TYPE IB AND IC SUPERNOVAE: MODELS AND SPECTRA

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1. Introduction

For the theorist, Type Ib and Ic supernovae are the explosion of massive stars that have lost their hydrogen envelopes. For the observer, Type Ib supernovae are those that show no evidence of hydrogen, a weak or absent Si II absorption feature near 6150 Å at peak light, and strong oxygen emission at late times. The light curves of Type Ib are also about four times fainter and somewhat broader than Type Ia. Unlike Type Ia, Type Ib supernovae can be strong radio sources and show a strong preference for star forming regions in spiral galaxies. No Type Ib supernova has ever been discovered in an elliptical galaxy. Type Ic greatly resembles Ib, but additionally is characterized by a weak or absent He feature at 5876 Å and, in at least one case, a narrower light curve.

Whether there is universal concordance between the theorist's and observers' views of what constitutes a Type Ib supernova and the extent to which Type Ic should be regarded as a separate class (with a separate kind of model) remain important unresolved issues.

In this paper we consider the properties of massive star models for Type Ib and Ic supernovae. There are two ways that a massive star can lose its hydrogen envelope - binary mass exchange and stellar wind. These are not mutually exclusive. A star might lose its envelope to a binary companion and still suffer appreciable mass loss as a detached Wolf-Rayet star. On the other hand, if the companion is very close, possibly due to common envelope interaction, binary mass exchange may continue even after the envelope is lost. In some cases the star's mass may even change appreciably even after carbon has ignited.

It turns out that common Type Ib supernovae require progenitors that, at the time of their explosion, have relatively small masses - about 3 - 4 $M_\odot$. The value has drifted down over the years since Ensman & Woosley (1988) first placed a limit of 6 $M_\odot$ on Type Ib progenitors owing to difficulty getting a fast enough light curve with realistic physics (see also Shigeyama et al. 1990; Swartz et al. 1993). The lower limit is set by the requirement that enough ^{56}Ni be produced in the explosion. There are three routes to such a progenitor: 1) a star of 12 to 15 $M_\odot$ on the main sequence loses its hydrogen envelope, but little more to a close binary companion; 2) a more massive star loses its envelope to a companion plus additional mass either to a wind as a WR-star or mass exchange to a very close companion; or 3) a single star of M $\gtrsim$ 35 $M_\odot$ (for solar metallicity) loses its envelope, and a large part of its ($\gtrsim$14 $M_\odot$) helium core as well, to a wind.

If all these possibilities are realized, one might expect more diversity in Type Ib observations than is seen, especially a considerable number of explosions in more massive cores and a corresponding number of supernovae with slow faint light curves. Perhaps such objects await detection. On the other hand Langer (1989ab) has provided a clue as to how "core convergence" might operate in Type Ib progenitors. The mass loss rate of Wolf Rayet stars may have a steep non linear dependence upon their mass, the more massive cores losing mass more than fast enough to compensate for their shorter lifetimes. Specifically the mass loss rate is $\dot{M} = -kM^{2.5}$ with k = 6×10^{-8} $M_\odot$ y^{-1} for surface carbon abundance less than 0.02 by mass, and 10^{-7} $M_\odot$ y^{-1} thereafter. The observational and theoretical basis for this prescription has been discussed by Langer (1989ab) and Langer et al. (1994). Calculations incorporating this prescription (plus other variations for the LBV, RSG, and WNL stars that retain hydrogen) have been carried out by Woosley, Langer, & Weaver (1993, 1995; hence WLW1 and WLW2). One finds that convergence to a final mass around 3 or 4 $M_\odot$ may be a common occurrence for all massive stars that lose their envelope sufficiently early during helium burning. This is gratifying, but given such supernovae as SN 1993J which lost all but $\sim$0.2 $M_\odot$ of its hydrogen envelope (Woosley et al. 1994), one wonders if there aren't other stars that lose their envelope too late to experience core convergence. The faint broad light curves of such Type Ib supernovae ought to exist.

Besides agreement with observed light curve, one must also produce models consistent with observed spectra. This is more constraining, and also more difficult to calculate accurately. Even the defining characteristic of Type Ib supernovae, namely the weak silicon feature at peak light, has not yet been demonstrated in some of the leading models (though see Swartz et al. 1993). Here we shall show that at least some of the models of WLW2 do agree spectroscopically with such Type Ib and Ic supernovae as SN 1984L and SN 1994I.

