THE OPTICAL RADIATION OF SUPERNOVAE

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1. Introduction

Most of our knowledge of supernovae comes from studies of their optical radiation. Very high quality optical spectra have been available for several years now. The new data have aided the development of theoretical models of supernova explosions, particularly Type I events, which until recently, were very poorly understood. Type II explosions, which are believed to arise from core collapse in massive stars (Woosley, this volume), produce optical spectra which can be simply interpreted in terms of a nearly blackbody continuum with prominent lines of hydrogen superimposed. The Type II atmosphere is of near solar composition, expanding at a characteristic velocity of 5000 km/s and at least bears some resemblance to a more familiar stellar atmosphere. Type I supernovae produce a much more violent expansion and the optical spectrum cannot be so easily accounted for. The progress made in the last few years stems mostly from the work of David Branch (Branch 1980,1984; Branch et. al. 1982,1983,1985). His synthetic spectra for Type I's showed that the spectrum can be explained in terms of the resonance lines of mostly singly ionised metals. The lines are formed in matter moving with a bulk velocity of about 11,000 km/s and at a characteristic temperature of approximately 10,000 K. Furthermore, Branch concluded that the density profile in this region should be relatively steep and that the matter was very deficient in hydrogen and helium. As we shall see, this description fits very well with the hypothesis that Type I supernovae originate in the incineration of white dwarfs. Following the focus of recent developments this discussion will be mainly limited to the early evolution of Type I models of this kind, although many of the important features of the radiation transport are directly relevant to Type II explosions.

2. Observational Considerations

A considerable amount can be learned from just the optical light curves of supernovae. The light curve provides some indication of the classification of the supernova. In general, Type IIs are characterised by their

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irregularity, but (normal) Type I light curves are highly uniform in their development. Although there is some degree of spread in the post-maximum decline rate (i.e. "fast" vs "slow", Branch 1982) the shape of Type I light curves is very similar. The similarity between different Type I events at the same stage in their evolution also extends to the spectra and it is here that the new digital data have allowed the direct comparison of individual Type I supernovae. The spectra are indeed very similar, both quantitatively as well as qualitatively and this fact has encouraged the feeling that Type I supernovae may be considered as standard candles (Cadonau et. al. 1985), with far reaching implications for the determination of the extragalactic distance scale. The new data (Wheeler 1985a) also show that there are small differences between some SN I. Owing to the considerable impact that Space Telescope observations of SN I could have for cosmological models, it has become vital to understand in detail the spectral evolution of these explosions. Distance determinations based on the Baade-Wesselink method have led to a large scatter in derived values of the Hubble constant, and although there are more model dependent means of using SN I as distance indicators (Arnett et. al. 1985), the simplicity of the Baade-Wesselink method makes it more attractive. However, before we can have much confidence in distances derived, the discrepancies must be resolved and "model atmospheres" for Type I supernovae may hold the key.

Consistent coverage of several supernovae is required for detailed comparisons. A good example is shown in Fig. 1. These observations of the Type I supernova 1981b were obtained by a collaborative effort of several persons at McDonald Observatory (Branch et. al. 1982, 1983) and display the kind of resolution, wavelength coverage and sampling frequency which is ideal. SN 1981b was a good example of a "normal" Type I event and as such has been the prototype for comparison with several theoretical attempts to model Type I supernova radiation output. The maximum light spectrum is a composite made up from observations over four nights. This is the best maximum light spectrum available for a Type I for which IUE coverage was also available (Benvenuti et. al. 1982). The absorption feature at 3200 Angstroms (see also Fig. 2) is generally believed to be due to a number of overlapping Co II lines. If this conclusion is supported by atmosphere models and near ultraviolet observations of other Type Is, it would add strong support to radioactive decay model of Type I supernovae. Unfortunately, it is extremely difficult to obtain reliable data at this wavelength due to the atmospheric cutoff and the spectra at later times do not extend so far to the blue. As the spectrum evolves, the near infrared feature due to Ca II becomes very strong and the general shift of the lines to longer wavelengths is apparent. This effective "deceleration"

