Mon. Not. R. Astron. Soc. **268,** 173–180 (1994)

# SN 1988Z: low-mass ejecta colliding with the clumpy wind?

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Accepted 1993 December 8. Received 1993 September 30; in original form 1993 May 4



## ABSTRACT

Two alternative models for the origin of the broad and intermediate-width lines in the spectrum of the peculiar supernova SN 1988Z are proposed. Both suggest that the optical emission is a result of the dynamical interaction of the ejecta with a two-component wind; the broad lines are identified with emission from shocked supernova material expanding in a relatively rarefied wind, while the intermediate-width lines originate from a shocked dense wind component. The latter may be associated either with dense wind clumps or with a dense equatorial wind. The clumpy-wind model is more attractive since it requires a lower mass loss. The optical emission of SN 1986J at $t=4$ yr, which in many respects is similar to the intermediate component of SN 1988Z, is probably also produced by shocked dense clumps in the circumstellar wind component. Dynamical properties and the luminosity of the broad lines imply that the mass of the SN 1988Z ejecta is unexpectedly low, $M<1$ $M_{\odot}$, suggesting that SN 1988Z may have originated from a star with a main-sequence mass of about 8–10 $M_{\odot}$.

**Key words:** shock waves – stars: mass-loss – supernovae: individual: SN 1988Z.

## 1 INTRODUCTION

Type II supernovae (SNeII) display a great variety of photometric and spectral characteristics, which are manifested in the existence of the two photometric classes, II-P and II-L (Barbon, Ciatti & Rosino 1979), and of a recently selected group of spectroscopically peculiar SNeII called SNeIIn (Schlegel 1990). However, two recently observed SNeII, namely SN 1987F (Filippenko 1989) and SN 1988Z (Filippenko 1991; Stathakis & Sadler 1991; Turatto et al. 1993), are exceptionally peculiar in their spectroscopic and photometric properties. Both SNe belong to the family of SNeIIn in which the profile of H$\alpha$ emission lacks a P Cyg absorption component; both are characterized by an extremely slow decay of luminosity after maximum light, which makes them at day 600 approximately 5 mag brighter in $B$ and $V$ compared to SNeII-P or SNeII-L; and both have strong H$\alpha$ emission with the luminosity exceeding $10^{41}$ erg s$^{-1}$ at $t\approx 200$ d. In SN 1988Z the H$\alpha$ luminosity is particularly prodigious, exceeding that of SN 1987A at $t\approx 3$ yr by 5 orders of magnitude.

The enormous H$\alpha$ and bolometric luminosities of SN 1987F and SN 1988Z have been interpreted as a result of the collision of the supernova ejecta with a very dense circumstellar wind (Chugai 1990, 1991, 1992; Turatto et al. 1993). In the model of the spherically symmetric wind the required wind density parameter $w=\dot{M}/u_{\rm w}$ has a value $\sim 2\times 10^{16}$–$10^{17}$ g cm$^{-1}$. SN 1988Z is very similar to SN 1987F in these respects, but shows a particularly extraordinary spectral development, which is not yet properly understood. The straightforward spherically symmetric model of ejecta–wind interaction predicts only two spectral components: broad lines from shocked (or photoionized) ejecta and narrow lines from the undisturbed photoionized wind. In contrast to this expectation, SN 1988Z revealed a so-called intermediate component with FWHM $\approx 2000$ km s$^{-1}$ which developed between days 50 and 100 (cf. Filippenko 1991; Stathakis & Sadler 1991; Turatto et al. 1993). At later times the intermediate component becomes dominant.

Here we formulate two alternative working models in an attempt to understand the coexistence of the broad and intermediate components in the spectrum of SN 1988Z. The crucial point is the assumption that the wind has a two-component structure comprising rarefied and dense components. The dynamics and luminosity of SN 1988Z are used to derive parameters of the wind and the ejecta. We also analyse the case of the unusually powerful radio supernova SN 1986J and argue that its optical emission is of the same origin as the intermediate component in SN 1988Z.

## 2 THE ORIGIN OF THE BROAD AND INTERMEDIATE LINES IN SN 1988Z

### 2.1 Phenomenological model

One of the most spectacular and unique properties of SN 1988Z is the presence of three different spectral components, namely broad, narrow and intermediate, during the interval from 1 month to 3 yr after explosion (Filippenko 1991; Stathakis & Sadler 1991; Turatto et al. 1993). The broad component, with FWHM evolving from $2\times10^4$ to $10^4$ km s$^{-1}$, was observed in H$\alpha$, the Ca II IR triplet and the O I 8446-Å line, and in the wide Fe II bumps between 4200 and 5500 Å. The narrow unresolved component, undoubtedly related to the undisturbed photoionized wind, is apparent in the nebular lines. The intermediate component, a new phenomenon for SNeII (although it might have been present in SN 1984e), was observed in hydrogen, He I and O I 8446 Å, and in Fe II lines. Its FWHM decreased from 2500 to 1500 km s$^{-1}$ between 2 month and 3 yr after explosion.

The broad H$\alpha$ component, which shows a parabolically shaped purely emission profile without P Cyg absorption and extended wings, reminds one of SN 1987F. The shape and width of the H$\alpha$ profile suggest that this line as well as the other broad emission originates from the shocked or photoionized high-velocity supernova material as a result of collision of the supernova envelope with the dense circumstellar wind (Chugai 1991). The intermediate component is also produced by the relatively dense gas, as is evidenced by the presence of the O I 8446-Å line pumped by Ly$\beta$ radiation. An estimate based on the ratio of the intensities of O I 8446 Å and H$\alpha$ for the intermediate component at 2–3 yr after explosion implies that the optical depth in H$\alpha$ is $\tau(\mathrm{H}\alpha)\geq10^3$.