We also find that the strength of the helium line in a Type Ib/c supernova is very sensitive to the degree to which ^{56}Ni and helium are mixed. This in turn is sensitive both to the mixing process and the amount of *oxygen* in the star. In massive stars, the oxygen layer provides the buffer region between helium and ^{56}Ni. The distinction between Type Ib and Type Ic supernovae may be the degree of mixing more than the absolute helium abundance. In particular, in contrast to claims by Swartz et al. (1993) that the helium abundance in Type Ic supernovae must have total abundance $\lesssim 0.15$ M$_\odot$, we find very good agreement with the observed spectrum of SN 1994I using a model that has a helium abundance of 0.40 M$_\odot$.

2. Type Ib supernovae from single massive progenitors

Since a single star can only lose its envelope to a stellar wind if its mass is $\gtrsim 30$ M$_\odot$(e.g., Chiosi & Maeder 1986), one expects this sort of event to be less frequent, probably rarer by about a factor of two than the number of supernovae in mass exchanging binary systems (Podsiadlowski, Joss, & Hsu 1992; Podsiadlowski 1996; Tutukov, Yungel'son, & Iben, 1992). Still they should occur and it is important to know their properties.

One possibility is that the star loses its envelope sufficiently late that it dies with a large helium core and simply fails to explode. Woosley & Weaver (1995) and Timmes, Woosley, & Weaver (1995) find that for helium cores above 6 M$_\odot$ the iron core becomes larger than 2.0 M$_\odot$, rather than the more typical 1.4 - 1.6 M$_\odot$ that characterizes the lighter stars. Bruenn et al. (1996) find that it is very difficult to explode the 2.07 M$_\odot$ core of 25 M$_\odot$ star with a helium core of 9 M$_\odot$. Successful explosions calculated so far have all been for lighter stars.

Thus it may be that the engine fails to produce an outgoing shock in these stars. Then either rotation and nuclear burning work together to produce a low energy explosion (Bodenheimer & Woosley 1983) or the star collapses completely and makes no ^{56}Ni. Woosley (1993) has speculated that such objects may produce gamma-ray bursts. In any case such "failed

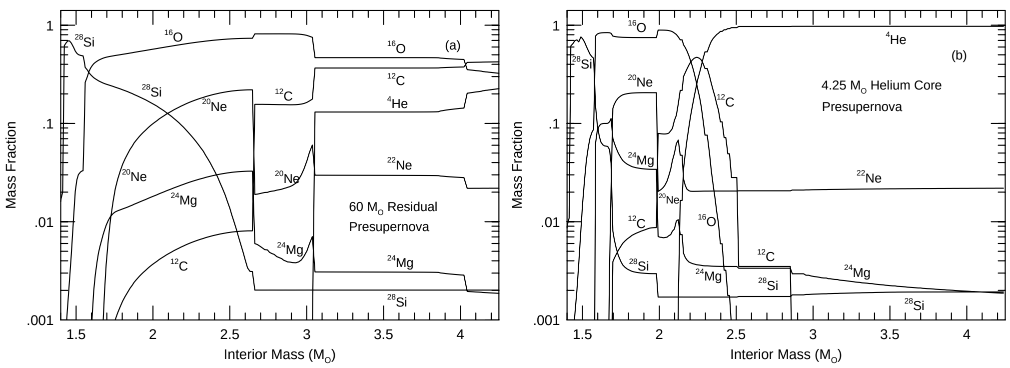

Figure 1. Final composition of Models 60WRA (left) and WR 4.25 (right)(WLW1).

supernovae" are not common Type Ib events.

WLW1 have explored the observable consequences of single stars that do lose their envelope and a large fraction of their helium core to a wind. Fig. 1 (left panel) shows the composition of the 4.25 $M_\odot$ remnant of a star that, on the main sequence, was originally 60 $M_\odot$. This is an enormous amount of mass loss, and while not unphysical, it is highly uncertain whether a 60 $M_\odot$ star really does this. On the other hand, Maeder (1990) obtains final helium core masses in the range 4.6 to 5.5 $M_\odot$ for a range of solar metallicity stars from 40 to 120 $M_\odot$. Also given for comparison is the final composition of a helium star of 4.25 $M_\odot$ evolved without mass loss. This would be the result if a star of about 15 $M_\odot$ lost its envelope and nothing more. The composition (as well as entropy, temperature, and density profiles - see WLW1) are quite different. The massive star remnant is essentially a core of oxygen, whereas the helium core is still predominantly helium. The ejected abundance of Model 60 WRA contains 0.21 $M_\odot$ of helium and 1.38 $M_\odot$ of oxygen. The presupernova model WR 4.25 (not exploded) had 1.89 $M_\odot$ of helium and 0.51 $M_\odot$ of oxygen. In both cases the iron core mass was about 1.4 $M_\odot$. One would expect observational differences, if only spectroscopic, between these two very different evolutionary paths.

