Supernova 1988A: another clumped supernova

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SUMMARY
The evolution of the forbidden multiplet (1F) oxygen lines in the optical spectrum of SN 1988A is used to determine the evolution of the optical depth in those transitions which in turn can be used to derive the number density of oxygen in the ejecta. It is shown that the oxygen in supernova 1988A is clumped with a filling factor of order 5 per cent.

1 INTRODUCTION
Our understanding of supernovae can be greatly advanced through modelling of their spectra. In order to make plausible models we require knowledge of the abundances and the conditions in the ejecta. A common approach to date has been to rely on self-consistent radiation-transport codes to produce a model spectrum assuming an initial distribution of elements as predicted by explosion models. These models do not predict density inhomogeneities or clumping in the ejecta. However, studies of SN 1987A have shown evidence for clumping for a number of species (Moseley et al. 1989; Spyromilio, Meikle & Allen 1990; Stathakis et al. 1991). To date no other supernova has been shown to have density inhomogeneities. Density inhomogeneities can be directly linked to instabilities occurring during the early expansion of the ejecta. Such instabilities lead to mixing of the slower inner regions into the faster moving regions of the envelope of the supernova. In the case of SN 1987A this led to the early escape of γ-rays produced from the decay of radioactive species created during the explosion. The study of clumping in other supernovae is therefore important in order to understand the physical processes occurring during the first few hours of the explosion of such objects.

Type II supernovae are believed to result from core collapse occurring in a massive (M > 8 M⊙) star. The exact abundance of oxygen in such supernovae is difficult to determine theoretically since it depends on the uncertain 12C/16O ratio and the fraction of the oxygen layer processed in the explosion to manufacture the iron-peak elements. However, by comparison with SN 1987A (Woosley, Pinto & Weaver 1988) a 20-M⊙ progenitor of a type II supernova would be expected to eject approximately 1–2 M⊙ of oxygen. Combined with the expansion velocities exhibited by the oxygen lines we can derive an expected number density for oxygen atoms in the ejecta. Here the evolution of the ratio of the 6363- and 6300-Å [O I] lines is used, as discussed by Spyromilio & Pinto (1991) and Li & McCray (1991), to determine the number density of oxygen in the ejecta of supernova 1988A. The derived and theoretical number densities of oxygen can be used to determine the degree of clumping in the ejecta. In the case of SN 1987A Spyromilio & Pinto (1991) have shown the oxygen filling factor to be of the order of 10 per cent.

2 OBSERVATIONS
Supernova 1988A was discovered by Kosai (1988) and Evans (1988) on 1988 January 18. The presence of strong Hα emission showing the characteristic P Cygni line profile classified SN 1988A as a type II supernova. The observations used here were obtained by Raylee Stathakis and Elaine Sadler at the Anglo-Australian Telescope (AAT) using the Faint Object Red Spectrograph during the first year after the discovery of SN 1988A as part of their ongoing programme to monitor the late-time behaviour of supernovae. The spectra have a resolution of 20 Å. A detailed description of the data reduction procedures and observation details is being prepared for publication.

In Fig. 1 we show the evolution of the 6300/6363-Å lines in the spectrum of SN 1988A. In order to determine accurately the ratio of the two lines we have first subtracted a continuum from the data. The continuum was determined by performing a spline fit to points free of line emission selected from the entire observed wavelength region (5200–10 000 Å). The line ratios were determined by fitting Gaussians of the same FWHM and the appropriate wavelengths to the 6300/6363-Å feature. The linewidths and central wavelengths are the same for both fits. Clearly the line ratio derived from the spectrum obtained in 1988 July is less reliable than that derived from the 1989 February spectrum.

3 DISCUSSION
A detailed description of the method used here has been presented in Spyromilio & Pinto (1991). Only a brief description is presented here. The use of line ratios to determine the optical depth of transitions is not new (see Jordan 1967) but...
Figure 1. Spectra of SN 1988A obtained at the AAT with the FORS spectrograph. The continuous line indicates the fit to the continuum and the 6300-, 6363-Å lines. Data courtesy of Raylee Shastakis and Elaine Sadler.

has not been used previously in the context of supernovae, where the evolution of the line ratio provides more information than is available in observations of stationary atmospheres.

Due to the large expansion velocities produced in a supernova during the explosion, the radiation-transfer problem is greatly simplified and can be solved using the escape-probability approximation. In a homologously expanding atmosphere ($v \propto r$) the optical depth of a transition from energy level $u$ to energy level $l$ in any given scattering layer in the ejecta is given by

$$\tau_{ul} = \frac{\lambda^3 g_u A_{ul} n_l}{8 \pi g_l} \left( 1 - \frac{g_u n_u}{g_l n_l} \right),$$

where $t$ is the time since the explosion, $\lambda$ is the wavelength of the transition, $A_{ul}$ the transition probability, $n$ and $g$ are the number density and degeneracy respectively for each level. The term in brackets accounts for induced emission from the upper level, and in most cases is close to unity. The probability that a photon escapes the scattering layer is

$$\beta_{ul} = \frac{1 - \exp(-\tau_{ul})}{\tau_{ul}}.$$

The effect of the line trapping in each scattering layer is to reduce the probability of spontaneous decay from level $u$ to level $l$ by a factor $\beta_{ul}$. It is important to note that since the number density in a homologously expanding atmosphere decreases as $t^{-3}$ the optical depth in an escape-probability approximation decreases as $t^{-3}$. Since the ejecta expand homologously the velocity widths of the observed line profiles determine the radius of the emitting material in the ejecta of the supernova.

