On the presence of Silicon and Carbon in the pre-maximum spectrum of the Type Ia SN 1990N

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ABSTRACT

The spectrum of the normal Type Ia SN 1990N observed very early on (14 days before \( B \) maximum) was analysed by Fisher et al. (1997), who showed that the large width and the unusual profile of the strong line near 6000Å can be reproduced if the line is assumed to be due to \( \text{C} \ II \) 6578, 6583Å and if Carbon is located in a high velocity shell. This line is one of the characterising features of SNe Ia, and is usually thought to be due to \( \text{Si} \ II \). A Monte Carlo spectrum synthesis code was used to investigate this suggestion further. The result is that if a standard explosion model is used the mass enclosed in the shell at the required high velocity (25,000–35,000 km s\(^{-1}\)) is too small to give rise to a strong \( \text{C} \ II \) line. At the same time, removing Silicon has a negative effect on the synthetic spectrum at other wavelengths, and removing Carbon from the lower velocity regions near the photosphere makes it difficult to reproduce two weak lines which are naturally explained as \( \text{C} \ II \), one of them being the line which Fisher et al. (1997) suggested is responsible for the strong 6000Å feature. However, synthetic spectra confirm that although \( \text{Si} \ II \) can reproduce most of the observed 6000Å line, the red wing of the line extends too far to be compatible with a \( \text{Si} \ II \) origin, and that the flat bottom of the line is also not easy to reproduce. The best fit is obtained for a normal SN Ia abundance mix at velocities near the photosphere (15,500-19,000 km s\(^{-1}\)) and an outer Carbon-Silicon shell beyond 20,000 km s\(^{-1}\). This suggests that mixing is not complete in the outer ejecta of a SN Ia. Observations at even earlier epochs might reveal to what extent a Carbon shell is unmixed.

Subject headings: supernovae: general – supernovae: SN 1990N – line: identification – line: formation – line: profiles
1. Introduction

The distinguishing spectral feature of SNe Ia is the Si $\text{II}$ 6347, 6371Å line. This line is strong in all photospheric-epoch spectra of SNe Ia, appearing near 6000Å from before maximum to at least one month after maximum. Its strength suggested that a large fraction of the material ejected in a SN Ia explosion is in the form of Si and other so-called 'Intermediate Mass Elements' (i.e. between CO and the Fe-group). These elements (mostly Si, S, and Ca) are synthesised in regions where thermonuclear burning of the progenitor Carbon-Oxygen white dwarf (WD) is incomplete, not leading to the production of $^{56}\text{Ni}$ (Nomoto et al. 1984). Since this is only possible if the burning wave that disrupts the WD is subsonic (aka a deflagration wave), the identification of this line was an important step in understanding that burning must must proceed subsonically in a significant fraction of the WD. Explosion models based on this assumption could successfully reproduce the light curve and spectra of SNe Ia starting from a Chandrasekhar mass CO WD (e.g. the deflagration model W7, Nomoto et al. 1984, Branch et al. 1985; or various delayed detonation and pulsational deflagration models presented by Woosley & Weaver (1994) and Woosley (1997).

Fisher et al. (1997) (hereafter FBNB) re-analysed the earliest spectrum ever recorded of a SN Ia, that of SN 1990N on 26 June 1990, which is as early as 14 days before maximum $B$ light (Leibundgut et al. 1991). Using a simple but powerful parametrised LTE code, FBNB reproduced the UV-optical spectrum satisfactorily, but noticed that the broad and flat-bottomed profile of the 'Si $\text{II}$' line, observed near 6040Å, could not be reproduced using Si and an exponential radial dependence of the line optical depth. Other authors (Jeffery et al. 1992, Mazzali et al. 1993) encountered essentially the same problem, even though they used more sophisticated codes. As an alternative solution, FBNB showed that the line profile could be successfully modelled by a high velocity Carbon shell ($26,000 \leq v \leq 35,000$ km/s).
km s$^{-1}$). This proposed alternative identification is not in contradiction with the basic properties of successful explosion models, which usually have a layer of unburned progenitor material (CO in this case) at the top of the ejecta and hence expanding at the highest velocities. Such a layer would be most easily detectable for its effect on the spectrum when it is not yet very far removed from the momentary and receding photosphere, and therefore it is natural to expect that the very early spectrum of the normal SN Ia 1990N would be one of the best places to find evidence for it.

