March 8, then it rose more slowly, reaching a maximum around 1998 March 12. Although the maximum light may occur between March 12 and 21 because there is a 9-day observational gap between them, we still take March 12 as the maximum for convenience. During the first 70 days after maximum, the light curves show a steep, almost linear, decline. A linear fit of the data gives $\beta^B_{100} = 5.4 \pm 0.2$, $\beta^V_{100} = 3.6 \pm 0.3$, $\beta^R_{100} = 2.7 \pm 0.3$ mag (100 d)$^{-1}$, which are typical of linear SNII (Patat et al. 1994). The fitting of the observed B magnitudes with the light curve of SN 1979C clearly shows that this SN belongs to the same subclass of SN II. It will be useful to note that the luminosity of SN 1998S at 230 days after the maximum is consistent with that of SN 1979C expected from the interpolation of the B and V light curves.

Adopting for the parent galaxy NGC 3877 a distance modulus $\mu = 31.15$ and reddening $A^b_B = 0.01$ (Tully 1988), we derive an absolute magnitude at maximum

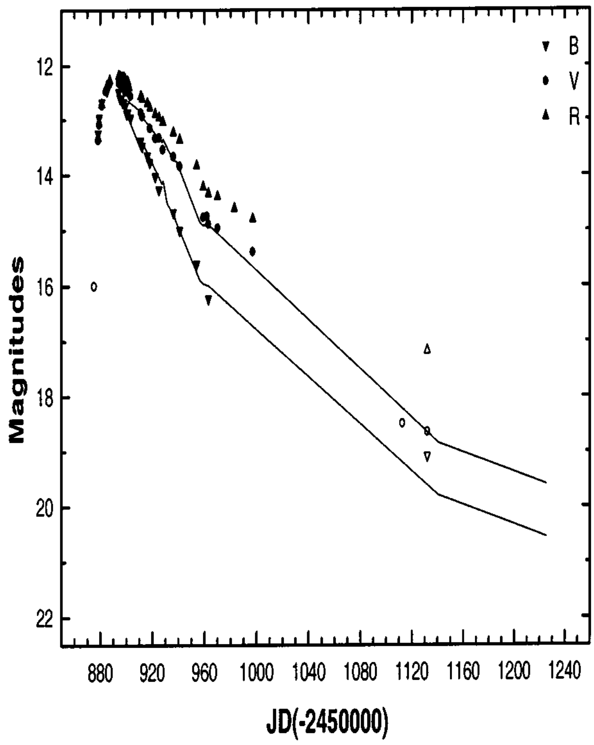

Fig. 1. Light curves of SN 1998S in NGC 3877. The lines represent the schematic B and V light curves of SN 1979C in NGC 4321 (Barbon et al. 1982), which have been arbitrarily shifted along both axes in order to obtain the best fit to the observations of SN 1998S. The solid symbols are obtained at BAO, and the open symbols are taken from IAU circulars

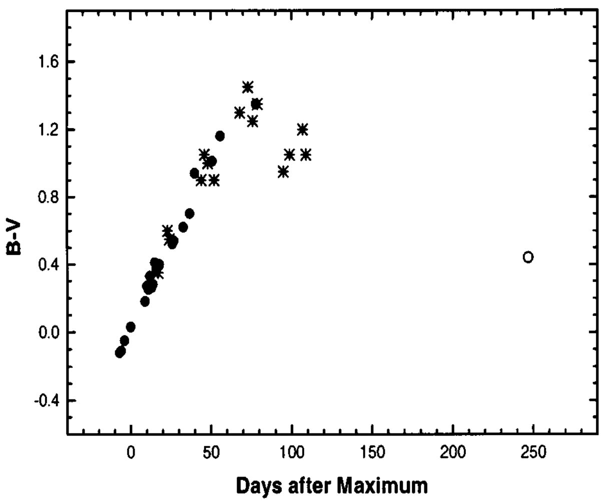

Fig. 2. Comparison of the $B-V$ color curve of SN 1998S with that of the well-studied type II-L SN 1980K in NGC 6946. The solid circles are obtained at BAO, and the open circle is taken from Garnavich et al. (1998b). The stars are the $B-V$ colour of SN 1980K (Barbon et al. 1982), which have been arbitrarily shifted along x-axis in order to obtain the best fit to the observations of SN 1998S

