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What was supernova 1988Z?

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SUMMARY

We present spectroscopy and photometry of the type II supernova SN 1988Z. This supernova was most unusual. Its characteristics include a high luminosity at maximum light, unusually slow fading at late times (0.005 mag d^{-1}), and strong narrow emission lines arising from dense ($>2\times10^6$ electrons cm^{-3}) circumstellar material. Broad emission features with $V\sim 10\,000$ km s^{-1} persisted for over a year and no absorption lines or P-Cygni profiles were observed, which is also exceptional for a type II supernova.

We argue that SN 1988Z does not belong to an exotic new class of supernovae, but was a normal type II supernova which had a progenitor at the upper end of the mass range for red supergiants (up to 40 $M_\odot$) with a dense, slow stellar wind which continued right up to core collapse. Most of the observed peculiarities can be understood in terms of an unusually massive stellar envelope. A pulsar formed during core collapse may be contributing to the slow decay in luminosity, but it is also possible that a substantial fraction of the excess energy comes from shocks.

1 INTRODUCTION

Our understanding of supernovae (SNe) continues to be limited by a lack of systematic observations over a long timescale. As van den Bergh (1988) points out, 'the discovery of a supernova contributes little to our knowledge if it is not followed up by detailed photometric and spectroscopic observations ... to determine its light curve and follow its spectroscopic evolution'. The explosion of SN 1987A has given new impetus to studies of supernovae, and has posed new questions. For example, is the late evolution of SN 1987A typical of type II supernovae? To what extent do type II supernovae differ, and are these differences related to physical characteristics of the progenitor star? Does the metallicity or morphology of a galaxy affect the type of supernova it produces?

In 1988, we began a program of regular observations of type II supernovae with the 3.9-m Anglo-Australian Telescope (AAT) in an attempt to address some of these questions. Our long-term aim is to observe about a dozen supernovae at several epochs spanning up to two years, and to examine the uniformity of their late-time evolution. So far, we have good coverage of three objects. Two of these, SN 1988A and SN 1988H, show evolution which is similar (though not identical) to SN 1987A, and we discuss them elsewhere (Stathakis *et al.* 1991, in preparation).

Here, we describe our spectroscopic and photometric observations of the 'peculiar' Type II supernova SN 1988Z, which has evolved very differently from other well-studied supernovae. Whether these differences warrant the establishment of a new subclass of supernovae, as suggested by Schlegel (1990), will depend on whether SN 1988Z is merely an extreme case of the usual phenomenon or is actually the result of a different explosion mechanism or a different kind of progenitor. We discuss this question on the basis of our results, with reference to current supernova theory.

2 OBSERVATIONS

SN 1988Z was discovered independently by Candeo at Asiago Observatory on a plate taken on 1988 December 12 00 UT (Cappellaro & Turatto 1988) and by Pollas at the Observatoire de la Cote d'Azur on a photograph taken on 1988 December 14 22 UT (Pollas 1988a). The supernova was already past maximum at this time, so the date of core collapse is not known. A previous observation at Asiago on 1988 March 13 does not show the supernova (Turatto, private communication), which still leaves an uncertainty of 270 d. Because the spectrum is so unusual and evolves very slowly, the explosion date cannot be estimated from the spectral evolution but it seems unlikely that the supernova could have exploded very much earlier than 1988 December because of its high luminosity when first observed. For convenience, we adopt 1988 December 1 as the date of core collapse and quote the age of the supernova from that date. If the supernova is older, then the unusual aspects discussed below become even more extreme.

Table 1. Details of observations.

UT Date	Age (days)	Observation	Instrument	Exposure (seconds)	Range	Position Angle
1989:01:04.73	34	photometry	RCA CCD	500	R	
				120	B V I	
1989:01:15.62	45	spectrum	FORS	2400	5300–10200	30°
1989:02:12.60	73	spectrum	RGO+IPCS	3600	3400–5370	206°
		spectrum	FORS	3600	5300–10200	206°
1989:06:29.39	210	spectrum	FORS	1500	5300–10200	140°
1990:03:21.53	475	spectrum	FORS	4500	5300–10200	206°
1990:06:22.35	568	photometry	RCA CCD	300	V	
				100	R	

Table 1 gives details of our observations of SN 1988Z, which comprise direct CCD frames at two epochs and spectra at four epochs. The CCD frames were taken on service observing nights at the AAT and calibrated using E-region standards listed by Graham (1982).

Four spectra were taken with the AAT Faint Object Red Spectrograph (FORS), a fixed format spectrograph with a 575 × 385 GEC CCD detector covering the 5300–10 200 Å spectral range with 10 Å pixel^{-1} dispersion. The spectral resolution is 20 Å for a slit width of 2 arcsec. On 1989 February 12 (day 73) the light was split using a dichroic mirror so that a simultaneous observation of the blue spectrum could be made with the 25-cm camera of the RGO spectrograph and the IPCS detector. This spectrum covers 3400–5370 Å at 3 Å resolution. In all cases, the spectrograph slit was aligned close to the parallactic angle to minimize the effects of differential refraction. This was particularly important in the case of SN 1988Z which, at declination +16°, is always at a high airmass as seen from the AAT.

All spectra were reduced with the FIGARO reduction package (Shortridge 1991). Observations of a hot metal-poor star with an essentially featureless continuum spectrum were used as a template to remove telluric absorption lines from the supernova spectrum, and the spectra were flux calibrated using a spectrophotometric standard star. However, both the narrow (2 arcsec) slit and the fact that conditions were not always photometric meant that a zero-point correction was needed. We extracted a pseudo *R*-band magnitude from each FORS spectrum using the transmission curve given by Bessell (1979), and applied a scaling correction to the fluxed spectra so that this matched the interpolated *R* magnitude from the photometric light curve. Corrections required were always less than a factor of 2. A resulting error of ~20 per cent in the final fluxes is likely, given the sparseness of the photometry at late times.