This suggestion has very interesting consequences, both because it sets some limit to the mixing taking place in the highest velocity part of the ejecta and because it points out a possible source of error in measures of very early spectra of SNe Ia, especially if the spectra are of poorer quality than that of SN 1990N, a typical situation for SNe at high redshift.

Independently of FBNB, we have been modelling the same UV-optical spectrum of SN 1990N in an effort to determine its epoch as accurately as possible so as to set some limits on the rise time to maximum, in view of the current debate about this parameter (Mazzali & Schmidt 2000, in prep.). We have used a Monte Carlo (MC) code based on that described in Mazzali & Lucy (1993), but modified to include an extended line list and photon branching (Lucy 1999, Mazzali 2000). Although we were trying to obtain a good overall fit of the spectrum, and did not pay much attention to small features, we noticed that in just about every synthetic spectrum we computed two rather weak features were always well reproduced as C II lines: a small absorption near 6350Å, which is attributed to C II 6578, 6583Å, and the absorption near 6900Å, attributed to C II 7231, 7236Å with a contribution from O II 7321Å to make the feature relatively broad. The strong absorption line near 6040Å was matched by the Si II line, but the line profile was not reproduced correctly, as in all previous work. In all models the abundances were homogeneous above the photosphere. The model we finally selected had an epoch $t = 5$ days (implying
$t(\text{Max}) = 19$ days), distance modulus $\mu = 32.00$ mag, luminosity $L = 2.30 \cdot 10^{42}$ erg and photospheric velocity $v_{\text{ph}} = 15750$ km s$^{-1}$. The synthetic spectrum is shown as the thin continuous line in Fig. 1. The velocity indicated by the two weak features in the red, if they are interpreted as C II lines, is about 12000 km s$^{-1}$, which is somewhat smaller than $v_{\text{ph}}$. In fact the synthetic C II lines, especially that at 6350Å, fall at a somewhat shorter wavelength than the observed ones. Nevertheless, the coincidence was striking.

Thus we turned our attention to the FBNB paper. FBNB show fits to the entire spectrum using different compositions in their Fig.1, which was unfortunately printed too small to verify whether the two small features discussed above are reproduced as C II. Nevertheless, in their Fig.2, where they show two different ways to reproduce the 6040Å feature - using Si and C, respectively, it is clear that neither the 6350Å feature nor the one at 6900Å are reproduced with the ‘high velocity C shell’ model. On the contrary, while in that model the C II 6578, 6583Å doublet gives rise to the strong and flat-bottomed 6040Å absorption, a weaker, broad and also flat-bottomed absorption is also visible near 6500Å, which is not present in the observed spectrum. This is exactly where the C II 7321, 7236Å doublet would fall if Carbon were located in a shell between 26,000 and 35,000 km s$^{-1}$. The ratio of the equivalent widths of the two features is large, with a value of at least 10, which is larger than the observed ratio but may result from the assumption of LTE since the redder doublet comes from a more highly excited level (16.33 v. 14.45 eV). We therefore considered it worthwhile to tackle once more the problem of what might give rise to the observed 6040Å line using synthetic spectra. In the next sections we discuss various alternatives.
2. Can Carbon replace Silicon?

We have shown that a fully mixed model reproduces two weak C II features, and gives a less-than-satisfactory fit of the 6040Å feature as Si II. If we are to explain this feature as due to C II instead, the first necessary step is to remove Silicon from the mixture (as FBNB did in the central panel of their Fig.1) and ascertain what influence this has on the synthetic spectrum. In Fig.1 we show two models obtained for a homogeneous composition: the dashed line is for a full W7 composition mix, including both Si and C, as discussed in the previous section. The peak at 3500Å, which is not reproduced by our synthetic spectrum, is in the MMT data. Since the calibration at the edge of the spectrum is tricky, the poor fit at this wavelength does not necessarily mean that the model is wrong.