Table 1. Photometric observations of SN 1998S

DATE	JD(−2450000)	B	V	R_c	$B-V$	t	Note
March 5	878.24012	13.246	13.362	13.326	−0.12	−7	
March 6	879.19821	12.965	13.077	13.054	−0.11	−6	*
March 8	881.20014	12.676	12.729	12.712	−0.05	−4	
March 11	884.16831	——	12.469	12.443	——	−1	
March 12	885.15253	12.462	12.435	12.371	0.03	0	*, B_{max}
March 14	887.21179	——	12.339	12.272	——	2	
March 21	894.16584	12.490	12.313	12.187	0.18	9	*, V_{max}, R_{max}
March 22	895.14534	12.601	12.328	12.199	0.27	10	
March 23	896.16741	12.609	12.361	12.217	0.25	11	*
March 24	897.14626	12.679	12.369	12.221	0.33	12	
March 25	898.13049	12.679	12.415	12.220	0.26	13	
March 26	899.15073	12.746	12.466	12.252	0.28	14	*
March 27	900.24368	12.883	12.471	12.300	0.41	15	
March 28	901.10917	12.865	12.490	12.294	0.37	16	
March 29	902.17131	——	——	12.396	——	17	
March 30	903.17039	12.962	12.559	——	0.40	18	
April 7	911.12118	13.382	12.863	12.561	0.52	26	
April 8	912.13229	13.475	12.933	12.606	0.54	27	
April 12	916.1162	13.649	——	12.688	——	31	
April 14	918.09834	13.768	13.148	12.774	0.62	33	
April 18	922.13403	14.029	13.329	12.895	0.70	37	
April 21	925.06375	14.263	13.327	12.961	0.94	40	
April 24	928.09568	——	13.538	13.035	——	43	*
May 2	936.05209	14.675	13.666	13.231	1.01	51	
May 7	941.04237	15.000	13.839	13.363	1.16	56	
May 20	954.06493	15.606	——	13.833	——	69	
May 25	959.04054	——	14.762	14.212	——	74	*
May 28	962.02126	——	14.741	——	——	77	
May 29	963.06325	16.235	14.884	14.330	1.35	78	
June 5	970.04291	——	14.957	14.390	——	85	
June 18	983.05329	——	——	14.604	——	98	
July 2	997.03228	——	15.391	14.790	——	112	*

Note to Table 1: * means that spectral observations are made simultaneously.

$M_B^0 \leq -18.7$, not considering the extinction in the parent galaxy. The maximum magnitude of SN 1998S is more than 2 mag brighter than the regular SNII and indicates this SN is a member of the rare class of Bright SNII (Patat et al. 1994), which include both type II-L SNe 1979C, 1980K, and 1990K and type IIn SNe 1983K, 1987F, and 1988Z.

The $(B-V)$ is only 0.03 at maximum light (Fig. 2). Patat et al. (1994) found that the behaviour of $(B-V)$ in SNe II-P and II-L is relatively homogeneous in the early 50 days. In general, the maximum $(B-V)$ of II-L is about +1.0, but the Type II-L SNe 1980K and 1959D reach a maximum $(B-V)$ value of +1.4 and 1.7 respectively. The maximum $(B-V)$ of another SN II-L 1990K also reached 1.45 (Cappellaro et al. 1995). The $B-V$ color exhibits a rapid evolution from blue to red and then linearly increased to a high value of 1.35 on May 29 at $t = 78$ days after maximum light, comparable with Type II-L SNe 1959D, 1980K, and 1990K. In Fig. 2, we compare the $B-V$ color curve of SN 1998S with that of the well-studied type II-L SN 1980K in NGC 6946 (Barbon et al. 1982). Because SN 1980K was discovered after maximum light, we have shifted the colours 7 days along x-axis in order to obtain the best fit to the observations of SN 1998S. We can see from the figure that the colour curve of SN 1998S is well fitted to that of SN 1980K. Although the photometric observations of SN 1998S only covered an epoch of about four months, the $B-V$ color evolution at early epoch is also typical of linear SN II due to its $\beta_{100}^{B-V} = 1.8$ (Patat et al. 1994) and similarity to SN 1980K.

