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SPECTRUM ANALYSIS OF THE TYPE Ib SUPERNOVA SN 1999dn: PROBABLE IDENTIFICATIONS OF C II AND Hα

J. S. DENG,[1,2] Y. L. QIU,[2] AND J. Y. HU[2]
Beijing Astronomical Observatory, Chaoyang, Beijing 100012, People's Republic of China;
djs@nova.bao.ac.cn, qiuyl@nova.bao.ac.cn, hjy@class1.bao.ac.cn

AND

K. HATANO AND D. BRANCH
Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019; hatano@mail.nhn.ou.edu, branch@mail.nhn.ou.edu
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ABSTRACT

Low-resolution spectra of SN 1999dn at early times are presented and compared with synthetic spectra generated with the parameterized supernova synthetic spectrum code SYNOW. We find that the spectra of SN 1999dn strongly resemble those of SN 1997X and SN 1984L, and hence we classify it as a Type Ib event. Line identifications are established through spectrum synthesis. Strong evidence of both Hα and C II λ6580 is found. We infer that Hα appears first, before the time of maximum brightness, and then is blended with and finally overwhelmed by the C II line after maximum; this favors a thin high-velocity hydrogen skin in this Type Ib supernova.

Subject headings: radiative transfer — supernovae: general — supernovae: individual (SN 1999dn)

1. INTRODUCTION

Types Ib and Ic supernovae (SNe Ib and SNe Ic) are distinguished from SNe Ia primarily by their lack of a strong 6150 Å Si II absorption feature in early-time spectra (Filippenko 1997). Their nature is still under debate due to their relative rareness (Cappellaro, Evans, & Turatto 1999) and faintness (Piemonte 1997). The most widely accepted scenario is the core collapse of a massive star that has lost its hydrogen (SN Ib) and possibly helium (SN Ic) envelopes through either a stellar wind or the effects of a close companion, although other models, like the thermonuclear explosions of white dwarfs, have not been completely excluded. Currently, there is intense interest in SNe Ib and Ic because of their possible connection with gamma-ray bursts (Wheeler, Höflich, & Wang 1999).

SN 1999dn, located in NGC 7714, was discovered by Qiu et al. (1999b) on August 19.76 UT with the Beijing Astronomical Observatory (BAO) 0.6 m telescope. It was originally identified as a Type Ic (Ayani et al. 1999; Turatto et al. 1999) or Ib/c event (Pastorello et al. 1999). The derived velocity of the weak "Si II λ6355" absorption line is much smaller than that of other lines, which encouraged us to reconsider the line identification and spectroscopic classification through spectrum synthesis. We used the fast parameterized LTE code SYNOW and early-time spectra observed with the BAO 2.16 m telescope. The observations, spectrum-synthesis procedure, and results are presented and discussed here.

2. OBSERVATIONS

Three spectra of SN 1999dn were obtained with the 2.16 m telescope of BAO. The first spectrum was taken with the BFSOC spectrograph with a 2048 × 2048 pixel CCD, just after the discovery of the supernova. The other two spectra were taken with the OMR spectrograph with a Tek 1024 × 1024 CCD. We used a grating of 200 Å mm^{-1}, whose spectral resolution is about 10 Å. The standard Image Reduction and Facilities (IRAF) package was used to reduce the spectra. The observations are listed in Table 1.

During the reduction process, the telluric emission lines were subtracted automatically. We did not remove any telluric absorption lines from the first two spectra. We used an early-type standard star, which has no strong features in the red part of its spectrum, to obtain the profiles of the telluric lines and remove them from the third supernova spectrum. The spectra of SN 1999dn are shown in Figures 1, 2, and 3.

3. SPECTRUM SYNTHESIS

To establish line identifications, we used the parameterized supernova spectrum synthesis code SYNOW to analyze the spectra of SN 1999dn. This code makes simplifying approximations, including the LTE, resonant-scattering, and Sobolev approximations (Jeffery & Branch 1990; Fisher et al. 1997).

Hatano et al. (1999) have calculated LTE Sobolev line optical depths for various temperatures and for six different compositions that could be encountered in supernovae. We used their results to determine which ions should be considered in our synthesis procedure. For each ion, the optical depth of a reference line is a fitting parameter. Optical depths of the other lines for that ion are calculated assuming Boltzmann excitation, with excitation temperature also a fitting parameter. The continuum is fitted with a blackbody; its temperature T_{bb} is not assigned much physical significance.

