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SN 1994I IN M51 AND THE NATURE OF TYPE Ibc SUPERNOVAE

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ABSTRACT

Early spectra of SN 1994I in M51 (NGC 5194) are presented along with arguments that it is a member of the class of helium-poor Type Ic supernovae. The issue of H and He in the spectra of Type Ib and Ic events is reexamined with the conclusion that Type Ib eject substantially less H than even transition events like SN 1993J and that Type Ic eject substantially less He than Type Ib and their optical spectra are consistent with no H or He. Type Ic show an absorption of the Si II $\lambda 6355$ blend that characterizes Type Ia. This feature requires only a solar abundance of Si. Some Type Ic show an absorption that is probably C II $\lambda 6580$. IR spectra are presented of SN 1990W which show the line of He I $\lambda 10830$. The strength of this feature and the rather slow decay of the late time light curve suggest that this event could be better classified as a Type Ib. Even if trace abundances of H are present in Type Ib and of He in Type Ic the spectral differences still imply a distinctly different evolution for the progenitors of Type Ib from both Type Ic and events like SN 1993J.

Subject headings: supernovae: individual (SN 1993J, SN 1983N, SN 1984L, SN 1987M, SN 1994I, SN 1990W)

1. INTRODUCTION

Supernovae with no spectral evidence of hydrogen, but evidence for He are classified as Type Ib (SN Ib) and those that show no strong evidence for either H or He nor the strong blend of Si II $\lambda 6355$ that characterizes Type Ia (SN Ia), but strong absorption of O I $\lambda 7774$, have been termed Type Ic (SN Ic). Wheeler et al. (1987) originally proposed categories of "helium-rich" and "helium-poor." Subsequently Harkness & Wheeler (1990) and Wheeler & Harkness (1990) advocated the specific terminology of Types Ib and Ic in order to focus on the differences in the spectra that signify some significant difference in the progenitor evolution. SN 1987K (Filippenko 1988) and SN 1993J (see Wheeler & Filippenko 1994 for a review) showed H near maximum light which faded with time as lines of He I became more prominent. In the later nebular phase, SN 1987K showed little evidence for H, although SN 1993J continues to do so (Clocchiatti & Wheeler 1994; Filippenko, Matheson, & Barth 1994).

A significant component of the discussion of the nature of the Type Ic category has been a controversy over whether there is or is not evidence for H in the spectra. In their discussion of the Type Ic SN 1987M, Filippenko, Porter, & Sargent (1990; also Filippenko 1988, 1992) say that the local maximum near 6500 Å in SN Ic 1987M might be Hα. Filippenko et al. also suggested that the minimum at 6170 Å might be a weaker version of the Si II $\lambda 6355$ blend that characterizes SN Ia. Jeffery et al. (1991) argued that the minimum at 6370 Å was, indeed, Hα and that the minimum at 6170 Å was Si II. To achieve this agreement, the abundances of O and Si had to be altered from solar ratios and the H was assigned a rather low velocity of 8900 km s^{-1} compared to O I $\lambda 7773$ at 10,300 km s^{-1} and especially compared to the Ca II lines at $\sim$14,000 km s^{-1}. The velocity inconsistency, in particular, is a major problem with this interpretation.

Wheeler, Swartz, & Harkness (1993) argued that the spectra of Type Ic near maximum light can be represented with an ejecta composed of almost pure O plus a solar abundance of metals heavier than oxygen. Swartz et al. (1993b) showed that a model of a helium core that otherwise reproduced the light curve of SN 1987M would show unacceptably strong lines of He I $\sim$60 days after maximum. Swartz et al. also added a layer of H to the ejecta and concluded that it would unacceptably contaminate the spectrum. They concluded that Type Ic had substantially less than 0.1 $M_\odot$ of both H and He.