2.2. Spectroscopy

The optical and near-infrared low-dispersion spectra of SN 1998S were obtained with the OMR spectrograph at the BAO 2.16 m telescope. The CCD is a Tektronix 1024

×1024. We used two low- dispersion gratings, the dispersions of which are about 200 and 400 Å mm^{-1}, respectively. The spectral coverage of the two gratings is about 3800 − 8200 and 3800 − 9200 Å. Their resolutions are about 4.9 and 9.8 Å $pixel^{-1}$, respectively. All the data were bias-subtracted, flat-fielded, and extracted with the IRAF packages. Wavelength calibrations were performed using the spectra of FeAr or HeNeAr lamps. The supernova flux was calibrated in reference to observations of spectroscopic standards (Oke & Gunn 1983).

The first spectrum of SN 1998S (Fig. 3), obtained about a week before maximum light, shows it to be quite unusual. The most prominent lines are readily identified with He II λ4686, the H I Balmer series, and the N III $\lambda\lambda$ 4634, 4640, 4641 and probable C III 4640 blend. The overall character is one of quite high excitation, strikingly similar to that observed in Wolf-Rayet stars (Garnavich et al. 1998a; Leonard et al. 1999), as noted by Niemela et al. (1985) in SN 1983K. The strengths of He II 4686 Å and N III/C III are comparable to the flux of Hβ. These features are identical with those seen in SN 1983K (Niemela et al. 1985), which was discovered two weeks before maximum light, but with a much weaker Hα emission intensity. A broad emission feature peaking at 5800 Å may be C IV, also found in Wolf-Rayet stars. Another emission at 5696 Å is likely to be C III line. There are also weaker He II lines seen at 5411 and 4541 Å, as well as the presence of a hint of weak emission of He I at 4471, 5876 and 6678 Å. Na I absorption with an equivalent width of 0.7 Å is measured. Although the H-Balmer lines are relatively narrow, they are still wider than those of typical IIn SNe 1988Z and 1994W are.

The second spectrum, taken at the maximum light, i.e., March 12, displays a nearly featureless blue continuum, superimposed by weak Balmer lines, Hα to Hϵ. The narrow component of Hα initially quite luminous, is now much weaker. The W-R star features near 4670 Å (He II and N III/C III) and 5800 Å (C IV) in the spectrum of March 6 are hardly discernable now. The weak He I $\lambda\lambda$ 6678 and 5876 can be detected. The most striking feature is the Hα and Hβ emission which had developed a notable red asymmetry, and the blue wings become steeper with little evidence of the P Cygni absorption. The equivalent widths of Hα and Hβ are −8.3 Å and −2.4 Å, respectively, compared to −32 Å and −13 Å on March 6. The full width at the base of Hα is 74 Å, implying an expansion velocity of 3380 km s^{-1}.

The next three spectra were taken between March 21 and 26. Because of the similarity of the three spectra, we have averaged them to improve signal-to-noise ratio. The extraordinary feature of the spectra is the narrow emission P Cygni profile superposed on a much broader absorption or P Cygni structure in all five Balmer lines, Hα to Hϵ. Such lines dominate the spectrum. The Hα line shows a narrow P Cygni emission, narrow absorption shifted by −1100 km s^{-1} from the emission, and a broad, shallow absorption extending to −10000 km s^{-1} with a minimum at −4700 km s^{-1}.

One month later, the continuum becomes significantly fainter and redder. The character of the spectrum changes radically. The forbidden lines of [O I] λ 5577 first appear as the density of the line emitting region decreases. The narrow component of Hα nearly disappeared by April 14. Like typical II-L SNe, no obvious P Cygni profile was present on the Hα line of SN 1998S. The overall feature of the spectra is similar to those of SNe 1979C and 1984E obtained a month after maximum light. The blueshifts of the absorption components of Hβ and Fe II λ 5018 are comparable with those of SN 1984E, but smaller than those of SN 1979C. We also notice that the Ca II near-IR triple is apparent although the spectra do not cover the full line.

The last two spectra, respectively taken on May 25 and July 2, show the further development of the April spectra. Broad emission line of the Ca II near-IR triplet ($\lambda\lambda$ 8498, 8542, and 8662) is very strong, and Ca II H, K lines are discernible. The Hα and the Ca II near-IR triplet are the dominant feature. The forbidden lines of [Ca II] $\lambda\lambda$ 7291 and 7324 and [O I] $\lambda\lambda$ 6300 and 6364 first appear (but can trace back to the April spectra) and progressively grows in strength.