The radial dependence of the line optical depths is taken to be exponential with the e-folding velocity $v_e = 1000$ km s^{-1}. The velocity interval within which an ion is present is characterized by such fitting parameters as the minimum and maximum velocities v_{min} and v_{max}. We use $v_{max} = 5 \times 10^4$ km s^{-1}, and in most cases v_{min} is the same as the velocity at the photosphere, v_{ph}. When we assign to some ion a v_{min} that is larger than v_{ph}, we mean that this ion is detached from the photosphere.

We have experimented with many combinations of fitting parameters. The best-fit synthetic spectra are compared

[1] Corresponding author.
[2] Chinese National Astronomical Observatories.

TABLE 1

THE BAO SPECTRA OF SN 1999dn

Date (UT)	Exposure (s)	Standard
1999 Aug 21.5......	3600	Feige 110
1999 Aug 31.6......	2400	BD 28°4211
1999 Sep 14.5	3600	BD 28°4211

with the observed spectra of August 21, August 31, and September 14 in the upper panels of Figures 1, 2, and 3, respectively.

The synthetic spectrum of August 21 has $T_{bb} = 7500$ K and $v_{ph} = 16{,}000$ km s^{-1}. As shown in the upper panel of Figure 1, the Fe II features from 4500 to 5500 Å and the Ca II IR triplet around 8200 Å are prominent. The inconspicuous absorption near 7160 Å can also be attributed to Fe II. The absorption near 7500 Å is usually attributed to O I λ7773, but the absorption here is too red for O I to fit it well. So we introduce Mg II $\lambda\lambda$7877, 7896 and blend them with the O I line. Both the Na I D lines and He I λ5876 are candidates for the strong P Cygni feature around 5700 Å. We favor He I because it can also account for other observed features with the $\lambda\lambda$6678 and 7065 lines. The absorption minimum at 6200 Å was originally identified as Si II λ6355 (Ayani et al. 1999; Qiu et al. 1999a; Turatto et al. 1999), but through spectrum synthesis we have found that it is better fitted by the λ6580 line of C II, detached at 20,000 km s^{-1}. C II $\lambda\lambda$4738, 4745 may also contribute to the absorption near 4500 Å.

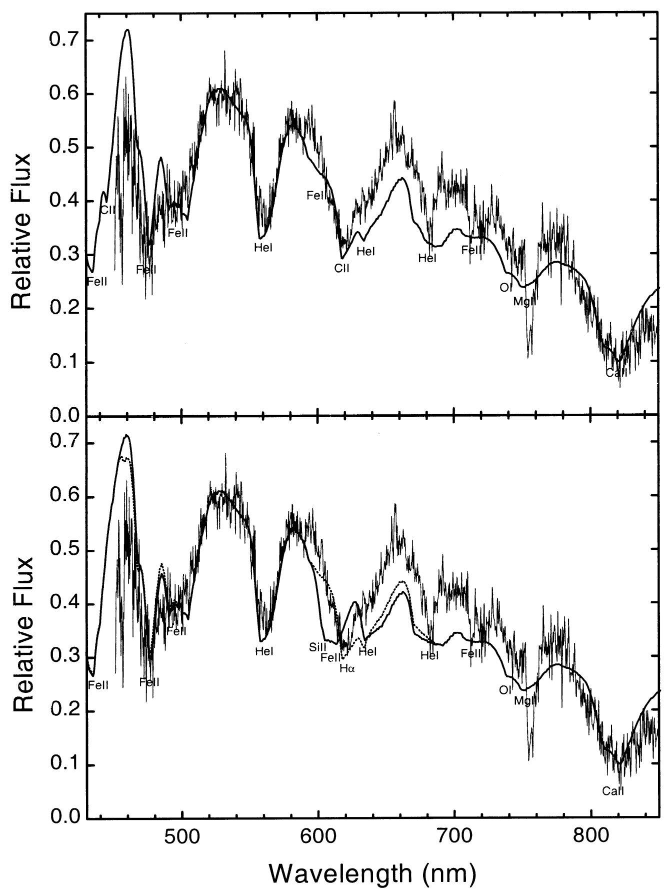

FIG. 1.—The observed spectrum of Aug 21 (*thin solid lines*) is compared with synthetic spectra which have $T_{bb} = 7500$ K and $v_{ph} = 16{,}000$ km s^{-1}. In the upper panel, the synthetic spectrum with C II is plotted on the thick solid line. In the lower panel, C II is replaced by Si II (*thick solid line*) and H I (*dotted line*), respectively.

