Hydrogen in Type Ic Supernovae?

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ABSTRACT. By definition, a Type Ic supernova (SN Ic) does not have conspicuous lines of hydrogen or helium in its optical spectrum. SNe Ic are usually modeled in terms of the gravitational collapse of bare carbon-oxygen cores. We consider the possibility that the spectra of ordinary (SN 1994I–like) SNe Ic have been misinterpreted, and that SNe Ic eject hydrogen. An absorption feature usually attributed to a blend of Si II λ6355 and C II λ6580 may be produced by He. If SN 1994I–like SNe Ic eject hydrogen, the possibility that hypernova (SN 1998bw–like) SNe Ic, some of which are associated with gamma-ray bursts, also eject hydrogen should be considered. The implications of hydrogen for SN Ic progenitors and explosion models are briefly discussed.

1. INTRODUCTION

A Type II supernova (SN II) has conspicuous hydrogen lines in its optical spectrum. A Type Ib supernova lacks conspicuous hydrogen lines but does have conspicuous He i lines. A Type Ic supernova has neither conspicuous lines of hydrogen nor He i. For a review of supernova spectral classification, see Filippenko (1997).

These types of supernovae are thought to result from core collapse in massive stars. A SN Ib is hydrogen deficient in its outer layers and displays He i lines, owing to nonthermal excitation by the decay products of radioactive 56Ni and 56Co (Lucy 1991). In recent years, it has become clear that at least some SNe Ib are not completely hydrogen-free; in fact, it is likely that most or even all SNe Ib eject a small amount of hydrogen at high velocities (Deng et al. 2000; Branch et al. 2002; Elhamditi et al. 2006). If some of the events classified as Type Ib had been observed earlier, hydrogen lines might have been conspicuous, in which case they would be classified as Type IIb—the designation used for events such as SN 1993J, which looked like a Type Ic event at early times but later looked like a Type Ib (Filippenko et al. 1993).

A SN Ic is either helium deficient in its outer layers or fails to nonthermally excite its helium (Woosley & Eastman 1997). It has become common practice to model SNe Ic in terms of core collapse in bare (or nearly bare) carbon-oxygen cores (Iwamoto et al. 1994; Foley et al. 2003; Mazzali et al. 2004).

Spectral features of supernovae are P Cygni features characterized by line-centered emission components and blueshifted absorption components, with the absorptions frequently being more identifiable. Spectral features are usually blended, owing to the huge Doppler broadening. Nevertheless, some identifications of spectral lines are definite. For example, blends of Fe II lines and features produced by Ca II H and K and the Ca II infrared triplet appear in all types of supernovae as long as the temperature is sufficiently low. However, there are also some serious identification ambiguities. The most well known involves the Na I D line doublet at mean wavelength λ5892 and the strongest optical line of He i, λ5876, which are separated by only about 800 km s⁻¹. If the corresponding observed feature is strong and other He i lines are not present, the feature is produced at least mainly by Na i, whereas if other He i lines are clearly present, then the feature is at least partly due to He i. But if the observed feature is not strong, it can be difficult to choose between Na i and He i.

When SNe Ic are interpreted in terms of bare carbon-oxygen cores, an absorption feature usually near 6200 Å (which we refer to here as the 6200 Å absorption) is attributed to the strongest optical line of Si ii, λ6355 (the transition that is definitely responsible for the similarly located deep absorption in Type Ia supernovae), perhaps blended with the strongest optical line of C ii, λ6580, forming in higher velocity ejecta than Si ii. Local thermodynamic equilibrium (LTE) calculations of Sobolev line optical depths for a composition that is dominated by carbon and oxygen (with hydrogen and helium burned to carbon and oxygen, and with solar mass fractions of heavier elements) show that within certain intervals of temperature, Si ii λ6355 and C ii λ6580 are expected to have significant optical depths (Hatano et al. 1999). Nevertheless, the identification of the 6200 Å absorption is plagued by ambiguities. The strongest line of Ne i, λ6402, is about 2200 km s⁻¹ to the red of Si ii λ6355, and Hz (λ6563) is only about 800 km s⁻¹ to the blue of C ii λ6580. Because these four ions, each of which could appear in supernova spectra (although Ne i would probably require nonthermal excitation), have their strongest optical lines to the red, but not too far to the red, of the 6200 Å absorption, the ambiguity is difficult to resolve when the observed feature
is weak and other lines of these ions do not produce identifiable features.