The light curve of Model 60WRA was computed by WLW1. The calculation assumed a minimal opacity, only electron scattering with the electron abundance calculated using a one temperature code and the Saha equation.

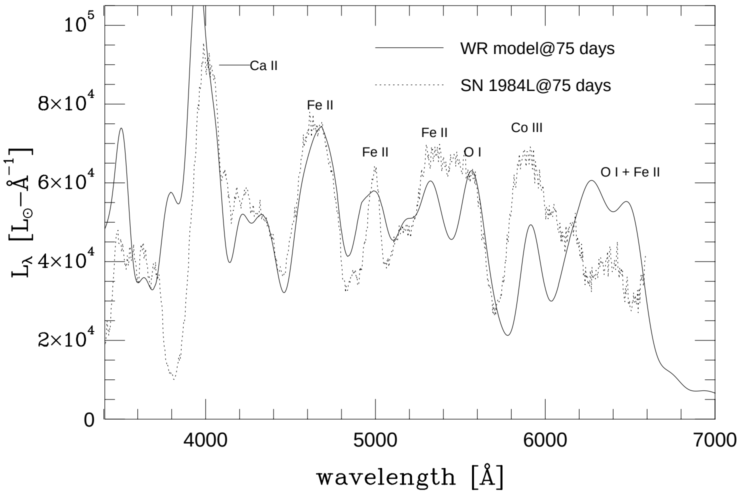

Figure 2. Spectrum of Model 60WRA (WLW1) compared to SN 1984L (Woosley and Eastman, 1995).

Even so, the light curve was overly broad compared to SN 1983N, a result that turned out to be virtually independent of the mixing. While both the simplicity of the model and the translation of observed magnitudes into a bolometric light curve may be questioned, the implication is that, for an explosion of $\sim10^{51}$ erg, a mass even lighter than 4.25 $M_\odot$ is preferred for the SN Ib progenitor.

The late time spectrum of Model 60WRA was computed some time ago (Woosley & Eastman, 1995) and is shown compared to SN 1984L in Fig. 2. The spectrum at peak late and very late times has not yet been computed for this model though one expects the late spectrum to be dominated by oxygen emission given the large abundance of this element. Over all it is a reasonably good fit. However, we shall see in the next section that models which may occur more frequently fit just as well or better.

3. Type Ib and Ic supernovae in binary systems

Given that a large fraction of supernovae should occur in binary systems where the envelope is lost to the companion, it is perhaps more realistic to consider the fate of such stars. WLW2 studied the evolution of mass losing *helium* stars, the essential assumption being that the envelope is removed sufficiently early during helium burning. Continuing to lose mass at a rate given by mass dependent ($M^{2.5}$) mass loss, a variety of helium cores in the range 4 to 20 $M_\odot$ (main sequence mass 15 to 45 $M_\odot$) converge on a final mass in the range 2.26 - 3.55 $M_\odot$. The convergence is a consequence of the non-linear dependence of $\dot{M}$ on mass. The actual numbers are uncertain.

Following explosion using pistons, the compositions of two representative models, 4B and 7A are given in Figs. 3 and 4. This series of models gave ^{56}Ni masses from 0.07 to 0.15 $M_\odot$ and light curves which, when calculated using an (overly) simple one-T diffusion approximation and opacity due to electron scattering (WLW2), agreed well with observations of SN 1983N and SN 1994 I, the latter nominally a Type Ic supernova. In this simple prescription the light curve shapes were not very sensitive to mixing, the earlier rise time of the mixed model compensating somewhat for the earlier escape of gamma-rays and dimming in the same model. The helium mass ejected in these models ranged from 0.76 to 0.24 $M_\odot$ with the larger helium masses corresponding to *smaller* initial helium core masses. The oxygen mass ranged from about 0.05 $M_\odot$ (lower mass helium cores) to 0.70 $M_\odot$ (heavier helium cores). As the figures show the helium was contaminated in the higher mass models (M_i(He) $\gtrsim 7$ $M_\odot$), even at the surface, by appreciable abundances of carbon and oxygen. High velocity oxygen and carbon lines should be a distinctive signature of such models as opposed to those manufactured by stripping the hydrogen envelope from a 15 $M_\odot$ star say with no further mass loss.

