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SUPERNOVAE 1983i AND 1983v: EVIDENCE FOR ABUNDANCE VARIATIONS IN TYPE Ib SUPERNOVAE

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ABSTRACT

Spectra are presented of SN 1983i 5 days after discovery and of SN 1983v 13 days after discovery. The similarity of these two spectra argue that they are of similar origin and phase. Theoretical atmosphere calculations provide evidence for a connection to the Type Ib supernovae 1983n and 1984l, with SN 1983i and 1983v having a similar structure but less helium and more carbon and oxygen. Available photometry suggests the spectra correspond to a phase about 20 days after maximum light. These spectra are consistent with an interpretation of Type Ib supernovae arising in the bare cores of moderately massive stars with individual events showing a range in mass ratio of He/O from approximately 10 to $\lesssim 1$.

Subject headings: abundances — stars: supernovae

I. INTRODUCTION

Understanding of the nature of hydrogen-deficient Type Ib supernovae (SN Ib) has increased dramatically in the last year. Wheeler and Levreault (1985) argued that the optical spectrum of SN 1984l near maximum light was very similar to that of SN 1983n (Panagia *et al.* 1987) and distinctly different from classical Type Ia supernovae (SN Ia). Study of the spectra of SN 1983n and 1984l near maximum light resulted in the discovery of strong evidence for appreciable amounts of helium in the ejecta (Harkness *et al.* 1987; Wheeler and Harkness 1986; Wheeler *et al.* 1986). Gaskell *et al.* (1986) discovered that SN 1983n made a startling transition to a "supernebular" phase dominated by [O I] $\lambda\lambda$6300, 6364 and identified SN 1985f (Filippenko and Sargent 1985, 1986) as a member of the class SN Ib on the basis of its similar spectrum. The optical light curve of SN 1983n was similar in shape to that of a typical SN Ia (Panagia *et al.* 1987), but SN 1983n and 1984l were dimmer at maximum by about 1.5 mag (Wheeler and Levreault 1985; Uomoto and Kirshner 1985; Branch 1986; Panagia *et al.* 1987). Infrared J, H, and K light curves seem to be homogeneous and differ from those of SN Ia in that they lack the absorption dip at ~ 20 days that characterizes SN Ia (Elias *et al.* 1985). SN 1983n and 1984l both have observed radio light curves (Sramek, Panagia, and Weiler 1984; Panagia, Sramek, and Weiler 1986).

SN Ib are associated with extreme Population I environments (Wheeler and Levreault 1985; Uomoto and Kirshner 1985; Harkness *et al.* 1987) and from the radio emission presumably have substantial circumstellar nebulae (Chevalier 1984). This evidence suggests an origin in massive stars. Wheeler and Levreault (1985) argued for an origin of SN Ib in massive stars but suggested that the relatively narrow light curve peak restricted the exploding core mass to less than 3–4 $M_\odot$ and hence the main-sequence mass to $\lesssim 20$ $M_\odot$. The estimated rates of explosions, which could be as high as those of SN Ia and SN II when selection effects are considered (Branch 1986), also argues against progenitors only of very large mass. Emission-line strengths in the supernebular phase tend to give higher masses for the ejecta ($\gtrsim 5$ $M_\odot$; Begelman and Sarazin 1986; Gaskell *et al.* 1986), but such estimates may not take complete account of the relevant physics.

SN 1983n and 1984l are very similar spectroscopically in the early phase near maximum light (Harkness *et al.* 1987) and in the later supernebular phase (Gaskell *et al.* 1986; Kirshner 1986). These supernovae represent the modern prototypes of the class SN Ib. Other candidates for SN Ib are the original "peculiar" Type I supernovae of Bertola, SN 1962l and 1964l (Bertola 1964; Bertola, Mammano, and Perinotto 1965), and SN 1975b, SN 1982r, SN 1983i, and SN 1983v on the basis of the hydrogen deficiency and the lack of the distinctive absorption at 6150 Å that characterizes SN Ia (Kirshner, Arp, and Dunlap 1976; Dennefeld 1982*a*, *b*; Branch 1986). Wheeler and Harkness (1986) noted that SN 1962l, 1964l, 1983i, and 1983v also seem to lack the deep absorption at 5700 Å that characterizes SN 1983n and 1984l, and which is identified as Doppler-shifted He I λ5876 (Harkness *et al.* 1987). Wheeler and Harkness noted the strong similarity between the spectra of SN 1983i and SN 1983v and suggested that they belong to yet a third spectrally distinct class of hydrogen-deficient supernovae, Type Ic. Theoretical models are presented here to argue that, rather than a distinct spectral class, SN 1983i and 1983v, along with SN 1962l and 1964l, and perhaps 1975b and 1982r, are members of the general class of SN Ib, but with markedly less helium and more carbon and oxygen in the ejecta than SN 1983n and 1984l.