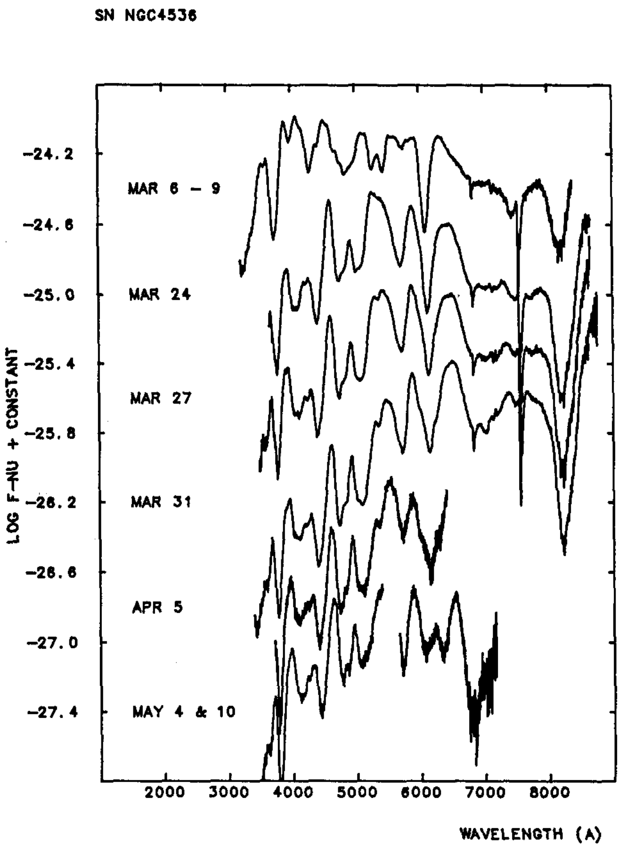

Fig. 1. McDonald Observatory spectra of the Type I supernova 1981b in NGC 4536. Maximum light occurred around March 7th. Two weeks later the spectrum has changed significantly as the supernova approaches the break in the light curve before entering the final steady exponential decline phase.

is due to the "photosphere" receding in the co-moving frame (although the photospheric radius continues to increase for more than 10 days after maximum light, Branch et. al. 1983) and hence lower velocity matter is exposed with time. In this sense, a series of spectra act as a probe of the chemical composition as a function of ejection velocity. The spectrum changes rapidly in the two weeks following maximum but thereafter changes relatively slowly. Over the last few years considerable progress has been made in interpreting the spectra of Type I's and it is now possible to make detailed models which can account for many of the observed features. The main conclusion is that a Type I supernova is due to the deflagration of a carbon/oxygen white dwarf near its Chandrasekhar limit. The dwarf is totally disrupted with up to one solar mass of matter being burned to radioactive Ni^{56} which subsequently decays to cobalt and finally iron. The latter decay provides the energy source for the (long known) "exponential tail" of the Type I light curve. The gradual change in the spectrum can be understood in the context of the deflagration model as the "photosphere" recedes first through the partially burned matter consisting of O-Ca, then through an intermediate stage consisting of a mixture of these elements with a large fraction of iron group elements and finally into the central region where the composition is essentially all iron, cobalt and nickel. Axelrod (1980) has demonstrated that the late time spectra can be accounted for in terms of permitted and forbidden emission lines of iron, with a small contribution from Co III. Until recently this was the principal evidence for the radioactive decay model. The recent detection of a large mass of iron (between 0.1 and 0.8 solar masses) in the ejecta of the supernova 1983n by Graham et. al. (1985) using infrared techniques adds credibility to the "standard model". However, SN 1983n was a "peculiar" Type I event, and furthermore, it is by no means certain that the iron mass is the result of the radioactive decay of Ni^{56}.