3. Comparison with other supernovae

In order to show how unusual SN 1998S is we compare SN 1998S to several SNe which share some characteristics.

3.1. SN 1983K

The first time Wolf-Rayet star lines were identified in a supernova was in SN 1983K before maximum light (Niemela et al. 1985). The Wolf-Rayet lines in the SN disappeared close to the maximum light. Niemela et al. (1985) suggested that the surface layers of the progenitor were significantly overabundant in nitrogen. The progenitor was assumed to be a red supergiant (Phillips et al. 1990).

To our knowledge, SN 1998S is the second one with those lines. The spectra of SN 1998S before maximum light are very similar to that of SN 1983K, but with a much stronger Hα intensity. Although only blue spectra of SN 1983K are available in the literature, the spectral evolution of the two SNe after maximum light is different. The most striking difference between the two SNe, however, is the evolution of light curves although their absolute magnitudes are comparable. After maximum light, the magnitudes of SN 1983K decayed very slowly and the supernova itself was defined as Type II-P by Phillips et al. (1990), while that of SN 1998S dropped dramatically (Fig. 1). Consequently, though the spectra before the maximum light are superficially similar to those seen in SN 1983K, there appears to be little relationship between the two supernova events.

Table 2. Journal of spectroscopic observations of SN 1998S

Date	t	JD (−2450000)	Exposure (s)	Range (Å)	dispersion (Å/mm)
March 6	−6	879.245	1200	3677-8644	200
March 12	0	885.238	600	3586-8408	200
March 21	9	894.225	600	3764-8730	200
March 23	1	896.198	600	3730-8696	200
March 26	14	899.186	600	3660-9264	400
April 14	33	918.174	600	3525-8493	200
April 24	43	928.172	600	3548-8514	200
May 25	74	959.126	900	3633-8505	200
July 2	112	997.124	1500	3599-9015	400

Note to Table 2: March 21, 23 and 26 spectra are co-added and marked $t = 9 - 14$ in Fig. 3.

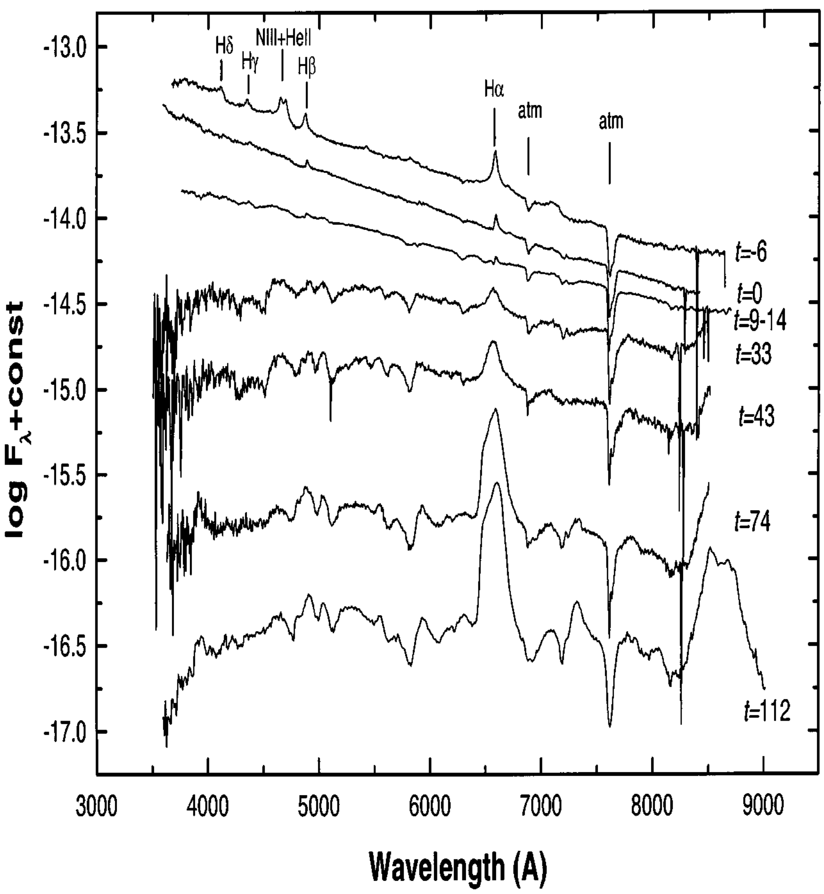

Fig. 3. Spectral evolution of the supernova in NGC 3877. Wavelength is in the rest frame of the parent galaxy

