SEARCHING FOR HYDROGEN IN TYPE Ib SUPERNOVAE

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ABSTRACT

We present synthetic spectral fits of the typical Type Ib SN 1999dn and the hydrogen-rich Ib SN 2000H using the generalized non-local thermodynamic equilibrium stellar atmospheres code PHOENIX. We fit model spectra to five epochs of SN 1999dn ranging from 10 days pre-maximum light to 17 days post-maximum light and to the two earliest epochs of SN 2000H available, maximum light and six days post-maximum. Our goal is to investigate the possibility of hydrogen in Type Ib supernovae (SNe Ib), specifically a feature around 6200 Å which has previously been attributed to high-velocity Hα. In earlier work on SN 1999dn we found the most plausible alternative to Hα to be a blend of Si iı and Fe iı lines which can be adjusted to fit by increasing the metallicity. Our models are simple; they assume a power-law density profile with radius, homologous expansion, and solar compositions. The helium core is produced by “burning” 4H → He in order to conserve the nucleon number. For models with hydrogen the outer skin of the model consists of a shell of solar composition. The hydrogen mass of the standard solar composition shell is \( M_H \lesssim 10^{-3} M_\odot \) in SN 1999dn and \( M_H \lesssim 0.2 M_\odot \) for SN 2000H. Our models fit the observed spectra reasonably well, successfully reproducing most features including the characteristic He i absorptions. The hydrogen feature in SN 1999dn is clear, but much more pronounced in SN 2000H. We discuss a possible evolutionary scenario that accounts for the dichotomy in the hydrogen shell mass between these two SNe.

Key words: supernovae: individual (1999dn, 2000H)

Online-only material: color figures

1. INTRODUCTION

1.1. Supernovae Nomenclature

Supernovae (SNe) are divided into two main subtypes, Type I and Type II, based on the presence of hydrogen in their spectra. SNe of Type I are then further subdivided into Types Ia, Ib, and Ic (Wheeler & Harkness 1990). SNe Ia are characterized by strong Si iı absorption near 6100 Å and a characteristic sulfur “W”-shaped feature at 5400 Å. SNe Ib are classified by the presence of optical He i lines in their spectra, and SNe Ic are noted for their lack of helium and silicon. SNe Ia are thought to be caused by the thermonuclear explosion of a Chandrasekhar mass white dwarf star while SNe II, Ib, and Ic are caused by the core collapse of a massive star. The general consensus is that most SNe Ib/c result from mass loss due to interaction with a binary companion and that SNe IIb also result from binary interaction (Podsiadlowski et al. 1992, 1993; Nomoto et al. 1995; Heger et al. 2003).

SNe are classified by their spectra. As early spectra become more commonly available, trends in the variation of certain SNe types over the course of time have emerged. This is apparent in SN 1993J which was originally classified as an SN Ia for its conspicuous hydrogen but later showed helium absorptions characteristic of an SN Ib. SN 1993J is now classified as an SN IIn which is believed to be the explosion of a star that has undergone enough mass loss to lose a large portion of its hydrogen envelope (Filippenko et al. 1993). SN 1987K (Filippenko 1988) and SN 2008ax (Chornock et al. 2010) are other examples of this transitory class of SNe. This explains the distinct Balmer lines seen at early times which give way to significant helium features as time progresses. This type of transition-like object was first suggested by Woosley et al. (1987). It has been suggested that if mass loss from an SN Ia progenitor can produce SNe Ib, then an even larger mass loss would result in further stripping of the hydrogen envelope and would be characteristic of SNe Ib (Filippenko 1988). This suggests that we might see hydrogen in early spectra of SNe Ib if there was a large enough mass of hydrogen left prior to explosion. Nomoto et al. (1995) also suggest several binary mass loss scenarios that might lead to a spectroscopic sequence of SN types from Ia → Ib → Ic. By understanding the behavior of these transitory types of SNe we are able to better extrapolate back to the state of the progenitor star. We therefore investigate the early and late time spectra of a typical Type Ib SN 1999dn and the early spectra of a hydrogen-rich SNe Ib SN 2000H (Branch et al. 2002) in search of clues as to whether or not a thin hydrogen skin exists prior to the SN explosion.