In this paper, we are primarily concerned with the possible presence of hydrogen in SNe Ic. This issue (and that of helium in SNe Ic) has been addressed in the literature before; for summaries, see Filippenko (1997), Matheson et al. (2001), and Branch (2002). The presence of hydrogen has been suggested, for example, by Filippenko (1988, 1992), Filippenko et al. (1990), Jeffery et al. (1991), and Branch (2002). However, the currently prevailing view is that hydrogen is absent and that the 6200 Å absorption is produced by Si ii and/or C ii (Wheeler et al. 1994; Millard et al. 1999). In § 2, based on a comparison of spectra of the Type Ib (or Type Ib/c) SN 1999ex, which we believe to contain hydrogen, and the Type Ic SN 1994I, we raise the question of whether hydrogen is also present in SN 1994I. In § 3, comparisons of SN 1999ex and SN 1994I spectra with synthetic spectra generated with the parameterized resonance-scattering code SYNOW are presented and discussed. In § 4, the implications of the presence of hydrogen in ordinary (SN 1994I-like) SNe Ic, and possibly even in hypernova (SN 1998bw-like; Foley et al. 2003) SNe Ic, are briefly considered.

2. COMPARISON OF SN 1999ex AND SN 1994I

SN 1999ex was initially classified as Type Ic, based on the resemblance of its early spectrum to SN 1994I (Hamuy & Phillips 1999), but because it later developed He i lines, Hamuy et al. (2002) revised the classification to intermediate Type Ib/c. Although the He i lines were not as deep as in most events that have been classified as Type Ib, their presence was definite, so Branch (2002) referred to SN 1999ex as a “shallow-helium” Type Ib. Hamuy et al. (2002) labeled the 6200 Å absorption as Si ii, but Branch (2002) argued that the correct identification is Hα, consistent with the presence of Hα in most if not all other SNe Ib. Recently, Elmhamdi et al. (2006) have reinforced the conclusion that SNe Ib, including SN 1999ex and another transition Type Ib/c event, SN 1996aq, ejected hydrogen. (The overluminous Type Ib SN 1991D [Benetti et al. 2002] could be an exception.)

The spectra of SN 1999ex and the Type Ic SN 1994I shown in Figures 1 to 3 are from Hamuy et al. (2002) and Filippenko et al. (1995), respectively. The horizontal scale for all figures in this paper is logarithmic wavelength, which allows the widths of Doppler-broadened features to be compared on an equal basis across the whole spectrum. The spectra are “tilted” by multiplying by \( \lambda^n \), where \( \alpha \) is chosen to make the flux peaks near 4600 and 6300 Å about equally high. The tilting makes it easier to compare spectral features. When comparing SN 1999ex and SN 1994I spectra, we artificially blueshift those of SN 1999ex in order to compensate for the different photospheric velocities and to roughly align the absorption features.

In Figure 1, a spectrum of SN 1994I obtained 2 days before the time of maximum light in the B band (day –2) is compared with a day –1 spectrum of SN 1999ex that has been blueshifted by 4000 km s\(^{-1}\). Figure 2 is like Figure 1, but for day +4 spectra of SN 1994I and SN 1999ex, with the latter blueshifted by 2000 km s\(^{-1}\). Figure 3 is for a day +10 spectrum of SN 1994I and a day +13 spectrum of SN 1999ex, with the latter blueshifted by 2000 km s\(^{-1}\). In all three figures, the spectra are similar in many respects, although the features are more washed out in SN 1994I, because of its higher photospheric velocity.
at each epoch (hence the necessity to blueshift SN 1999ex to illustrate the similarities). Otherwise, the main differences are that He I λ6678 and λ7065, although weak, are clearly present in SN 1999ex (making it a Type Ib or at least a Type Ib/c), but they are not clearly present in SN 1994I (making it a Type Ic). However, it is not possible on the basis of Figures 1–3 to exclude the presence of weak He I features in SN 1994I. Given the similarities in these figures—and they are rather striking—the question becomes, Are the Na I and Si II/C II identifications correct for SN 1994I? If so, then the resemblance of the SN 1999ex and SN 1994I spectra from about 5500 to 6300 Å is coincidental.