Section II presents the spectral data on SN 1983i and 1983v which establishes the close similarity of these two events and a theoretical model that illustrates the connection of SN 1983i and 1983v to SN 1983n and 1984l. Section III discusses the available photometry, and §IV, the implications of these results.

II. SPECTRA

a) *Observations*

SN 1983i was reported by Aksenov (1983) in NGC 4051 on 1983 May 12. A spectrum was obtained on May 17, 5 days after discovery, by D. Wills using the IDS (Intensified Dissector Scanner) spectrograph on the 2.7 m telescope at McDonald Observatory at a resolution of ~ 10 Å FWHM (see Wills, Netzer, and Wills 1985 for a description of the instrument and reduction procedures). The entrance aperture was 6″.6 × 6″.5. This spectrum is presented in Figure 1. SN 1983v was discovered by Evans (1983) in the bar of NGC 1365 on 1983 November 25. The supernova is coincident with an H II region (Lindblad 1986). A spectrum was obtained on December 8, 13 days after discovery, by E. Barker and A. Cochran using the IDS on the 2.7 m at a resolution of ~ 10 Å and a 4 arcsecond^2 entrance aperture. This spectrum is also presented in Figure 1.

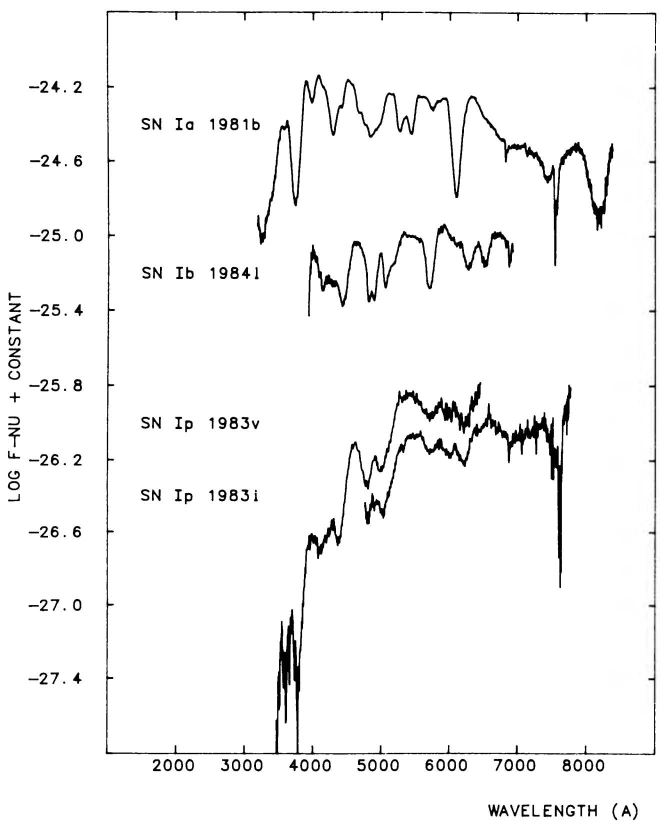

FIG. 1.—The upper trace is the composite maximum light spectrum of the Type Ia supernova 1981b (Branch *et al.* 1983). Note the characteristic absorption at 6150 Å. The second trace is the near-maximum light spectrum of the Type Ib supernova 1984l. Note the lack of absorption at 6150 Å, but the deep absorption at 5700 Å associated with He I λ5876 (Harkness *et al.* 1987). The bottom two traces are new data presented here of SN 1983i and 1983v. Note the close similarity in slope and individual features, the lack of deep absorption at 6150 Å, and the shallow minimum at 5700 Å which is also interpreted as blueshifted He I λ5876.