3. General Properties of SN I Atmospheres

The high expansion velocities in Type Is make them a particularly attractive problem in radiation hydrodynamics. The range of physical conditions found in these explosions are quite distinct from those encountered in, for example, the winds of hot massive stars or most other areas of conventional stellar atmosphere modelling. The major differences can be summarised as follows:-

(1) The density profile $\rho(r)$ resulting from the initial explosion becomes "frozen in" after just a few minutes as the matter expands and pressure gradients drop to zero. For the white dwarf deflagration this profile is characterised as an increasingly steep function of radius (or mass fraction), typically $\rho \propto r^{-m}$ with $m < 5$ for the inner 0.8M and $5 < m < 10$ for the outer 0.2M. Although this may be considered steep in comparison with $\rho \propto r^{-2}$ in a steady state wind, such a profile has considerable extension and spherical geometry is required. The radius of unit optical depth can be very frequency dependent, so the term "photosphere" becomes somewhat ambiguous. Unless stated otherwise we shall take "photosphere" to mean the radius at which the co-moving electron scattering optical depth is 2/3.

(2) The velocity profile v(r) rapidly tends to a homologous expansion. The initial configuration has a radius $\approx 3 \times 10^8$ cm, which is negligible in comparison with the maximum light "photospheric" radius $\sim 10^{15}$ cm and $v \approx rt$ to a very good approximation. It is important to note the obvious point that

v=0 only at r=0 and that the velocity field and gradient exist also in the optically thick matter. The dominant transport mechanism for the radiation in this region is advection, not diffusion. The matter visible near maximum light certainly has velocities greater than 10,000 km/s. There is presumably some small mass fraction with velocities much greater than this. For these reasons the radiative transfer problem is most easily solved in the "co-moving frame" approach, using the exact special relativistic radiative transfer equation in spherical geometry (Mihalas 1980). This has the particular advantage that all the opacity calculations can be carried out in the normal manner and there are no inherent difficulties defining "expansion opacities". Of course, the price one pays for this is that a separate calculation is necessary to transform the co-moving radiation field to the stationary (observer's) frame. Both the co-moving and observer frame solutions are computationally intensive. Fortunately, the co-moving problem is highly parallel and computationally tractable on a vector processor (and in fact can also be multi-tasked on a multiple vector processor system such as the Cray X-MP/48).

(3) The elemental abundances can be strongly dependent upon radius (see, for example Nomoto et. al. 1984, figure 7a). As the deflagration dies out progressively lighter α-chain nuclei are produced, leading to a systematic stratification of elements. Within a certain radius the composition is essentially determined by nuclear statistical equilibrium (i.e. it is mainly Ni^{56}). Usually the burning front dies out leaving a region near the surface where the composition is determined by the (presumed) accretion process, typically almost pure carbon and oxygen. There is effectively no observational evidence for the presence of either hydrogen or helium. Thus, a Type I atmosphere is composed <u>entirely of metals</u>.

(4) The small initial radius and rapid expansion lead to large adiabatic losses and a Type I would be a dull event if it were not for the heating due to the radioactive decay of Ni^{56} synthesised in the explosion. The Ni^{56} decays to Co^{56} with a half life of 6.1 days and the Co^{56} subsequently decays to Fe^{56} with a half-life of 78.8 days. The initial nickel decay powers the supernova through maximum light, while the cobalt decay is thought to be responsible for the long exponential decline phase of the light curve after 30-40 days. Both decays produce gamma rays and positrons, which are initially locally deposited in the ejecta, and presumably degraded to thermal energies. As the supernova expands, however, it becomes increasingly transparent to the gamma radiation and energy is deposited non-locally with an increasing fraction escaping completely. The positrons can remain trapped until much