3. COMPARISONS WITH SYNTHETIC SPECTRA

To further investigate the possibility of hydrogen (and He I) in SN 1994I, we have used the parameterized resonance-scattering code SYNOW (Branch et al. 2002) to generate synthetic spectra for comparison with spectra of SN 1999ex and SN 1994I.

3.1. SN 1999ex

In Figure 4, the day +4 spectrum of SN 1999ex is compared to a synthetic spectrum in which the 6200 Å absorption is produced by Hα. In the synthetic spectrum, the velocity at the photosphere is 8000 km s$^{-1}$. Hydrogen is detached from the photosphere at 13,000 km s$^{-1}$, where Hα has an optical depth of 0.5. Hydrogen-line optical depths decrease outward exponentially, but very slowly, with an e-folding velocity $v_e = 20,000$ km s$^{-1}$ up to an imposed maximum velocity of 20,000 km s$^{-1}$. Given the closeness of the fit to the 6200 Å absorption, we know that with fine adjustments of the optical depth profile, we could refine the fit to be practically perfect. Thus, at the SYNOW level of analysis, Hα is completely adequate, and we would not prefer a different identification without other evidence. Table 1 gives reference-line optical depths and $v_e$-values (in units of 1000 km s$^{-1}$) for all ions used in Figure 4.

Elhamidi et al. (2006) show that Si II λ6355 alone cannot account for the 6200 Å absorption of SN 1999ex, because even when it is undetached from the photosphere, its synthetic absorption feature is too blue. It is unlikely that the 6200 Å absorption is due mainly to Ne I λ6402, because the observed feature is strong enough that when it is fitted with Ne I λ6402, other Ne I lines appear in the synthetic spectrum, and the fit deteriorates. This conclusion is based on LTE excitation and must be tested against detailed non-LTE calculations that take into account nonthermal excitation.

Hamuy et al. (2002) also obtained a day +4 spectrum of SN 1999ex that extends to nearly 2.5 μm. SYNOW fitting parameters used to fit the optical He I lines also give satisfactory fits to features attributed to He I λ10830 and He I λ20851 (Branch

| Species | Figure 4 | Figure 5 |
|---------|----------|----------|
| He I    | 6563     | 0.5      | 0.4 |
| He II   | 5876     | 2.5      | 1.2 |
| O I     | 7773     | 1        | 2   |
| Mg II   | 4481     | 2        | 1   |
| Ca II   | 3934     | 80       | 80  |
| Ti II   | 4550     | 0        | 5   |
| Fe II   | 5018     | 15       | 2   |

FIG. 3.—Same as Fig. 1, but for a day $+10$ spectrum of SN 1994I (top) and a day $+13$ spectrum of SN 1999ex (bottom). The latter is blueshifted by 2000 km s$^{-1}$.

FIG. 4.—Comparison of day $+4$ spectrum of SN 1999ex (solid line) to a SYNOW synthetic spectrum (dashed line) that has $v_e = 8000$ km s$^{-1}$ and includes lines of hydrogen, He I, O I, Mg II, Ca II, and Fe II.
2. SN 1994I

SYNOW fits to SN 1994I spectra in which the 6200 Å absorption is attributed to Si ii and/or detached, high-velocity C ii are shown in Millard et al. (1999) and Elmhamdi et al. (2006). For this paper, we first tried to fit the day +4 spectrum of SN 1994I by varying the input parameters that were used for the synthetic spectrum shown in Figure 4 for SN 1999ex (i.e., we assumed the presence of hydrogen and He i lines).

Figure 5 is the same as Figure 4, but for SN 1994I. The synthetic spectrum has a photospheric velocity of 11,000 km s\(^{-1}\) (compared with 8000 km s\(^{-1}\) for SN 1999ex). Hydrogen lines are detached from the photosphere at 15,000 km s\(^{-1}\), where H\(\alpha\) has an optical depth of 0.4. Hydrogen-line optical depths decrease outward exponentially at \(v_e = 20,000\) km s\(^{-1}\) up to an imposed maximum velocity of 22,000 km s\(^{-1}\). This hydrogen optical depth profile is quite similar to that used for SN 1999ex in Figure 4, and in Figure 5 the 6200 Å absorption is a nice fit. The 5700 Å absorption is also nicely fitted by He i \(\lambda 5876\).