3 THE PARENT GALAXY

SN 1988Z occurred in MCG + 03 − 28 − 022 (Zw 095 − 049), a low-surface-brightness spiral galaxy with $cz = 6670$ km s^{-1} and $B = 15.6$. The two CCD frames taken in the *R* band on days 34 and 568 are shown in Fig. 1. The galaxy has an indistinct nucleus and a cluster of H II regions, probably including the faint features at the north edge of the frame. A red object lies just north of the supernova, and is resolved in the image taken on day 568. A poor-quality spectrum of this object suggests that it is a foreground star rather than a H II region, though a blue spectrum is required for confirmation. High-resolution spectroscopy of the galaxy nucleus is still needed to determine the metallicity of MCG + 03 − 28 − 022 and to understand the local environment of SN 1988Z in detail, but this is best done once the supernova has faded.

4 THE LIGHT CURVE

The photometry in all bands is listed in Table 2, and plotted in Fig. 2, together with photometry reported in the IAU circulars (Cappellaro & Turatto 1988; Pollas 1988b; Pollas 1989; Gaskell & Koratkar 1989). As a reference, the average *B* and *V* type II plateau light curves (Doggett & Branch 1985), are also plotted, shifted vertically to match SN 1988Z on days 11 and 34 respectively.

As noted above, the supernova lies about 2.2 arcsec south of a second object, probably a foreground star, which can be seen in Fig. 1. Particular care was therefore taken in measuring the magnitudes on day 568, when the supernova was roughly the same brightness as the foreground star. Table 2 quotes the integrated magnitude in an aperture of 2.5 arcsec radius centred on the supernova. The sky background (which here includes light from the galaxy disc) was measured in an annulus of inner radius 5 arcsec and outer radius 6 arcsec, also centred on the supernova. Clearly this will exclude some of the supernova light, and include some light from the adjacent star, but we believe that the error bars quoted in Table 2 accurately reflect the uncertainty involved. We also checked our measurements by fitting Gaussians to the integrated luminosity profile of the supernova plus foreground star in the north–south direction. The composite profile is well fitted by two Gaussians, each with $\sigma = 1.3$ arcsec (chosen to match the seeing), if the supernova is roughly 0.3 mag brighter than the star in *R* and 0.2 mag fainter than the star in *V*. Eventually, once the supernova has faded below magnitude 23–24, it will be possible to measure more accurate magnitudes by subtracting a reference frame from the data obtained here.

SN 1988Z was bluer than usual at early times, but the most remarkable feature is its brightness on day 568. The decay in the *V* band between days 102 and 568 is

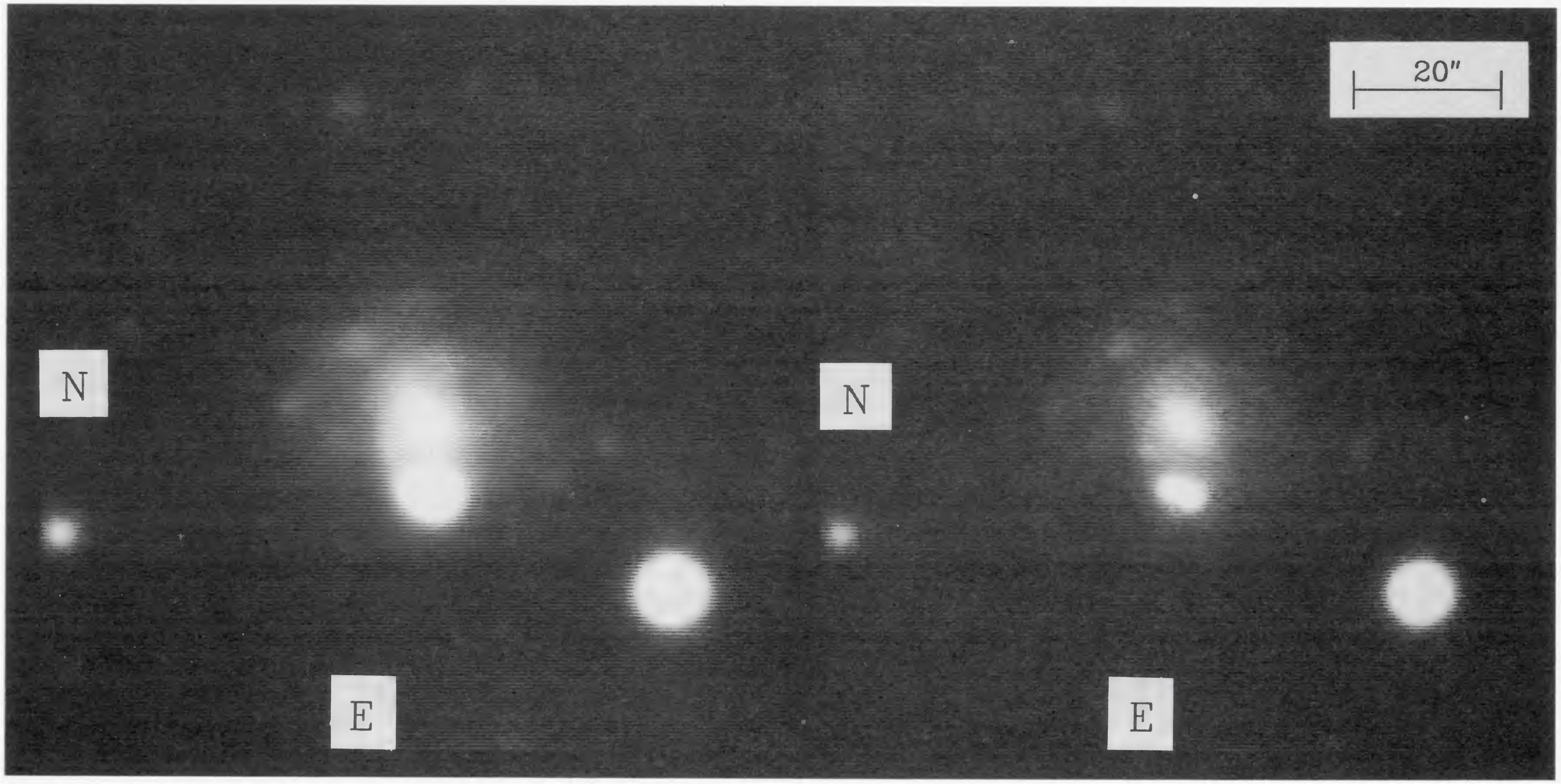

Figure 1. CCD frames of MCG $+03-28-022$ taken on 1988 January 4 and 1990 June 22. The supernova SN 1988Z is visible on both frames below the nucleus. In the later frame the supernova has faded sufficiently that we can resolve the nearby foreground star (the SN is on the right).