The 6363- and 6300-Å transitions share the same upper energy level ($D_2$) and therefore their branching ratio is simply $A(6363)/A(6300)\beta(6363)/\beta(6300)$. The lower states of the two transitions are separated by 158 cm$^{-1}$ and we expect their populations to be determined solely by their quantum numbers. Moreover, since the lower levels of these transitions form part of the ground state of O I, we expect the number density in those levels to correspond closely to the total number density of O I. The observed branching ratio will therefore depend solely on the escape probabilities of the transitions and therefore on the total number density of O I. The observed line ratio will follow the branching ratio assuming that absorption of $\lambda$6300 photons by the $\lambda$6363 transition is negligible. The separation of the two lines (3000 km s$^{-1}$) is larger than twice the FWHM of the Doppler-broadened line profiles and therefore only a small fraction of the flux would be subject to absorption. The transition probabilities used are from Mendoza (1983) ($A_{6300} = 6.34 \times 10^{-3}$ s$^{-1}$ and $A_{6363} = 2.11 \times 10^{-3}$ s$^{-1}$). In the limit where $\beta \rightarrow 1/\tau$ the ratio of $I(6363)/I(6300) \rightarrow 1.05$. As the supernova ejecta expand the optical depth $\tau \rightarrow 0$ and $I(6363)/I(6300) \rightarrow 0.33$. Fig. 2 [from Spyromilio & Pinto (1991)] with data from
Figure 2. The evolution of the 6300-, 6363-Å line ratio in SN 1987A (from Spyromilio & Pinto 1991) compared with models for a uniform distribution of oxygen. The curves from top to bottom are for 1000, 2000, 3000, 5000 and 10 000 K. Circles are AAT data (Spyromilio et al. 1991) and boxes are CTIO data (Phillips & Williams 1991).

Figure 3. The evolution of the 6300-, 6363-Å line ratio in SN 1988A compared with models for a uniform distribution of oxygen. The number density in the ground energy level of oxygen on day 173 was $1 \times 10^{10}$ cm$^{-3}$. The curves from top to bottom are for 1000, 2000, 3000, 5000 and 10 000 K.

Spyromilio et al. (1991) and Phillips & Williams (1991) show the application of this theory to SN 1987A.

Although the temporal coverage of the spectrum of SN 1988A is poor and the 1988 July spectrum does not yield a very accurate line ratio, the evolution of the line ratio is from the optically thick to the optically thin case as described above. It should be noted that the method outlined above uniquely determines the number density of neutral oxygen with only one observation between the optically thick and optically thin limits. For this purpose we require know-
ledge of the explosion date which in the case of SN 1988A is not known with great accuracy. Spectra of SN 1988A obtained on 1988 January 22 by Cochran & Barker (Wheeler 1988) and by Peters (Schlegel 1988) show a strong featureless continuum with broad H/β and Hα emission indicating that the supernova was caught not long after maximum light. We therefore use the discovery data as the explosion date. Backdating the explosion by a few tens of days does not affect our conclusions significantly.

In Fig. 3 we compare the evolution of the line ratio with that predicted by a uniform distribution of O i. We assume that the expansion is homologous and so the number density at any epoch determines the evolution of the number density both before and after that epoch. We have arbitrarily set the number density of oxygen at a given date after explosion (day 173 for lack of a better choice and historical reasons). Since a single point on the curve is sufficient to determine the number density we shall do so. From the spectrum obtained in 1988 July we derive a neutral oxygen number density for day 173 of $8 \pm 5 \times 10^9$ cm$^{-3}$. From the more accurate measurement obtained in 1989 February we derive $1.0 \pm 0.2 \times 10^{10}$ cm$^{-3}$. Since both measurements are consistent we shall use the second more accurate one for our discussion. In the absence of a detailed model for the progenitor of SN 1988A we have assumed that 1.5 $M_\odot$ of oxygen should be present in the ejecta. For such a mass of neutral oxygen our derived number density corresponds to a filling factor of 5 per cent in a volume expanding at 2000 km s$^{-1}$. The expansion velocity has been determined by the FWHM (2000 km s$^{-1}$) of the Gaussian functions used to fit the line profiles. In Fig. 3 we show the variation in the evolution of the line ratio with temperature. The lack of significant variation at intermediate optical depths and little variation at temperatures above 2000 K is a good indication of the power of this method. Although it is highly unlikely that any supernova will maintain the same temperature throughout the first year after its explosion our derivation of the number density is unaffected.

Oxygen and hydrogen have very similar ionization potentials. Williams (1973) has shown that charge-transfer effects will couple the ionization structure of the two elements. Models of the ionization structure of SN 1987A (Xu 1989) suggest that hydrogen will be predominantly neutral. By analogy we suggest that the number density and filling factors derived here are for oxygen as a whole. However if a large fraction of the oxygen were ionized even smaller filling factors would be needed.

Large filling factors would result in much higher abundances of oxygen than would be expected. This would have implications for the $^{12}$C(αγ)$^{16}$O rate which dominates the production rate of oxygen in massive stars. Moreover we believe it to be rather unlikely that 10 $M_\odot$ of oxygen are made in the explosion of a 20-$M_\odot$ star would be required in order to account for the number density derived here in a uniform distribution.

4 CONCLUSIONS

We have shown that a small filling factor in the distribution of oxygen in the ejecta of supernova 1988A is needed to explain the observations. Clumping, which to date had only been observed in SN 1987A, may be present in all type II supernovae.

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