later times and are an important energy source for the nebular phase up to hundreds of days. The initial thermal energy of the explosion is rapidly disspated and after a matter of hours the supernova is powered by an extremely non-thermal energy source comprising of about 20 discrete gamma ray lines of 2-3 Mev. This is a major problem for atmosphere models if the gamma radiation cannot be thermalised at a significant optical depth. Near maximum light the electron scattering optical depth to the centre of the supernova may be less than 20. Thus, the "supernova atmosphere" is actually a model of the entire star. The fact that the radioactive matter is somewhat confined in radius eases the situation slightly, but as we shall see, there must not be substantial energy deposition above the electron scattering photosphere, or else it would be difficult to account for the low state of ionisation apparent near maximum light. Examination of the frequency dependence of the opacity due to iron, cobalt and nickel at energies above 1 Kev suggests a plausible explanation. A 2 Mev gamma ray will most probably suffer a Compton scattering, losing on average more than 50% of its initial energy to an electron. The scattered gamma ray has a greater probability of suffering a second Compton scattering, again losing perhaps half of its energy because the cross section increases with decreasing frequency. After a few scatterings the gamma ray energy is reduced to a value at which the most likely interaction is now a photoionisation of iron, cobalt or nickel. Since the photoionisation cross sections go roughly as ν^{-3}, it becomes increasingly unlikely that the gamma ray will escape. The Compton electrons can travel some distance, causing extensive ionisation, but at early times the density should be sufficiently high to ensure rapid thermalisation. The very large opacity of the "all metals" plasma in the extreme ultraviolet may thus provide a means of trapping the decay energy at least until maximum light, with at least a reasonable chance that the radiation field may be Planckian at moderate electron scattering optical depth. As the gamma radiation escapes and the supernova moves into a more nebular stage, the physics becomes more complex and equilibrium processes are an increasingly poor approximation.

The combination of these features implies that the supernova atmosphere cannot be characterised by any choice of simple parameters (e.g. luminosity, effective temperature etc.). The atmosphere calculation is therefore highly dependent upon the precise details of the explosion model. However, comparison with observed spectra can place some restrictions on permissible configurations.

4. Simple Models

Before considering more realistic atmospheres derived from explosion models it is worth considering simple cases such as atmospheres with power-law density profiles or fully mixed chemical composition. It is much easier to disentangle the various physical influences by comparing closely related models. For example, the effects of varying the ratio of scattering to pure absorption can be determined. The continuum slope is quite dependent upon this ratio because it determines the radius at which the radiation field is thermalised and hence the characteristic temperature. This is clearly of some significance to the application of the Baade-Wesselink method in which the effective (colour) temperature must be estimated and represents a problem for distance determinations using either class of supernova (Harkness 1985). The effects of atmospheric extension must be taken into account also. Atmospheric extension results in a flatter continuum than would be expected from a plane-parallel atmosphere at the same characteristic temperature. In the Baade-Wesselink method, this would result in an under-estimate of the luminosity and hence distance.

Figure 2 shows the emergent flux from a radiative equilibrium, LTE atmosphere with the Nomoto et. al. (1984) W7 model density profile, but in which the metal abundances were taken to have solar ratios and the matter was assumed to be fully mixed. The cobalt abundance was adjusted to obtain a reasonable "fit" to the presumed 3200Å feature in the SN 1981b maximum light spectrum. The "photospheric" radius, velocity and temperature were chosen to be in accord with Branch's best estimates (i.e. 11,000 km/s and 10,000K , Branch et. al. 1982). This model demonstrates a number of interesting facts. Firstly, there cannot be a large amount of "invisible" helium present; the abundances are absolute so any large helium mass would wash out some of the weaker features. Also, the mass of cobalt visible at maximum light must not exceed a few percent or else the red wing of the P-Cygni profile interferes substantially with the Ca II line. The abundance in this model was fixed such that Co/Fe = 0.1 by number. The actual ratio for freshly synthesised cobalt and iron is expected to be around 11 at maximum light.