Two alternative models for the wind structure that are relevant to the three-component spectrum of SN 1988Z are conceivable (Fig. 1). Model A suggests a spherically symmetric wind, which consists of the relatively rarefied substrate with a large filling factor $f\approx1$, and very dense clumps with a small filling factor $f\ll1$. The interface between the ejecta and the rarefied wind is composed of the outer shock wave (or main shock wave) propagating in the wind, and the inner shock wave propagating into the SN ejecta (for details, see Chevalier 1982; Nadyozhin 1981, 1985). In the case of the dense wind, the shocked ejecta cool quickly compared to the expansion time and create a cool dense shell, which may reprocess the X-rays from the inner shock wave into optical radiation (Chevalier & Fransson 1985). The broad component is presumably associated with this cool dense shell. The high density of the material responsible for the broad component in SN 1988Z is manifested by the strong fluorescent line O I 8446 Å and by the absence of forbidden lines in the broad spectrum. As an alternative, the broad lines may be emitted by the unshocked photoionized ejecta inside the inner shock wave (region 1), the possibility considered by Fransson (1984) in connection with the interpretation of UV lines and H$\alpha$ from SN 1979c.

The intermediate component in model A (Fig. 1a) is emitted from the radiative shock wave, which is driven into the very dense clumps of wind material by thermal and dynamical pressures behind the main shock, and/or by the dynamical pressure of the unshocked ejecta. The cloud shock wave will be relatively slow if the cloud density exceeds significantly the density of the fast supernova material. The shocked cloud gas cools by X-ray emission, while the optical spectrum is presumably a result of reprocessing of X-rays by the cooled dense material behind the cloud shock wave. Basically, the intermediate component is analogous to the optical emission of the quasi-stationary filaments of Cas A in the model of shocked clouds (McKee & Cowie 1975).

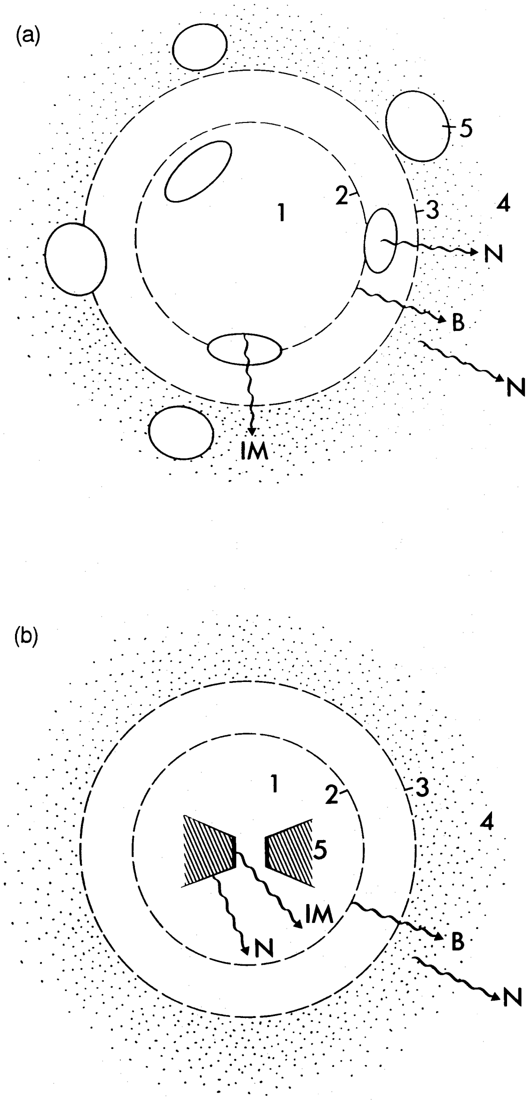


**Figure 1.** Two models for the intermediate component in SN 1988Z. (a) In model A, ejecta (1) expanding in the rarefied wind (4) create inner (2) and outer (3) shock waves, which outline the shocked wind and the ejecta. A slow shock wave driven into the dense wind clumps (5) by the dynamical pressure of the ejecta is the site of the intermediate-component (IM) emission. The broad component (B) originates from the shocked and/or photoionized ejecta, while the narrow component (N) is emitted by the undisturbed, photoionized, rarefied and clumpy wind. (b) In model B structures 1, 2, 3 and 4 are as in (a), but the intermediate component originates from the radiative shock wave propagating in the dense equatorial wind (5).

In model B (Fig. 1b) the dense equatorial wind is superimposed on the spherically symmetric rarefied wind. The radial size of the equatorial component may be relatively small compared to the radius of the main shock. As in the previous model, the broad component is produced as a result of the interaction of the ejecta with a rarefied wind, while the intermediate component originates from the shocked material of the dense equatorial wind. It should be emphasized that this model requires a relatively homogeneous equatorial wind. Otherwise, it is simply a version of model A with the clumps lying mostly close to the equatorial plane.

The two proposed models of the wind structure seem to be equally conceivable from the observational point of view. The concept of the dense equatorial wind is actively exploited in the context of the interpretation of the structure of some planetary nebulae (Balick 1987) and of the nebular ring around SN 1987A (Wampler et al. 1990). On the other hand, there is observational evidence for the existence of strong clumpiness in red giant and supergiant winds. Clumpiness of the wind of a red giant at a radius $\approx 10^{15}$ cm is indicated by the variability of VLBI maps of SiO maser lines (Alcock & Ross 1986), while CO maps of carbon stars show wind clumpiness at a radius of $10^{17}$ cm (Heske, te Lintel Hekkert & Maloney 1989). Nevertheless, the data relating to the structure of winds in red supergiants are still scanty and permit some freedom in the choice of the structure of a pre-SNII wind.