1991MNRAS.250..786S

Table 2. Photometry results.

UT Date	Age (days)	Band	Magnitude	Uncertainty
1989:01:04.73	34	B	16.92	±0.04
		V	16.62	±0.04
		R	16.16	±0.04
		I	16.01	±0.04
1990:06:22.35	568	V	19.7	±0.3
		R	18.5	±0.3

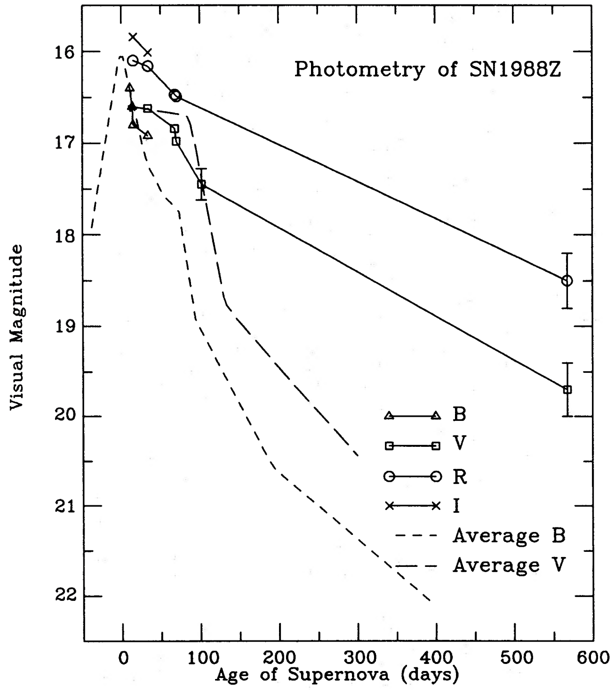

Figure 2. Photometry of SN 1988Z. The age of the supernova is quoted from 1988 December 1. The observations on days 34 and 568 were taken at the AAT. The other photometry were reported in the IAU circulars (references in text). Error bars are shown where significant. Also shown are the average *B* and *V* light curves from Doggett & Branch (1985), scaled to the data on days 11 and 34 respectively.

0.005 ± 0.001 mag d^{-1}. Turatto *et al.* (1990) find an average type IIP decay rate at late times of 0.0088 mag d^{-1}, while the average for all type II supernovae is 0.0089 ± 0.0004 mag d^{-1}. SN 1988Z is completely outside this range, and contamination from the nearby star cannot account for the extra luminosity. While the lack of photometry between days 102 and 568 is a handicap, spectra taken between these dates support a linear interpolation to within ± 1 mag.

The average absolute magnitude at maximum is not well determined for type II supernovae, and there are clearly large intrinsic variations. Young & Branch (1989) find a scatter of about 6 mag in M_B at maximum, which cannot be explained by extinction. They find a mean of ~ -16.1 mag ($H_0 = 100$ km s^{-1} Mpc^{-1}), with most objects falling within ±1.5 mag of this. SN 1988Z, with $(m-M) = 34.08$, $M_B = -17.6$ at maximum, is brighter than average but not unusually so.

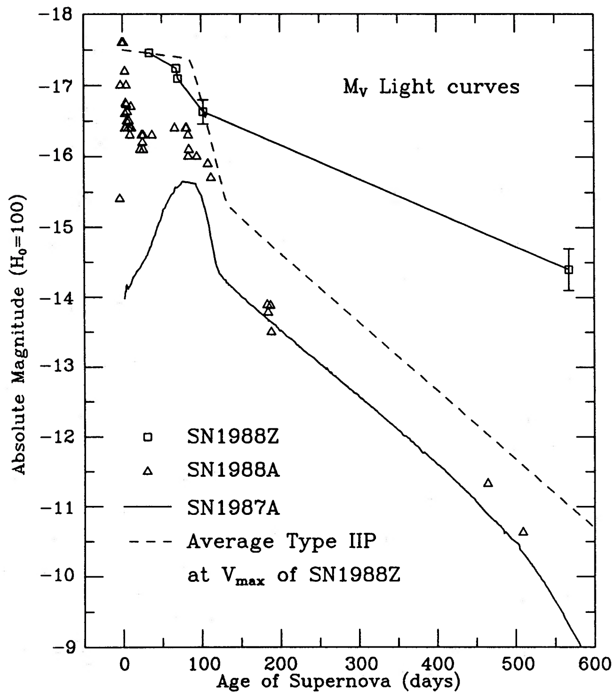

Figure 3. Absolute magnitude light curves of SN 1988Z, SN 1988A (a typical type II supernova) and SN 1987A. Also plotted is the average *V* light curve (Doggett & Branch 1985), scaled to SN 1988Z at day 34, as in Fig. 2, and extrapolated to day 600.

In Fig. 3 we compare the evolution of absolute magnitude M_V for SN 1988Z with that of SN 1988A, a typical type IIP SN, and SN 1987A. The photometry of SN 1987A is from SAAO (Menzies *et al.* 1987; Catchpole *et al.* 1987; Catchpole *et al.* 1988; Whitelock *et al.* 1988; Catchpole *et al.* 1989), while the light curve of SN 1988A is taken from Ruiz-Lapuente *et al.* (1990), who list the sources for the individual observations. We adopt a distance modulus of 31.13 (Tully 1988) for SN 1988A, which lies in the Virgo cluster.

Fig. 3 also shows the average *V* light curve for type IIP supernovae from Doggett & Branch (1985), shifted to match SN 1988Z as in Fig. 2. At day 568, SN 1988Z is 5.3 mag brighter than SN 1987A and 3.4 mag brighter than expected if it had followed the same path as the average *V* light curve. This implies an excess energy output of 2.2×10^{40} erg s^{-1} in the *V* band compared with a normal type II plateau supernova with the same maximum brightness.