Comparison with the maximum light spectrum of SN 1981b shows suprisingly good agreement, given the simplicity of the assumptions. In particular, note the excellent correspondence of the features due to Mg II at 4200Å and the O I line at 7500Å. The "W" feature centred at 5500Å which is due to very highly excited S II is also well represented, although a little weak in this model. The infrared Ca II line seems to be too strong in this case, but later

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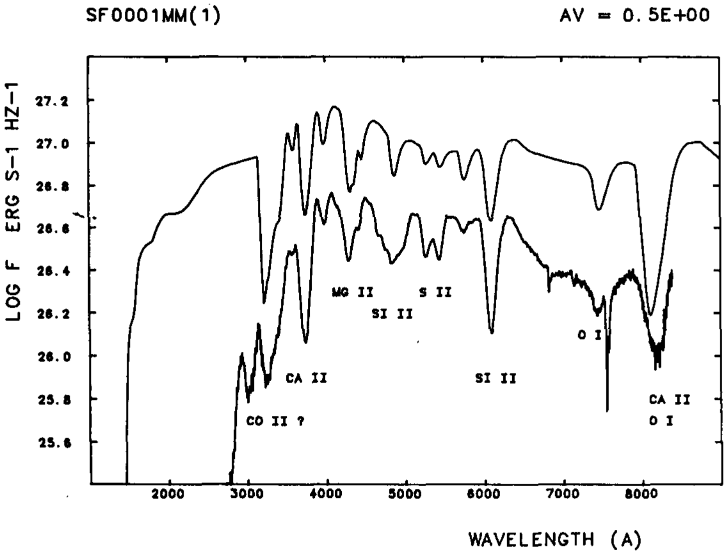

Fig. 2. The emergent spectrum from a model atmosphere based upon the Nomoto et. al. W7 density profile, but with fully mixed solar abundance ratios. The cobalt abundance was adjusted to mimic the observed feature in the spectrum of SN 1981b (below), resulting in a Co/Fe ratio of 0.1. Photospheric velocity and temperature are 12,500 km/s and 11,000 K respectively. The 9th March IUE spectrum (Benvenuti et. al. 1982) has been appended to the McDonald maximum light spectrum, illustrating the pronounced ultraviolet deficiency of Type I supernovae. A reddening correction of $A_\nu = 0.5$ has been applied to the model.

observations of SN 1981b (see Fig. 1) exhibit a very similar absorption trough. No lines with (rest) wavelengths less than 3300A were included in this model.

5. Hydrodynamical Models

Supernova atmosphere models constructed on the basis of thermonuclear explosion models provide a means of verifying that a given model can be observationally justified. The most important point is that the elemental abundances are totally defined by the explosion mechanism and the only ad hoc assumptions concern the way in which mixing occurs in the outer layers. Hopefully, future studies of the deflagration process may shed some light on this problem.

The starting point for the calculations illustrated below is the Nomoto et. al. (1984) W7 deflagration model at a time of just a few seconds after ignition. This model is then evolved using a variant of the hydrodynamic code of Sutherland and Wheeler (1984), including the time-dependent heating due to the decay of the radioactive Ni^{56} produced in the W7 model. At present the gamma rays are assumed to be deposited locally according to the initial radial distribution of the nickel. Furthermore, this energy is assumed to be rapidly thermalised, such that the source term can be represented by the Planck function. These approximations may not be entirely valid even as early as maximum light and obviously become worse at later times. The ejecta cool extremely rapidly because of the huge adiabatic losses, passing through a partially degenerate phase and rapidly assume a nearly perfect homologous expansion. From this point of view, the "hydrodynamics" is completely irrelevant after just a matter of hours and the atmosphere becomes completely radiation dominated with $\gamma = 4/3$. The radioactive decay energy diffuses outwards (and inwards because the innermost 0.1M is mainly Fe^{56}) causing the cold outer layers to be reheated and also providing some minor acceleration due to the increased radiation pressure. The maximum surface temperature of 11,000K is reached after about seven days and declines slowly while the luminosity increases as the "photospheric" radius increases. Maximum (bolometric) luminosity occurs at about 16 days, but the photosphere continues to expand for several days. The maximum light model discussed here was evolved to a time of 16.75 days and has the characteristics of a typical Type I near maximum (i.e. T = 10,000K, V = 12,000 km/s at the "photospheric" radius of 2×10^{15} cm). The density, velocity and energy deposition profiles as a function of radius are the basic input for the atmosphere calculations. Of course, there are several inconsistencies in the present approach. In particular, the hydrodynamic expansion phase is handled with a flux-limited diffusion scheme with a constant opacity. It turns out, however, that because the optical opacity is dominated by electron scattering, the precise temperature distribution in the outer layers of the evolved model is of very little consequence. The initial temperature distribution in the co-moving frame is also very accurately determined by a grey (electron scattering) opacity for the same reason. The only arbitrary input is the degree of mixing introduced into the outer 0.6M of matter. In the W7 model the abundances of O-Ca are strongly radially (and hence velocity) dependent. Unmixed models give a relatively unsatisfactory spectrum, a conclusion first reached by Branch, Doggett, Nomoto and Thielemann (1984) and supported by atmosphere models. For comparison with Branch's spectral synthesis the matter is assumed to be fully mixed only at velocities greater than 8000 km/s. The actual degree of mixing has not yet been addressed by the nuclear burning models, but the conditions in the burning phase can be strongly Rayleigh-Taylor unstable and turbulent mixing can also be expected behind the deflagration front (see Woosley, this volume). It is important to keep most of the iron and cobalt "buried" near maximum light so the mixing must not be too effective and extend down to velocities any lower than, say, 8000 km/s.

