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The late evolution of the type II SN 1990E*

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Abstract. New observations of SN 1990E in NGC 1035 are presented, mostly obtained long after maximum, during the linear decline phase. The B, V and R photometry closely resembles, up to late epochs, that of other SNII Plateau. In particular the shape of the light curves and, after correction for extinction, the absolute magnitudes are very similar to those of SN 1988A. Also for this SN the light curve appears to be powered by the ^{56}Co to ^{56}Fe radioactive decay until 500d after maximum.

The spectrophotometric evolution of the strongest emission lines during the nebular phase is analysed. The fluxes of the lines of H, [OI], CaII] and CaII IR show a temporal behaviour similar to that of SN 1987A, but are always significantly fainter (2 to 3 times) than in SN 1987A, while being very similar to those of SN 1988A. On the other hand there is photometric evidence that the [FeII] emission lines (emerging in the V band) at late epochs are comparable for SN 1990E, 1988A and 1987A. Since the iron lines arise from the deepest layers of the ejecta while the lines of lighter elements originate in the outer regions, this is an indication that the inner structures of the stars exploding as SNII are similar while the envelope may have different structures.

Key words: supernovae: general – supernovae: 1990E

1. Introduction

Supernovae are conventionally classified by the appearance of the spectrum near maximum: when it shows hydrogen lines, the SN is classified as type II, otherwise as type I. Among SNII a further classification in *Plateau* and *Linear*, has been proposed by Barbon et al. (1979) on the basis of the morphology of the light curve. It is puzzling that the best ever studied (type II) SN 1987A in LMC, had a unique photometric behaviour: after a initial narrow spike there followed a slow rise in luminosity during the first 100 days leading to a relatively faint absolute magnitude at maximum. On the basis of the photometric behaviour, SN 1987A could be assigned neither to Plateau nor to Linear SNII.

It is not yet clear if there are differences between the spectra of SNII Plateau and Linear, though it has been tentatively suggested that the absorption troughs of the Hα P-Cygni profiles in the spectra of Plateau SNII are deeper than in those of Linears (Barbon et al. 1993).

At present, it is not clear if the two subclasses need to be related to completely different progenitors and/or explosion mechanisms or can be explained by a single model with an appropriate tuning of physical parameters such as the envelope mass, the amount of radioactive ^{56}Ni synthesized, or the amount of nearby circumstellar material.

In spite of the different behaviours at early phases, in general SNII converge (SN 1987A included) toward an homogeneous behaviour at late phase (Turatto et al. 1990). There are a few remarkable exceptions reported in literature, e.g. SN 1987F (Filippenko 1989) and SN 1988Z (Turatto et al. 1993a). This homogeneity, and the increasing faintness of evolved SNe, explains why observations of SNII at late phases raised in the past only little attention.

But actually good signal-to-noise late observations can help us understand several different phenomena. In particular, as demonstrated by SN 1987A, the late photometric behaviour is determined by the input from radioactive decay of different nuclear species (where ^{56}Co dominates during the first years). Moreover, the absorption by dust formed within the expanding envelope may affect significantly the late light curve (Danziger et al. 1991). Also, there is evidence that the ejecta–wind interaction, which is thought to be responsible for the narrow lines in the late spectra of SN 1987A (Lundqvist & Fransson 1991) may play an important role in powering the Hα emission in other SNII (Chugai 1991), particularly when the wind is dense and close to the exploding star.

It has also been suggested that light echoes from circumstellar matter can contribute to the light curve of most SNII and some SNIa, thus increasing the apparent late luminosity when

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* Based on observations collected at ESO-La Silla (Chile) and Asiago (Italy)

compared to that due simply to radioactive decline. However, occasional reports of a similar effect (e.g. for SN 1986G, Schaefer 1987) have not been confirmed (Turatto et al. 1990).

It thus appears worthwhile to use the nearby SN 1990E to verify the supposed homogeneity of SNII one year after maximum, and also to draw a comparison with the detailed observations of SN 1987A and the related models. The present paper deals with the observations taken with the telescopes of the Asiago and ESO-La Silla Observatories in the framework of a long term program for the study of Supernovae.

2. Observations

SN 1990E (Fig. 1) was discovered by the Berkeley Automated Supernova Search on Feb. 15.12 U.T. (Pennypacker et al. 1990), 3.0″ W and 9.4″ S (Benetti et al. 1990) of the nucleus of NGC 1035, a nearly edge–on (i = 84°) Sc galaxy (Tully 1988). Prompt observations by several observers showed that the SN was of Type II (Pennypacker et al. 1990). Little data were obtained during the early post maximum phase, most of that is from Schmidt et al. (1993), because the galaxy was far to the west. We observed the SN five months later, during the nebular phase, and followed its late evolution for over one year.

Particular care was devoted to obtain accurate photometry. The SN was embedded in an HII region, within a spiral arm of the galaxy, and the emission lines clearly appear in the spectra. Aperture photometry can be inaccurate especially when the SN fades. In order to minimize this problem we determined the SN magnitudes with the ROMAFOT program in the ESO–MIDAS package which, by fitting the observed point spread function to the object of interest, allows an adequate subtraction of complex backgrounds (cf. Turatto et al. 1993b). This explains the differences ($\leq$ 0.1 mag) for the 1990 Feb. 23 observations between the values reported here and our preliminary estimates obtained by aperture photometry (Benetti et al. 1990).

As a rule the absolute calibrations were obtained by observing Landolt's standard stars (Landolt 1983). The magnitudes of SN 1990E are listed in Table 1, where in col. 6 we list the equipment used. The errors were estimated to be about 0.02 mag when the SN was bright, and extending up to 0.4-0.5 mag for the latest observations.

The journal of spectroscopic observations is shown in Table 2. It reports for each spectrum, along with the dates of observations, the phases (relative to the adopted maximum, cf. Sect. 3), the equipment used, the exposure times and the wavelength range. In order to improve the signal-to-noise ratio, separate spectra taken during the same night or in consecutive nights have sometimes been averaged. In these cases the cumulative exposure time is reported. The spectral resolution is always ~ 20Å, except for the NTT spectrum, whose resolution is 12Å. Spectrophotometric standard stars from the list of Oke (1984), Stone (1977) and Oke & Gunn (1983) were used for the flux calibration. The accuracy of the flux calibration was checked for the spectra obtained at dates when broad-band photometry was also available. The agreement was found to be fair.