### 2.2 The broad component and the mass of the ejecta

The evolution of the width of the broad spectral lines, if compared with the predictions from the hydrodynamics of the expansion of the ejecta, can be used to derive some relevant parameters of the wind and the ejecta. We believe that the broad component is emitted by the cool ($10^4$-K) thin ($\Delta r/r \ll 1$) outer shell of the shocked supernova envelope. This shell presumably has a low velocity gradient, $d \ln v / d \ln r \ll 1$ (Chevalier 1982). In this case the profile of the optically thick line (e.g. H$\alpha$) has a parabolic shape, provided that the width of the shell is not extremely small, $\Delta r/r \gg v_{\rm th}/v \approx 10^{-3}$ (where $v_{\rm th}$ is the ion thermal velocity and $v$ is the expansion velocity). Generally, the red wing of the emission line may be skewed by continuum absorption effects in the supernova envelope (cf. SN 1987F; Chugai 1991). The 'blue' velocity at zero intensity (BVZI) is normally expected to coincide with the expansion velocity of the shell. Values of the BVZI for H$\alpha$ and O I 8446 Å in SN 1988Z are available between days 45 and 475 (Stathakis & Sadler 1991). Several caveats must, however, be considered before using these data.

At late times the BVZI value for H$\alpha$ is systematically higher than that for O I 8446 Å (cf. Stathakis & Sadler 1991). In our opinion this is probably caused by the presence of the emission band $\lambda \approx 6200$–$6400$ Å composed of the Fe II lines of multiplets 74, 40 and 46. This band is clearly seen in the spectrum of a similar supernova, SN 1987F (cf. Filippenko 1989). Fe II emission bands at 4600 and 5200 Å in SN 1988Z are strong enough for the Fe II 6300-Å band to contribute notably to the blue wing of H$\alpha$ in accordance with the observed relative intensity of this feature in SN 1987F. The BVZI value for O I 8446 Å therefore reflects the expansion velocity more realistically than does H$\alpha$.

In the case of a supernova envelope with a power-law density distribution $\rho \propto v^{-k}$, freely expanding ($v = r/t$) in the spherically symmetric wind ($\rho \propto r^{-2}$), a double-shock structure is formed, which expands in a self-similar fashion, $r_{\rm s} \propto t^{\delta}$, where $\delta = (k-3)/(k-2)$ (Chevalier 1982; Nadyozhin 1985). We adopt a simple model for the density distribution in the supernova envelope: $\rho = \rho_0 =$ constant in the central region, where $v < v_0$, and $\rho \propto v^{-k}$ in the outer region. Such a model closely corresponds to results of numerical hydrodynamics calculations of supernova explosions provided that $k > 6$. For $k = 7$ one obtains

$$v_0 = 9.1 \times 10^8 E_{51}^{1/2} (M/{\rm M}_\odot)^{-1/2} \quad {\rm cm\,s^{-1}}, \tag{1}$$

$$\rho_0 = 1.2 \times 10^{-17} E_{51}^{-3/2} (M/{\rm M}_\odot)^{5/2} t_{\rm yr}^{-3} \quad {\rm g\,cm^{-3}}. \tag{2}$$

Here $M$ is the mass of the ejecta, $E_{51} = E/10^{51}$ erg and $t_{\rm yr}$ is time in years. The velocity of the double-shock structure, according to the self-similar solution by Chevalier and Nadyozhin in the case $k = 7$, is

$$v_{\rm s} = 7.46 \times 10^8 \, E_{51}^{0.4} (M/{\rm M}_\odot)^{-0.2} w_{16}^{-0.2} t_{\rm yr}^{-0.2} \quad {\rm cm\,s^{-1}}, \tag{3}$$

where $w = \dot{M}/u_{\rm w}$ is the wind density parameter and $w_{16} = w/10^{16}$ g cm$^{-1}$. The radius of the shell is determined by the relationship $r = \delta^{-1} vt$.

When the reverse shock crosses the density kink at velocity $v_0$, the above expansion law (equation 3) is no longer valid. In order to describe the expansion of the swept-up shell in this case, we may use the equation of energy conservation:

$$(M + wr)\,\dot{r}^2 = 2\alpha E, \tag{4}$$

where $\alpha$ is the ratio of kinetic energy to total energy. With the initial condition $r = 0$ at $t = 0$ this equation has a simple solution:

$$r = R\left(\frac{t}{1+t_1}\right)^{2/3} - R, \tag{5}$$

$$v = v_1\left(1 + \frac{t}{t_1}\right)^{-1/3}, \tag{6}$$

where $v_1 = (2\alpha E/M)^{1/2}$, $t_1 = (2M/3wv_1)$, $R = (3/2)v_1 t_1$. As expected, for $t \gg t_1$ (when the ejecta mass is negligible) the solution turns into the Sedov self-similar solution for the blast-wave expansion $r \propto t^{2/3}$ for a medium with density $\rho \propto r^{-2}$. (Note that the solution presented by equations 5 and 6 is also self-similar for variable $r + R$.) In order to distinguish between the two regimes of the expansion of the supernova envelope in the dense circumstellar wind we will refer to the model corresponding to the Chevalier–Nadyozhin self-similar solution (equation 3) as the free-expansion (FE) case, and the model described by the equations (5) and (6) as the blast-wave (BW) case.

The dynamical evolution of the broad component in the two cases is compared to the BVZI values for the O I 8446-Å line in Fig. 2. In the FE case the model curve corresponds to the parameter

$$\eta = E_{51}^{0.4} (M/{\rm M}_\odot)^{-0.2} w_{16}^{-0.2} = 1.5. \tag{7}$$

The best-fitting model for the BW case with a ratio of the internal to the total energy of $\alpha = 0.5$ results in $M = 0.1 E_{51}$ M$_\odot$ for the mass of the SN envelope and a wind density parameter of $w = 1.8 \times 10^{16} E_{51}$ g cm$^{-1}$. For $E = 10^{51}$ erg we obtain $M = 0.1$ M$_\odot$ and $w = 1.8 \times 10^{16}$ g cm$^{-1}$.