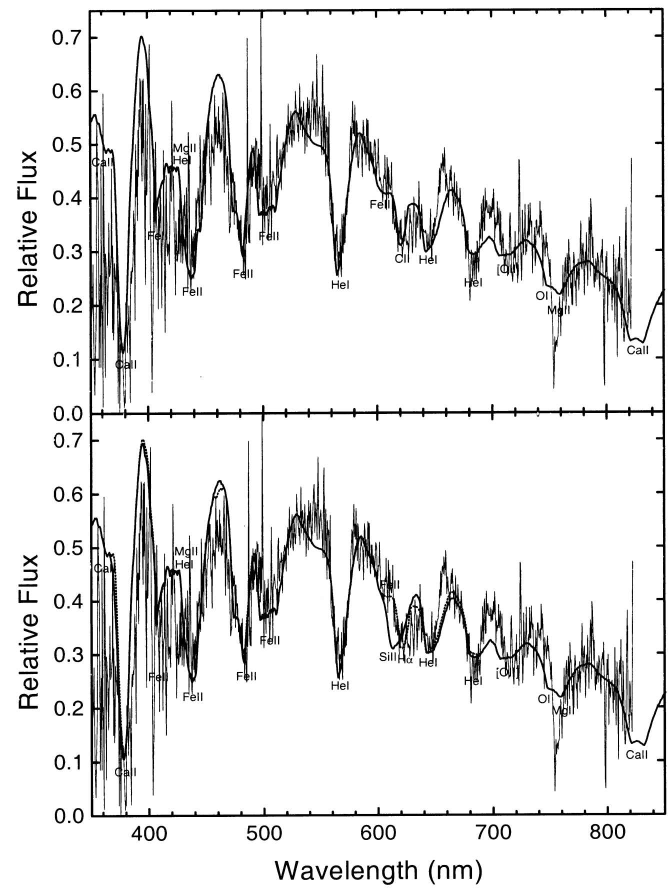

FIG. 2.—The observed spectrum of Aug 31 (*thin solid lines*) is compared with synthetic spectra which have $T_{bb} = 7000$ K and $v_{ph} = 12{,}000$ km s^{-1}. In the upper panel, the synthetic spectrum with C II is plotted on the thick solid line. In the lower panel, C II is replaced by Si II (*thick solid line*) and H I (*dotted line*), respectively.

The observed spectrum of August 31 is similar to that of August 21 in the overall shape and can be synthesized with $T_{bb} = 7000$ K and $v_{ph} = 12{,}000$ km s^{-1}. Now the C II λ6580 P Cygni feature becomes distinct from that of He I λ6678. The minimum velocity of the detached C II is now taken to be 19,000 km s^{-1}. Now the optical depth of Fe II is too small to produce the observed absorption around 7190 Å. We find that only [O II] $\lambda\lambda$7320, 7330 can match it while not contaminating the synthetic spectrum elsewhere. But we are not sure that the physical conditions to form the forbidden lines can be satisfied (see also Fisher et al. 1997; Millard et al. 1999). The strong P Cygni feature near 3800 Å is Ca II H and K.

We use the parameters $T_{bb} = 5300$ K and $v_{ph} = 9000$ km s^{-1} to synthesize the spectrum of September 14. From the upper panel of Figure 3, we can see that the He I P Cygni lines of $\lambda\lambda$5876, 6678, and 7065 are strong. He I also helps to form the observed features near 4360, 4580, and 4860 Å. The deep absorptions at 4360 and 9000 Å can be matched mostly with Mg II λ4481 and $\lambda\lambda$9218, 9244, which supports our identification of this ion above. The gentle slope from 6210 to 6410 Å is produced by Ca I lines, Fe II lines, and C II λ6580 detached at 10,000 km s^{-1}. C II $\lambda\lambda$4738, 4745,