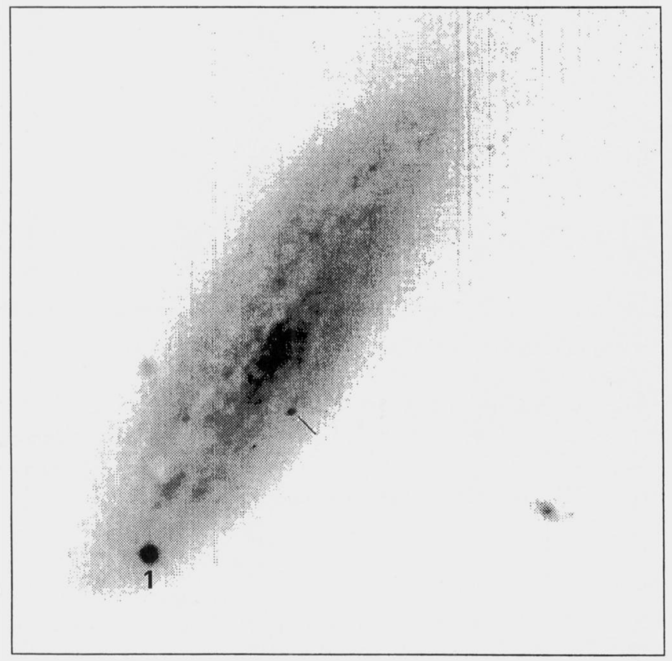

Fig. 1. SN 1990E in NGC 1035. North is top, east is left. The SN is marked with an arrow

3. Photometry

Figure 2 shows the B, V and R light curves of SN 1990E, including the m_V magnitude (IAUC 4965) and the observations by Schmidt et al. (1993). While our single V observation at the early phase coincides with the observations of Schmidt et al. (1993), at late phase the V magnitudes show a nearly constant difference of about 0.4 mag. The disagreement could be explained by the difficulty to subtract appropriately the contribution of the galaxy background when the SN becomes very faint. We can exclude systematic differences in the calibration with respect to the Schmidt et al. data, since we found the same B, V, R magnitudes for the field star near SN 1990E (labelled 1 in Fig. 1). The R magnitudes show a better agreement between the two data sets. The very last R estimate (coincident with the last spectrum of Table 2) is uncertain and should be read as R$\geq$ 21.2.

After a steep rise the SN shows a small luminosity spike in the V band, similar to that observed, in the visual, for SN 1988A. This allowed us to restrict the epoch of the maximum light to J.D. 2447939 $\pm$ 1 (16 Feb. 1990) at V = 15.2 $\pm$ 0.2. Since B and R observations were obtained only few days later, we can give only lower limits for the maximum magnitudes in these bands, B$\leq$16.1 and R$\leq$15.1.

During the first month after maximum the luminosity remained almost constant suggesting that the SN is of the Plateau type.

Because the SN disappeared behind the Sun, the epochs of late plateau and the beginning of the second rapid decline have not been observed, while the phase of the late linear decline has been intensively monitored in the V and R bands. Using only

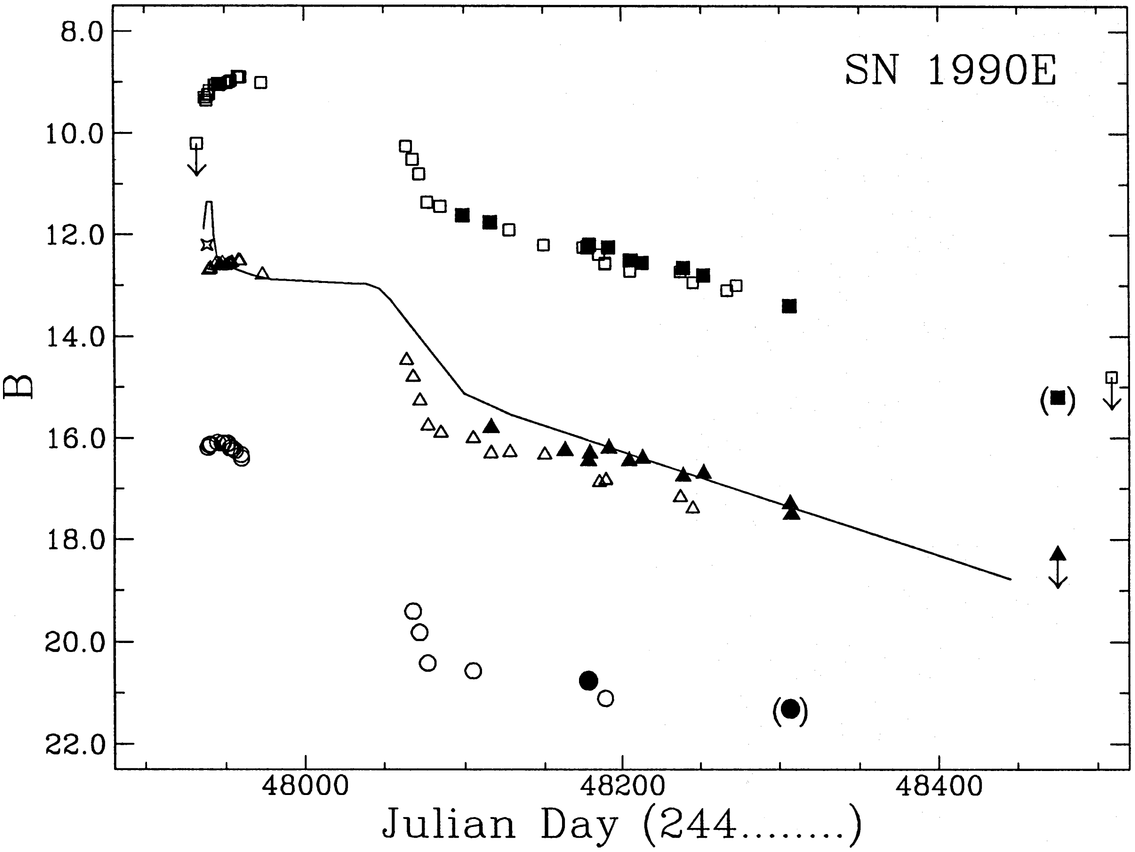

Fig. 2. B (circles), V (triangles), R (squares) light curves of SN 1990E. V and R data have been up shifted by 3 and 6 magnitudes, respectively. The open symbols are data from Schmidt et al. (1993) and open starred marks indicate m_V magnitude from IAUC 4965. Also the V light curve of the plateau SN 1988A (Benetti et al. 1991) is sketched for reference. The light curve of SN 1988A has not been adjusted to fit the data of SN 1990E but only scaled to the distance and reddening of SN 1990E as discussed in the text

our observations obtained in the phase range 200 ÷ 400*d* we derived the following linear decline rates: γ_V= 0.81 ± 0.10 and γ_R= 0.89 ± 0.07 mag (100d)$^{-1}$; these values are consistent with those calculated with the Schmidt et al. (1993) data.