3.2. SN 1984E

The first time CSM lines were identified in a supernova was in SN 1984E close to maximum light. These lines were very luminous, but only short-lived. The line widths imply a velocity of $250 - 350$ km s^{-1}, which is faster than typical red supergiant winds. Schlegel (1990) defined the sub-class Type IIn to emphasize the presence of the narrow emission components. Recently there have been a substantial number of other SNe IIn discovered, including SNe 1988Z, 1994Y, and 1994ak. Filippenko (1997) suggested that SNe 1983K and 1984E might also be variants of SNe IIn. Dopita et al. (1984) suggested that the CSM was the product of a superwind shortly before collapse, but Gaskell & Keel (1988) found that the material had been ejected from the progenitor in a relatively discrete event less than 30 years before the explosion. The CSM emission in SN 1984E had disappeared by one month after maximum (Henry & Branch 1987), and the supernova itself decayed rapidly, with a light curve of a typical type II-L.

Light curves of SN 1998S are similar to those of SN 1984E, but the maximum magnitude of SN 1998S is over 2 mag brighter than that of SN 1984E. Although no spectrum before maximum light in SN 1984E was reported, its post-maximum spectrum looks very similar to that of SN 1998S, except for the very strong narrow lines. The narrow lines in SN 1998S also disappeared one month later.

3.3. SN 1979C

SN 1979C in NGC 4321 is one of the prototypes of Linear SNII. The photometric evolution of SN 1998S is consistent with that of SN 1979C (Fig. 1), and the maximum absolute magnitude is comparable. Although no premaximum spectrum is available, a glance at the spectral evolution can find the similarity of SN 1998S with SN 1979C (Branch et al. 1981). Similar weak, narrow H I absorption lines were observed just after maximum in the Type II supernova 1979C. A comparison of the April 24 and May 25 spectra with the spectra of SN 1979C at nearly same epochs after maximum light shows good qualitative agreement (Fig. 4). However, there are also some differences between the two SNe. For example, the emission line intensity of SN 1998S within one month after maximum is a little weaker than that seen in SN 1979C, which may imply the difference of the CSM between them. P Cygni absorption is not very apparent in the spectra of SN 1979C, while in SN 1998S, it is obviously present in the early spectra. It is interesting to note that although the width of the emission line profile in SN 1998S is roughly similar to that observed in SN 1979C at a corresponding phase, the profiles are much different (Fig. 4).

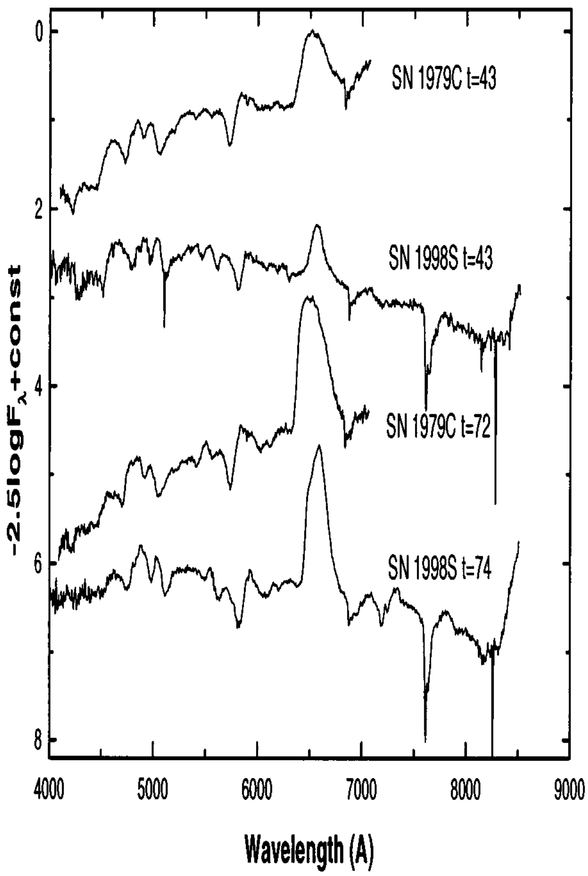

Fig. 4. The spectra of SN 1998S obtained on April 24 and May 25 are compared to the spectra of SN 1979C at nearly the same epochs. Wavelengths are in the rest frames of the parent galaxies