In the synthetic spectrum, He i \(\lambda 6678\) and \(\lambda 7065\) are weak and rather washed out, owing to the high photospheric velocity, but they are useful nonetheless, and their presence in the observed spectrum cannot be excluded. (However, regarding the strong observed absorption near 1 \(\mu\)m, the situation remains as illustrated and discussed by Millard et al. [1999]: the synthetic He i \(\lambda 10830\) absorption is too weak and narrow to entirely account for the observed absorption.) Reference-line optical depths and \(v_e\)-values for Figure 5 are given in Table 1.

The synthetic spectrum in Figure 6 is like that of Figure 5, except that it includes Si ii lines instead of hydrogen lines. The figure illustrates that in SN 1994I, as in SN 1999ex, Si ii \(\lambda 6355\) is too blue to account for the 6200 Å absorption on its own (flux differences between the observed and SYNOW spectra are to be expected, but differences in the wavelengths of absorption features are regarded as serious discrepancies), although it is possible to obtain a fit by invoking detached, high-velocity C ii. Because the 6200 Å absorption is less deep in SN 1994I than in SN 1999ex, and since the SN 1994I features are more smeared out by the higher photospheric velocity, it is also difficult to exclude Ne i \(\lambda 6402\) in SN 1994I.

4. DISCUSSION

4.1. Spectroscopy

We have discussed the possibility of H\(\alpha\) absorption in the spectrum of the Type Ic SN 1994I. As shown in Figure 7, this is an issue for SNe Ic in general; the spectra within the wavelength interval emphasized in this paper have strong similarities. Other evidence for hydrogen in SNe Ic was emphasized by Filippenko (1988, 1992), in the apparent presence of broad H\(\alpha\) emission in near–maximum-light spectra. This feature can be seen in the day –2 spectrum of SN 1994I in Figure 1 (beneath a narrow H\(\alpha\) emission due to an H ii region).

In order to produce a peaked rather than a flat H\(\alpha\) emission component, the hydrogen would have to be present down to the photosphere, rather than being confined to a detached, high-velocity shell such as we have invoked for the absorption component. In this regard, it is interesting to note that in Figures 1–3, the red edges of the putative H\(\alpha\) and He i \(\lambda 5876\) absorptions in SN 1994I are less sharp than in SN 1999ex; a detached shell produces sharp red edges. A continuous H\(\alpha\)

3 Filippenko (1988) referred to the events suggested as having hydrogen as Type Ib, because the Type Ic classification (Wheeler & Harkness 1986) was not yet commonly used; however, these events are now classified as Type Ic.
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Fig. 7.—Comparison of day +10 spectrum of SN 1994I with spectra of four other SNe Ic (from Matheson et al. 2001). The flux scale is arbitrary, and the spectra have been tilted to facilitate the comparison of spectral features. The spectrum of SN 1990B was obtained on day +5. The spectra of SN 1988L, SN 1995F, and SN 1997ei were obtained 11, 10, and 6 days after discovery, respectively; the dates of B maximum are unknown.

optical depth distribution that peaks at 15,000 km s\(^{-1}\) but extends down to the photosphere might suffice to produce a peaked H\(\alpha\) emission. This can only be tested by non-LTE calculations, because the resonance-scattering approximation on which SYNOW is based is known to be a poor approximation for H\(\alpha\) in SNe II. It is not clear that a large hydrogen mass would be required, because the appearance of hydrogen and He \(i\) lines depends on the radial optical depth profiles (Branch et al. 2002) and the distribution of \(^{56}\)Ni (Woosley & Eastman 1997).

At present, it is difficult to establish the presence or absence of hydrogen in SN 1994I–like SNe Ic, but the issue should be considered further. A large-scale comparative study of observed spectra, like that of Elmhambdi et al. (2006) but including SNe Ic as well as SNe Ib, would probably yield clues. In addition, detailed non-LTE spectrum calculations for a grid of explosion models are needed. Such calculations, even if based on parameterized explosion models rather than full hydrodynamic calculations, could probe several issues. For example, is Ne \(i\) \(\lambda 6402\) really a candidate to be the source of 6200 \(\AA\) absorption, and under what circumstances can peaked H\(\alpha\) emission be produced? In the only full non-LTE calculations for SNe Ic published so far (Baron et al. 1999), synthetic spectra for models that did not contain hydrogen failed to provide good fits to the 6200 \(\AA\) absorption in SN 1994I.