It has been shown (Turatto et al. 1990) that the luminosity decline rate of SNII in the interval 200 ÷ 400d is independent of the morphology of the early light curve, and is close to the expected value if the input energy source is the radioactive decay of ^{56}Co, i.e. 0.98 mag (100d)$^{-1}$ for the bolometric magnitude. The average values for SNII were found to be γ_V= 0.89 and γ_R= 0.99 mag (100d)$^{-1}$. Thus the data for SN 1990E are marginally smaller than the average values but consistent, within the errors.

In Fig. 3 are shown the (B-V) and (V-R) color curves of SN 1990E. For comparison we also report the color curves of SN 1988A corrected for galactic extinction (full lines). Schmidt et al. (1993), using different methods, found evidence for significant extinction (E(B-V)=0.5). This stands out clearly in Fig. 3 where we plotted the color curves of SN 1988A reddened by E(B-V)= 0.4 and, following a standard extinction law, E(V-R)= 0.32 (dotted lines), similar to the values adopted by Schmidt et al. (1993). Since the galactic extinction for NGC 1035 is very small (A_B = 0.05, Burstein & Heiles 1978), the observed color excess is due to absorption within the host galaxy. Using the relation $A_V = 3 \times E(B-V)$ we derive a total absorption $A_V = 1.2 \pm 0.3$ mag.

An independent confirmation of the presence of a significant extinction comes from the examination of the spectra. As will be shown in the next section, the spectra of the SN are contaminated by the presence of narrow lines which we believe are due to a superimposed HII region. If the HII region is associated with the SN and, hence, suffers a similar amount of extinction, its Balmer decrement should reflect this. Since Hβ emission is not detected, we can only estimate a lower limit of the Balmer decrement F(Hα)/F(Hβ)$\gtrsim$5. Assuming an average intrinsic recombination ratio F(Hα)/F(Hβ)=2.85 for the nebula (Brocklehurst 1971), this corresponds to c(Hβ)$\gtrsim$ 0.75, i.e. to E(B-V)$\gtrsim$ 0.5. Hence, the reddening determined from the Balmer decrement of the HII region is even larger than that determined from the SN photometry.

Using the extinction derived above, we show in Fig. 2 the schematic V light curve of SN 1988A scaled to the distance (μ = 30.88, Tully 1988), and reddening (A_V = 1.2) of SN 1990E. The agreement between the two light curves, both in shape and absolute scale, is impressive considering also the uncertainties on the relative distance and extinction.

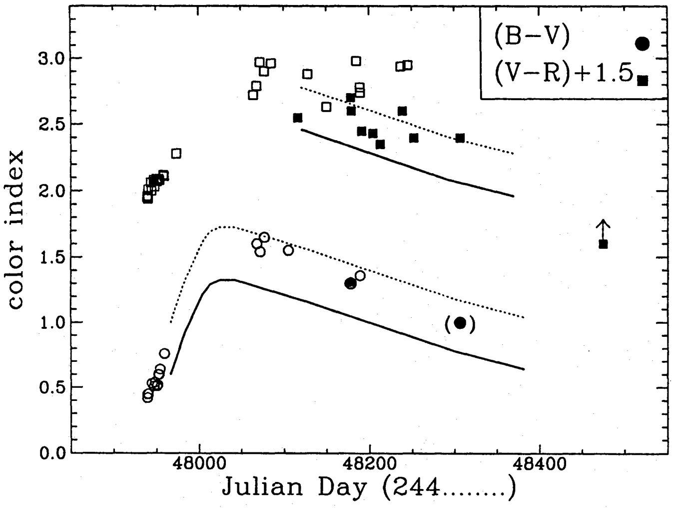

Fig. 3. (B-V) and (V-R) color curves of SN 1990E. Open symbols are data from Schmidt et al. 1993. The schematic color curves of SN 1988A, corrected for galactic absorption (full lines) are reported for reference. The dotted lines are the color curves of SN 1988A reddened by $E(B-V) = 0.4$ and $E(V-R) = 0.32$ mag

Table 1. Photometry of SN 1990E

date	J.D. 2400000+	B	V	R	tel.
23/2/90	47946.3		15.61	15.04	1.8
26/7/90	48098.9			17.61	3.6
12/8/90	48115.9		18.80	17.75	1.5D
28/9/90	48162.8		19.25		3.6
13/10/90	48177.8	20.75	19.45	18.25	1.5D
14/10/90	48178.7		19.30	18.20	NTT
26/10/90	48190.8		19.20	18.25	3.6
8/11/90	48203.8		19.45		2.2
9/11/90	48204.8			18.50	3.6
10/11/90	48205.6			18.50	NTT
16/11/90	48212.4		19.40	18.55	1.8
13/12/90	48238.5		19.75	18.65	1.5D
26/12/90	48251.5		19.70	18.80	1.5D
19/2/91	48306.5	21.30:	20.30	19.40	3.6
20/02/91	48307.5		20.50		3.6
6/8/91	48474.9		>21.3	21.20:	3.6

1.8 = Asiago 1.8m telescope + CCD Camera
3.6 = ESO 3.6m telescope + EFOSC1
1.5D = ESO/Danish 1.5m telescope + CCD camera
NTT = ESO NTT + EMMI
2.2 = ESO 2.2m telescope + CCD Camera

Turatto et al. (1990) noted that although SNII exhibit quite different behaviour near maximum (e.g. SN 1988A was about 3.5 mag more luminous than SN 1987A in the V band), at phases $\geq$ 200d they have about the same absolute V luminosity. In particular, at phase 300d, the V absolute magnitude of SNe 1987A ($V = -12.6$), and 1988A ($V = -12.4$) are very similar, considering the uncertainties in the distance moduli and extinction within the host galaxies. Our photometry for SN 1990E confirms this finding. After correction for extinction, the absolute magnitude of SN 1990E at 300d is $V = -12.3 \pm 0.3$ in fair agreement with the other SNe.
These conclusions are valid in the hypothesis of $H_0 = 75\ kms^{-1}Mpc^{-1}$. Adopting $H_0 = 50\ kms^{-1}Mpc^{-1}$ (e.g. Sandage et al. 1992 and Branch & Miller 1993) SN 1987A remains subluminous ($\sim$ 0.7mag in V) also at late epochs, compared with other more distant SNII.