Several additional models were explored by WLW2, wherein Models 5 and 7, derived from 5 and 7 $M_\odot$ helium core respectively, with mass dependent mass loss, were subjected to simulated mass exchange with a close binary companion. Such a possibility has been suggested by Nomoto et al. (1994) as necessary for the progenitors of Type Ic supernovae (see also Wheeler 1987; Yamaoka, Shigeyama, & Nomoto 1993; and Swartz et al. 1993) and would be a consequence of common envelope evolution providing a companion so nearby that the Roche radius is $\lesssim 10^{11}$ cm. In such a system mass transfer continues at an appreciable rate even after helium core burning. The goal (Nomoto et al.) is to produce a star which has lost essentially all its helium layer so as to explain the absence of He I 5876 Å line in Type Ic by virtue of having the helium abundance go essentially to zero. Swartz et al. (1993), in particular, have claimed that an upper

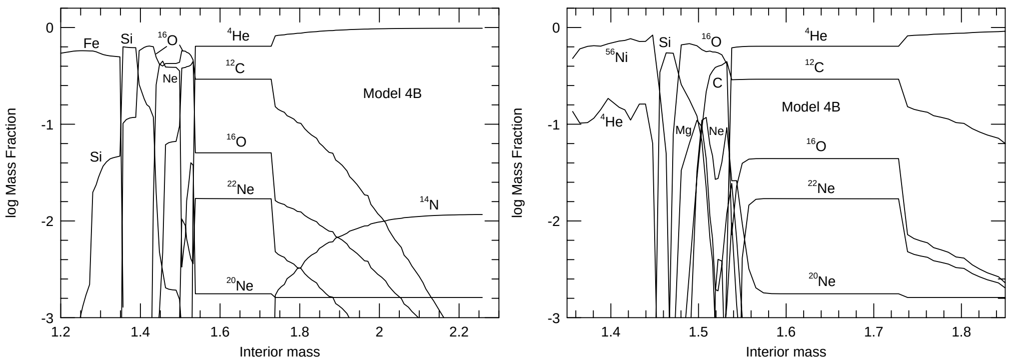

Figure 3. Presupernova composition of Models 4B (left) and interior abundances external to the piston after an explosion of 8.5×10^{50} erg (right). This explosion made 0.07 $M_\odot$ of ^{56}Ni and ejected 0.64 $M_\odot$ of helium (WLW2).

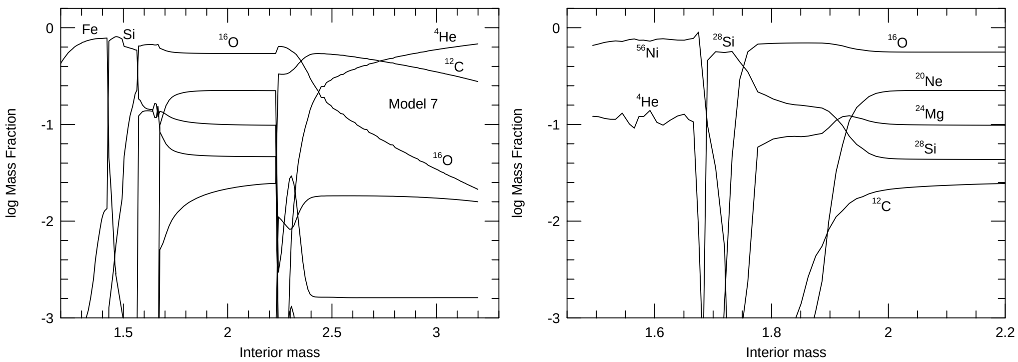

Figure 4. Presupernova composition of Models 7A (left) and interior abundances external to the piston after an explosion of 1.5×10^{51} erg (right). This explosion made 0.15 $M_\odot$ of ^{56}Ni and ejected 0.41 $M_\odot$ of helium (WLW2).