1.2. Prior Investigations

The idea that there exists an underlying physical connection between SNe II and SNe Ib is not a new one. As more SNe are discovered at earlier times we see a number of these SNe Ib, which appear to be transition-like objects from Type II → Ib. The recent discovery of SN 2008ax (Chornock et al. 2010) has led to more detailed investigations into the connection between SNe Ib and SNe Ic, and Chornock et al. (2010) suggested that a full non-local thermodynamic equilibrium (NLTE) treatment is necessary for a conclusive analysis of the details of the hydrogen skin.

Branch et al. (2002) conducted a direct analysis of a selection of SN Ib spectra obtained by Matheson et al. (2001) using the SN spectrum synthesis code SYNOWN. They concluded that a small amount of hydrogen is present in perhaps all SNe Ib spectra, specifically SN 1999dn, and that even more is seen in what they term hydrogen-rich SNe Ib: 2000H, 1999di, and 1954A. Others (Eilhami et al. 2006; Deng et al. 2000; Parrent et al. 2007)
have also used SYNOW to investigate the presence of hydrogen in SNe Ib.

Because of the relative simplicity of SYNOW a first principle NLTE treatment is needed to analyze the presence of hydrogen in detail. While a SYNOW analysis can determine whether a particular ion is there or not and can also indicate the relative strength and velocity extent of that species, one cannot use SYNOW to determine quantitative abundances. We use the NLTE stellar atmospheres code PHOENIX (Hauschildt & Baron 2004, 1999) to accomplish this. We perform a time-series analysis of the spectra of SN 1999dn, a typical SN Ib, as well as some calculations of early time spectra of another SN Ib, SN 2000H. Benetti et al. (2000) originally classified SN 2000H as an SN IIb due to strong Hα absorptions.

We wish to accomplish the following: (1) produce hydrogen and hydrogen-free fits to relevant epochs of SN 1999dn and SN 2000H; and (2) constrain the possible ejection velocity and mass of the hydrogen skin.

2. METHODS

2.1. General Methods

We generate synthetic spectra of SNe Ib using the NLTE stellar atmospheres code PHOENIX (Hauschildt & Baron 2004, 1999, and references therein). The inclusion of NLTE calculations allows us to investigate the importance of non-thermal processes in reproducing SN Ib spectra. We explore the possibility of the existence of hydrogen in SNe Ib by adding a thin skin of solar composition material (Grevesse et al. 2007) to a helium core (which also has solar compositions of metals). The helium core is constructed by beginning with material at solar composition and then “burning” 4H → He. We then add the hydrogen skin with solar abundances by replacing the abundances above a specified velocity, \( v_H \), which is varied to find the best fit without disturbing the helium core interior to \( v_H \). Our models extend out to a maximum velocity of 21,000 km s\(^{-1}\) regardless of whether they are pure helium cores or include a hydrogen skin.

We approximate the gamma-ray deposition function by a constant parameter that is adjusted for each epoch. The assumption of a sharp boundary between the hydrogen and helium layers is not realistic, but is simple and eliminates the need to add extra parameters. This approximation should not significantly affect our conclusions.

The earliest model of SN 1999dn is only \( M = 0.85 M_\odot \) as compared with all the other days that are \( M = 38 M_\odot \). This difference in mass was necessary in order to deal with the large variation in the dynamic range of the atmosphere. Nevertheless our models are internally consistent. The very large mass of the progenitor is due to the straightforward extrapolation of the steep power-law density profile to low radii. Here, it is just a calculational expedient and does not imply that the progenitor was anywhere close to this massive.

3. RESULTS

3.1. SN 1999dn

Figure 1 shows the observed spectra for several epochs of SN 1999dn (Matheson et al. 2001; Deng et al. 2000). While we seek the overall best fit to the spectra, emphasis is placed on the 6200 Å feature which fades after maximum light. The observed spectra are smoothed with a 10 point boxcar average in order to remove some noise.

We explored variations in multiple parameters for each epoch adjusting the total bolometric luminosity in the observer’s frame (specified by a temperature, \( T_{\text{model}} \), the photospheric velocity, the metallicity, the density profile, gamma-ray deposition, and hydrogen mass. By varying these parameters we have arrived at a set of parameters which we consider the best and we follow that model through each epoch. The relevant parameters for SN 1999dn are given in Table 1 and for SN 2000H in Table 2.