The phases of the spectra of SN 1983i and 1983v in Figure 1 are not well known in the absence of detailed photometry (see §III). The very close similarity of the spectrum of SN 1983i 5 days after discovery to that of SN 1983v 13 days after discovery in the common wavelength range (4700–6500 Å) argues that these two events were very similar and that these two spectra were obtained at roughly comparable phase. Figure 1 also shows the spectra of the SN Ia 1981b and the SN Ib 1984l near maximum light to illustrate the distinct absence of both the strong 6150 Å and 5700 Å features, respectively, in the spectra of SN 1983i and 1983v. An examination of archival McDonald Observatory spectral data shows no other event, SN Ia, SN Ib or SN II, at any phase with a spectrum that resembles the spectra of SN 1983i and 1983v as closely as they resemble one another in Figure 1.

A reexamination of the photographic spectra of SN 1962l and 1964l reveals that these events seem to be missing the deep 5700 Å absorption of SN 1983n and 1984l as well as the 6150 Å feature of SN Ia that led to their classification as "peculiar" Type I supernovae. The same may be true of SN 1975b (Kirshner, Arp, and Dunlap 1976). Dennefeld's (1982*a*, *b*) description of spectra of SN 1982r is consistent with the spectra of SN 1983i and 1983v in Figure 1. The lack of absorption at 6150 Å is explicitly mentioned, but the implicit absence of absorption at 5700 Å and the absence of a peak at 5900 Å which characterize SN 1983n and SN 1984l (due to He I λ5876) and post-maximum SN Ia (due to Fe II) is further evidence that SN 1982r belongs to neither of those categories, but rather to that defined by SN 1983i and 1983v. Thus SN 1962l, 1964l, 1975b, 1982r, 1983i, and 1983v cannot simply be placed in a single spectral category of "peculiar Type I supernovae" along with SN 1983n and SN 1984l. The question is whether SN 1983i and 1983v are a variation of the spectral type represented by SN 1983n and 1984l, or are they the prototypes for a separate spectral classification that perhaps signifies an appreciably different physical basis.

b) *Theoretical Models*

Wheeler and Harkness (1986) noted the similarity of the spectra of SN 1983i and 1983v depicted in Figure 1 and suggested they might constitute a separate spectral subclass of Type I supernovae. The process of calculating supernova atmospheres for SN 1983n and 1984l (Harkness *et al.* 1987) has led to the alternative suggestion that these four supernovae belong to the same basic classification, SN Ib, but are differentiated within that class by the variation of another parameter, the ratio of helium to carbon and oxygen.

Harkness *et al.* (1987) present models for SN 1983n and 1984l near maximum light based on the ejecta from cores of massive stars. The density structure is approximated in these models by a power law $\rho \propto r^{-n}$ with $n \approx 7$ favored over $n \lesssim 5$ or $n \gtrsim 10$. The velocity is proportional to radius with the inner radius $r_{in} = 8.6 \times 10^{14}$ cm corresponding to matter moving at 5000 km s^{-1} for 20 days. The model formally includes 31 $M_\odot$ distributed from r_{in} with density 1.5×10^{-11} g cm^{-3} to an outer radius $r_{out} = 4.5 \times 10^{15}$ cm determined by a decrease in the density by a factor of 10^5. Only the outer ~ 9 $M_\odot$ actually contributes substantially to the formation of spectral features. The temperature structure is fixed with