In the co-moving frame solution for the angle, frequency and depth dependence of the radiation field, the spectral lines are assumed to be formed by pure scattering, while the continuum opacity consists of pure absorption and electron scattering. The ionisation and excitation equilibrium is in LTE, with the matter and radiation being in local radiative equilibrium. Every available source of continuous absorption has been included, together with an estimated contribution from excited states of iron, cobalt and nickel for which no such data seems to be available. The radioactive decay energy term in the source function is assumed to be the Planck function corresponding to the local energy density. In this particular calculation no iron or cobalt lines were included, but the expected effects of cobalt can be seen in an earlier calculation (Fig. 2) using a similar density profile and a fully mixed abundances of near-solar ratios with Fe/Co = 10.

The observer frame spectrum of this model is shown in Fig. 3. The agreement with the optical spectrum of SN 1981b is excellent. The fit of each of the major lines is close, both in intensity and also in wavelength (i.e. the line is formed with the correct velocity range) and the continuum has approximately the correct slope. The equivalent blackbody temperature which would be obtained from broad band colours would be considerably in excess of the actual ionisation temperature due to the combination of scattering and atmospheric extension. Comparing this spectrum with Fig. 2, note that the Ca II lines and the S II "W" are a better fit, but that the Mg II line is not as good. In particular, note the absence of the neutral oxygen line at 7500Å! This infrared triplet, at a rest wavelength of 7773Å, is conspicuous in all of the SN 1981b spectra up to the end of March (see Fig. 1) and would perhaps have been visible even later.

Given the excellent agreement with observation, a deflagration model similar to that calculated by Nomoto et. al. (1984) must be considered a very strong contender for the basic Type I mechanism. It seems that only models of this type can produce enough matter composed of intermediate mass elements moving with a sufficiently high expansion velocity.

The main shortcoming of the atmosphere model is its failure to account for the ultraviolet deficiency. However, only a few ultraviolet lines (of Si