5 THE CIRCUMSTELLAR LINES

The most noticeable features in the supernova spectrum are the strong narrow emission lines at $z = 0.0222$ which are typical of hot nebulae. These lines are unresolved (FWHM < 200 km s^{-1}) on day 73, and careful inspection of our spectral frames confirms that they are associated with the supernova rather than the nearby object. Also, the lines are seen to evolve and broaden with time, which is most easily explained by their association with the supernova event. Similar narrow lines have been seen in SN 1987A (e.g. Wampler & Richichi 1988) and analysed in detail by

Lundqvist & Fransson (1991). The lines arise in circumstellar material (CSM) released from the progenitor as a stellar wind and excited by the UV pulse shortly after core collapse.

The measured line fluxes and widths are listed in Table 3. The combined spectrum in the red and blue taken on day 73 is plotted in Fig. 4, and the evolution of the red spectra is shown in Fig. 5, normalized to the continuum at 8000 Å. The narrow lines detected on day 73 are the Balmer lines of hydrogen, strong [O III] and [Ne III] lines and weak lines of [O II], He I and He II. There is a notable absence of [S II] 6716, 6731 Å.

The Balmer decrement is much steeper than expected for Case B recombination, especially for the lower terms. This is to be expected for Case C recombination, where the Lyman and Balmer continua are optically thick (Xu 1989). The He I line ratios also fail to match Case B recombination. The He I 7056 Å to He I 5876 Å ratio changes from 1.04 on day 73 to 0.36 on day 475, which is much closer to the Case B ratio of ~0.12 (Osterbrock 1989) and probably indicates a decline in optical depth in helium. On day 475, O I 8446 Å was seen for the first time. The absence of O I 7774 Å, which is stronger than O I 8446 Å in recombination and collisional excitation spectra, suggests that the 8446 Å line is produced by Ly β pumping (Grandi 1980). This mechanism is favoured when hydrogen and oxygen coexist and are mostly neutral, and when the material is optically thick in Hα. The Balmer decrement, He I ratios and the presence of O I 8446 Å all suggest that the CSM has high optical depth.

The ratio of [O III] 4969, 5007 Å to [O III] 4663 Å is generally used to determine an electron temperature. In the day 34 spectrum this ratio is 2.9, which is far lower than is possible in the low density regime. At higher density (Osterbrock 1989),

$$\frac{I_{4959}+I_{5007}}{I_{4363}} \approx \frac{7.73\exp[(32.29\times 10^{4})/T]}{1+4.5\times 10^{-4}(N_{\rm e}/T^{1/2})}.$$

Though both the temperature and the density are unknown, at a ratio of 2.9 the electron density has a minimum of 1.89×10^{6} cm^{-3} at $T_{\rm e}=90\,000$ K. The actual electron temperature is most likely to be in the range 10 000–20 000 K in order to produce the line species we observe. At these temperatures, the electron density will be between 1.6×10^{7} and 4×10^{6} cm^{-3}.

The line profiles of Hβ and Hγ on day 73 are peculiar, with a weak broad component (FWHM ~ 2000 km s^{-1}) and a strong unresolved component. Though the resolution is too poor to separate the two components in Hα, the profile is consistent with that of Hβ (Fig. 6). Unfortunately we have no later observations of the blue lines, so the evolutionary information is confined to three CSM lines: Hα, He I 5876 Å and He I 7065 Å. All three of these lines broadened between day 73 and day 210 to a FWHM of between 1200 and 1800 km s^{-1} (see Table 3) and remained constant up to day 475. We suggest that on day 73 we observed two spatially distinct regions of the CSM. The narrow component arises from material which has been excited by the UV flash, as observed in SN 1987A, while the weak broad component could be produced by accelerated material at the shock caused by the collision of the supernova envelope with the CSM. The broadened lines at later epochs are dominated by the ac-

Table 3. CSM lines: fluxes and velocity widths.

Age (days):		45		73		210		475	
Line	λ_0	FWHM	Flux	FWHM	Flux	FWHM	Flux	FWHM	Flux
Hα	6563	<1000	370	<1000	500	1860	1200	1840	1400
Hβ	4861			<200	70				
Hβ*	4861			<200	26				
Hγ	4340			<200	17				
Hγ*	4340			<200	7.9				
Hδ	4101			<200	5.6				
Hϵ	3970			<200	4.9				
HeI	5876	<1000	26	<1000	21	1220	24	1450	17
HeI	7065	<1000	27	<1000	20	2170	16	1240	6.2
HeI	6678	<1000	4.6	–	–	–	–	–	–
HeI	3889			<200	4.3				
HeII	4686			<200	7.2				
OI	8446	–	–	–	–	–	–	1220	16.5
[OII]	3727,9			<200	8.4				
[OIII]	4363			<200	14				
[OIII]	4959			<200	7.8				
[OIII]	5007			<200	32				
[NeIII]	3869			<200	46				
[NeIII]	3966			<200	17				

Fluxes in units of 10^{-16} erg s^{-1} cm^{-2}. Velocity in km s^{-1}. A dash indicates a non-detection.

*Measurement not including the broad base.