The dotted line in Fig.1 is a model where Silicon has been removed and its abundance (0.2 by mass) is assigned to Carbon instead. In this model both C II lines, but especially the 6580Å one, are too strong, and are not compatible with the observations. Removing Si, and not placing C in a high velocity shell, clearly destroys the fit of the 6040Å feature. Furthermore, removing Si has negative consequences elsewhere in the spectrum, which cannot be remedied by introducing C at high velocities: 1) the weak Si III 4553, 4568Å line, observed near 4400Å, a typical feature of all but the coolest SNe Ia before and near maximum, is now lost; 2) the strong absorption near 4800Å has about equal contributions from Si II 5041, 5056Å (falling near 4750Å) and Fe III 5156 + Fe II 5169 Å (falling near 4850Å) in the spectrum obtained for a W7 mix: when Si is removed, only the red part of the absorption is left, and this absorption is too weak to cause a strong re-emission peak, which is observed near 5100Å; 3) the shape of the spectrum near 5500Å is influenced mostly by Si III 5740Å (near 5425Å) and Si II 5979Å (near 5600Å), although the broader absorption extending to 5200Å is due to several lines of S II. When Si is removed from the mixture, only the S II lines are left and the absorption in the model is too far to the blue. These
three points show clearly that Silicon cannot be completely removed from the relatively high velocity regions near the photosphere. But if Si is allowed in the mix, then the doublet 6347, 6371 Å is the strongest Si line. Therefore, it appears unavoidable to conclude that Si II contributes significantly to the 6040 Å feature even at this early epoch.

3. A Carbon-shell model?

FBNB could fit the 6040 Å feature placing Carbon at high velocity, but since they used a parametrised model they did not quantify the mass of C required to obtain such a strong synthetic line. Since the C II lines are weak even in a fully mixed model, this is an interesting numerical experiment. The model shown as a dotted line in Fig.1, where Si had been replaced by C, had a Carbon abundance of 0.25 by mass. Since the total mass above the photosphere in this model is 0.072M⊙, the C mass was 0.018M⊙, and the strength of the C II 6578, 6583 Å line was comparable to that of the observed 6040 Å feature, but the velocity was wrong. The velocity can be reconciled if C is enhanced only for velocities larger than v_{sh} = 26000 km s^{-1}, as FBNB suggested. In our next synthetic spectrum we replaced Si with C only above this velocity, while between v_{ph} and v_{sh} we just redistributed the Si abundance among all elements, proportionally to their respective abundances (the composition is dominated by Oxygen). Because of the steeply falling density (\rho \propto r^{-7}), when C is confined to very high velocities its mass is reduced. This reduces the C mass to only 10^{-3}M⊙. The result is shown in Fig.2 (thin continuous line): both C II lines are so weak that they do not produce a noticeable feature in the spectrum. This calculation reproduces all essential features of the FBNB ‘high velocity C shell’ model, and at the same time is consistent with the hydrodynamical model of a SN Ia: the result is that not only the synthetic spectrum does not reproduce the strong 6040 Å feature, but the absence of Si creates the three problems listed in Sect.2, and the displacement of C in velocity space...
means that the two weak features which are attributed to C II are not reproduced either.

Obviously, it must be possible to fit the 6040Å feature as C II by increasing the C II line opacity in the high velocity shells. We show this as the dashed line in Fig.2. The values by which we had to multiply the Sobolev optical depth to obtain this spectrum are an increasing function of velocity, ranging from 10 at 22500 km s\(^{-1}\) to 10\(^6\) at 30000 km s\(^{-1}\), the outer limit of the assumed ejecta distribution. Although these values do give a very good fit to the observed feature, they really have no physical basis. If the increased optical depth is attributed to the number of absorbing C II ions, this would lead to a completely unrealistic C mass, more than 1M\(_\odot\), at these large velocities. Furthermore, all the problems raised by the absence of Si remain, and the two small features are not fitted at all.

It is interesting to note that although we increased the optical depth for all C II lines, we obtained a strong 6578, 6583Å line, but not a strong 7231, 7236Å line. This is because the latter doublet comes from a more highly excited level, whose population falls more steeply with radius, and so even larger factors would be required to enhance the line at very high velocities.

This test confirms that the 6040Å feature must be at least predominantly due to Si II, and that placing Carbon in a high velocity shell does not give sufficient opacity, even if C dominates the composition.