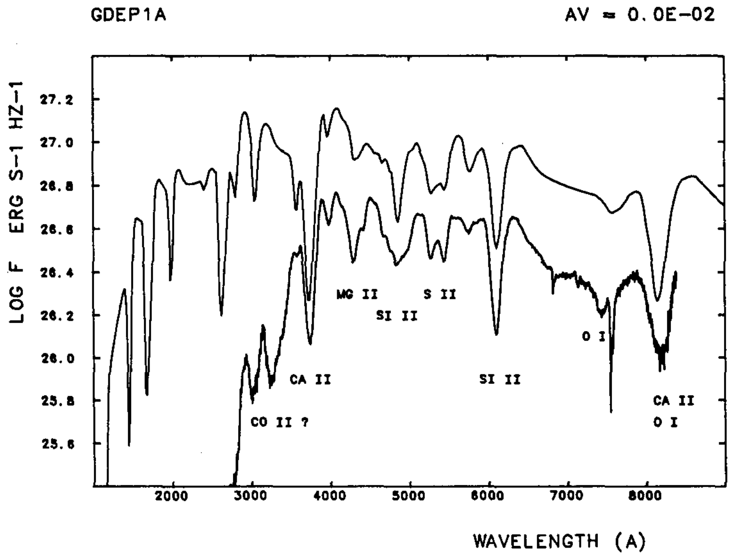

Fig. 3. The emergent spectrum of a hydrodynamically evolved Nomoto et. al. W7 model with the corresponding elemental abundances. The matter is assumed to be fully mixed at velocities greater than 8000 km/s, while the original abundance profile is used for the slower moving material. The spectrum of SN 1981b (below) is again a composite of IUE and McDonald Observatory data. Line identifications are given for the major features of the observed spectrum. The sharp, near-ultraviolet lines in the model spectrum are due to unresolved lines of Si II (see text).

II) were included in this model and the radial zoning was inadequate to resolve them on the same grid as the optical lines due to the much greater opacity of the ultraviolet lines which arise from ground states as opposed to excited states as is the case for optical transitions.

There are several possible reasons for the ultraviolet deficiency. It could simply result from the overlapping of thousands of weak lines. A neater explanation, due to Stirling Colgate, is that the deficiency is due to just a few resonance lines which would be opaque even at very low densities and but very high, almost relativistic, velocities. These lines would be seen to overlap in the observer frame due to their enormous Doppler widths. Only lines arising from ground states of neutral and singly ionised atoms have sufficiently long wavelengths to be effective at blocking the near ultraviolet. At very low densities neutral atoms would occur only at very low temperatures (i.e. large radii where $M_r < 10^{-6}\ M_\odot$). In the co-moving frame

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atoms in the outer atmosphere see a much cooler radiation field due to redshifting of the photospheric radiation than they would in a comparable static atmosphere, but if a large flux of gamma radiation escapes at at early times it would cause extensive ionisation and there would no longer be a source of near ultraviolet opacity. The details of this mechanism are currently under study.

The third, and most alarming possibility, is that the radiation field is never Planckian at any depth. If the radiation field were far from Planckian and formed by the same kind of mechanisms responsible for the late time spectra, it could simply be always UV deficient just because iron is efficient at converting the gamma radiation to optical wavelengths and the lack of true absorption at these wavelengths would allow this spectrum to scatter to the surface essentially unchanged. If this is the explanation of the ultraviolet deficit, then a radically different theoretical approach to the calculation of the spectra will be required. However, it seems likely that one (or both) of the first two hypotheses may be correct and it is still not possible to rule out continuous absorption arising from highly excited ions of the heavier (iron group) elements because the atomic data is not available. In these calculations the excited state opacities of iron, cobalt and nickel have been estimated assuming Boltzmann excitation equilibrium, with all the known energy levels having a constant 10 Mb cross-section. It is difficult to believe that the cross-sections could exceed this figure, but one can obtain a correct UV deficiency if one allows the excited state opacity to be roughly one hundred times greater than present data predict. In any event, the ultraviolet flux emerging from this model is an over-estimate because the local deposition of the gamma radiation causes the central region to be hotter than it would be if one solved for the gamma transport self consistently. This could be done with the present program if one considers the gamma ray interaction to be an absorption process (in the same way that Sutherland and Wheeler (1984) treat the deposition function in their calculations of SN I light curves). The emitting volume at intermediate temperatures would increase, softening the continuum at shorter wavelengths.