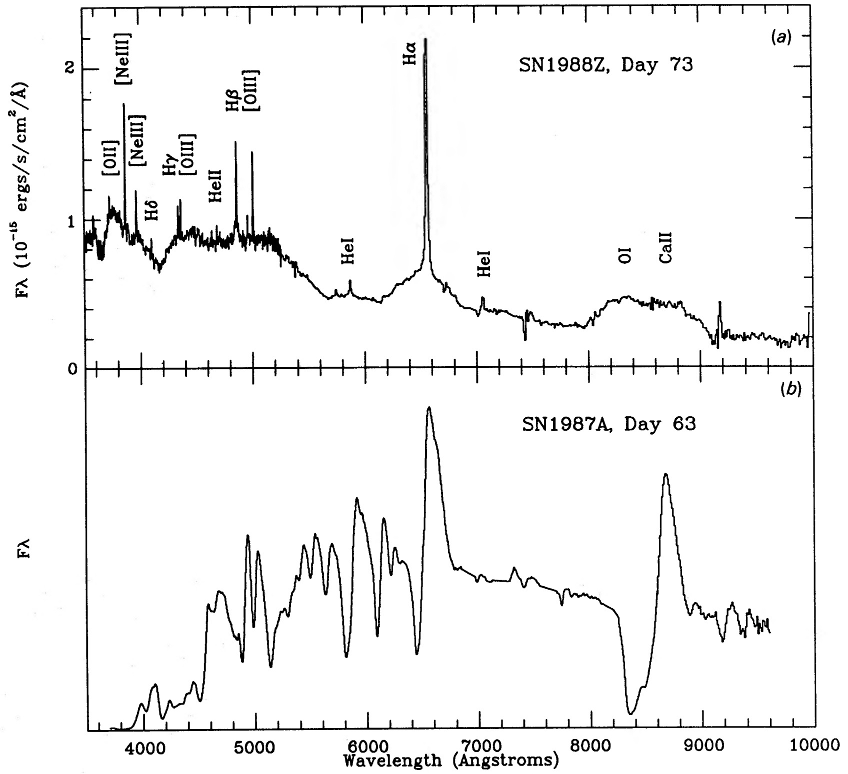

Figure 4. Combined red and blue spectra of SN 1988Z taken on 1989 February 12 (day 73). The strong narrow lines originate in the CSM formed by the stellar wind. The lower panel is a spectrum of SN 1987A over the same wavelength range, and at a similar epoch (day 63). The two spectra are very different.

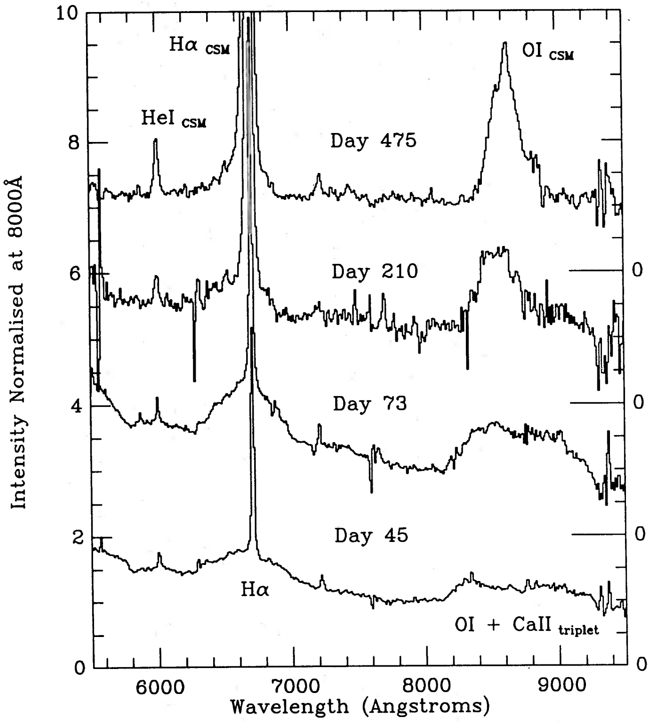

Figure 5. The spectral evolution of SN 1988Z. The spectra have been normalized at 8000 Å, which we believe is a line-free part of the spectrum. The zero level for each spectrum is shown at the right. Note the broadening of the narrow component of Hα, and the strengthening of O I 8446 Å, which has developed a narrow component by day 475.

celerated material at the shock front. It is most unusual to observe the collision of the envelope with the CSM at such early times, and this suggests that the progenitor of SN 1988Z had a very dense, slow stellar wind which continued right up to core collapse.

6 THE SUPERNOVA SPECTRUM

Underlying the narrow nebular lines, the spectrum of SN 1988Z has very broad emission lines which originate in the supernova envelope (Figs 4 and 5). Fluxes and velocity measurements are listed in Table 4. The variation in velocity width of the broad component of Hα is shown in Fig. 6. The broad and narrow components are quite distinct on day 210, supporting the view that the 1800 km s^{-1} component is a broadened CSM line rather than a narrowed SN line. The maximum velocity observed, 20 000 km s^{-1} on day 45, is typical of a supernova within one or two days of maximum. The broad component narrows with time, but around 20 times more slowly than in SN 1987A. The broad components of Hα and O I 8446 Å are blueshifted relative to the CSM component by 2000–3000 km s^{-1}. A blueshifted profile could be produced by high optical depth, since the red wing of the line which corresponds to material on the far side of the supernova from us has a longer path-length to travel and could be damped compared to the blueshifted emission.

The other line species observed are typical of young type II SNe – He I 5876 Å, the IR Ca II triplet and probably a blend of iron group, calcium and Balmer lines in the blue. The broad depression between 4000 Å and 4200 Å is likely