The models of Swartz et al. (1993b) that added a layer of H to a He core did not resemble the Type Ic SN 1987M, but they did resemble SN 1993J as it expanded and began to show substantial lines of He I (Swartz et al. 1993a; Filippenko, Mathewson, & Ho 1993). Atmosphere models of SN 1993J that fit the data extremely well (Swartz et al. 1993a) showed that SN 1993J was consistent with a helium-enriched H envelope of only $\sim$0.1 $M_\odot$ and an underlying He layer of $\sim$0.5 $M_\odot$. The fact that this small amount of H and He showed up in the spectrum of SN 1993J exactly as anticipated by the models of Swartz et al. (1993b) supported the conclusion that the SN Ic must have little, if any, H and He.

From the perspective of how the features of H and He I commingle in SN 1993J, one can imaging the same phenomena in the "Type Ib" and the "Type Ic." This suggested continuity is illustrated in Figure 1 which gives, from top to bottom, the spectra of SN Ic 1994I, SN Ic 1987M, SN Ib 1983N, SN Ib 1984L, all near maximum, and SN 1993J near its second maximum. This similarity of the portion of the spectrum between 6000 and 7000 Å suggests that one is seeing H and He

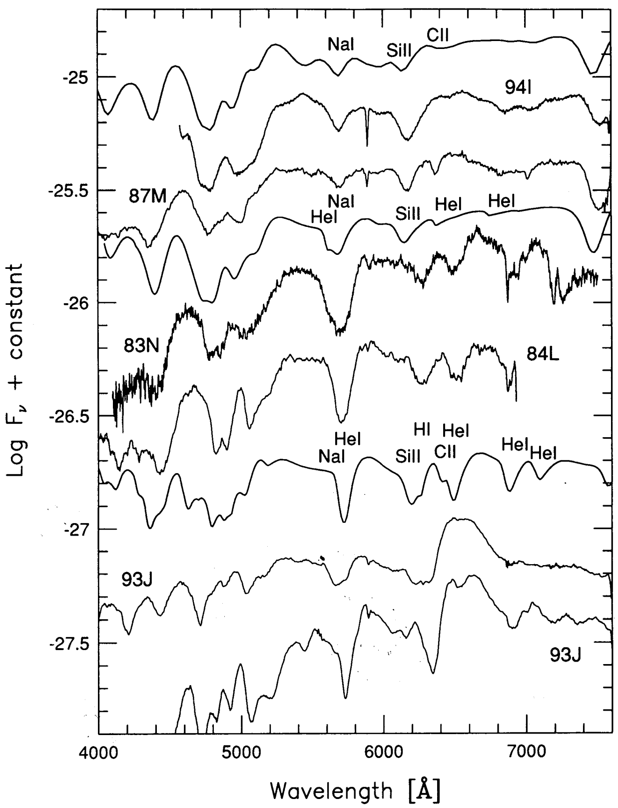

FIG. 1.—Spectra are given for the SN Ic's 1994I and 1987M (Filippenko, Porter, & Sargent 1990), the SN Ib's 1983N and 1984L and the transition object SN 1993J. Also given are power-law atmosphere models for SN Ic and SN Ib as described in the text (see § 3). Abscissae give wavelength in angstroms, ordinates give logarithm of flux per unit frequency plus an arbitrary constant. From top to bottom the different curves are a power-law atmosphere model for an oxygen star with solar abundance of elements heavier than oxygen; SN 1994I on April 10 (see § 2); SN 1987M on 1987 September 28; the same power-law model as before with 0.026 $M_\odot$ of He with solar abundance of heavier elements in the outermost layers and the departure coefficient for He set to 10^7; SN 1993N on 1983 July 19; a composite spectrum of SN 1984L on 1984 August 30–31, a power-law atmosphere model for a He + O star with a layer of hydrogen plus solar metals above 14,000 km s^{-1} (see § 3); and SN 1993J on 1993 April 14; SN 1993J on 1993 April 28 1993.

at progressively higher speeds from bottom to top of the figure. More careful consideration buttressed by atmosphere models shows that the apparent continuity can be misleading.