4. A Silicon model?

We believe we have provided ample evidence that the 6040Å feature cannot be entirely - or even mostly - due to C II lines. As an alternative solution, can the distribution of Silicon be modified so that a better fit to the line can be obtained? If we look back at Fig.1 we notice that the profile of the Si II 6347, 6371Å line is too sharp, and that
absorption is missing both in the blue (between 5800 and 5900Å) and in the red (between 6100 and 6200Å). These regions correspond to Si velocities of about 23000 and 10000 km/s, respectively. Therefore, we can expect that we can produce more blue absorption by increasing Si at high velocity, but the velocity required to fit the red part of the absorption is significantly smaller than that of the photosphere.

In Fig. 3 we show a model where the Si abundance has been increased by a factor of 3 above 23000 km s\(^{-1}\), at the expense of all other elements. This gives a reasonably good fit to the blue side of the line. Other Si \textsc{ii} lines are weaker, so they are not much affected by this change, and the rest of the spectrum is not very different from that of Fig. 1. As regards the red part of the line though, setting the photospheric velocity at 15750 km s\(^{-1}\), imposes the constraint that the reddest wavelength of Si \textsc{ii} is about 6050Å. The velocity of the photosphere cannot be reduced to about 10000 km s\(^{-1}\) without changing the aspect of the synthetic spectrum completely (see Mazzali & Schmidt 2000, in prep.). Therefore we agree with FBNB that Si alone is unable to explain the observed width and profile of the 6040Å feature.

5. A possible solution: Silicon and Carbon

On the basis of the models presented above we suggest that Si is responsible for most of the 6040Å feature in SN 1990N, and in particular for its extended blue side, but an alternative origin must be found for the red part of the line. At the same time, we have shown that the small feature near 6300Å is most likely due to C \textsc{ii} at a near-photospheric velocity. Our line list, which was derived from that of Kurucz & Bell (1995) does not seem to offer any reasonably strong line with a rest wavelength of about 6450Å, which would naturally explain the red extension of the 6040Å feature by redshifting at the velocity of the photosphere. The nearest strong lines to the red of the Si \textsc{ii} doublet are indeed the
C II ones. A Carbon shell centred at about 20000 km s\(^{-1}\) might explain the observations. The questions are can C be responsible for both the small absorption at 6300 Å (via its near-photospheric distribution) and the red wing at \(\sim\) 6100 Å (via an enhanced C abundance at \(v \sim 20000\) km s\(^{-1}\)), and if so is the required C enhancement compatible with the hydrodynamical structure of a SN Ia?

The answer is shown in Fig. 4. This is a model computed with the same parameters as the previous ones and the following distributions: Carbon: 0.05 by mass up to \(v = 18500\) km s\(^{-1}\), then increasing smoothly and reaching a peak value 0.50 above \(v = 21500\) km s\(^{-1}\); Silicon: 0.20 by mass up to \(v = 21500\) km s\(^{-1}\), and then increasing to 0.5 above \(v = 22500\) km s\(^{-1}\). The integration is limited to an outer velocity of 30000 km s\(^{-1}\).

The model reproduces the observed profile reasonably well. The observed flat bottom of the line may require more ad hoc adjustments of the distribution of the elements. The ‘average’ positions of the near-photospheric and of the high velocity components of the synthetic C II 6578, 6583 Å absorption are marked in Fig. 4. The near-photospheric component falls at a longer wavelength than the the observed 6300 Å feature. The difference in velocity is about 3600 km s\(^{-1}\). If the adopted photospheric velocity is correct, this offset is a puzzle. We have no alternative identification other than C II to offer for that feature, since our line list offers only very weak Ti II lines with rest wavelength of about 6700 Å. But even if the 6300 Å feature is not C II, our conclusion regarding the origin of the 6040 Å feature does not change.

The scenario we are faced with is then the following: a mixed W7 composition (C=0.05 and Si=0.20 by mass, respectively) holds out to \(v \sim 19000\) k.ms, but outside that velocity a C-Si shell develops. The near-photospheric C abundance may be lower if the line at 6300 Å is not C II. With the exception of the Si shell, this is consistent with incomplete mixing in the SN ejecta. Maybe S II lines are responsible for the extra absorption between 5800 and
5900Å, but our line data do not support that.