In order to find an estimate of the ejected mass in the FE case the value of $w$ is needed. The lower limit of $w$ is determined by the observed luminosity according to the general expression for the luminosity of the shock wave

$$L = \tfrac{1}{2} \psi w v_{\rm s}^3, \tag{8}$$

where $\psi$ is the efficiency of the conversion of mechanical energy into optical energy in the shock wave. For $t = 0.2$ yr

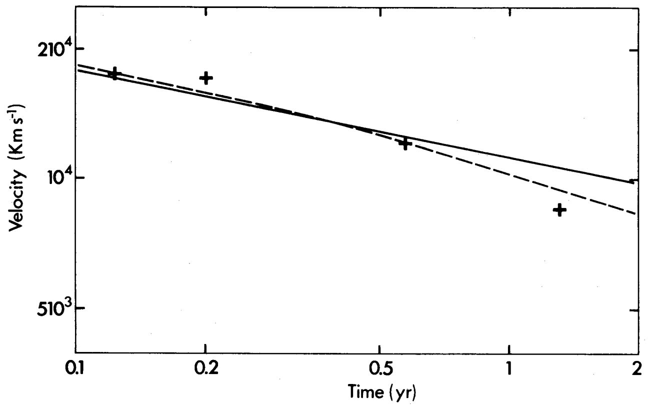


**Figure 2.** The evolution of the broad component. Values of the BVZI for the O I 8446-Å line (crosses) are compared to the model evolution of the velocity of the double-shock layer which is produced by the dynamical interaction of the ejecta with the spherically symmetric wind. The solid line shows the self-similar solution by Chevalier–Nadyozhin for $\eta=1.5$ (solid line), while the dashed line corresponds to the blast-wave model for $M=0.1E_{51}$ $M_\odot$ and $w=1.8\times10^{16}E_{51}$ g cm$^{-1}$. Uncertainties in the velocities are of the order of 10 per cent.

the velocity of the shell is close to $1.7\times10^9$ cm s$^{-1}$ (Fig. 2). Adopting for this phase the observational value of the optical luminosity $L=4\times10^{42}$ erg s$^{-1}$ (Stathakis & Sadler 1991) and $\psi=1$, we obtain from equation (8) the lower limit $w=1.6\times10^{15}$ g cm$^{-1}$. For this value of $w$ and $E=10^{51}$ erg, equation (8) gives $M\approx0.4$ $M_\odot$.

Both descriptions of the expansion of the supernova envelope in the circumstellar wind, when applied to the evolution of the broad O I 8446-Å line, result in a very low value for the mass of the ejecta, $M\sim0.1$–$0.4$ $M_\odot$, provided that the initial kinetic energy $E\approx10^{51}$ erg. A higher value of $E$ would increase the mass estimates according to the relations $M\propto E^2$ for the FE case and $M\propto E$ for the BW case. Thus a value of $M\approx1$ $M_\odot$ in the FE case is feasible, if the value of the energy $E=1.5\times10^{51}$ erg. It should, however, be emphasized that this estimate of $M$ is a very stringent upper limit, since the efficiency adopted above is $\psi=1$. For the conservative value of the kinetic energy $E\approx10^{51}$ erg the upper limit of the ejecta mass $M\approx0.5$ $M_\odot$.

The wind density parameter implied by the FE and BW cases lies in the range $2\times(10^{15}$–$10^{16})$ g cm$^{-1}$, with the logarithmic mean $6\times10^{15}$ g cm$^{-1}$. We note that this estimate refers only to the smooth rarefied component of the wind.

### 2.3 Effect of a leading low-mass shell

The small value of the ejecta mass obtained above provokes the interesting speculation that the broad-line component might be produced by a leading low-mass shell with a substantially higher expansion velocity than the rest of the supernova ejecta, which may prove to be massive and slowly expanding. This possibility at first sight seems to be consistent with the known effect of the sweeping action of the radiatively damped outbreaking shock wave and its ejection of the outermost stellar material (Grasberg, Imshennik & Nadyozhin 1971; Imshennik & Nadyozhin 1988).

The radiative damping of the shock with a velocity $D$ becomes important at the optical depth $\tau\approx c/D$. Allowing for the subsequent radiative acceleration of the fast shell (resulting in a velocity increase of a factor of roughly 1.6) (Imshennik & Nadyozhin 1988) and adopting a terminal velocity of 20 000 km s$^{-1}$ we have for the outbreaking shock a velocity $\approx12\,000$ km s$^{-1}$. This gives an estimate of the optical depth at the damping phase, $\tau\approx23$, and of the mass of the fast shell,

$$M_f\approx4\pi R_0^2\tau\kappa^{-1}\approx5\times10^{-4}(R_0/500\ R_\odot)^2\ M_\odot, \qquad (9)$$

where $\kappa\approx0.3$ cm$^2$ g$^{-1}$ is an opacity, and $R_0$ is the radius of the pre-SN. This estimate shows that for $R\approx500$ $R_\odot$, which is a standard value for the red supergiant, the mass of a fast shell with a velocity of 20 000 km s$^{-1}$ hardly exceeds $10^{-3}$ $M_\odot$, while the kinetic energy is lower than $4\times10^{48}$ erg. Even allowing all this energy to transform into radiation on a timescale of $10^7$ s, we find that the characteristic luminosity is one order of magnitude lower than the observed luminosity of SN 1988Z, $L\approx4\times10^{42}$ erg s$^{-1}$ at $t\approx75$ d (Stathakis & Sadler 1991). Thus the idea of a leading fast shell as a cause of the broad-line emission in SN 1988Z seems unpromising.

### 2.4 The intermediate component

#### 2.4.1 *Model A: clumpy wind*

Basically, the presence of a clumpy component in the wind does not affect noticeably the dynamics of the broad-component material provided that the covering factor (the fraction of the sphere occupied by clouds) is small. On the other hand, a particular clump overtaken by the main shock wave is strongly affected by the thermal and dynamical pressures in the double-shock layer, and by the dynamical pressure of the undisturbed supernova ejecta. The radiative shock wave driven by external pressure into the dense cloud is presumably responsible for the emission of the intermediate component in the spectrum of SN 1988Z. We shall determine the restrictions imposed on the cloud parameters by dynamical and luminosity requirements at the phase $t=492$ d, when the intermediate component was at its maximum intensity (Turatto et al. 1993).