Here we reexamine the spectral nature of the SN Ib and Ic events. In § 2, spectra of SN 1994I in M51 are presented and the argument is given that it is classified as a SN Ic. In § 3, atmosphere models are used to resolve the controversy concerning the evidence for H in the spectra of SN Ic and to raise the issue for SN Ib. IR spectra of SN 1990W are presented in § 4 to show that this event, tentatively classified as a Type Ic, is better classified as a Type Ib. In § 5, the distinctions of SN Ib, SN Ic, and SN 1993J are emphasized.

2. OBSERVATIONS OF SN 1984I IN M51

A spectrum of SN 1994I is shown in Figure 1, together with spectra of SN 1983N, SN 1984L, SN 1987M, SN 1993J, and three model spectra. The spectrum of SN 1994I was obtained from McDonald Observatory on UT April 10.17, in coincidence with maximum in *B*. The spectrum is very similar to that of SN 1987M on 1987 September 28 with the exception of the feature at 6370 Å which is much weaker, or absent. The lines of He are extremely weak, if present at all. Subsequent optical spectra, which will be published elsewhere, did not show an increased strength of the He I line series. SN 1994I belongs to the "helium poor," category; i.e., it is a Type Ic event.

3. ATMOSPHERE MODELS FOR SN Ib AND SN Ic

If the absorption at 6370 Å is to be identified as He I λ6678, then it is moving at 14,000 km s^{-1}, as compared to a characteristic velocity of the He I in SN 1983N and SN 1984L (cf. Fig. 1) of 9000 km s^{-1}. In that case He I λ5876 should be at 5600 Å, which is to the blue of the minimum of the absorption at 5700 Å. The question arises as to whether the He I line could be blended with the Na D feature to give a single minimum as observed or whether both minima must be evident for He I to be present in the spectrum.

Figure 1 also shows some simple atmosphere models for SN Ic and SN Ib. These models have a power-law density profile with $\rho \propto r^{-n}$ and $n = 7$. The parameters are chosen to reflect appropriate conditions at 20 days postexplosion, near estimated maximum light. The inner radius of the power-law grid is 8.64×10^{14} cm (5000 km s^{-1} for 20 days). The grid covers five orders of magnitude in density, so the outer boundary is located at 4.48×10^{15} cm corresponding to a maximum expansion velocity of 25,900 km s^{-1}. The temperature profile is obtained from a spherical extended gray comoving frame radiative equilibrium calculation. The observer-frame luminosity is 2.4×10^{42} ergs s^{-1}. Since the atmosphere is extended it cannot be characterized by a single radius and effective temperature. At an electron scattering optical depth of 0.66 the temperature is 7150 K, the radius is 2.0×10^{15} cm, velocity 11,600 km s^{-1} and density is 8.5×10^{-14} g cm^{-3}. The lines are treated as pure scattering lines with a small (1.0×10^{-6}) thermal component. A thermal boundary condition is imposed on the inner boundary. The outer boundary condition assumes no incident flux.

The fourth line from the top in Figure 1 shows a model in which the bulk of the mass is O with solar abundances of heavier elements. The outer portions of the model, ∼0.026 $M_\odot$, are He with solar abundances of heavier elements. The ionization and excitation is assumed to be in LTE with the exception of He and Na. The line list below 3000 Å was truncated to save computer time. This model is similar to the one presented in Figure 8 of Wheeler, Swartz, & Harkness (1993), but a blend of lines of multiplet 32 of O I that had appeared at the line λ6157 when using the data of Weise, Glennon, & Smith (1966) becomes less significant with the data of Kurucz (1993). The effect of the Si II λ6355 is now clear. It makes a P Cygni profile for which the absorption minimum is at 6170 Å. Note that this Si II feature and the absorption due to O I λ7774 with the proper amplitude arise naturally in this model with a large mass fraction of O and a solar abundance of Si even in LTE. This is in contrast with the conclusions of Jeffery et al. (1991) who found they needed a reduction of the Si abundance along with an enhancement of O by a factor of 10 to reproduce the spectrum. This model spectrum puts essentially all the absorptions in the right place, a necessary criterion, but does not generate the peak in the flux at ∼6600 Å that typifies many SN Ic. There may be continuum as well as lines from nearby H II regions adding to the observed flux here.