bound on the helium abundance in a Type Ic supernova is $\lesssim 0.15$ $M_\odot$, and the tendency lately has been to strive for even smaller values. Model 5 of WLW1 had, at the end of helium burning, a mass of 2.82 $M_\odot$ and a helium abundance of 0.74 $M_\odot$. However, for mass transfer with a point mass of 2 $M_\odot$ initially (again at the end of helium burning) at 0.02 AU, the final mass of Model 5 was reduced to 2.38 $M_\odot$ and the helium mass to 0.33 $M_\odot$. In the most extreme case, A version of Model 7 was calculated with a point mass of 1.2 $M_\odot$ (white dwarf?) located at 10^{11} cm. During carbon burning the mass of the primary was reduced from 3.23 to 2.40 $M_\odot$. The helium mass declined from 0.63 $M_\odot$ to 0.09 $M_\odot$, well within the limit of 7% of the mass of the star imposed by Swartz et al. (1993).

It does not appear likely that still smaller helium abundances can be obtained. The helium shell powers the light output of a presupernova star. If all the helium were removed its radius would shrink cutting off any transfer. There is also a limiting rate at which mass can be transferred given essentially by the luminosity and the bining energy of the helium layer. The model that gave 0.09 $M_\odot$ was already extreme in invoking a companion located right at the edge of the primary. It is not clear why a common envelope evolution would frequently give such a finely tuned separation.

As we shall see in subsequent sections however, there may be no need to reduce the helium abundance in a Type Ic supernova below what already exists in the unmodified models of WLW2. This is because the strength of the helium line feature is even more sensitive to the amount of mixing that occurs in the explosion and the extent to which ^{56}Co and helium are brought into close proximity than it does to the absolute helium abundance. The degree of mixing is uncertain but is thought to be considerably less in Type Ib supernovae than in Type IIp (e.g., Hachisu et al. 1991) because the former lacks an appreciable reverse shock. However, this means that the mixing is even more sensitive to the uncertain multi-dimensional aspects of the explosion mechanism. Herant & Woosley (1996) are exploring this issue.

4. Light Curves

We have calculated the light curves of WLW2, Models 4B and 7A with the multigroup radiation transport code EDDINGTON (Eastman & Pinto 1993; Woosley et al 1994; Eastman et al 1994). In these calculations, the radiation field was represented by 500 variable width energy groups ranging from 30 Å to 200 μ. Opacity contributors included electron scattering, bound-free, free-free, and bound-bound transitions. These were represented using an expansion opacity approximation (Eastman & Pinto 1993; see also the chapters in this volume by Eastman, and by Pinto). In these time dependent evolutionary calculations the gas was assumed to be in LTE. The shortcomings of this approximation are discussed in the chapter by Eastman.

The central temperature in Models 4B and 7A near maximum light are $\gtrsim 2 \times 10^4$ K, and consequently the radiation field peaks in the ultraviolet where line absorption dominates the opacity (Eastman, this volume), and this has a marked effect on the light curve around maximum light. Figure 5 compares the bolometric light curves of Model 7A computed with KEPLER and with EDDINGTON. In the former, the radiation transport is computed using flux limited radiative diffusion assuming a single temperature for all components and an opacity only from free electrons. The inclusion of line opacity in the EDDINGTON calculation results in a decrease in the luminosity at maximum by ~ 40 percent. Most of the line opacity is due to the lowest three or four ionization stages of iron peak elements. Prior to maximum, when temperature and ionization are higher, electrons do provide most of the opacity and the two codes predict nearly identical luminosities. The decline rates on the tail are slightly different in the two calculations. EDDINGTON performs a deterministic γ-ray line transfer calculation for each γ-ray line of interest which is more accurate than the method employed in KEPLER, where the escape and deposition fractions are approximated with an exponential escape probability.

In 1988 Ensman and Woosley lamented the scarcity of reliable bolometric light curve data for Type Ib supernovae. Eight years later, the available bolometric light curves of Ib/c supernovae continues to be frustratingly sparse. There have been only two SN Ib/c in the last 12 years which were observed well enough during maximum light to derive a bolometric light curve, and these are SN 1983N (Panagia 1985; Blair & Panagia 1987) and SN 1994I (Schmidt & Kirshner 1994). The former was what is now commonly refered to as a Ib–it showed strong optical wavelength He I absorption features–while the latter is called a Ic, because the helium lines were weak, although present (Filippenko et al. 1995; Clocchiatti et al. 1996). The small amount of bolometric light curve makes it difficult to gauge the range of diversity allowed in the models.