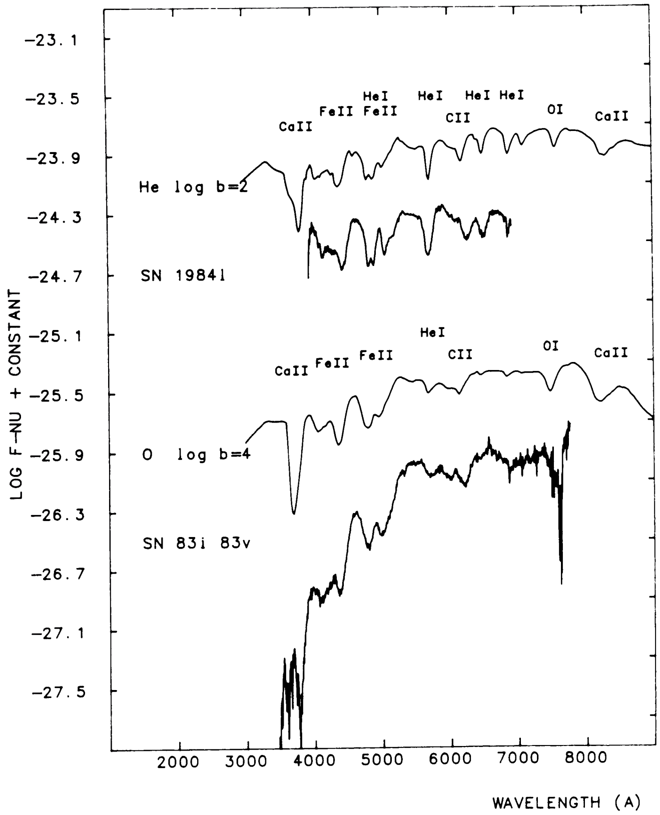

FIG. 2.—The upper pair of traces are the theoretical supernova atmosphere model from Harkness *et al.* (1987) with $\rho \propto r^{-7}$, $X_{He} = 0.9$, $X_c = 0.01$, $X_0 = 0.9$, and $b = 10^2$ and the near-maximum light spectrum of SN 1984l. The lower pair of traces are the model from Harkness *et al.* (1987) with $\rho \propto 10^{-7}$, $X_{He} = 0.1$, $X_c = 0.1$, $X_0 = 0.8$, and $b = 10^4$ and a composite spectrum of SN 1983i (> 5200 Å) and SN 1983v (< 5200 Å) from Fig. 1. The theoretical spectra are reddened with $A_v = 0.5$, and the observations are uncorrected. Note particularly the common identification of the 5876 Å line of He I and the 6580 Å line of C II between SN 1984l and SN 1983i.

$T \propto r^{-1/2}$ and $T = 11{,}700$ K at r_{in}, $T = 5145$ K at T_{out}. The resulting photospheric velocity (~ 7500 km s^{-1}), temperature (~ 9000 K), and luminosity (~ 2.5×10^{42} ergs s^{-1}) correspond to typical maximum light conditions for a Type Ib supernova, about 4 times dimmer than a Type Ia. The composition was taken to be 90% He, 9% O, 1% C, and heavier elements distributed in solar ratios, all by mass. The helium lines appear stronger than can be attributed to LTE. In the calculations, the LTE populations are enhanced by a departure coefficient, b, to produce a first-order correction for non-LTE effects. The departure coefficient is taken to be the same for all lines and independent of radius.

Figure 2 gives the spectrum of SN 1984l near maximum light and the theoretical spectrum from Harkness *et al.* (1987) derived from the helium-rich power-law density structure with $b = 100$. A departure coefficient of unity produces helium lines that are too weak. Larger departure coefficients, $b \gtrsim 10^4$, produce lines that are too strong for maximum light, but the helium lines grow deeper and more distinct as the supernova evolves, suggesting that departure from LTE may become more severe with time. Figure 2 also gives a spectrum in which the data from SN 1983i and 1983v are artificially combined to extend the wavelength range. The data from SN 1983i are plotted for wavelengths > 5200 Å and from SN 1983v for < 5200 Å in order to utilize the best signal-to-noise data from each. In conjunction with the combined spectrum of SN 1983i and 1983v is shown the theoretical spectrum from a model with $\rho \propto r^{-7}$, 80% O, 10% C, 10% He, and the heavier elements in solar ratios, all by mass. In this model only the outer ~ 4.5 $M_\odot$ substantially affects the emitted spectrum. The departure coefficient is taken to be $b = 10^4$. The models illustrate that even with an increase in b from 10^2 to 10^4 the helium lines are much less strong in the latter case if the helium is reduced by a similar factor of 100 from $X_{He} \approx 0.9$ to $X_{He} \approx 0.1$. The decrease in the helium abundance is thus the dominant effect. To produce the He I λ5876 line at the observed strength in SN 1983n or SN 1984l, the mass ratio of He/O must be ~ 10 to avoid excessively large departure coefficients ($b \gtrsim 10^6$). A simple interpolation among calculated spectra suggests that the He/O must be $\lesssim 1$ for $b \gtrsim 10^2$ to match the line strength in SN 1983i and 1983v. Unless these supernovae are much closer to LTE than SN 1983n and 1984l, they must have a significantly smaller helium abundance and a correspondingly larger abundance of C and O.