The late bolometric luminosity of SNII is thought to be directly related to the mass of ^{56}Ni produced in the explosion. The fact that the late V luminosity (which at least in SN 1987A is found to track very well the bolometric luminosity at this phase) is very similar (within a factor 1.5) among different SNe may be considered an indication that in all these cases the mass of ^{56}Ni produced is very similar.

Finally the value of the absolute B magnitude at maximum for SN 1990E, corrected for extinction, $M_B \leq -16.4$, is consistent with the average value for SNII given in Miller & Branch (1990), $M_B = -16.53 \pm 0.32$.

Table 2. Journal of the spectroscopic observations

Date	phase (days)	equipment	exp (min)	range (Å)
1/3/90	+13	1.8m+B&C	30	4500-8000
26/7/90	+160	3.6m+EFOSC1	20	4300-9700
22/8/90	+187	1.8m+B&C	30	5000-8000
12/9/90	+208	1.8m+B&C	120	5000-8500
28/9/90	+224	3.6m+EFOSC1	20	3900-7100
11-12/10/90	+238	1.8m+B&C	120	5000-9100
28/10/90	+254	1.8m+B&C	120	4800-9200
10/11/90	+267	NTT+EMMI	60	4300-7800
24/11/90	+281	3.6m+EFOSC1	30	5400-9000
14-15/12/90	+302	1.8m+B&C	205	4650-8900
9-10/1/91	+328	1.8m+B&C	180	4500-8500
13/2/91	+362	1.8m+B&C	60	5000-8800
20-21/2/91	+369	3.6m+EFOSC1	40	4000-9900
7/8/91	+537	3.6m+EFOSC1	120	5800-9000

4. Spectroscopy

4.1. The spectral evolution

The spectral evolution of SN 1990E, between phase +13 and +537d is shown in Fig 4, where only the most representative spectra are plotted. After a single spectrum taken in proximity of maximum, we observed regularly the nebular phase.

The spectrum at maximum, taken in poor conditions at a very large zenith distance, is typical for a type II SN: a featureless continuum with only a broad Hα emission and a barely visible P-Cyg absorption from which an envelope expansion velocity of $\sim$ 11000 $km\ s^{-1}$was estimated.

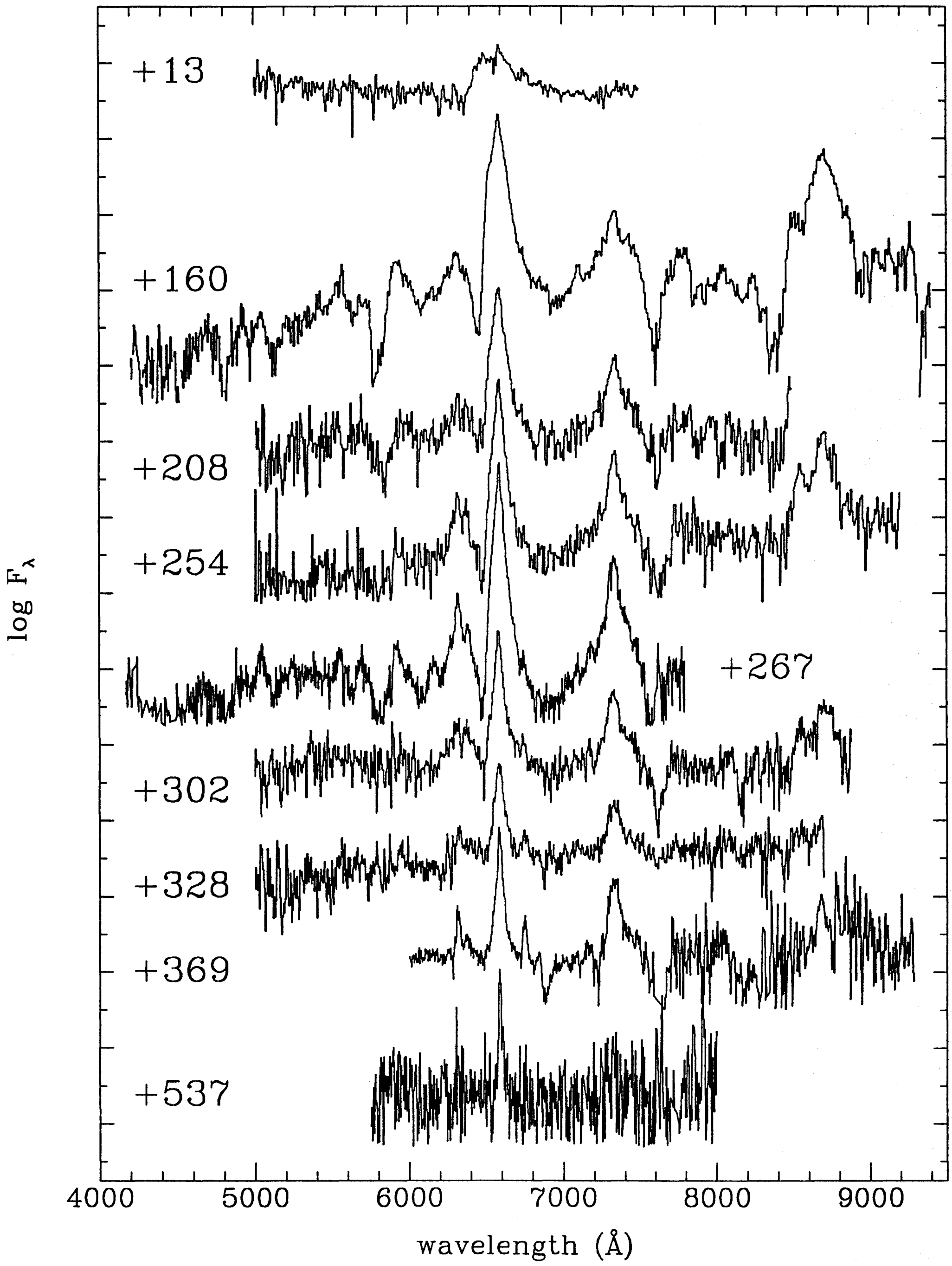

Fig. 4. Spectral evolution of SN 1990E. The abscissa is observed wavelength, whereas ordinate is an arbitrary scale for log F_λ

The second spectrum, taken ~ 150 days later shows several emission and absorption features (cf. Sect. 4.2) and reveals that the SN had not yet completed the evolution from the photospheric to the nebular phase. Besides Hα, the IR CaII triplet is very strong and at this epoch much stronger than the CaII] 7291-7332 Å lines. As the SN ages and the envelope progressively thins out, forbidden line emissions increase, and so does the CaII]/CaII ratio. Also the [OI] 6300-64 Å lines become stronger and the Hα emission profile becomes more symmetric.