As discussed earlier, one of the great uncertainties in models of Ib/c evolution is how far out the ^{56}Ni is mixed. These stars, lacking a hydrogen envelope, do not form strong reverse shocks, and the Rayleigh-Taylor instability is weak. The effect of outward ^{56}Ni mixing on the bolometric light curve is modest, but, as we shall see, has greater influence on the effective temperature and spectrum.

Figure 6 shows the effect of mixing and of varying the ^{56}Ni mass on the bolometric light curves (L_{bol}) of Models 4B and 7A, and compares these to SN 1983N and SN 1994I. For each supernova, the reddening is uncertain,

Figure 5. Comparison of bolometric light curves computed with KEPLER and with EDDINGTON. The difference in maximum light behavior is due to the inclusion of line opacity in the EDDINGTON calculation.

and, for 94I, the figure displays L_{bol} for three values of A_V: 0.6, 1.0 and 1.6. For 83N, Panagia (1985) took $A_V = 0.6$, but the possibility exists that it could be larger. It can be seen by comparison of the 1994I light curves for different A_V that the effect of underestimating the extinction is to make the light curve broader. If the extinction to 83N were larger than $A_V = 0.6$, L_{bol} will be narrower than shown. It should also be noted that the distance to M83, assumed by Blair & Panagia to be 4 Mpc, is uncertain, but likely to be in the range 3.3-4.9 Mpc.

As discussed earlier, mixing ^{56}Ni outward tends to make the light curve peak a little earlier because the diffusion to the surface, for some of the deposited energy, is quicker. This need not always be the case, however. Comparison of L_{bol} for the mixed and unmixed 4B with 0.087 $M_\odot$ ^{56}Ni in Fig. 6 shows that, in this case, the mixed model actually peaks later. This is because mixing the ^{56}Ni outward into the helium increases both the helium ionization and the electron scattering opacity, which slows the diffusion and causes the maximum in L_{bol} to occur later.

Both the mixed and unmixed bolometric light curves of Model 4B with $^{56}\mathrm{Ni} = 0.043\ M_\odot$ agree with the light curve of 94I if $A_V = 1.0$. However, 94I has been classed as Type Ic, whereas the maximum light spectrum of Model 4B (next section), especially for the mixed model, will show a strong

Figure 6. This figure shows the effect of mixing and of varying the ejected ^{56}Ni mass on the bolometric light curve of Model 4B (left panel), and on Model 7A (right panel), and compares them to the light curve of the SN Ib 1983N (Blair & Panagia 1987–long dash line and open circles), assuming $A_V = 0.5$ and D(M83) = 4 Mpc and to the Type Ic 1994I (Schmidt & Kirshner 1994–dotted line), assuming D(M51) = 7 Mpc and $A_V = 0.6$ (filled circles), 1.0 (filled triangles) and 1.4 (filled squares). Left: the 4B models (left panel) are for the unmixed (solid curve) and mixed (short dashed curve) compositions shown in Figures 3 and 7, and three ^{56}Ni masses of (from brightest to faintest): 0.087, 0.043 and 0.022 $M_\odot$. Right: the 7A models are for the unmixed (solid curve) and mixed (short dashed curve) compositions shown in Figs. 4 and 7, and three ^{56}Ni masses of (from brightest to faintest): 0.15, 0.074 and 0.037 $M_\odot$.

helium line characteristic of Type Ib. The bolometric light curve of the Type Ib SN 1983N was much broader than both SN 1994I and Model 4B.

The right panel of Fig. 6 shows the effect of mixing and ^{56}Ni mass on Model 7A, and also compares it with SN 1983N and SN 1994I. Model 7A has a larger ejected mass than Model 4B (0.91 $M_\odot$ versus 1.66 $M_\odot$) and a broader light curve. It is too broad in comparison with 94I, but the model with 0.074 $M_\odot$ of ^{56}Ni agrees well with 83N.

5. Spectra

To investigate the maximum light behavior of these models, a "snap shot" non-LTE spectrum calculation was performed with EDDINGTON. In these calculations, the temperature of the ejecta was taken from a time-dependent LTE calculation, and held fixed. A modified version of the comoving frame

Figure 7. Composition of mixed Model 4B (left) and of mixed Model 7A (right). The extent of the mixing was identical in both calculations, but in Model 7A the oxygen shell mass is larger, and so less ^{56}Ni was mixed into the helium layers than in Model 4B.

transport calculation was solved (Eastman & Pinto 1993; Eastman, Schmidt & Kirshner 1996) which approximated the time rate of change of the radiation field (in the gas frame) as being due entirely to expansion. The γ-ray deposition was computed with a Monte Carlo code, and ionization from non-thermal electrons approximated in the "continuous slowing down approximation" (Axelrod 1980). The atomic model included He I-II, C I-IV, O I-IV, Na I-II, Si I-IV, S I-IV, Ca I-IV, Fe I-IV and Co I-IV. The remaining ^{56}Ni was mapped into ^{56}Co.