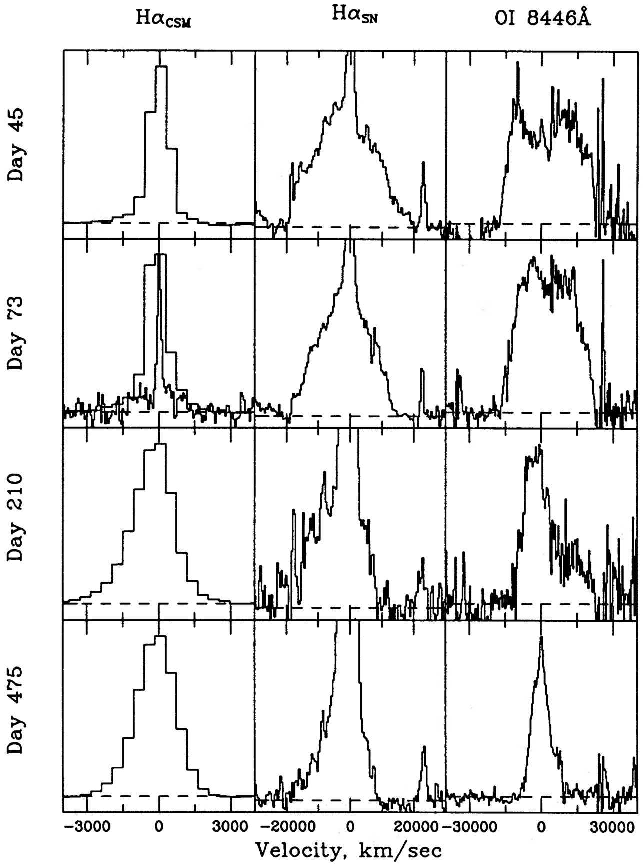

Figure 6. Evolution of velocity widths. The circumstellar component, and the broad component of Hα, and Lyβ pumped O I 8446 are plotted for each epoch after subtraction of the underlying spectrum. O I is blended with the Ca II triplet lines. The broad component of both Hα and O I is blueshifted with respect to the CSM emission, probably an effect of the high optical depth in the envelope. On day 73 the profile of CSM Hβ is plotted on top of Hα to show that the line is unresolved, and that the broad wing seen in Hβ is also present in Hα. This intermediate width component strengthens by day 210 to dominate the CSM lines, and arises from the region of the CSM accelerated by the SN shock.

Table 4. SN lines: fluxes and velocity widths.

Age (days):	45	73	210	475
Hα				
FWHM	27700	22300	22300	19200
CVHM	-2350	-2000	-3800	-3100
HWZI	20100	17000	12200	14700
BVZI	-20200	-18900	-16200	-20200
RVZI	+20000	+15000	+8300	+9200
FLUX	950	990	255	79
OI 8446Å				
FWHM	18300:	15800:	12200	9400
CVHM	-6200:	-3700:	-1900	-500
BVZI	-17300	-17000	-12100	-8600
FLUX	633	915	608	246

Notes on Table 4: fluxes in units of 10^{-16} erg s^{-1} cm^{-2}; velocity in km s^{-1}; FWHM – full width at half maximum; CVHM – central (mean) velocity at half maximum; HWZI – half width at zero intensity; BVZI – blue edge of line at zero intensity; RVZI – red edge of line at zero intensity; O I 8446 Å is blended with Ca II triplet, so some values are uncertain and others cannot be measured. The contribution of the CSM component to the flux has been removed.

to be a gap between emission regions rather than an absorption line. Surprisingly, we see no sign of the supernebular forbidden lines such as [O I] 6300, 6363 Å and [Ca II] 7320 Å which normally appear a few months after maximum in type II SN. Very slow spectral evolution is implied.

The presence of strong O I 8446 Å implies that the emitting region of the envelope has oxygen and hydrogen in the same volume and is optically thick in Hα, using the same arguments as in Section 5. Blackbody curves fitted to the spectra on days 45, 73 and 210 suggest a continuum temperature of 5750 ± 750 K, which is not unusual for supernovae in the plateau phase. The unusually blue colour of SN 1988Z mentioned in Section 4 is not due to high temperature, but rather to the strength of the emission lines in the blue.

The most peculiar feature of the broad line spectrum of SN 1988Z is the absence of absorption lines and P-Cygni profiles which normally dominate the spectrum of type II supernovae at early times, especially when the lines are broad (note the spectrum of SN 1987A at a similar age in Fig. 4, lower panel). The lack of absorption might be explained by a very low-mass envelope, but the slow evolution, broad lines and Lyβ pumped O I 8446 Å are all consistent with a massive envelope of high optical depth. A second possibility is that the radius of the photosphere is far smaller than the radius of the emission line region (Spyromilio, private communication). The absorption produced by envelope material in the line-of-sight of the photosphere would then be very weak compared to the emission from the full envelope.

Applying Stefan's Law to the blackbody fit obtained on day 73 suggests that the photosphere radius is 12 per cent of the emission line region radius, assuming free expansion. A rough calculation shows that only ~1.2 per cent of the volume would produce absorption, so this result is consistent with the observed line profiles. To have such a large emission line region compared to the photosphere requires a progenitor with a very large radius and a low density envelope which, because of its size, contains a great deal of mass.

7 WHAT WAS IT?

We will now attempt to determine, from the evidence assembled above, exactly what kind of event gave rise to SN 1988Z. We know that this supernova was brighter than average at maximum light, which implies that its progenitor had a large radius and hence was a red supergiant rather than a more compact blue supergiant (Young & Branch 1989). There is independent evidence for this: the lack of absorption lines in the spectrum also implies that the progenitor had a large radius, and furthermore that its density was low. The slow decrease in velocity width, the slow spectral evolution, the presence of Lyβ pumped O I 8446 Å and the blueshifted line profiles all imply a very massive envelope with high optical depth. In addition, we know from the behaviour of the circumstellar lines that the star must have had a slow, dense stellar wind which continued up to core collapse.

All of this is consistent with the progenitor of SN 1988Z being an unusually massive red supergiant, possibly with $M \approx 40\ M_\odot$. We know that the event which produced SN 1988Z must be intrinsically rare, since this supernova is both luminous and peculiar. At the distance of the Virgo cluster SN 1988Z would have been brighter than 13th magnitude at maximum and brighter than $V = 15$ for more than a year, so it is most unlikely that a large population of similar objects would have escaped attention. Since stars above 40 $M_\odot$ comprise perhaps 1 per cent of red supergiants massive enough to explode as type II supernovae (i.e. above 8 $M_\odot$), one might expect objects like SN 1988Z to comprise only a tiny fraction of all observed type II supernovae. On the other hand, both their high luminosity at maximum and the fact that they decay relatively slowly in brightness means that they can be seen at larger distances and for a longer time above any given survey threshold, so that one might not be too surprised to find them comprising up to 10–20 per cent of all observed type IIs.

Could a large population of supernovae like SN 1988Z have escaped detection? There are very few supernovae for which good spectra and light curves extend for more than a year after core collapse, and many of SN 1988Z's peculiarities became apparent only after several months of evolution. A recent study of extended light curves by Turatto *et al.* (1990) is consistent with an upper limit of 10–20 per cent of all supernovae, but far better statistics will be needed before a more definitive estimate can be made.