A narrow Hα emission component is superimposed on the broad line, its presence becoming more evident as the SN fades and the exposure time increases. Since its position and intensity remain constant over the phase range studied, we believe that it arises from the HII region possibly associated with the SN. We attribute the emission centered at 6750Å to the redshifted [SII] lines from the HII region. The FWHM of this feature corresponds to the blend of two unresolved lines placed 14Å apart. At the very last epoch (537d) the SN faded below the detection limit of our equipment and only narrow emission lines from the

HII region were detected. When reducing the spectrum taken at this phase we in fact tried to subtract as much as possible the contribution of the HII region in order to enhance any contribution from the supernova.

The heliocentric recession velocity at the location of SN 1990E has been obtained by averaging the velocities determined from the narrow lines at different epochs. The resulting average velocity, v= 1080 $\pm$ 30 $km\, s^{-1}$, has been adopted throughout the present work. The difference between this value and the velocity of the host galaxy deduced from 21cm line (1236 $km\, s^{-1}$, Tully 1988), can be explained with the differential rotation of NGC 1035.

4.2. The line identifications and fluxes

To assist in identifying the lines, we compared our +160d spectrum with a synthetic spectrum (Fig 4.2). The synthetic spectrum was modeled using an LTE radiative transfer code (see Jeffery & Branch (1990) for details). The free parameters are the temperature and velocity at the photosphere, the radial dependence of optical-depth and the integral optical depth at the photosphere for the strongest lines of each ion of interest. This last parameter is fixed so that the model line intensity fits the observed one. The optical depths of the other lines are then fixed by assuming LTE. Since at the epoch modeled the SN envelope has become extended, some of the approximations adopted for the computation are approaching their limit of applicability; in particular the simple power-law representation of the line optical depths may not be adequate. Moreover, we do not expect to fit very well the strong emission lines (i.e. Hα and IR CaII triplet) because collisional excitation is becoming important (Branch et al. 1981). The ions included in the synthetic spectrum calculation are H, OI, KI, CaII, NaI, ScII, FeII and BaII.

The synthetic spectrum convolved with a standard interstellar reddening law scaled to a color excess of E(B-V)= 0.4 is shown in Fig. 4.2. It was calculated adopting a continuum color temperature of 6800 °K, an excitation temperature of 6800 °K and a velocity at the photosphere of 4500 $km\, s^{-1}$. The last value was chosen for the best fit in the bluer part of the spectrum where FeII lines, Hβ and NaI-D lines still seem to exhibit P-Cygni profiles. An inverse power-law density profile with index 4 was adopted. The fit with the observed spectrum, expecially in the bluer region (below 6200Å) is reasonable. It indicates that, at this phase, most of the lines are due to FeII, BaII and ScII besides the obvious contribution of HI, NaI and CaII. BaII and ScII have also been identified in spectra of SN 1987A up to 150 days after explosion (Mazzali et al. 1992; Jeffery & Branch 1990). For the emission observed at $\sim$ 5560Å contributions of [FeII] and [OI] lines are also possible (Danziger et al. 1988). The strong P-Cyg feature at $\sim$ 7700Å is matched reasonably well by a blend of KI and OI lines. The presence of KI multiplet has been proposed also in SN 1987A (Meikle et al. 1989 and Danziger et al. 1988) approximately at the same phase. In the spectrum of SN 1990E a contamination by the telluric band is possible.

As time goes on, an increasing fraction of the total flux goes into forbidden lines. In particular the contribution of CaII] and [OI] and of several lines of [FeII] increases. The line observed at 7100 Å at 160d could be attributed to mult. 31F [FeII] 7075 Å. In spectra of SN 1987A and 1988A at similar epochs this line was stronger than the [FeII] 7155 Å, that eventually becomes a typical feature on the blue wing of CaII]. In SN 1990E this latter line was never more than barely visible. Together with the wavelength offset, this makes the identification of the 7100 Å line uncertain.

Due to [FeII] is also the line emerging at 8620 Å in the 369d spectrum, when the CaII IR faded away (cf. Sect. 4.4). This line appeared in SN 1987A two years past maximum (Spyromilio 1991a), but an earlier occurrence was already noted in SN 1988H (Turatto et al. 1993b).

The temporal evolution of the flux of the principal emission lines is reported in Table 3. In Fig. 6 these luminosities, calculated for an $H_0 = 75\ kms^{-1}Mpc^{-1}$ and corrected for extinction, are compared with those of SN 1987A and 1988A. For all the lines, the temporal behavior of SN 1990E is very similar to that of SN 1987A, but the flux emitted is a factor 2 to 3 smaller. This may appear inconsistent with the result, reported in Sect. 3, that the late absolute V luminosity of SN 1990E is very similar to that of SN 1987A. It should be noted, however, that the strong emission lines are in the redmost part of the optical spectrum, while the V band encompasses a multitude of relatively faint emission lines, mostly due to [FeII], which are only barely visible in our spectra of SN 1990E. The different intensity ratio between the red and the yellow late spectra of SN 1990E and 1987A is confirmed by their colors. While the (V-R) color curves during the photospheric phase are very similar (once the SN 1990E data are corrected for extinction) at late epochs SN 1990E becomes bluer than 1987A.

It is also interesting to note that, just as it was the case for the light curve, a much better agreement is obtained with the observations of SN 1988A for the line fluxes as well (Turatto et al. 1993b). This may be related to the fact that the progenitors of SN 1988A and SN 1990E had a similar structure of the outer layers, both probably having a red supergiant progenitor, whereas the precursor of SN 1987A was a blue supergiant.

4.3. The Hα line

It has been noted that in SN 1990E, at early phases, the P-Cygni trough of the Hα line was shallower than in SN 1987A. Moreover, in our spectra, the absorption is barely visible at 250d, while in 1987A it was seen until 600d (Phillips & Williams 1989). This can be related to the different density structure of the exploding star or to strong density fluctuations (Schmutz et al. 1990). The Hα flux in SN 1990E is on average a factor $\sim$ 2.5 below that of SN 1987A.