The velocity of the swept-up shell, as indicated by the broad component, is $v_s\approx9000$ km s$^{-1}$ on day 492 (Section 2.2). For an adopted mass of the ejecta of 0.5 $M_\odot$ and a kinetic energy of $10^{51}$ erg s$^{-1}$ this value lies significantly below the characteristic velocity of the SN envelope $v_0=13\,000$ km s$^{-1}$; the maximal dynamical pressure is therefore attained in the swept-up shell and is of order $\sim E/V$, where $V$ is the volume of the shell. The dynamical pressure in the cloud shock wave is determined by the pressure equilibrium equation

$$\rho_c u_c^2=\xi\frac{3E}{4\pi r_s^3}, \qquad (10)$$

where $\rho_c$ is the cloud density, $u_c$ is the cloud shock-wave velocity, which should coincide with the FWHM of the intermediate component, $r_s\approx5\times10^{16}$ cm is the shell radius on day 492, and $\xi$ is the structure parameter, which we adopt as unity.

A lower limit on the size of clumps is provided by the requirement that the cooling time in the cloud shock wave must be short compared to the time of fragmentation of the cloud due to Rayleigh–Taylor and Kelvin–Helmholtz instabilities. Both instabilities develop on the time-scale $t_c \approx a/u_c$, where $a$ is the cloud radius. 2D computations of the interaction of the fast rarefied flow with the dense cloud for a wide range of density contrasts have demonstrated (Klein, McKee & Colella 1991) that the cloud lifetime is of the order of $t_c$. Thus the condition that the cloud shock wave cools fast enough is

$$\frac{3kT_{s,c}}{4n_c\Lambda} < \frac{a}{u_c}, \tag{11}$$

where $T_{s,c} = 1.36 \times 10^7 (u_c/10^8 \text{ cm s}^{-1})^2$ K is the temperature at the shock front, $n_c$ is the atomic concentration in the cloud, and $\Lambda$ is the cooling function. Obviously, the cooling time must be also less than the age of the SN.

The luminosity of the intermediate component provides yet another restriction on the parameters of the clumped wind. The intermediate component is presumably formed in the cooled cloud material behind the cloud shock wave. The cool gas radiates due to reprocessing of X-ray emission from the hot shocked cloud gas. The luminosity of the ensemble of $N_c$ shocked clouds at about their maximum luminosity is

$$L = \tfrac{1}{4}\pi a^2 \rho_c u_c^3 N_c, \tag{12}$$

where an additional factor of 0.5 is introduced to allow for geometrical effects.

From equation (10) with $E = 10^{51}$ erg, $r_s = 5 \times 10^{16}$ cm and $u_c = 1600$ km s$^{-1}$ we obtain the density in clumps, $\rho_c \approx 7 \times 10^{-17}$ g cm$^{-3}$, which corresponds to the hydrogen concentration $n_H \approx 2.5 \times 10^7$ cm$^{-3}$ for an H abundance of $X = 0.6$. Equation (11) with this density, $T_{s,c} = 3.5 \times 10^7$ K and $\Lambda = 2 \times 10^{-23}$ erg cm$^3$ s$^{-1}$ gives a lower limit to the cloud radius of $a > 10^{15}$ cm, and a cooling time of $t_{cool} \geq 8 \times 10^6$ s. Given the luminosity of the intermediate-width lines $L = 2.3 \times 10^{41}$ erg s$^{-1}$ (Turatto et al. 1993), we find from equation (12) the number of emitting clouds and their filling factor:

$$N_c = 900 a_{15}^{-2}, \qquad f \approx N_c (a/r)^3 = 0.008 a_{15}, \tag{13}$$

where $a_{15} = a/10^{15}$ cm. The requirement $N_c \gg 1$ results in $a \ll 2 \times 10^{16}$ cm. We adopt $a = 3 \times 10^{15}$ cm, which is close to the logarithmic mean between the upper ($2 \times 10^{16}$ cm) and lower ($10^{15}$ cm) limits and is consistent with the characteristic size of density clumps in the Helix planetary nebula at a radius of $10^{17}$ cm (Meaburn et al. 1992).

The parameters of the wind clouds in model A are summarized in Table 1. The density parameter $w$ for the cloudy component of the wind is one order of magnitude greater than that for the rarefied wind estimated in Section 2.2. This means that in model A the bulk of the wind material around SN 1988Z, at least at a radius $\approx 5 \times 10^{16}$ cm, is confined in dense clumps. The column density of a clump for the parameters in Table 1 is about $10^{23}$ cm$^{-2}$. Such clumps could be optically thick at early times, given a reasonable dust/gas ratio. For the parameters in Table 1 the covering factor $(r/a)f \approx 0.1$, so that the probability of screening of SN 1988Z is low. In order that the clouds at larger radii do not screen the supernova, the filling factor must decrease outwards faster than $r^{-1}$.

**Table 1.** Parameters of the clumpy wind at $r = 5 \times 10^{16}$ cm.

| | |
|---|---|
| Cloud radius, $a$ | $\sim 3\,10^{15}$ cm |
| Density in clouds, $n_c$ | $2\,10^7$ cm$^{-3}$ |
| Mass of a cloud | 0.004 $M_\odot$ |
| Number of emitting clouds, $N_c$ | $10^2$ |
| Filling factor of clouds, $f$ | 0.02 |
| Wind density parameter, $w$ | $5\,10^{16}$ g cm$^{-1}$ |
| Mass loss rate | $7\,10^{-4}$ $M_\odot$ yr$^{-1}$ |

### 2.4.2 *Model B: equatorial wind*

A simple version of model B (Fig. 1) is a dense equatorial wind independent of latitude $\phi$ in the range $|\phi| < \phi_e$. The shock wave, which propagates in the equatorial wind, may be approximated by a spherical belt. The model presumes that the equatorial wind is homogeneous; otherwise we will have only a variant of model A with a global axial distribution of clouds.