The results of the NLTE PHOENIX calculations are shown in Figures 2–8. We treat the following species in NLTE: H i, He i–ii, C i–iii, N i–iii, O i–iii, Ne i, Na i–ii, Mg i–iii, Si i–iii, Ca i–iii, and Fe i–iii. In all the spectra we successfully reproduce the characteristic He i absorptions at 5876 Å, 6678 Å, and 7065 Å.

Figure 2 shows the early epoch 1999 August 21 for SN 1999dn (Matheson et al. 2001, −10 days). The synthetic spectrum with hydrogen at 19,000 km s\(^{-1}\) fits the 6200 Å feature better than a pure helium core. In the maximum light spectrum, August 31, the hydrogen feature at 19,000 km s\(^{-1}\) does not properly blend with the feature just to the red (Figure 3), but this is likely
due to our assumption of a sharp abundance boundary. The detached-like profile (blueshifted absorption with flat topped emission) is a consequence of the abrupt cutoff of our model. The hydrogen velocity is 19,000 km s$^{-1}$ and the outer velocity layer of our model is 21,000 km s$^{-1}$. A smoother variation in the abundances would reduce the sharp cutoff that leads to the detached profile.

By September 10 the hydrogen feature has faded in both the observed spectrum as well as the synthetic spectra as seen in Figure 4. This is reinforced by the lack of a feature in the later days of the observed spectra.

In Figures 5 and 6, on September 14 and 17, respectively, we find that the inclusion of hydrogen has little if any effect on the spectrum and so conclude that the thin skin of hydrogen is no longer visible due to geometric dilution.

Figure 4. SN 1999dn (+10) observed spectrum (Matheson et al. 2001) smoothed with a 10 point boxcar compared to synthetic spectra with and without hydrogen at $v_H = 19,000$ km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 5. SN 1999dn (+14) observed spectrum (Deng et al. 2000) smoothed with an 8 point boxcar compared to synthetic spectra with and without hydrogen at $v_H = 19,000$ km s$^{-1}$.

(A color version of this figure is available in the online journal.)

The He I absorptions in many of the spectra appear to be slightly to the red of the observed absorptions. This is probably due to the assumption of a constant gamma-ray deposition parameter. By increasing the amount of gamma-ray deposition we increase the non-thermal components of the spectrum which increases the depth of the He I absorptions and also the speed of highly non-thermal lines. A more thorough treatment of the nickel distribution would likely improve this, but examining the exact amount of nickel mixing is beyond the scope of the present work.

3.2. SN 2000H

The earliest spectrum available of SN 2000H is at maximum light, 2000 April 21 (Barbon et al. 2009). Figure 7 shows a very deep and wide absorption trough in the region of H$_\alpha$ absorption. Part of the absorption feature could be due to blending with other
elements due to circumstellar interaction. Toward the end of this section we discuss the narrow Na D absorption near 5800 Å and the information we can gather about the circumstellar medium (CSM) from it.

Part of the line profile could be due to a low-velocity CSM region but the depth of the line would suggest that we should also see evidence of \( H_\beta \), which is lacking. This SN is highly reddened. We adopt a reddening value of \( E(B - V) = 0.61 \) (Benetti et al. 2000) and a recession velocity of \( v_{\text{rec}} = 3945 \) km s\(^{-1}\) taken from the NED\(^3\) database.

We find that the spectrum of SN 2000H at +6 days post-maximum light (Barbon et al. 2009) can also be well reproduced by adding hydrogen to our models as is shown in Figure 8. We find that a hydrogen velocity of \( v_H = 15,000 \) km s\(^{-1}\) is necessary to fit the hydrogen feature around 6200 Å. The amount of hydrogen included in the 2000H model (\( M_H \sim 0.2 M_\odot \)) is significantly greater than in our SN 1999dn models, \( M_H \lesssim 10^{-3} M_\odot \), which is consistent with the classification of a hydrogen-rich SN Ib by Branch et al. (2002). This is necessary to fit the hydrogen feature that persists to as late as +6 days post-maximum light. A larger amount of hydrogen suggests that SN 2000H is closer to the Type IIb subtype due to a lower degree of envelope stripping than in SN 1999dn (Benetti et al. 2000; Blondin & Tonry 2007; Chornock et al. 2010).