6. Peculiar SN I and the Future

From new spectroscopic data it now seems certain that there are two main classes of "Type I" supernovae. The "peculiar" Type I event SN 1983n in M83 (Panagia et. al. 1985) had a radically different maximum light spectrum when compared with a "normal" Type I such as 1981b. In particular, the prominent Si II line at 6150A which identifies a Type I was missing. Observations of two other supernovae, 1983v in NGC1365 (Branch and Cannon 1985) and 1984l in

NGC991 (Wheeler and Levreault 1985) show very similar spectra to the M83 event. Apart from the very clear Ca II H+K P-Cygni line, most of the features in these spectra are unfamiliar, except perhaps when compared to normal Type I spectra at a much later stage after maximum. Then one can find some similarities in features which are almost certainly due to Fe II lines, but several unexplained features remain. It could be that there are major differences due to excitation effects: SN 1983n and SN 1984l as well as earlier examples of this type are known to have been subluminous with respect to the normal Type Is. This possibility can be explored with the supernova atmosphere program. The apparent absence of intermediate mass elements suggests that these supernovae may be due to a detonation process, except that the velocities may be too low and they are not sufficiently luminous.

The new class may represent a tenth of all known "Type I" supernovae. As a result the "standard candle" approach to distance determination may need to be reconsidered, as a detailed spectrum of each candidate will be required to establish its subclass. With relatively few examples and a comparative lack of understanding of both the spectrum and possible explosion mechanisms the new Type I subclass remains somewhat enigmatic.

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Discussion

Icke: The blue wing of the Cobalt line appears to join the adjacent continuum at about a right angle. Isn't that a bit odd? (Refer to Fig. 2)

Harkness: Yes. It's due to insufficient resolution in terms of radial grid points. The Nomoto et. al. W7 model does not treat the hydrodynamics of the outermost zones in detail; the fastest grid point has an expansion velocity of about 24,000 km/s whereas one would actually have a profile extending to relativistic velocities. Mixing uniformly above 8,000 km/s results in very strong cobalt lines which are not properly resolved in radius on the same grid which properly accounts for the weaker lines. I hope to double the size of my grid to account for these and stronger ultraviolet lines while retaining the zoning appropriate for the weaker optical lines. It would be nice to have a calculation which gave the detailed density profile extending to relativistic velocities.

Woosley: The new subclass of SN I could be a consequence of the explosion of a massive star that has lost its hydrogen envelope. One would still have some radioactive energy input from cobalt-56 (although a lesser amount), but a larger mass of overlying [matter] and a different composition. One would also have a neutron star (or black hole) remnant unlike the usual SN I case. The high velocity iron present in the outer layers is primordial and reflects the population of the star that formed the white dwarf. Definite restrictions on its presence could tell us the population to which the white dwarf belonged. Chuck Evans of LLNL has calculated the break out of the shock wave in an exploding white dwarf using a relativistic hydrodynamics code.

Harkness: I would be very interested in seeing that! The effects of high velocity iron and cobalt really depend on how deep the complete mixing is allowed to go. This is particularly so for cobalt, because there is no pre-existing cobalt it is effectively confined to velocities less than 10,000 km/s. The iron is a nuisance if it is really abundant at high velocity.

Starrfield: The primordial iron can settle into the core because of gravitational settling and diffusion. This can remove it on a rapid timescale from a massive white dwarf.

Shull: Now that you have a reliable code for SN atmospheres, could you describe how one could "correct" the Baade-Wesselink method to derive distances?

Harkness: It would be difficult to quantify a "correction" for the Baade-Wesselink method in a way that did not depend on the details of the explosion model, although one can look at the effects of, say, extension or ionisation systematically with a power-law model. The biggest problem is scattering and the location of the "thermal photosphere". On a rather different note, the model atmospheres show that the maximum light luminosity is indeed close to the instantaneous radioactive decay energy deposition rate, so if the Ni^{56} mass can be constrained, so can the distance.

Blandford: Elias, Frogel and Persson have reported that infrared light curves of some Type I supernovae exhibit two maxima. What do you think is going on?

Harkness: I am not aware of those observations. I have not considered the spectra beyond one micron. I really don't want to have to consider grains etc.!

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