Still, the kinematical evolution of Hα in SN 1990E was similar to that in SN 1987A. In Fig. 7 the expansion velocity of the envelope of SN 1990E, obtained from the FHWM of the Hα emission, is compared with the same measurements for

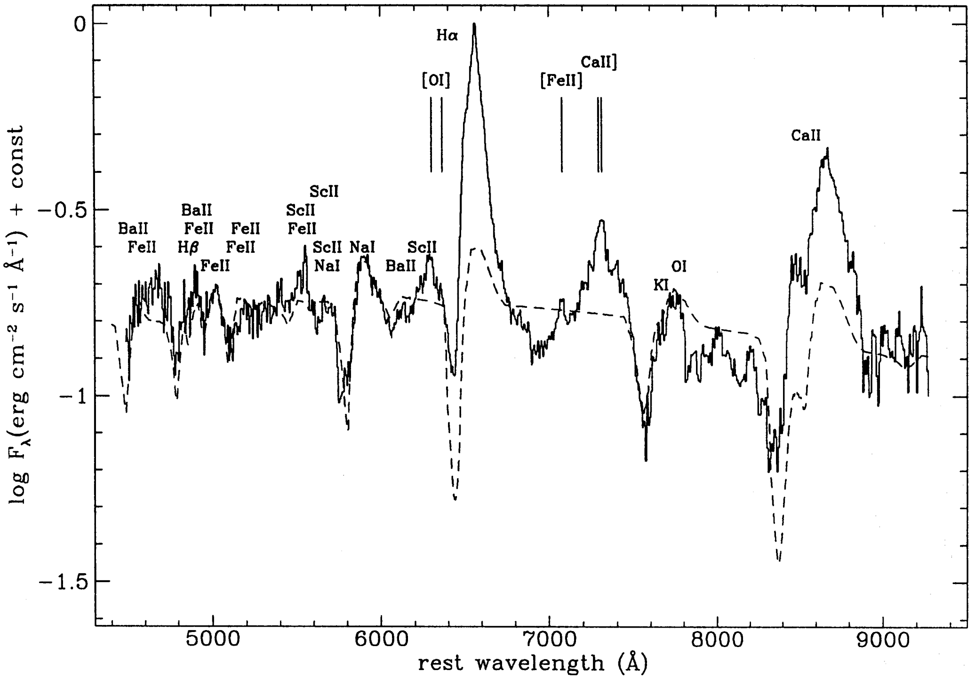

Fig. 5. A synthetic spectrum is compared with that observed at phase 160d. The strongest lines reproduced are marked above the spectrum and vertical signs indicate the forbidden lines. The parameters used were T_{BB} = 6800 °K, T_{ex} = 6800 °K, v= 4500 $km\,s^{-1}$and n= 4. An extinction A_V = 1.2 was adopted

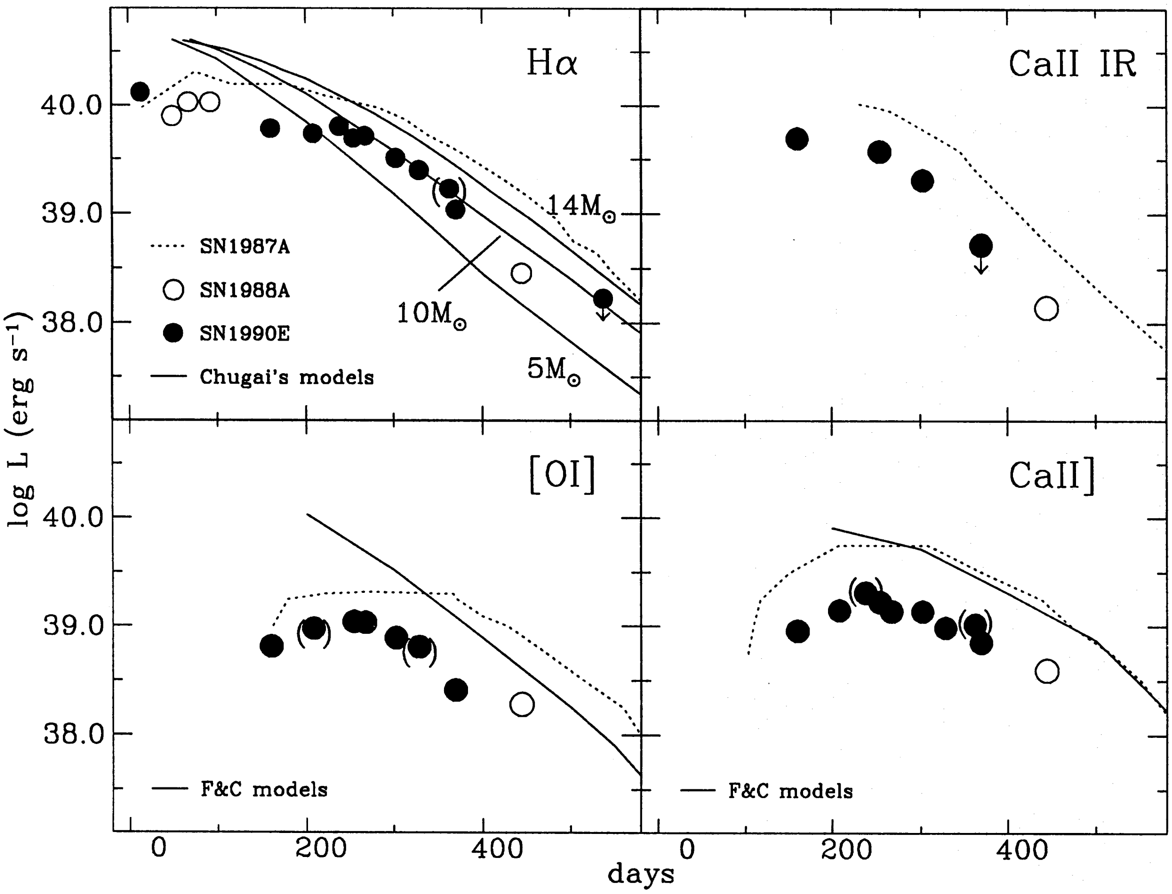

Fig. 6. Line luminosity evolution of the most intense emissions observed in SN 1990E (calcutated for an H_0 = 75 $kms^{-1}Mpc^{-1}$, and corrected for extinction A_V = 1.2). For comparison data of SN 1987A are also plotted (Danziger et al. 1991, Menzies et al. 1991, Spyromilio et al. 1991a) and of 1988A (Turatto et al. 1993b). The predicted evolution of the emissions of Hα (Chugai 1991) and of [OI] and CaII] (Fransson & Chevalier 1987) are also reported

Table 3. Measured fluxes$^{(*)}$ of the principal lines

phase (days)	[OI]	Hα	CaII]	CaII IR
+13		1940		
+160	91	899	149	946
+208	133:	808	231	
+238		940	335:	
+254	154	730	275	720
+267	151	769	226	
+302	109	480	226	390
+328	90:	370	160	
+362		250:	170:	
+369	36	161	117	<100
+537		<25		

$(*) \times 10^{-16} erg\,cm^{-2}\,s^{-1}$

SN 1987A. The two SNe exhibit a very similar behavior with a rapid initial decline and a much slower evolution at late phases.