5.1. TYPE IB – SN 1984L

The He I λ5876 transition which typifies Ib supernovae arises from the $1s2p\ ^3P^o$ state, which is 20.9 eV above the ground. At maximum light, the UBVR color temperature of SN 84L was $\sim 5500 - 6000$ K, which is inadequate to excite the $^3P^o$ state, either directly or by recombination cascade. The most likely mechanism for exciting the metastable triplet states of He I is through non-thermal excitation and ionization by non-thermal Compton electrons, and, in order for this to occur, there must be sufficient γ-ray flux in the helium. Model 4B had only 0.048 M$_\odot$ of oxygen, and so γ-rays from ^{56}Ni and ^{56}Co decay were able to penetrate into the helium

Figure 8. Comparison of mixed Model 4B with ^{56}Ni $= 0.074$ M$_\odot$, at $t = 15$ days after explosion (dotted curve), with spectrum of SN 1984L taken 2 Sep 1984 (solid curve). Note the strong He I lines which makes this a Type Ib.

layer, producing strong optical He I lines.

Figure 8 compares the mixed Model 4B spectrum with that of SN 1984L near maximum light. No parameters have been varied in this model in the sense of trying to obtain a best fit. Nonetheless the agreement with SN 1984L is quite good. The strongest line in both model and observed spectra is the He I λ5876 line, followed by lines of Fe II and Ca II.

The importance of the mixing is shown in Fig. 9, which compares the same maximum light spectrum as in Fig. 8 with a spectrum of the unmixed Model 4B at 15 days, both with 0.074 M$_\odot$ of ^{56}Ni. In the unmixed model, the optical photosphere, which is formed by electron scattering, is located further in where the helium mass fraction is smaller and oxygen mass fraction larger. The unmixed model has a higher effective temperature, but the helium lines are also much weaker. This is despite the fact that the

Figure 9. This figure shows the effect of mixing on the spectral appearance of Model 4B. In the unmixed model (solid curve), the photosphere is deeper in where the helium mass fraction is smaller and oxygen mass fraction larger, the effective temperature is higher, and the strength of the helium lines is substantially reduced.

$UBVR$ color temperature in the mixed model was ~ 7400 K, whereas in the unmixed model it was $\sim 13,000$ K.

5.2. TYPE IC – SN 1994I

Model 7A, with its larger ejected mass and larger oxygen shell mass, is spectroscopically similar to SN 1994I. The comparison is made in Fig. 10 for the mixed Model 7A with 0.074 $M_\odot$ of ^{56}Ni. The observations were corrected for an extinction of $E(B-V) = 0.2$. The agreement is not perfect, but similar enough to conclude that Model 7A is a viable representation of a weak helium line Type Ic object. Despite having 0.41 $M_\odot$ of helium, there are no strong optical helium lines. The electron scattering photosphere in this model forms at the base of helium layer, with free electrons provided by C and O. Although this model was mixed in exactly the same fashion as Model 4B, the larger oxygen shell mass (0.439 $M_\odot$ versus 0.048 $M_\odot$ for Model 4B) is enough to substantially attenuate the flux of γ-rays reaching the helium.

The maximum light spectrum of Model 7A does show a strong P-Cygni feature where He I 10830 Å would be expected, as did SN 1994I (Filippenko et al. 1995), and is due in part to He I, but interestingly, the blue edge of this feature is due to lines of the C I $2p3s\ 3P^o - 2p3p\ 3D$ multiplet, such as C I 10730 Å. Thus, the conclusion by Filippenko et al. (1995) that the He I 10830 Å line in 1994I extends to $29,900$ km s^{-1} is probably an overestimate. The identification of C I is confirmed by the presense of other C I features seen in both the maximum light spectrum of Model 7A (Fig. 10) and in spectra of 1994I during the first month (Fig. 1 of Filippenko et al. 1995). Clocchiatti et al. (1996) identified weak He I λ5876 in the spectrum of SN 1994I during the first month with a blue-shift velocity of $16,900$ km s^{-1}. We believe that X-rays produced in the circumstellar interaction region ionize the high velocity helium, and the He I $1s2p$ triplet states in this high velocity material are populated by recombination.