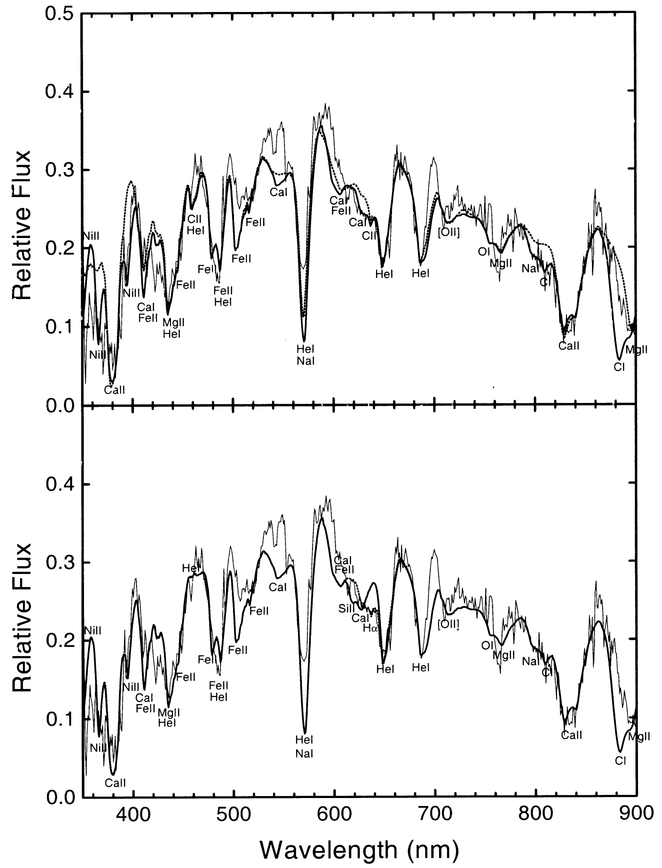

FIG. 3.—The observed spectrum of Sep 14 (*thin solid lines*) is compared with synthetic spectra which have $T_{bb} = 5300$ K and $v_{ph} = 9000$ km s^{-1}. In the upper panel, the synthetic spectrum with C II is plotted on the thick solid line, while on the dotted line Ca I, Ni II, Na I, and C I are removed. In the lower panel, C II is replaced by Si II (*thick solid line*) and H I (*dotted line*), respectively.

blended with He I λ4713, can also account for the absorption at 4580 Å. Similarly, the absorptions at 4150, 5420, and 6130 Å can be partially or entirely explained by Ca I. The Ni II line is used to fit the absorption at 3930 Å. Note that the signal-to-noise ratio per pixel around this feature is $\sim$50. This ion also brings two absorption features around 3660 and 3500 Å. Another slope from 7900 to 8150 Å is explicable if Na I $\lambda\lambda$8183, 8195 and C I λ8335 are introduced, but then the synthetic spectrum around 5700 and 9000 Å gets worse. For comparison, we plot the synthetic spectrum without Ca I, Ni II, Na I, and C I as the dotted line in the upper panel of Figure 3.

TABLE 2

FITTING PARAMETERS FOR FIGURE 1

Ion	λ (Å)	τ	v_{min} (10^3 km s^{-1})	v_{max} (10^3 km s^{-1})	T_{exc} (10^3 K)
He I	5876	10	16	50	7.5
O I	7772	1	16	50	7.5
Mg II......	4481	3	16	50	7.5
Ca II	3934	500	16	50	7.5
Fe II.......	5018	15	16	50	7.5
H I	6563	3	19	50	7.5
C II........	4267	0.02	20	50	7.5
Si II	6347	3	16	50	7.5

NOTE.—$T_{bb} = 7500$ K, $v_{ph} = 16{,}000$ km s^{-1}.

TABLE 3

FITTING PARAMETERS FOR FIGURE 2

Ion	λ (Å)	τ	v_{min} (10^3 km s^{-1})	v_{max} (10^3 km s^{-1})	T_{exc} (10^3 K)
He I	5876	7	12	50	7
O I.........	7772	1	12	50	7
Mg II	4481	3	12	50	7
Ca II.......	3934	200	12	50	7
Fe II	5018	10	12	50	7
[O II]......	7321	0.5	12	50	7
H I.........	6563	1	18	50	7
C II	4267	0.005	19	50	7
Si II	6347	2	12	50	7

NOTE.—$T_{bb} = 7000$ K, $v_{ph} = 12{,}000$ km s^{-1}.

The optical depths of the reference lines and other fitting parameters for Figures 1, 2, and 3 are listed in Tables 2, 3, and 4, respectively.

4. DISCUSSION

Pastorello et al. (1999) indicated that the spectra of SN 1999dn were very similar to those of SN 1997X and identified it as a Type Ib/c event in accordance with the previous classification of the latter (Garnavich, Kirshner, & Berlind 1997; Munari et al. 1998), while others noted both as Type Ic supernovae (Suntzeff et al. 1997; Benetti et al. 1997; Ayani et al. 1999; Turatto et al. 1999). But by comparing the spectra of SN 1999dn of August 31 and of SN 1997X, presented by Munari et al. (1998), with that of the prototypical Type Ib SN 1984L of August 30, plotted by Harkness et al. (1987) in their Figure 3, one can see that those three spectra, all near maximum light, strikingly resemble each other in almost all features and differ with the early-time spectrum of Type Ic supernovae mainly in two aspects: (1) the He I optical P Cygni lines of SN 1999dn, SN 1997X, and SN 1984L are prominent, while in the prototypical Type Ic SN 1994I He I lines are hardly discernible, although Clocchiatti et al. (1996) claimed evidence of very weak He I lines in spectra with good signal-to-noise ratios; and (2) unlike the 6150 Å absorption feature usually seen in the early-time spectra of SNe Ic, the minimum at $\sim$6200–6400 Å in SN 1999dn, SN 1997X, and SN 1984L is hard to attribute to Si II λ6355, as demonstrated in the lower panels of Figures