The weakness of the $H\alpha$ feature in SN 1990E suggests that, if other physical conditions (Ni mass, density, temperature) were similar to those of SN 1987A, the H envelope mass in SN 1990E was smaller.

A simplified model of the evolution of the $H\alpha$ luminosity of the SN has been presented by Chugai (1991), assuming that at late times a SNII is powered only by radioactive decay of ^{56}Co into ^{56}Fe. The SN envelope, whose mass is the main parameter of the model, is represented by an homogeneous sphere of H and He in homologous expansion. In Fig. 6 the observed $H\alpha$ luminosity evolution of SN 1990E is compared with three Chugai's (1991) models with three different envelope masses, respectively of $5M\odot$, $10M\odot$ and $14M\odot$. The agreement, considering the simplification of the model, is fairly good and suggests an envelope mass somewhat smaller than for SN 1987A ($\leq 10M_\odot$). Alternatively, differences in the ^{56}Ni mass and/or kinetic energy may be required.

4.4. The CaII and CaII lines

The IR CaII triplet is the strongest feature in the $+160^d$ spectrum. Relative to other SNII its profile shows some interesting differences. In particular, in other SNII at this epoch the two peaks at 8542-8662 Å of IR CaII have comparable intensity or the bluer one is stronger (cf. SN 1987A, 1988A and 1988H in Sadler & Stathakis 1991). On the contrary, in SN 1990E the red line is stronger.

The emissions are rather broad, although the widths are difficult to measure because of the blending. The 8542 Å line remains always narrower than that at 8662 Å, probably due to the blending with the P-Cyg absorption of 8662 Å. As predicted by the nebular spectrum models of Swartz et al. (1989), increasing the mixing increases the line broadening and the profiles of the IR CaII lines more closely resemble those observed in SN 1990E. Note, however, that the mixed composition of Swartz et al. (1989) predicts also an increased intensity of [OI], which is observed neither in SN 1987A nor in SN 1990E.

The luminosity evolution of the IR CaII, shown in Fig. 6, tracks very well that of the $H\alpha$. As for the $H\alpha$ flux, also the strength of the CaII IR triplet is a factor $\sim$ 3.5 smaller than in SN 1987A. At day 369 this emission drops below our detection threshold and a different feature emerges in the same position, probably due to [FeII] 8620 Å (cfr Sect. 4.2). Interestingly, both in SN 1987A and SN 1988A at the same phase the CaII triplet is still the dominant feature of the near IR, the [FeII] feature becoming dominant in SN 1987A only about a year later. SN 1990E resembled SN 1988H in this respect (Turatto et al. 1993b). The different evolution of this feature in otherwise similar SNe may be an indication of the different degree of mixing of CaII within the envelope.

The evolution of the relative intensity of CaII]/CaII emission lines has been discussed in detail by Kirshner & Kwan (1975). SN 1990E exhibits a normal trend (Fig. 6) with the forbidden 7300 Å CaII] line reaching the peak at about 250d, as in SN 1987A, but remaining always a factor $\sim$ 4 below the values of SN 1987A.

Close inspection of the line profile of the CaII] of SN 1990E shows that the lines have broad wings. This can be due either to possible blending of faint, unresolved lines, such as [FeII] (cf. 1988A in Turatto et al. 1993b) or to components originating in the high velocity envelope. It should be noted that the relative flux in these wings (the red one in particular) is larger than in SN 1987A at similar phases.

4.5. The [OI] lines

The [OI] 6300-64 doublet is already recognized in the 160d spectrum when the two components are not yet resolved. The maximum of the stronger emission has been measured around 6292 Å showing that the [OI] lines were slightly blueshifted at this epoch, similarly to SN 1987A (Menzies 1991). At later phases the doublet lines were resolved and centered at the rest wavelength.

The evolution of the integrated luminosity of the doublet is shown in Fig. 6. The flux in the [OI] feature in SN 1990E follows the pattern exhibited in SN 1987A, reaching the maximum emission about 250d after maximum. Just as for the other emission lines, the luminosity is a factor $\sim$ 2 smaller than is SN 1987A.

The relative strength of the two lines of the doublet changes with the expansion of the envelope. The late spectra of SN 1990E show the evolution of [OI] from optically thick to optically thin (Fig. 8) and can be used, according to Spyromilio & Pinto (1991b), to estimate the OI density. The comparison of the evolution of the 6364/6300 Å line ratio of SN 1990E with that of SN 1987A and SN 1988A (Fig. 8) shows that, within the errors, the line ratios of the three SNe are, at the same phase, very similar. Spyromilio & Pinto (1991b), comparing the observed 6364/6300 Å line ratio of SN 1987A with the expected evolution assuming homologous expansion and uniform distribution, calculated the OI number density as $8.9 \times 10^9\ cm^{-3}$ at 173d, in good agreement with the value deduced by Schmidt et al. (1993) for an age of 270d. Estimating the occupied volume

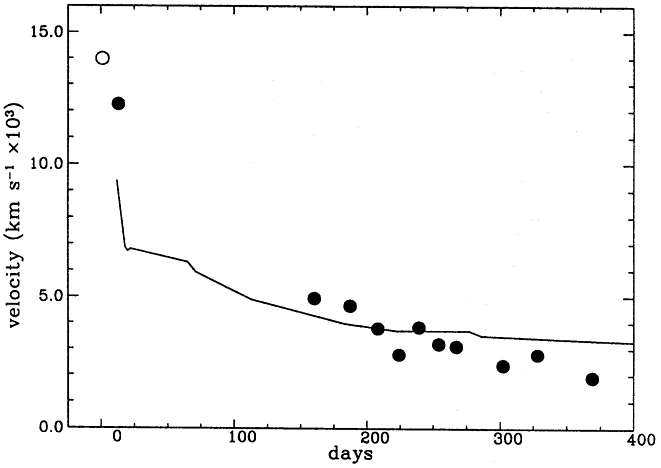

Fig. 7. Temporal behaviour of the width (FWHM) of Hα emission. The open symbol represents a measurement reported in IAUC 4965. For comparison, the data of SN 1987A from the ESO data set are also reported