6. Conclusions

We have shown that the strong and broad absorption near 6040Å in the d -14 spectrum of SN 1990N must be predominantly due to Si ii 6347, 6371Å. If we reproduce the line as C ii, eliminating Si from the mixture as suggested by FBNB, other regions of the spectrum where Si lines are strong are not well reproduced. Also, the mass enclosed in the high velocity shell which could give rise to a blueshifted C ii line is very small, so that the synthetic line is much too weak, and the observed profile can only be reproduced if the optical depth of the C ii lines is increased by unrealistic factors (up to $10^6$). On the other hand, we have confirmed the result of FBNB that Si ii alone cannot reproduce the entire feature because the red edge of the line has a blueshift much smaller than that of the Si ii line at the velocity of the momentary photosphere.

As a possible contribution for that part of the feature we also suggest C ii in a high velocity shell, but unlike FBNB we enhance C in a shell between 19000 and 30000km s$^{-1}$, which contains a small (0.04M$_\odot$), but nevertheless large enough mass to give rise to a rather strong line without resorting to artificially large departure coefficients to increase the line optical depth. The increased C abundance in this outer shell does not significantly affect the total mass of C in the ejecta. At the same time, mixed C at near-photospheric velocities gives rise to two weak synthetic absorptions at 6250 and 6900Å, which are a reasonable match for two observed features at 6300 and 6900Å. The blending of the Si ii and C ii lines may give rise to the flat bottom of the observed 6040Å feature, although our model does not reproduce that.

The implications of our result are that an outer zone where Carbon is not fully mixed
does indeed appear to exist. This zone is narrow, and contains only a small mass, so the photosphere passes through it rapidly. Our models suggest that Si is also present there. Therefore, observing a SN Ia very early on, when the photosphere is still at $v \sim 20000\text{km s}^{-1}$, would be very interesting. If both Si and C are present at high velocities, we do not expect that the feature should appear very different from what is observed in the spectrum of SN 1990N we have analysed in this paper. Alternatively, if only C were present, the ‘Si II’ absorption would be much redder ($\lambda \sim 6150\text{Å}$) and caused mostly by C II. This would require observations very soon after the explosion, roughly 16 days before maximum, which this may not be so very difficult with SNe at high redshift, whose observed evolution is slowed down by the factor $(1 + z)$. Such observations would be extremely interesting because they would probe the outermost part of the ejecta and could thus clarify by direct observation to what extent mixing actually takes place. Finally, our findings must serve as a caveat against deriving SN Ia properties from the ‘Si II’ line if the SN is observed very early on.

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Fig. 1.— The −14d UV-optical spectrum of SN 1990N (thick solid line) is compared to: a) a synthetic spectrum computed with a W7-mixed composition (thin solid line), which reproduces the overall spectrum, including several Si II and Si III features. The Si II 6347, 6371Å line is too narrow, and two C II lines are seen: one, near 6250Å, may be compatible with the feature at 6300Å, while the other is a good match for the line at 6900Å; b) a synthetic spectrum where Si has been replaced by C throughout the envelope (dotted line). The C II lines (especially the one at 6250Å) are too strong, while many Si features are missing.
Fig. 2.— The −14d UV-optical spectrum of SN 1990N (thick solid line) is compared to: a) a synthetic spectrum where Si is eliminated, but it is replaced by C only at $v \geq 26000\,\text{km}\,\text{s}^{-1}$, in analogy with FBNB (thin solid line). The C II lines are too weak to leave a signature in the synthetic spectrum; b) a synthetic spectrum similar to the one above, but with artificially increased C II line opacities. This fits the 6040Å line, but fails to reproduce other Si II and Si III lines and the two weak lines at 6300 and 6900Å.
Fig. 3.— The −14d UV-optical spectrum of SN 1990N (thick solid line) and a synthetic spectrum computed for an increased Si abundance above 23000 km s\(^{-1}\) (thin solid line). This reproduces the blue side of the 6040 Å line, but not the red side.
Fig. 4.— The $-14$d UV-optical spectrum of SN 1990N (thick solid line) and a synthetic spectrum computed with increased Si and C abundances above about 20000 km s$^{-1}$ (see text for details). This reproduces most observed features, including the broad 6040Å line and the two weak C II lines, although the near-photospheric component of the 6578, 6583Å line does not match the wavelength of the observed 6300Å absorption.