The evolution of the shock wave propagating in the equatorial wind passes through two phases. In the initial phase the shock wave is driven into the equatorial wind by the dynamical pressure of the supernova ejecta. This stage lasts $t_1 \approx r_1/v_0$, where $r_1$ is the inner radius of the dense equatorial wind. During the subsequent stage the swept-up cylindrical shell slows down in the radiative regime. The dynamical evolution of the radius of this shell, $r_{se}$, at $t > t_1$ can be described in the approximation of momentum and mass conservation

$$M_{se}\dot{r}_{se} = (\Omega/4\pi) M v_0, \tag{14}$$

$$M_{se} = M(\Omega/4\pi) + w_e(r_{se} - r_1), \tag{15}$$

where $\Omega = 4\pi \sin\phi$ is the solid angle occupied by an equatorial wind with a density parameter $w_e$. In terms of parameter $R = (\Omega/4\pi) M w_e^{-1}$, the solution of equations (14) and (15) with the initial condition $r_{se}(0) = 0$ is

$$r_{se} = R\left(1 + \frac{t}{t_0}\right)^{1/2} - R, \tag{16}$$

$$v_{se} = v_0\left(1 + \frac{t}{t_0}\right)^{-1/2}, \tag{17}$$

where $t_0 = R/(2v_0)$.

The evolution of the velocity of the shell in the equatorial wind as determined by equation (17) is compared in Fig. 3 to the data for the FWHM of the intermediate component of H$\alpha$ in SN 1988Z obtained by Turatto et al. (1993). The model corresponds to the fitting parameter $t_0 = 0.03$ yr with adopted parameters for the supernova of $E = 10^{51}$ erg and $M = 0.5$ M$_\odot$. The parameters of the equatorial wind in this case are given in Table 2 for two inclination angles (between the line of sight and the polar axis of the wind), 90° and 60°. The wind density parameter $w_e$ is obtained from the luminosity of the intermediate component $L = (1/2) w_e v_{se}^3 \approx 2.3 \times 10^{41}$ erg s$^{-1}$ on day 492, while $\phi_e$ is determined by $w_e$ and $t_0$. The value of $w_e$ in the equatorial wind exceeds by 4–6 times that of the clumpy-wind model (Table 1).

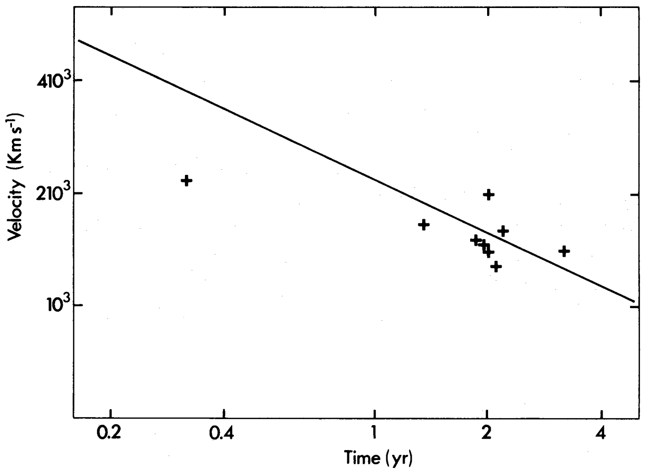


**Figure 3.** The evolution of the intermediate component. FWHM data for H$\alpha$ (crosses) are compared to the evolution of the velocity of the radiative shock wave in the dense equatorial wind with a constant parameter $w$ for $t_0 = 0.03$ yr, $E = 10^{51}$ erg and $M = 0.5$ M$_\odot$ (solid line). Uncertainties in the velocities could be as high as 20 per cent.

**Table 2.** Parameters of the equatorial wind at $r \approx 10^{16}$ cm.

| $\theta$ | $w_e$ (g cm$^{-1}$) | $\Omega/4\pi$ | $\phi_0$ | $\dot{M}$ ($M_\odot$ yr$^{-1}$) |
|---|---|---|---|---|
| 90 | 2 $10^{17}$ | 0.48 | 27° | 3 $10^{-3}$ |
| 60 | 1.3 $10^{17}$ | 0.3 | 18° | 2 $10^{-3}$ |

At an early phase ($t \approx 100$ d) the model predicts an unreasonably high velocity (Fig. 3). To save the model, the initial deceleration of the equatorial shell must be strong, which suggests that the density of the equatorial wind in the inner part is significantly higher than assumed. Estimates based on momentum and mass conservation show that the required mass of the circumstellar material inside a radius $\approx 10^{15}$ cm is of the order of 0.5 M$_\odot$. The corresponding mass-loss rate must in this case be incredibly high, $\dot{M} \approx 1.5 \times 10^{-2}$ M$_\odot$ yr$^{-1}$ at a stage $t \approx 300$ yr prior to the explosion.

The degrees to which the parameters of models A and B meet dynamical and energy requirements show that model A is more realistic, since it suggests a one-order-of-magnitude lower mass-loss rate. Nevertheless, the ultimate choice should be postponed until the results of future observations become available.

## 3 POSSIBLE TESTING OF MODELS

The belt-like distribution of emitting material in model B will result in a central depression on top of the profile for intermediate-component lines, if the inclination angle is large enough. The most appropriate line for this test is the O I 8446-Å line, which must trace the most dense shocked material of the cylindrical shell. H$\alpha$ and other lines are not sensitive to this test since they may originate partially from other regions. Unfortunately, the available spectra of SN 1988Z are rather noisy at late times and no definite conclusions can be drawn concerning the shape of the O I line.

The clumpiness of the wind, which is characteristic of model A, should produce an irregular structure of the line profile since the expected number of clouds is relatively small, $\sim 10^2$. The strong H$\alpha$ line makes this test very promising. The required spectral resolution would be $\lambda/\Delta\lambda > 1000$.