Figures 9 and 10 show two of the observed spectra of SN 2000H, both with and without a 20 point boxcar smoothing. The narrow Na D absorption around 5800 Å appears to fade quickly since it is not seen in the spectrum taken six days later. In Figure 11, we present a comparison of a SYNOW spectrum of only Na i constrained to 3000–5000 km s\(^{-1}\) as well as the case where the Na i is detached from the photosphere but constrained to 3000–3500 km s\(^{-1}\) with the maximum light spectrum of SN 2000H with 20, 10, and 5 point boxcar smoothing. The Na i and the 20 point boxcar spectrum look like the best fit, but since the SYNOW spectrum appears too broad to fit the 5 point boxcar the detached spectrum is a better fit in that case. In either case one finds a characteristic velocity of the Na D line to be about 3000 km s\(^{-1}\).

While the Na D feature could be an artifact of the data reduction, it is possible that the feature formed in the surrounding CSM. The SYNOW velocity is large compared to typical wind velocities. Yoon et al. (2010) found wind velocities for different SN Ib/c progenitors ranging from ~200 km s\(^{-1}\) to ~2400 km s\(^{-1}\), which at the upper limit could explain the high velocity we find for the Na D feature from the CSM; however, with a hydrogen shell of ~0.1 \( M_\odot \), the wind is more likely to be of order 500 km s\(^{-1}\). The high velocity could also be due to radiative acceleration at shock breakout. We

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\(^3\) http://nedwww.ipac.caltech.edu/
find the total energy required to accelerate this mass to be
\[ E_{\text{kin}} = 2 \times 10^{47} \, \text{erg} \left( \frac{\rho}{10^{-15}} \, \text{g cm}^{-3} \right), \]
where the density is obtained from the SYNOW fit assuming an ionization fraction of \( 10^{-3} \).

4. DISCUSSION

We find that the results from the PHOENIX calculations suggest a hydrogen mass of \( M_H \lesssim 10^{-3} \, M_\odot \) for SN 1999dn. This corresponds to a hydrogen velocity \( v_H \gtrsim 19,000 \, \text{km s}^{-1} \). Tanaka et al. (2009) placed a limit of \( M_H \lesssim 5 \times 10^{-2} \, M_\odot \) on the hydrogen mass in SN 2008D and a limit on the Doppler velocity of approximately \( v_H \approx 18,500 \, \text{km s}^{-1} \). Others have also suggested that hydrogen is responsible for this feature around 6200 Å. Deng et al. (2000) suggested a hydrogen velocity for SN 1999dn of 19,000 km s\(^{-1}\) on August 21, and 18,000 km s\(^{-1}\) on August 31, and that the feature becomes blended and then taken over by C II in later days. Ketchum et al. (2008) investigated C II, Si II, Fe II, and Ne I as possible candidates as well but found that without increasing the metallicity and abundances beyond physically reasonable amounts the 6200 Å feature was not easily reproduced in early epochs. This seems to be consistent with our calculations, reinforcing the existence of hydrogen in early spectra of SNe Ib.

We also find that the results from the PHOENIX calculations suggest a hydrogen mass of \( M_H \lesssim 0.2 \, M_\odot \) for SN 2000H. This corresponds to a hydrogen velocity in our models of \( v_H \approx 15,000 \, \text{km s}^{-1} \). This mass estimate is likely an upper limit since we assume a single power-law density profile for both the helium core and hydrogen shell. The width of the 6200 Å feature early on is likely due to some blending with some circumstellar material since it disappears in the spectrum six days later and the hydrogen feature is more clear. We know that circumstellar interaction was taking place at maximum light from the presence of the narrow Na D feature that quickly fades. The larger amount of hydrogen is more characteristic of that seen in an SN IIb such as SN 1993J or SN 2008ax with mass estimates on the order of \( M_H \gtrsim 0.1 \, M_\odot \) (Wheeler et al. 1994; Chornock et al. 2010).