To investigate the nature of the absorption at 6370 Å the LTE level populations of He I were multiplied by an enhancement coefficient, *b*, until the feature at 6370 Å was reproduced.

The level populations of solar abundance Na I in LTE were then enhanced until the strength of the minimum at 5700 Å was reproduced. The model shown had $b = 10^7$ for He and $b = 10^3$ for Na. In atmosphere models with low-frequency resolution, the He and Na features did blend, but not in a model with higher frequency resolution, as shown. If the feature at 6370 Å were He $\lambda6678$ then there should be a separate, bluer minimum of He I $\lambda5876$, distinct from Na D, that is not observed. This conflict, and, especially, the unphysically large value of the enhancement coefficient necessary to produce the absorption at 6370 Å with He I $\lambda6678$ convinces us that this feature cannot be He. On the other hand, this analysis shows that a small amount of He with a more reasonable enhancement coefficient could easily go undetected in this region of the spectrum. We note that the model spectrum with weak optical He I features predicted a strong absorption of He 10830. This IR line would be a more sensitive test of small amounts of He as emphasized by Wheeler et al. (1993).

What, then, is the absorption at 6370 Å that shows distinctly in SN 1987M and the shallow trough in other SN Ic, including SN 1994I, at ~ 6450 Å? Our best guess is that they are C II $\lambda6580$. Figure 1 also shows an atmosphere model which omits any H or He (first line from the top). The agreement with the observations is moderately good. The C II line shows as a depression at ~ 6400 Å which agrees rather well with the spectrum of SN 1994I. If this interpretation is correct, then Wheeler et al. (1987) misidentified the absorption at 6170 Å as C II in both the observations and in their atmosphere models of SN 1983V. We now believe, as argued above, that the model feature identified as C II was instead that of Si II. The sharp feature at 6370 Å in SN 1987M is probably C II $\lambda6580$ with the strength of the line increased by non-LTE effects. If the LTE population of the C II levels in the model described before are enhanced by a factor of ~ 100 the line at 6370 Å is reproduced much better without changing the rest of the spectrum. Even though the profile obtained is not a perfect match for that observed, the fact that this is a high-excitation line susceptible to non-LTE effects supports the identification. A contribution of He I $\lambda6678$ in absorption cannot be discounted, but He alone could hardly explain the total strength of the feature.

The question then arises of the Type Ib. Are the spectral features from 6000 to 7000 Å again a single broad P Cygni profile cut by He I $\lambda6678$, and, if so, what is the broad feature, H as it is in SN 1993J or Si II, as it is in SN Ic? If the absorption at 6300 Å in SN 1984L is Si II, then it is moving at only 3800 km s^{-1}. If it is Hα then it is moving at 13,200 km s^{-1}. One might thus conclude that both of the SN Ib events may also show a broad P Cygni feature of Hα interrupted in the middle by He I $\lambda6678$.

To test this hypothesis we have also made $n = 7$ power-law atmosphere models similar to those presented in Harkness et al. (1987), but including H in the atmosphere with an adjustable LTE enhancement coefficient. A model with mass fractions of He and O of 0.9 and 0.1, respectively, an enhancement coefficient of $b = 10^2$ for He, and the new line list reproduces the corresponding model of Harkness et al. very well. An otherwise identical model omitting the O is similar, but the line of O I $\lambda7774$ disappears. Unfortunately, the wavelength region of this O I line has not been observed with decent signal to noise in any SN Ib. This model also shows more fine structure in the blue, due mostly to ubiquitous lines of Fe II, and stronger He I lines since there are fewer free electrons.