Woosley & Weaver (1982, 1986) have modelled supernova events for stars more massive than 100 $M_\odot$. These stars have a different collapse mechanism from less massive supergiants. Oxygen burning is not ignited in a stable fashion, the high temperatures ($T \sim 2 \times 10^9$ K) lead to rapid creation of e, e^+ pairs and this energy loss leads to collapse of the star. The predicted light curves for these objects bear no resemblance to our observations of SN 1988Z, so it is unlikely that SN 1988Z resulted from this collapse mechanism and hence its progenitor was probably less massive than 60 $M_\odot$.

One peculiarity of SN 1988Z which remains unexplained is the slow decay in brightness with time. One possible explanation for unusually high supernova luminosity at late times is a strong contribution from a light echo (Schaefer 1987). In the case of SN 1988Z this cannot explain the observations since, though the spectral evolution is slow, the spectrum on day 475 is markedly different from the spectrum on day 45. A light echo, on the other hand, would have the spectrum of the SN at about maximum light. Another possibility is that by day 568 we are detecting excess energy from a source other than the normal radioactive decay processes. This excess energy might perhaps be due to a pulsar which formed during core collapse, which appears plausible since type II SNe are believed to form pulsars. However, the excess energy required (2.2×10^{40} erg s^{-1} in V) is very high compared to X-ray luminosities measured for well-known pulsars. Typical energies are around 10^{37} erg s^{-1}, while the most energetic, SMC X-1, emits 10^{39} erg s^{-1} (Trumper & Fink 1982). One way to provide more energy is via a mechanism first proposed for SN 1987A, in which the neutron star formed by the initial collapse collapses again to form a black hole (Hillebrandt *et al.* 1987). The envelope of the SN would not be affected at first, and the energy released would be far greater than for a pulsar. At the distance of SN 1988Z, these two compact sources would be difficult to differentiate. If all the excess energy was due to a pulsar or black hole, the light curve should remain essentially constant at the level observed on day 568.

An alternative explanation is that the high optical depth of the envelope has temporarily trapped the radioactive decay energy and that this energy is now escaping, thereby slowing the decay of the light curve (Woosley & Weaver 1986). In this case, the supernova light curve would slowly approach that for normal type II supernovae as the optical depth in the envelope decreased. The luminosity would continue to decline at an accelerating rate until it reached the canonical decay rate of roughly 0.01 mag d^{-1}. Indeed, both mechanisms might operate, since an optically thick envelope could store, and therefore magnify, the energy output from a pulsar (Peterson, private communication). In this last case, the decay rate of the light curve would accelerate and then level off at the energy level of the pulsar once the envelope became optically thin. Photometric observations of SN 1988Z in the third season would differentiate between these cases.

Another possibility, discussed recently by Chugai (1991), is that shock heating from the ejecta-wind interaction may be an important source of power at late times. Chugai notes that plots of Hα line luminosity as a function of time appear to offer the most promising diagnostic for discriminating between radiation and shocks, but also points out that modelling is still in progress and the physics of the interaction between shock and wind is not yet well understood.

Perhaps the most important point for SN 1988Z is that there are several plausible mechanisms which might provide the excess late-time luminosity. There is also a good chance that observations of both the light curve and the Hα luminosity at even later epochs will allow the dominant mechanism to be determined.

8 COMPARISON WITH OTHER SNe

How unusual is SN 1988Z, and have other similar objects been observed or modelled? To explore this question we compare SN 1988Z to several SNe which share some common characteristics.

8.1 SN 1984E

The first time CSM lines were identified in a supernova close to maximum light was in SN 1984E. These lines were very luminous, but only short-lived. The density of the gas was estimated to be 3×10^8 cm^{-3} (Gaskell & Keel 1988), which is 10–100 times more dense than the CSM around SN 1988Z. The line widths imply a velocity of 250–350 km s^{-1}, which is faster than typical red supergiant winds. Dopita *et al.* (1984) suggested that the CSM was the product of a superwind shortly before collapse, but Gaskell & Keel (1988), after examining pre-discovery images, found that the material had been deposited as a discrete 'event' between 1961 and 1981. The CSM emission had disappeared by one year after maximum, and the supernova itself decayed rapidly, with a light curve typical of a type IIL. The underlying supernova spectrum was not unusual, and the lines showed P-Cygni profiles. The rapid decline of SN 1984E suggests that there was only a small mass of hydrogen remaining in the envelope. The CSM appears to have been dense, but small in extent and mass, and was probably disrupted when it was hit by the expanding SN envelope.

Consequently, though the strong CSM lines are superficially similar to those seen in SN 1988Z, there appears to be little relationship between the two supernova events. Subsequent observations have shown that CSM lines are not uncommon in supernovae (Schlegel 1990). Since mass loss is expected during the later stages of supergiants, especially for the more massive stars, CSM line emission is to be expected. It was probably often missed in the past either because the narrow emission lines were assumed to come from a nearby H II region or the galaxy nucleus, or else because of the steep Balmer decrement, since photographic spectra often only covered the blue part of the spectrum.

The existence of CSM lines probably has little to do with the type of progenitor or physical mechanism of the explosion. Falk & Arnett (1977) have modelled the effect of CSM on a supernova explosion. They find that it broadens the initial peak, but only by ~20 d. Since most massive stars undergo mass loss, the presence of CSM lines does not indicate a particular type of progenitor. So, though the details of the CSM emission are certainly useful in obtaining characteristics of the progenitor evolution in the last epoch before collapse, it is not appropriate to base a new supernova type on the detection of CSM lines, as suggested in Schlegel (1990). Some of the supernovae he presents may well be similar to SN 1988Z, but this can only be determined by comparing the broad line spectra and the late-time light curves.

8.2 SN 1961V

Other supernovae have been observed to have very slow decay times. These 'slow' supernovae are often classed as Zwicky type V supernovae, and the canonical example of this class is SN 1961V. The progenitor of this supernova was very bright, at $M_{pg} = -12$, for at least 24 yr before outburst (Branch & Greenstein 1971). During the outburst it peaked at $M_{pg} = -18$ in 1961 December, dropped to $M_{pg} = -11.5$ after 15 months, and then decayed very slowly, dropping only three more magnitudes in 8 yr (Bertola & Arp 1970). Its average decay rate of 0.001 mag d^{-1} was 10 times slower than for typical type II SNe. Though both SN 1988Z and SN 1961V both have slow decay times, their light curves are quite different since SN 1988Z did not undergo a rapid drop in brightness after maximum. The spectral lines of SN 1961V were unusually narrow (~2000 km s^{-1}) during the outburst, and had P-Cygni profiles, so the spectral characteristics were also unlike those of SN 1988Z.