The possibility of a hydrogen skin existing prior to the SN explosion is interesting. Podsiadlowski et al. (1992) first discussed the evolution of binary systems that would lead to mass stripping. Nomoto et al. (1995) discuss a continuum of SNe types from IIn → IIb → Ib → Ic which would be consistent with the idea of a varying degree of hydrogen mass loss due to a strong wind or binary interaction in a non-conservative mass transfer scenario. The energy released in a binary merger would be sufficient to eject some of the envelope. Wheeler et al. (1994) suggested that if hydrogen is present in SNe Ib then the amount of hydrogen in SNe Ib is less than that found in the Type IIb SN 1993J, which was about 0.1–0.5 \( M_\odot \) (Filippenko et al. 1993). This is consistent with our results for SN 1999dn but suggests that SN 2000H is more accurately classified as an SN Ib. Chevalier & Fransson (2006) also suggest that there is a continuous distribution of SNe between SNe Ib where the hydrogen is clearly present and SNe Ib where the hydrogen is quite weak. This continuous distribution is likely to be the explanation for the sequence of SNe between type Ib and Ib, and the varied amounts of envelope stripping are a result of binary interaction and/or strong stellar winds. SN 1993J is
known to have been in a binary and as a result lost some of its hydrogen envelope due to the merging of the two stars in the binary (Podsiadlowski et al. 1993; Nomoto et al. 1995).

Recently, Yoon et al. (2010) studied binary progenitors of SNe Ib/c including the effects of rotation and various reduced wind-loss formulations. They found that even in the case of Case A and B mass transfer the mass transfer is non-conservative and for a limited range of helium cores \(3.5 \lesssim M \lesssim 4.5 M_\odot\), for solar metallicity and \(3.5 \lesssim M \lesssim 8 M_\odot\), for \(Z_\odot/20\) that the wind loss in the helium Wolf-Rayet stage is low enough that a hydrogen skin of the order of \(M_H \sim 10^{-2} - 10^{-3}\) can be retained.

Even though there is a rather continuous distinction between SNe IIb and hydrogen-rich SNe Ib, the total hydrogen mass in the envelope is rather similar \(M_H \sim 0.1 - 0.3 M_\odot\). These objects are likely from binary progenitors with stable Case C mass transfer, which leads the donor to shrink below the Roche limit when the envelope reaches a critical mass of about \(0.3 M_\odot\) (Podsiadlowski et al. 1992, 1993). Further reduction of the envelope mass then follows via ablation of the hydrogen envelope from the wind of the secondary (Podsiadlowski et al. 1992, 1993). However, studies of SNe Ib suggest that many if not most have a much thinner skin of hydrogen similar to what we find here for SN 1999dn (Branch et al. 2002; Chornock et al. 2010). This could likely be explained by a binary scenario that leads to a common envelope that is ejected from the system (Podsiadlowski et al. 1992). As described in Podsiadlowski et al. (1992) this will lead to either a cataclysmic variable (if the core mass is less than \(1.4 M_\odot\)) or to a low-mass helium core, which would explode as an SN Ib, but in the common envelope environment it would not be hard to keep a thin hydrogen skin. If this is a common channel for SNe Ib formation then one would expect many to have thin hydrogen envelopes which will be visible in early spectra. Since massive helium cores will blow strong winds that would quickly remove a \(10^{-3} M_\odot\) envelope, this lends support to the idea that many SNe Ib progenitors are the result of relatively low-mass helium cores.

5. CONCLUSION

Our results indicate that hydrogen does exist in the Type Ib SN 1999dn and SN 2000H with an upper mass limit of \(M_H \lesssim 10^{-3} M_\odot\) and \(M_H \lesssim 10^{-1} M_\odot\), respectively. The existence of such a small amount of hydrogen is to be expected as suggested by the continuous spectrum of SN types from II to Ic. Further analysis of a more robust sample of SN Ib is needed for a definitive claim, but the existence of a hydrogen skin in SNe Ib is seen in the observed spectra as well as supported by synthetic calculations. This implies that the typing of core-collapse SNe is more useful as a means of determining the state of the ejecta at a given epoch as opposed to inferring the state of the progenitor at the time of explosion. While it is still useful to determine an SN type we need to set a uniform epoch, such as maximum light or later, in order to be consistent and conclusive when it comes to classification.

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