The seventh curve from the top in Figure 1 shows a model atmosphere in which H is assumed to be present above 14,000 km s^{-1} with an abundance of 0.05 *by number* and an enhancement coefficient of 10. This model contains only 0.005 $M_\odot$ of H. In these models, Si II $\lambda6355$ forms an absorption at ~ 6200 Å, too blue for the corresponding observed absorption feature in SN 1984L. For $b = 10^3$ (unreasonably large), a strong line of Hα appears at ~ 6300 Å, blending with and swamping the Si II and forming a slightly flat-bottomed absorption. In the model shown both the Si II and the Hα minima and that of C II $\lambda6580$ can be discerned. There is an absorption due to Hβ which may shave the observed peak at 4500 Å and no perceptible feature at Hγ.

Another set of models was computed with the other layers beyond $v = 14{,}000$ km s^{-1} assumed to be composed of matter with an abundance of H of 0.8 by number with the remainder He and solar metals. This corresponds to a mass of H of 0.042 $M_\odot$. The presence of the H added electrons that increased the scattering optical depth and resulted in a model that more strongly resembled the data in the blue by smoothing the fine structure. The same effect, however, drastically reduced the strength of the He I and Na D lines. The Hα absorption was at about the right wavelength to account for the observed absorption, but was far too strong.

These models suggest that while some source of electrons may be conducive to smoothing the blue spectrum of a nearly pure He atmosphere, it is difficult to show that H is the source of those electrons or to rule out the presence of some small abundance of H. Si II alone does not seem to account for the absorption at 6300 Å in SN Ib as it does for the absorption at 6200 Å in SN Ic. H can provide an absorption at the proper wavelength without obscuring the He lines in an unacceptable way. The line of C II $\lambda6580$ may still contribute at some level in SN Ib at a wavelength that depends on the composition and structure of the atmosphere (Wheeler et al. 1987). We note that the spectrum of SN 1993J on April 14 shows a wide, flat, even doubled minimum from 6200 to 6300 Å. This could plausibly be the result of blended absorption of Si II and Hα.

4. THE FIRST IR SPECTRA OF A SN Ibc: 1990W

SN 1990W was observed on 1990 September 8 at the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope using the facility infrared spectrometer (IRS). DePoy et al. (1990) give a description of the instrument and data reduction techniques. A 2″ wide, north-south oriented slit was used with a 12 lines mm^{-1} grating, which gave a resolution ($\lambda/\Delta\lambda$) of ~ 150 for all observations. At this low resolution the wavelength coverage of the IRS was sufficient to observe an entire atmospheric window simultaneously. Four grating settings were used to cover the 0.9–2.4 μm region. A different grating order was used at each setting; the unwanted orders were blocked by broadband filters. The wavelength scale was set by measurement of argon and xenon calibration lamps and the planetary nebula NGC 7009. Comparison of the two calibrations indicates the wavelengths are known to ~ 0.3 pixels (~ 0.001 μm around 1.1 μm). Standard stars from Elias et al. (1982) were observed to provide the correction for atmospheric absorption. These stars were assumed to have no significant spectral features throughout the observed wavelength region and were observed in the same manner as SN 1990W. Thin cirrus present during the observations prevented accurate flux calibration and the relative intensities of the four spectral segments are uncertain by at least 20%.