The theoretical spectrum with lower helium abundance in Figure 2 provides a very good representation of the spectra of SN 1983i and 1983v. The observed spectra decline more steeply at short wavelengths than does the theoretical version, suggesting that the present model may be somewhat too hot (see Harkness and Wheeler 1987 for a more thorough discussion of the UV spectra of SN Ia and Ib), but the basic features in the blue are reproduced, primarily by blends of Fe II. The steep minimum at 4900 Å which is produced by the 4921 and 5015 Å lines of He I in the model for SN 1984l is muted in accordance with the smaller helium abundance and may be due entirely to Fe II lines at 4923 and 5018 Å. Toward the red there is a shallow absorption at 5700 Å, the remaining effect of He I λ5876 in the model, and maybe a suggestion of He I λ6678 at 6450 Å and λ7065 at 6850 Å. A theoretical spectrum similar to that shown but with $b = 1$ is basically unchanged except for the failure to show any helium line minima. The minimum observed at 6200 Å is probably associated with C II λ6580. The noisy minimum at 7600 Å is provided by O I λ7773 in the theoretical calculation. The carbon feature is present in the theoretical spectra, but is not appreciably stronger in the model with larger carbon abundance. The reason for this is that the larger carbon and oxygen abundances produce more free electrons and hence larger electron scattering opacity which masks the lines. The same effect causes the blueward shift of features in the oxygen-rich theoretical spectrum. The larger electron scattering opacity causes the lines to form further out in high velocity material. The calculated C II minimum is somewhat too blue (by ~ 70 Å, ~ 3300 km s^{-1}) with the adopted density structure implying that, if the interpretation is correct, the C II line is being formed too far out in the model ($v \approx 18{,}000$ km s^{-1}). Note, however, that the feature shifts to the blue by ~ 50 Å between the spectra of SN 1984l and that of SN 1983i, and the C II line shifts by a similar amount between the corresponding theoretical spectra. The observed shift could be associated with differences in structure in addition to the opacity effects that are the sole cause in these models.

III. PHOTOMETRY

Photometric data also provide useful information on the various SN Ib events. The shapes of the V band light curves of SN 1962l (Bertola 1964) and SN 1983n (Panagia *et al.* 1987) are very similar. The $B - V$ color curves for SN 1962l and SN 1983n are nearly parallel with SN 1983n being bluer by ~ 0.2 mag. Both are significantly redder than typical SN Ia events by ~ 0.8 mag. The photographic light curve of SN 1964l (Bertola, Mammano, and Perinotto 1965) is brighter than that of SN 1962l at maximum light by ~ 0.5 mag, but very similar for $t \gtrsim 10$ days past maximum. There is very little optical photometric information on SN 1984l. Photometric colors derived from the spectra presented in Harkness *et al.* (1987) give V and B light curves similar to, but perhaps somewhat flatter than, SN 1962l and 1983n. The $B - V$ color curve so obtained parallels that of SN 1962l in the region of overlap, up to 15 days past maximum, but it is bluer by ~ 0.4 mag. Unlike that for SN Ia (which turn bluer), the $B - V$ curve for SN 1984l between 20 and 60 days is at an approximately constant value, $B - V \approx 1.2$, the maximum value reached by SN Ia at about 30 days after maximum. SN 1962l, 1983n, and 1984l have similar peak absolute B and V magnitudes. Optical photometry thus seems to differentiate SN Ib from SN Ia, but not to differ significantly between "helium-rich" and "oxygen-rich" SN Ib.