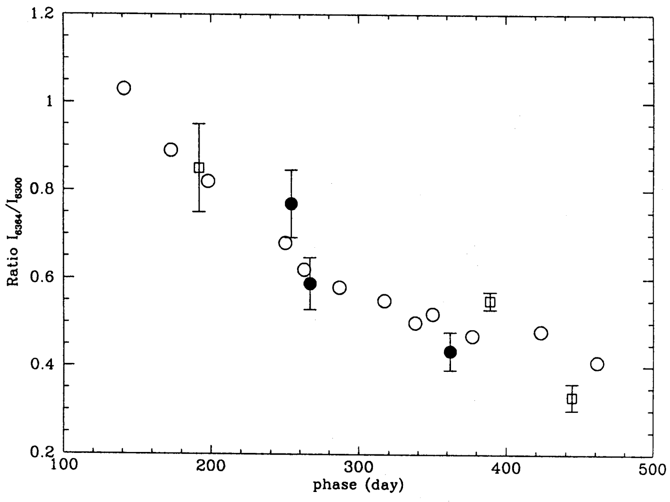

Fig. 8. The evolution of the 6364/6300 [OI] line ratio. The full circles are relative to SN 1990E. The data for SN 1987A (open circle, Spyromilio & Pinto 1991a) and SN 1988A (open squares, Spyromilio 1991, Turatto et al. 1993b) are reported for comparison

from the expansion velocity and the time since the explosion, a mass of 16 $M_\odot$ for the OI can be derived. This is unacceptably large compared with standard model predictions, suggesting a filling factor for oxygen of only $\sim$ 10%. The same argument applies to SN 1990E and SN 1988A, given the similar emission line widths and line ratios. Therefore, since similar line ratios and expansion velocities are shown by the three SNe at approximatively the same phase, also the oxygen density were probably similar.

5. Conclusions

SN 1990E is an unusual case of a SN studied in more detail during the radioactive decline than near maximum light. The broad band photometry in the early phases shows a close resemblance to SNII of the plateau type (in particular SN 1988A) with respect to absolute magnitudes and light curve shape, once allowance is made for the reddening within the parent galaxy (E(B-V)= 0.4 ± 0.1). The similarity with normal SNII holds up to the latest observations (500d) indicating that no additional source of energy besides the radioactive decay of ^{56}Co to ^{56}Fe is required for powering the light curve.

The resemblance of the photometric behaviour of SN 1990E with that of 1988A supports the hypothesis that the structure of the outer layers of the precursor star was normal, i.e. that of a red supergiant rather than that of a blue supergiant as in the case of SN 1987A. Also the line fluxes of the lighter elements such as H, Ca and O lines (Fig.6) were similar in the two SNe.

Although the time evolution of the fluxes emitted by the Hα, CaII IR, [OI], CaII] lines of SN 1990E follows closely those of SN 1987A and 1988A, the absolute line fluxes in SNe 1990E and 1988A are a factor 2-3 smaller than in SN 1987A ($H_0 = 75\ kms^{-1}Mpc^{-1}$).

On the other hand, the V-band light curve , which at late phases is mainly determined by the light from [Fe II] emission lines, is similar for SNe 1990E and 1987A. This suggests that the intensities of the iron group elements' lines are similar in SNe II plateau and in the unusual SN 1987A, and thus that the amount of Ni ejected is not strongly dependent on progenitor type.

The differences in the line fluxes are an indication of a different envelope structure, and perhaps progenitor properties, for SNe 1990E and 1987A. For the latter SN, the observed emission line strengths and the light curve indicate that the explosion released $\sim$ 0.075 $M_\odot$ of ^{56}Ni (Danziger et al. 1988). Nucleosynthesis studies showed that this amount of Ni is compatible with the explosion of a 6 $M_\odot$ He core, i.e. the core of an 18-20 $M_\odot$ (ZAMS) star (Hashimoto et al. 1988; Woosley et al. 1988). It is also well known that the progenitor of SN 1987A exploded as a blue supergiant. The final evolution back to the blue was probably ensured by the low mass loss suffered by the progenitor during its evolution (Weiss 1988), a peculiarity due to the low metallicity of the LMC stars (Kudritzki et al. 1987).

The general agreement is that Sk -69 202, the progenitor of SN 1987A, was originally a $\sim$ 20 $M_\odot$ star, and it exploded as an $\sim$ 18$M_\odot$ star with a 6 $M_\odot$ core and a 12 $M_\odot$ envelope, while not more than 2 $M_\odot$ were lost during its evolution. Upon core collapse, about 1.3 $M_\odot$ ended up in the collapsed nucleus, while the rest ($\sim$ 4.6 $M_\odot$) of the He envelope gave rise to the typical onion shell structure of intermediate mass elements and was ejected, including 0.075 $M_\odot$ of ^{56}Ni and its decay products. Fransson & Chevalier (1987, 1989) showed that the Fe II emission at late times in SN 1987A came essentially from the innermost region of the ejecta, while the IME lines (Ca, Mg, Si) came from further out, although some degree of mixing must have occurred, as indicated by the presence of s-process elements on the outer part of the ejecta (Mazzali et al. 1992).

In conclusion, the late time light curves and the energy released by the explosion are similar in SNe 1987A and 1990E. Moreover, the similarity of the V curves indicates that the [FeII] emissions are comparable in the two objects. On the other hand, the H and IME emissions are different, and thus, it may not be unreasonable to assume that the envelope mass of SN 1990E was smaller than that of SN 1987A. This could be due to either an initially smaller progenitor mass, or to a higher mass loss rate on SN 1990E, which could have kept the star in the RSG region of the HR diagram up to explosion, or to both circumstances. The mass difference between the SN 1990E and the SN 1987A envelopes can be roughly calculated assuming that the nebular emission depends on the square of the emitting mass (Ruiz-Lapuente & Lucy 1992). A line intensity smaller by a factor 3 would then imply an envelope mass smaller by a factor 1.7, i.e. an H envelope mass of only about $7 M_{\odot}$(consistent with the estimate derived from the simplified Chugai's model, cf. Sect. 4.3), and a smaller He core than in SN 1987A. Given this large difference, it seems likely that a lower initial mass for the progenitor of SN 1990E is the most likely explanation. This suggestion should be checked carefully by modeling the nebular spectrum of SN 1990E, since the line intensities and their ratios depend sensitively on temperature. Knowledge of the galaxy's metallicity would also help discriminate between evolutionary models, in order to determine the role played by mass loss.

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