TABLE 4

FITTING PARAMETERS FOR FIGURE 3

Ion	λ (Å)	τ	v_{min} (10^3 km s^{-1})	v_{max} (10^3 km s^{-1})	T_{exc} (10^3 K)
He I	5876	10	9	50	5.3
O I.........	7772	0.3	9	50	5.3
Mg II	4481	4	9	50	5.3
Ca II.......	3934	700	9	50	5.3
Fe II	5018	5	9	50	7.0
[O II]......	7321	0.2	9	50	5.3
H I.........	6563	0.8	9	50	5.3
C II	4267	0.0005	10	50	5.3
Si II	6347	0.5	9	50	5.3
C I.........	9095	6	9	50	5.3
Na I	5890	12	9	50	5.3
Ca I........	4227	3	9	50	9.0
Ni II	4067	2.5	9	50	7.0

NOTE.—$T_{bb} = 5300$ K, $v_{ph} = 9000$ km s^{-1}.

1, 2, and 3. It has been supposed that C II $\lambda 6580$ is responsible for this feature in SNe Ib (Harkness et al. 1987); this is supported by our spectrum synthesis here and, in particular, by the identification of C II $\lambda\lambda 4738$, 4745 in the September 14 spectrum of SN 1999dn. We regard both SN 1999dn and SN 1997X as typical Type Ib supernovae.

The relative strengths of the He I lines $\lambda\lambda 5876$, 6678, and 7065 cannot be completely fitted by SYNOW. In Figures 1 and 2, we choose to fit $\lambda 5876$ best, and then $\lambda\lambda 6678$, 7065 are somewhat weaker than observed. In Figure 3, the calculated $\lambda 6678$ is the right strength, but $\lambda 5876$ is too strong and $\lambda 7065$ is too weak. Such non-LTE effects may be caused by nonthermal excitation from Comptonized gamma rays released in the decay of ^{56}Ni that has been mixed into the helium envelope (Shigeyama et al. 1990; Lucy 1991). Note the Ni II line which we introduced above to fit the 3930 Å absorption in the spectrum of September 14. This could be direct early-time spectral evidence of ^{56}Ni mixing in the explosion of a Type Ib supernova. As for the August 31 spectrum, despite its poor signal-to-noise ratio, we are sure that the introduction of Ni II lines to the synthetic spectrum cannot improve the fit. The velocity upper limit of the mixed ^{56}Ni may be $\sim$10,000 km s^{-1}, which is larger than the value predicted by explosion simulations (Harchisu 1994; Kifonidis et al. 2000).

One question remains of the minimum velocity of C II that we used to explain the absorption near 6300 Å. Why should this ion be detached around 20,000 km s^{-1} at the earliest times, but then detached at a much lower velocity of $\sim$10,000 km s^{-1} on September 14? Does it imply two different C II velocity components in the helium layer? An alternative scenario that seems more attractive and probable is that at the earliest times this feature is produced by Hα, which always fits as well as C II $\lambda 6580$ (see the dotted lines in the lower panels of Figs. 1, 2, and 3). In the August 21 and August 31 spectra, H I would be detached by 19,000 km s^{-1} and 18,000 km s^{-1}, respectively. In the September 14 spectrum, on the other hand, the identification of C II $\lambda 6580$ is unambiguous because H I cannot explain the observed absorption at 4580 Å. Actually, on August 31 a contribution from C II cannot be excluded because the observed feature is stronger than on August 21 and September 14. The other synthesized H I lines like Hβ are swamped by Fe II lines and are too weak to be identified.

To summarize, we suppose that a thin high-velocity hydrogen skin exits outside of the helium layer in SN 1999dn, with Hα appearing only before and near maximum light. As the envelope expands and the photosphere recedes deeper into the helium layer, the optical depth of Hα diminishes naturally and eventually is overwhelmed by C II $\lambda 6580$. We note that other authors (Filippenko, Porter, & Sargent 1990; Jeffery et al. 1991) have presented some evidence, though inconclusive, of Hα in some Type Ic supernovae, especially SN 1987M, and argued that SNe II and SNe Ic have similar physical origins. Similarly, our identification of Hα in SN 1999dn provides a link between the progenitors and explosion mechanisms of Type Ib supernovae and Type IIb events such as 1987K and 1993J.

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