A recent analysis by Goodrich *et al.* (1989) suggests that SN 1961V was a superoutburst of a luminous blue variable (LBV) like η Carinae, rather than a supernova. They argue that the bolometric magnitude remained constant even though the photographic magnitude varied, and that the observed evolution was due to temperature changes which altered the bolometric correction. This behaviour is typical of LBV outbursts.

Goodrich *et al.* are able to account for the energy released in SN 1961V without the need for a supernova explosion because the velocities observed in the 1961V event were 10 times lower than typical maximum velocities for SNe. In the case of SN 1988Z the colour remains fairly constant so that we know the bolometric luminosity must vary. Because very high velocities are observed in SN 1988Z, the energy involved is far greater than in SN 1961V even though the two supernovae had similar absolute maximum brightnesses. It is unlikely, therefore, that SN 1961V and SN 1988Z are physically related, and we are confident that SN 1988Z is a true supernova.

8.3 SN 1986J

Rupen *et al.* (1987) describe some intriguing features of SN 1986J, which lies in the disc of a nearby edge-on spiral galaxy, NGC 891, and was first detected in the radio continuum rather than optically. SN 1986J is presumed to have exploded in late 1982 or early 1983, but because of its late detection the first optical spectrum was taken only in 1986 September when the supernova was probably between three and four years old. From the sparse information available, SN 1986J appears to resemble SN 1988Z both in the appearance of its late-time spectrum (in particular, both objects show strong He I recombination lines at late times, and SN 1986J also appears to have the Ly β-pumped 8446 Å O I line identified in SN 1988Z) and in fading unusually slowly. SN 1986J has a decay rate of only 0.001 mag d^{-1} in R between 1984 January and 1986 September, which is an even slower decline than SN 1988Z.

Rupen *et al.* suspect that SN 1986J results from the explosion of an unusually massive star, which again suggests a physical similarity to SN 1988Z. They also tentatively classify SN 1986J as a type V supernova, but this seems unlikely to us both on the basis of the same arguments applied to SN 1988Z in Section 8.1 above and because the narrow lines seen in the 1986 September spectrum, on which Rupen *et al.* base their type V classification, also occur in most normal type II supernovae at late times. As Chevalier (1987) points out, the low velocities seen at late times simply indicate that we are seeing slow-moving material which originated in the central regions of the supernova. We have no way of knowing what the line widths were at earlier epochs in SN 1986J.

Perhaps the most unusual feature of SN 1986J is its high radio luminosity. The recent VLA detection of SN 1988Z in the radio continuum (Sramek, Weiler & Panagia 1990) suggests that it too is an unusually luminous radio source. SN 1986J had a peak 6-cm radio flux of 128 mJy in 1986 May, roughly 1300 ± 250 d after explosion (Rupen *et al.* 1987; Weiler, Panagia & Sramek 1990). This corresponds to a 6-cm radio luminosity around $10^{20.9}$ W Hz^{-1} if we adopt the distance of 7.7 Mpc ($H_0 = 100$ km s^{-1} Mpc^{-1}) used by Rupen *et al.* (1987). For SN 1988Z, at a distance of roughly 67 Mpc, the 6-cm flux of 1.21 ± 0.07 mJy observed in 1990 May, around day 560 (Sramek, Weiler & Panagia 1990), corresponds to a luminosity of $10^{20.8}$ W Hz^{-1}. Thus the radio output of SN 1988Z is already more than half the peak output of SN 1986J, and may still be increasing.

It remains somewhat disconcerting that SN 1986J was not detected optically even though it occurred in a nearby galaxy which was regularly monitored (Cappellaro & Turatto 1986).

If SN 1986J is indeed a member of the same class as SN 1988Z, this once again raises the question of the true frequency of such events. One possibility discussed by Rupen *et al.* is that SN 1986J lies in a region of high optical extinction, though they conclude that the extinction is more likely to be around 2 mag in *V*. If this is correct, SN 1986J was probably intrinsically less luminous than SN 1988Z. If, on the other hand, SN 1986J had the same luminosity as SN 1988Z, it would require at least 5 mag of extinction in *B* to prevent it having been seen on at least one of Cappellaro & Turatto's plates (which were taken roughly 100 d apart). This certainly cannot be ruled out at present, and it may be that the anaemic nature of SN 1988Z's host galaxy (MCG $+03-28-022$, at $M_B = -18.5$, is about 1.5 mag less luminous than NGC 891 and appears from our CCD frames to contain little dust) gave us a rare glimpse of an event which is more usually hidden by dust.

9 CONCLUSION

We believe that SN 1988Z was a normal type II supernova whose unusual appearance comes about because its progenitor star was a red supergiant at the upper end of the mass range. This progenitor also had a dense, slow stellar wind which continued right up to core collapse, giving rise to the strong, narrow emission lines which characterize our spectra of this object. More detailed modelling of this supernova would be desirable to further quantify these conclusions. We suggest that the unusual luminosity of SN 1988Z on day 568 could be due to a superluminous pulsar or black hole or, more likely, to trapping of the radioactive decay energy in the optically thick envelope or shock heating from the ejecta-wind interaction. A normal pulsar might also be amplified by a dense envelope. These mechanisms could be distinguished by extending the *V* light curve with further photometry, and by continuing to monitor the evolution of the Hα luminosity.

Further spectroscopic and photometric observations of evolved supernovae would provide useful statistics concerning the frequency of objects similar to SN 1988Z. Radio and optical observations of SN 1988Z for several years would help determine whether SN 1986J is a similar object. If our assumptions about the progenitor of SN 1988Z are correct, determining the true fraction of type II supernovae which fall into this mass range should give valuable information about the initial mass function of star-forming regions in different environments.

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