An interesting recent case is that of SN 2005bf (Anupama et al. 2005; Tominaga et al. 2005; Folatelli et al. 2006), which like SN 1999ex was initially classified as Type Ic but later developed definite He \(i\) lines, making it either Type Ib or Type Ib/c (or Type Icb?). In each of these three papers, the 6200 \(\AA\) absorption was attributed to H\(\alpha\). Strong support for the identification was provided by the presence of Ca \(ii\) and Fe \(ii\) in early spectra at the same high velocity (15,000 km s\(^{-1}\)) as the H\(\alpha\) absorption (Folatelli et al. 2006). The very long rise time of 40 days to maximum light indicates that the progenitor was massive. In addition, SN 2005bf showed evidence for high-velocity polar ejection, reminiscent of SN 1998bw–like explosions of massive stars, some of which produce gamma-ray bursts (GRBs). In view of the high ejected mass and the polar ejection, Folatelli et al. suggested that SN 2005bf may have been a transition event between ordinary SNe Ib/c and hypernovae. Therefore, if SN 2005bf ejected hydrogen, we should consider the possibility that SN 1998bw–like SNe Ic do too.

In SN 1998bw–like spectra, the 5700 and 6200 \(\AA\) absorptions are assumed to be Na \(i\) and Si \(ii\), respectively. These identifications were initially adopted (Iwamoto et al. 1998; Branch 2001) in part because they were assumed to be correct for SN 1994I (SN 1998bw–like spectra were and still are regarded as Doppler-broadened versions of SN 1994I–like spectra), and also because Monte Carlo spectrum calculations for bare carbon-oxygen cores do provide reasonable fits to SN 1998bw–like spectra (e.g., Mazzali et al. 2000, 2002), with Si \(ii\) and/or C \(ii\) producing the 6200 \(\AA\) absorption. Thus, even if the 6200 \(\AA\) absorption in SN 1994I–like SNe Ic is produced by H\(\alpha\), it may still turn out to be produced by Si \(ii\) in SN 1998bw–like SNe. Nevertheless, the possibility should be considered that even in SN 1998bw–like SNe, the correct identification is H\(\alpha\) rather than Si \(ii\) (and perhaps He \(i\) rather than Na \(i\)). Full non-LTE spectrum calculations for comparison with SN 1998bw–like spectra are in their initial stages (E. Baron & M. Troxel 2006, in preparation).

4.2. Implications for Progenitors and Explosion Models

Ideas concerning the progenitors of SNe Ib and SN 1994I–like SNe Ic have been reviewed by Podsiadlowski (1996), who concluded that most of the progenitors are stars that have main-sequence masses \(<20 M_\odot\) and that lose their envelopes by means of binary interaction. In standard binary evolutionary scenarios, if all or even just a substantial fraction of the helium envelope is lost, all of the hydrogen is also lost. For example, Nomoto et al. (1994) favored a scenario involving two common-envelope episodes that results in a carbon-oxygen core containing little or no helium and no hydrogen. However, as
emphasized by Podsiadlowski, there are many unresolved questions in binary stellar evolution. If SN 1994I–like SNe Ic eject hydrogen (and therefore also helium), some modification of the standard evolutionary scenarios, perhaps involving substantial mixing of hydrogen prior to or during the explosion, will be needed.

SN 1998bw–like SNe Ic, including those that produce GRBs, are usually regarded as coming from stars of sufficiently high main-sequence mass that they can lose their envelopes by means of single-star winds. Those that produce GRBs may have to be in binary star systems in order to have sufficient angular momentum at the time of core collapse for the collapsar model (McFadyen & Woosley 1999) to be viable (Fryer & Heger 2005; Petrović et al. 2005). The uncertainties involved in the evolutionary scenarios for SN 1998bw–like SNe are even greater than for SN 1994I–likes, and if SN 1998bw–like SNe eject hydrogen, current scenarios will require revision. Particularly interesting in this regard are recent results on the chemically homogeneous evolution of rapidly rotating massive stars (Yoon & Langer 2005; Woosley & Heger 2006). Some of these GRB-candidate models contain hydrogen at the time of core collapse.

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