Elias *et al.* (1985) established that SN 1983n, SN 1984l, and SN 1983i map out common loci for the H band light curve and $J - H$, $H - K$ color curves that are distinctly different than those of SN Ia. They identify SN 1983i as an SN Ib on this basis alone, without the support of spectral data. They note that despite the similarity of infrared light curves, SN 1983i may be about 1 mag dimmer at H in absolute magnitude than SN 1983n and SN 1984l. This statement may depend on their adopted Virgo infall model by which they determine distances. They put SN 1984l 1.7 times more distant than SN 1983i, whereas de Vaucouleurs (1979) assigns virtually equal distances despite the discrepant radial velocities (763 km s^{-1} for NGC 4051, 1533 km s^{-1} for NGC 991, Elias *et al.* 1985). For equal distances SN 1983i would be dimmer than SN 1984l by only 0.3 mag at H.

The IR light curves argue that SN 1983i peaked in the H band 85 days before SN 1983n (Elias *et al.* 1985). If the delay between V maximum and H maximum were the same as for SN 1983n, ~ 7 days (Panagia *et al.* 1987), then SN 1983i peaked in the V band on about 1983 April 22, consistent with the light curve of Tsvetkov (1985). The spectrum in Figure 1 was obtained about 25 days later.

The agreement of the spectra of SN 1983v and SN 1983i in Figure 1 argue that they were obtained at roughly the same phase. Evans (1986) reports a flat peak at a visual magnitude of about 13.8 from about November 27 to December 10, spanning the epoch of the present spectrum. He reports a similar 16 day flat peak for SN 1983n (July 8–24) for SN 1983n, at some variance with the data of Panagia *et al.* (1987). Linblad (1983) gives $V = 13.8$ and $B - V = 0.9$ on 1983 November 27.17, 10 days prior to our spectrum. Colors derived from the spectrum give $V = 14.28$ and $B - V = 1.32$. The declining brightness indicates that the supernova was past maximum. The $B - V$ color derived from the spectrum is consistent with the colors of SN 1984l if the phase is $\sim +25$ days, with SN 1983n if the phase is $\sim +15$ days, and with SN 1962l if the phase is $\sim +10$ days. Comparison with the data of Lindblad suggests that SN 1983v evolves in B − V at the same rate as SN 1962l and SN 1984l and perhaps a bit slower than SN 1983n. Mack (1983) gives $V = 14.23$ and $B - V = +0.41$ on 1983 November 27.9, the same epoch as Lindblad's data. A recent rereduction (Mack 1986) gives nearly the same values. The V magnitude and color are discrepant with the values of Lindblad, although curiously the implied B magnitudes, 14.64 and 14.7, respectively, are very similar. The color given by Mack is bluer than any SN Ib more than 10 days after maximum by $\gtrsim 0.5$ mag, but is comparable to SN 1983n about 5 days prior to maximum.

Whitelock (1983 and private communication) gives the following IR photometry for SN 1983v—1983 November 27: $J = 14.22 \pm 0.05$, $H = 14.38 \pm 0.05$, $K = 14.3 \pm 0.12$; December 17: $J = 13.64 \pm 0.03$, $H = 14.06 \pm 0.05$; December 18: $J = 14.11 \pm 0.10$, $H = 14.2 \pm 0.13$; December 26: $J = 13.78 \pm 0.05$, $H = 13.76 \pm 0.05$, $K = 13.86 \pm 0.09$. These data suggest that SN 1983v was still brightening in the IR during this epoch. The $J - H$ color appears to be reddening more slowly than the curve established by Elias *et al.* (1985) so a comparison with other SN Ib may not be meaningful in that regard, but the color is roughly consistent with a phase 5 to 25 days *prior* to maximum. The superposition of SN 1983v on the bar of NGC 1365 may have resulted in contamination, but there is no obvious way to rationalize the apparent discrepancy between the optical and infrared photometry.