4. Discussion and conclusions

We have presented and discussed the photometric and spectroscopic observations of supernova SN 1998S in NGC 3877 made in the first four months after discovery, namely in the period March 6 - July 2. The maximum magnitude of SN 1998S is more than 2 mag brighter than the regular SNII and indicates this SN is a member of the rare class of Bright SNII (Patat et al. 1994). Nearly all the Bright SNeII are found with a type of SN II-L or IIn. The progenitor of SN 1998S is likely to be a red supergiant instead of a Wolf-Rayet star according to $M_B^0 \leq -18.7$ (Phillips et al. 1990). Both the light curves and the $B-V$ color evolution at early epoch are supported that the SN is typical of linear SN II.

The spectrum of SN 1998S is unusual. The H I Balmer and weak He I lines observed around maximum light almost certainly were produced in a preexisting circumstellar shell, implying that the progenitor of SN 1998S had undergone significant mass loss. The most noticeable feature in the spectrum before maximum light is the presence of high-excited lines such as He II λ 4686 and λ 5411, C III and C IV, and N III λ λ 4634, 4640, 4641. SN 1998S is one of the only two SNe with those lines at pre- maximum light. The prominent nitrogen lines very likely imply that at least some of the gas in the progenitor star was significantly nitrogen enriched. This spectrum abruptly disappeared at the approach of maximum light, which is the point at which the shock wave most likely emerged at the photosphere. The similarity of the high-excitation lines in two different SNII, 1983K and 1998S suggests that nitrogen abundant and excited state in CSM of the progenitor before maximum light are not very different.

The rapid decline of light curves suggests that SN 1998S has relatively low-mass hydrogen envelope. The CSM is likely dense, but small in extent and mass, and was probably disrupted when collided with the expanding SN envelope. Rapid spectral evolution also suggests that the photon diffusion time in envelope is short, thereby implying a low-density envelope, with which a linear light curve will be expected.

The extraordinary feature of the post-maximum spectra is the narrow emission P Cygni profile superposed on a much broader absorption or P Cygni structure in all five Balmer lines, Hα to Hϵ. This behaviour does not approximate that of the proposed SN IIn. The narrow emission lines are typical of hot nebulae and arise in circumstellar material released from the progenitor as a stellar wind and excited by the UV flash shortly after core collapse, while the weak broad component could be produced by accelerated material at the shock caused by the collision of the supernova envelope with the circumstellar material. When the CSM matter was eventually engulfed by the expanding SN ejecta at later epochs, the spectra are dominated by the broadened lines produced by the accelerated material at the shock front.

Panagia et al. (1980) suggested presence of a shell where the gas is highly ionized. It is likely that the shell consists of gas originally ejected by the progenitor in the form of a more or less continuous wind. The wind material may have subsequently been compressed and accelerated as a result of the SN explosion, possibly by the radiation pressure of an initial soft X-ray burst (Klein & Chevalier 1978). The narrow P Cygni feature at H-Balmer may also be explained by this accelerated, extended shell. Such a narrow P Cygni feature, superposed upon a broad, partially filled in P Cygni line, could give a line profile such as we observed.

The comparison of the observations of this supernova with those of other SN II suggests that most of the features of SN 1998S may not be consistent with that of the type IIn, and that the SN may be suitable to classify as a type II-L, although the narrow lines exist at the early spectrum. SN 1998S provides strong evidence for a physical continuity between the features of CSM and likely explosion mechanisms of type II-L SNe and type IIn SNe. We suggest that a SN IIn should exhibit slowly declining light curves and slow spectral evolution besides the presence of narrow lines, since narrow lines are easily present at the early spectrum due to the significant mass loss of the progenitor as pointed out by Stathakis & Sadler (1991). From this viewpoint, the SN 1984E may not be classified as a SN IIn although there are very narrow and strong lines at the early spectrum.

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