The radial distribution of the emitting gas is essentially different in the two models. In model A the characteristic radius of the intermediate-component material is of the order of the radius of the main shock wave in the rarefied wind, i.e. $r_A \approx v_0 t$. On the other hand, for model B the radius of the emitting shell for the intermediate component is $r_B = v_{im} t$, where $v_{im}$ is the velocity of the intermediate component. There is a corresponding difference in radii of the order of a factor of 5–10, which permits an unambiguous choice between the models provided that the envelope is resolved. This test could become feasible with the advent of interferometric facilities on the VLT.

In both models the X-rays emitted by the shock wave in the dense wind component (clumps or equatorial wind) create a leading H II region in the undisturbed gas ahead of the shock. The overall luminosity of the leading H II regions should be roughly equal to that of the intermediate component. The bulk of the energy of the narrow lines is, however, expected to be emitted in the UV. Calculations of the spectrum of the leading H II region for a shock wave with a velocity of 1000 km s$^{-1}$ and a pre-shock density of $10^7$ cm$^{-3}$ (Daltabuit, MacAlpine & Cox 1978) show that the spectrum is dominated by O VI 1035 Å, C IV 1549 Å, and two-photon emission of hydrogen. The H$\alpha$ line and [O III] 5007 Å contain respectively 0.01 and 0.02 of the total luminosity. Unfortunately, in SN 1988Z the contribution of the narrow H$\alpha$ on day 492 is difficult to estimate. The narrow line [O III] 5007 Å has a luminosity of 0.025 of the total luminosity of the intermediate component (Turatto et al. 1993), which is consistent with expectations. This coincidence suggests that the radiative precursor of the cloud shock wave may contribute the bulk of the emission of the narrow component observed in SN 1988Z at $t \sim 1$–2 yr.

## 4 IS SN 1986J AN OLDER VERSION OF SN 1988Z?

Stathakis & Sadler (1991) noticed that the extremely luminous radio supernova SN 1986J discovered in the radio band in 1986, probably 4 yr after the explosion, had at that phase an optical spectrum (Rupen et al. 1987) that in many ways resembled the intermediate component of SN 1988Z. In both supernovae the dominant line at $t \sim 3$–4 yr is the unusually strong H$\alpha$ emission with FWHM $\approx 10^3$ km s$^{-1}$. The H$\alpha$ luminosity of SN 1986J at 4 yr is $L \approx 4 \times 10^{38}$ erg s$^{-1}$ (Leibundgut et al. 1991), which may be somewhat lower than the extrapolated H$\alpha$ luminosity of SN 1988Z, but is enormously high compared to normal Type II supernovae, for example $\approx 3 \times 10^{35}$ erg s$^{-1}$ for H$\alpha$ in SN 1987A at 4 yr. Both supernovae are characterized by remarkably steep Balmer decrements (H$\alpha$/H$\beta \approx 30$), and by the presence of the fluorescent line of O I 8446 Å, which is indicative of a large optical depth in H$\alpha$ which we estimate as $\tau \approx 10^3$.

The physical resemblance of these SNe is supported by the fact that they are the most powerful radio SNe, with luminosities $L_\nu \approx 10^{28}$ erg s$^{-1}$ Hz$^{-1}$ at 6 cm on day 1300 in SN 1986J (Rupen et al. 1987) and on day 560 in SN 1988Z (Sramek, Weiler & Panagia 1990).

The analogy between SN 1986J and SN 1988Z becomes even more significant if we take into account that, according to VLBI data (Rupen et al. 1987), the SN 1986J envelope is in fact expanding with a high average velocity of 15 000 km $s^{-1}$ ($D = 10$ Mpc). Coexistence of rapidly expanding ejecta with slow-moving optical material, and the spectral characteristics of the latter, leaves little doubt that SN 1986J at $t \approx 4$ yr is just an older example of SN 1988Z, the optical emission being dominated by the intermediate component and the broad component having already disappeared. To be specific, we identify the optical emission of SN 1986J with the radiation from the shocked dense component of the pre-SN wind (clumps or equatorial wind).

The radio data for SN 1986J provide some additional evidence in favour of the model of a clumpy wind. First, the irregular structure of the radio image of SN 1986J (Bartel, Rupen & Shapiro 1989) is consistent with a clumpy structure of the circumstellar wind. Clumpiness of the ejecta is another possibility. The problem with the latter is that the early optical spectra of SNeII do not provide any evidence for clumpiness in the outer layers of the envelope, which makes the idea of a clumpy wind more attractive. The second line of evidence for wind clumpiness arises from the results of modelling the radio variability. Weiler, Panagia & Sramek (1990) found that the evolution of the radio flux and of its spectrum in SN 1986J cannot be reproduced in a model of a purely external absorber, i.e. for the case of a spherically symmetric wind. Instead, they proposed that the absorbing plasma exists in the form of clumps which are partially mixed with the gas of relativistic electrons. This overall picture, in our opinion, is consistent with model A (Fig. 1a).

In contrast to the close similarity between SN 1988Z and SN 1986J at late times, there is strong evidence that their early behaviours were different. According to Cappellaro & Turatto (1986), between 1977 and 1986 this supernova never appeared above the limit $B = 18$ mag, which, for $D = 10$ Mpc and $A_V = 1.5$ mag, gives $M_B > -14$ mag. In spite of the annual lacuna 7–8 month after explosion in this photometry set (Cappellaro, private communication), the data completely rule out the possibility that SN 1986J might have a light curve similar to that of SN 1988Z with a width of 1.8 yr at the level $B = -14$ mag. The data for SN 1986J are consistent with the normal SNII light curve (Weiler, Panagia & Sramek 1990).