The flux of SN 1983v at 5500 Å ($\log f_\nu = -25.6$) is a factor of 2 less than that of SN 1983i ($\log f_\nu = -25.3$) for the spectra in Figure 1. The spectral flux is not necessarily absolute, but this suggests that the detected flux was significantly higher for SN 1983i. De Vaucouleurs (1979) gives the distance to NGC 4051 as only slightly greater than that of NGC 1365, suggesting that the absolute flux of SN 1983i exceeds that of SN 1983v by a factor of ~ 2. Branch (1986) assigns a peak B magnitude to SN 1983v comparable to those of SN 1983n and SN 1984l, assuming that SN 1983v was first observed near maximum light and that all three supernovae have similar colors. SN 1983v might have been somewhat brighter at maximum if it was not discovered at maximum. If the spectra of SN 1983i and 1983v were obtained at nearly the same phase, then SN 1983i might have been somewhat brighter than SN 1983n and SN 1984l, in contrast to the evidence from IR data.

IV. DISCUSSION

A comparison of the observed and theoretical spectra of Figure 2 leads to the conclusion that SN 1983i and 1983v do not represent a separate spectral class from SN 1983n and 1984l. Rather, it seems appropriate to assign them all to the classification SN Ib, recognizing that the SN Ib grouping is not as homogeneous as that of SN Ia. The current theoretical atmosphere calculations suggest that members of the class SN

Ib are differentiated by the helium abundance in the ejecta with SN 1983n and SN 1984l having a relatively large helium-to-oxygen ratio and SN 1983i and 1983v, along with SN 1962l, 1964l, 1982r (and perhaps 1975b) having a lower helium-to-oxygen ratio. The non–LTE nature of the helium features makes a specific estimate of the helium abundance difficult at this time. The change in the He/O ratio from 10 to $\lesssim 1$ for $b \gtrsim 10^2$ approximately accounts for the change in the helium line strengths between SN 1984l and SN 1983i. A proper non–LTE analysis, even for He alone, remains a significant computational challenge.

The assumption that carbon and oxygen represent the bulk of the nonhelium matter in the present models is based in part on the presumption that SN Ib are associated with massive stars. The specific manifestation of oxygen in the calculated spectra is the presence of O I λ7773. This feature is predicted to occur with only slightly diminished amplitude in the helium-rich SN 1983n and SN 1984l (Fig. 2), but observations at the appropriate wavelength tend to be contaminated by terrestrial lines. These events are characterized by strong oxygen emission ≥ 8 months past maximum (Gaskell *et al.* 1986). Emission lines of [O I] λ5577 began to be apparent in SN 1983n and 1984l from 10 to 20 days after maximum light, and [O I] λ6300 is seen 60 days after maximum in SN 1984l. No such emission lines are apparent in Figure 1 despite our interpretation of a higher oxygen abundance than for SN 1983n and 1984l and a phase of about 15–25 days past maximum. If the interpretation of SN Ib as the cores of massive stars is correct, then perhaps either a greater portion of the nonhelium abundance is C rather than O, or the structure is sufficiently different to suppress the oxygen forbidden line emission. Unfortunately, there are no late-time spectral data on SN 1983i and 1983v to ascertain whether or not they made the transition to the oxygen-rich supernebular phase that so characterizes SN 1983n, SN 1984l, and SN 1985f.

Interpretation of the spectral variations among SN Ib in terms of a difference of helium and oxygen abundance is not consistent with an origin in detonating white dwarfs as suggested by Branch and Nomoto (1986). The evidence presented here for a significant variation of helium and oxygen abundance among SN Ib is consistent with an origin in the cores of stars of at least moderate mass which differ in mass, mass-loss rate, or other parameters. The fact that there is some evidence for appreciable amounts of helium in SN 1983i and 1983v suggests that the progenitors are not so massive as to have ejected all the helium, i.e., they are not extreme WO Wolf-Rayet stars. The progenitors of these events may, however, prove to be more massive than the more helium-rich SN Ib typified by 1983n and 1984l. Supernova atmosphere calculations based on the ejecta structure of stellar evolutionary calculations of massive stars will be very useful to determine the mass and composition of the various Type Ib supernovae.

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