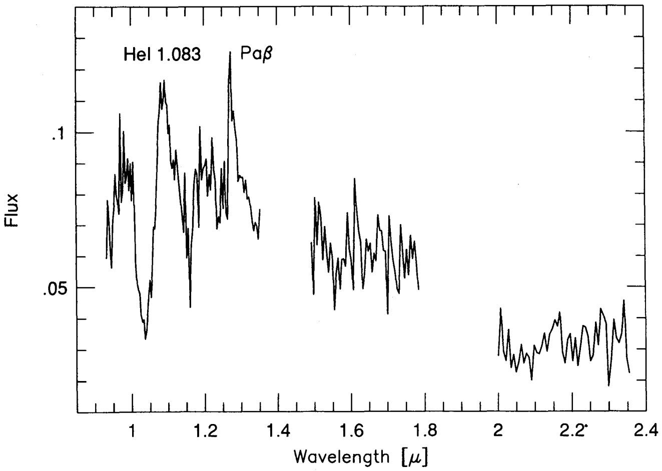

FIG. 2.—The infrared spectrum is given of SN 1990W on 1990 August 23. Flux is given in arbitrary units per unit wavelength.

Figure 2 gives the spectrum of SN 1990W which shows clear evidence for the strong P Cygni profile of He I λ10830, thus confirming that this event contained some He. There is little evidence for He I λ20581. Note the strong line of Pa β at 1.282 μm. This line apparently arises in a nearby H II region and is apparently blended with another stronger line to the blue, which may be Fe II at 1.27 μm. There is otherwise no evidence for broad H coming from the supernova itself. We have not attempted to model this line to determine the quantity of He. The apparent velocity of the He 10830 line determined by the absorption minimum is 11,900 km s^{-1}, somewhat higher than for the optical He I lines observed in SN 1983N and SN 1984L and somewhat higher than the He I λ10830 feature observed in SN 1993J (Swartz et al. 1993a).

SN 1990W was originally identified as a Type Ic because the optical He I lines were weak or absent (Phillips 1990; Filippenko 1990). The current evidence for He suggests that either some Type Ic contain He or that SN 1990W is more properly classified as a Type Ib. Optical spectra from Asiago Observatory (Capellaro et al. 1994) show a double minimum near 5700 Å that closely resembles the model of Figure 1 that contained enhanced He and hence blended, but identifiable He I λ5876 and Na D (fourth line from the top). That model did not suffice for SN Ic 1987M nor SN 1994I, but is a good representation of SN 1990W. We thus conclude that there is evidence for He in the optical spectra of SN 1990W. Unpublished Asiago photometry also show that SN 1990W faded more slowly on the tail than canonical SN Ic, but similar to observed SN Ib. We thus propose that SN 1990W is more appropriately classified as a Type Ib, albeit with somewhat weak helium compared to SN 1984L. This event deserves closer study in its own right.

We note that Gómez & López (1994) argue that the SN Ic 1990U was somewhat helium-rich compared to the SN Ic 1991A. Their arguments are somewhat indirect, but suggest that the issue of He in SN Ic is not yet closed. It would be interesting to study the light curves of these events.

5. DISCUSSION: THE SN Ibc–II CONNECTION

This analysis confirms the original suggestion of Wheeler et al. (1987) that Type Ib supernovae are helium-rich and that Type Ic supernovae are helium-poor. We cannot claim to have an explanation for the details of the departures from LTE; however, it seems plausible that these will be seen in the highest excitation lines where the LTE level populations are extremely small and where relatively large changes in level population can be caused by weaker effects such as recombination into those levels, particularly since there is a nonthermal source of ionization in the gamma-ray photons from radioactive decay (see Lucy 1991). Although the present conclusions must be supported by full non-LTE treatment of the He, Na, and H, the results of the current study and that of Swartz et al. (1993b) are consistent with SN Ic containing little, or no, helium. SN Ic cannot simply be helium cores. They have undergone a substantially different evolution than SN Ib in some way. The evidence for H in SN Ib in the form of the absorption at about 6300 Å, is consistent with an amount of H substantially smaller than that in SN 1993J, where estimates give about 0.1–0.3 $M_\odot$. This implies that SN Ib must typically go through a rather different evolution than events like SN 1993J which is believed to have undergone Roche lobe overflow to a companion with little wind mass loss.

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