The different optical behaviours of SN 1988Z and SN 1986J close to light maximum suggest that the wind density in the immediate proximity of SN 1986J, $r \lesssim 5 \times 10^{16}$ cm, was lower than in the case of SN 1988Z, so that the early-time ejecta–wind interaction did not contribute substantially to the optical output of the former. An alternative possibility is strong obscuration of SN 1986J at early times by optically thick dusty clumps. The question of whether SN 1986J and SN 1988Z have identical natures is therefore open. However, they probably had similar mass-loss rates on a time-scale of (several)$\times 10^4$ yr and similar wind structures dominated by the clumpy component.

So far, only SN 1987F and SN 1988Z have been recognized as supernovae with high luminosities energized by an ejecta–wind interaction beginning at maximum light. These supernovae are observationally distinguished by (i) an unusually slow decay of the optical flux with a fall of $\Delta B = 2.5$ mag during the first year; (ii) high H$\alpha$ luminosity, exceeding $10^{41}$ erg $s^{-1}$ at 0.3–1 yr after explosion; and (iii) a specific H$\alpha$ profile without a P Cyg absorption component. We tentatively propose to call SNeII having all these properties SNeIIsw, with 'sw' standing for 'super-wind' or 'shock wave' – either is appropriate. We expect all SNeIIsw to be strong radio and X-ray emitters. Type II supernovae assigned by Schlegel (1990) to subclass SNIIn have at least property (iii) in common with SNeIIsw. One cannot therefore rule out the possibility that some (or even all) SNeIIn may prove to be SNeIIsw.

## 5 PROGENITOR OF SN 1988Z

The dynamics and energetics of the broad component of SN 1988Z indicate that the mass of the ejected envelope is surprisingly small, $M \lesssim 1$ $M_\odot$, and probably close to 0.5 $M_\odot$ (Section 2.2). With the reasonable assumption that about 1.5 $M_\odot$ of the pre-SN formed a neutron star during the explosion, one concludes that the mass of the pre-SN prior to the explosion was 2–2.5 $M_\odot$. Since the ejected supernova material contains a noticeable amount of hydrogen, the mass of the helium core in the pre-SN did not exceed 2.5 $M_\odot$.

Theory predicts that an He core of 2–2.5 $M_\odot$ at the final stage is a result of the evolution of a star with a main-sequence mass of 8–10 $M_\odot$ (Nomoto 1984). The distinguishing property of these pre-supernovae is the strongly degenerate O/Ne/Mg core, in contrast to the moderately degenerate Fe core produced by stars with initial masses $\gtrsim 12$ $M_\odot$. One may conjecture that strong degeneracy of the O/Ne/Mg core somehow favours an enormously high mass-loss rate for these pre-SN at the final stage of their evolution. In some respects the situation may be similar to that of intermediate-mass stars of 3–8 $M_\odot$, which lose all the massive envelope during the phase of the growth of a strongly degenerate C/O core. With the initial mass presumably equal to $\approx 9$ $M_\odot$, pre-SN 1988Z had to lose 7 $M_\odot$, i.e. nearly all the initial mass. For a mass-loss rate of $7 \times 10^{-4}$ $M_\odot$ $yr^{-1}$ (Table 1) this requires about $10^4$ yr.

If SNeIIsw originate from 8–10 $M_\odot$ main-sequence stars, their expected mass-loss rate for an IMF$\propto M^{-2.4}$ is $\approx 0.25$ of the overall rate of SNeII (i.e. SNe with $M_{ms} \geq 8$ $M_\odot$ including SNeIb/c). This frequency is qualitatively consistent with the rare occurrence of SNeIIsw.

## 6 CONCLUSION

The unusually high optical luminosities of the peculiar Type II supernovae SN 1988Z and SN 1987F were already recognized as being a result of the dynamical interaction of the supernova envelope with an extremely dense circumstellar wind, characterized by the parameter $w \sim 10^{17}$ g $s^{-1}$. Now it is becoming clear that the peculiar spectrum of SN 1988Z, particularly the coexistence of the broad and intermediate components, may be explained by the introduction of a two-component wind structure: dense clumps or a dense equatorial wind embedded in a spherically symmetric wind with a lower density. From the point of view of the minimal requirements of the mass-loss rate, the clumpy wind seems to be more realistic than the equatorial wind, although the ultimate choice should be postponed until the results of future observations become available.

It is not clear whether the clumpiness is a common phenomenon of dense winds around SNeII. SN 1987F seems to show no trace of the intermediate component, at least during the first year after the explosion. On the other hand, the model of the interaction of the ejecta with the clumpy wind accounts for the characteristics of SN 1986J at late times (4–7 yr), because it has a fast-moving radio shell and slow-moving optically emitting material. The same interpretation may be appropriate for the recently discovered radio and X-ray supernova in NGC 1313 (Ryder et al. 1992).

One of the unexpected results of the analysis of the dynamics and energetics of the formation of the broad component in SN 1988Z is the conclusion about the low mass of the ejecta, $<1\ M_\odot$, which indicates that this supernova originates from a main-sequence star with a mass of about 8–10 $M_\odot$. We propose that all SNeII with extremely high mass-loss rates (or SNeIIsw) arise from the lowest mass stars exploding as SNeII. If this is the case, SNeIIsw should be oxygen-poor, in contrast to SNeII-P, which originate from more massive stars.

An alternative view of the origin of SNeIIsw is that they originate from the same mass range as normal SNeII, but that the unusually large mass loss from the progenitors of the former is a result of common-envelope formation in close binaries at the red supergiant stage of pre-SN. In this case the low mass of pre-SN 1988Z might be just the accidental realization of one of numerous possibilities. This alternative has an obvious implication. If the phenomenon of a high mass-loss rate among pre-SNeII is associated only with the properties of binary systems, we expect that SNeIIsw, as well as SNeII-P and SNeII-L, could be of both types, oxygen-rich ($M_{ms} > 12\ M_\odot$) and oxygen-poor ($M_{ms} \sim 8$–$12\ M_\odot$). Extension of the sample of spectroscopically studied SNeII may test this conjecture.

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