Mixing has a much smaller effect on Model 7A than it did on Model 4B. The 15 day spectrum of Model 7A, mixed and unmixed, are compared in Fig. 11. The unmixed model has a slightly higher effective temperature, but they are otherwise similar. This amount of mixing, which was the same amount applied to Model 4B, is inadequate for allowing the decay γ-rays to penetrate through the oxygen shell and into the helium at maximum light.

6. Discussion

The spectra and light curves of Type Ib and Ic supernova can be well fit by models derived from massive stars in which the envelope as well as an appreciable fraction of the helium core mass is lost before explosion. Desirable masses for common events are about 2.3 - 4.0 $M_\odot$. The mass may be lost either as a sequence of winds, especially mass dependent mass loss during the wolf-rayet stage, or to a binary companion or both. It seems most of the common events should occur in binaries, though an appreciable fraction of Type Ib supernovae may still come from single massive stars. It is anticipated that they would have appreciably different properties, or it may be that they fail to explode.

What is particularly new to the present work, beyond what was already discussed in WLW1 and WLW2 is a) the calculation of spectra in good agreement with both typical Type Ia and Ib supernova observations and b) the realization that these spectra are a very sensitive diagnostic of mixing in the model. Stars that have less mixing or a thicker layer of oxygen

Figure 10. Comparison of mixed Model 7A, with ^{56}Ni = 0.074 M$_\odot$, at $t = 15$ days after explosion (dotted curve), with the MMT spectrum of SN 1994I taken 7 Apr 1994 (solid curve) by Kirshner. Note in this case the lack of strong optical He I lines. There is strong He I λ10830, as was found for 94I, but is is also blended with strong C I.

and intermediate mass elements between the radioactive ^{56}Co and helium after the explosion will have weaker helium lines. The distinction between Type Ib and Ic may then be more a distinction of these factors than of the absolute helium abundance. A star with a larger helium abundance than a successful Type Ib model that mixes less or has a larger oxygen layer may exhibit weaker helium lines and be classified as Type Ic.

We have not yet investigated the spectral appearance of Models 4B and 7A at times later than maximum light. One might worry about the possibility that at later times, as the ejecta becomes transparent to γ-rays, that optical helium lines will appear, in contradiction to the behavior observed, for instance, in SN 1987M and SN 1994I. In the model studied by Swartz et al. (1993), this was found to be the case when $M(\mathrm{He}) \gtrsim 0.15$ M$_\odot$. However,

Figure 11. This figure shows the effect of mixing on the spectral appearance of Model 7B. The unmixed model (solid curve) has a slightly higher effective temperature, but they are otherwise similar. This amount of mixing, which was the same amount applied to Model 4B, is inadequate for allowing the decay γ-rays to penetrate through the oxygen shell and into the helium at maximum light.

in their model, the radioactive ^{56}Ni moved with a velocity $v \lesssim 3000$ km s^{-1}, while the helium was in the velocity range 3700 km s$^{-1} \lesssim v \lesssim 17,000$ km s^{-1}. This is important, because the relevant quantity is not so much the helium mass or abundance, as the helium column density times the γ-ray flux. The reason is because the population of He I $1s2s$ and $1s2p$ is proportional to the excitation rate, which is proportional to the γ-ray flux. If helium is moving at a characteristic velocity v(He), then the γ-ray flux is proportional to $M(^{56}\mathrm{Ni})/v(\mathrm{He})^2$. Likewise, the helium column density is proportional to M(He)/v(He)**2, so the optical depth in optical helium lines is proportional to $M(^{56}\mathrm{Ni})M(\mathrm{He})/v(\mathrm{He})^4$. The model studied by Swartz et al. had slow moving helium, which led them therefore to conclude that

$M(\mathrm{He}) \gtrsim 0.15\ \mathrm{M}_\odot$. In Model 7A, the inner edge of the helium is moving at a much greater velocity of $8,000\ \mathrm{km\ s}^{-1}$. Partly this is due to differences in ejected mass (2.10 $\mathrm{M}_\odot$ versus 1.66 $\mathrm{M}_\odot$ for Model 7A), but also it is a consequence of the different core structure obtained when evolved self-consistently with mass loss.

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