

The type Ia supernova 1994D in NGC 4526: the early phases

F. Patat,^{1,3} S. Benetti,² E. Cappellaro,⁴ I. J. Danziger,¹ M. Della Valle,³ P. A. Mazzali^{5,1} and M. Turatto^{4,1}

¹ESO, Karl-Schwarzschild Strasse 2, D-85748 Garching bei München, Germany

²ESO, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago 19, Chile

³Dipartimento di Astronomia, Università di Padova, vicolo dell'Osservatorio 5, I-35122 Padova, Italy

⁴Osservatorio Astronomico, Via dell'Osservatorio 5, I-35122 Padova, Italy

⁵Osservatorio Astronomico, Via G.B. Tiepolo, 11, I-34131 Trieste, Italy

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ABSTRACT

The type Ia supernova SN 1994D in NGC 4526 was extensively observed as a target of opportunity at ESO. In this paper, we present and discuss the *UBVRI* photometry and the spectra collected during this campaign from 11 days before maximum to about two months afterwards.

Several absorption components of the Na I D lines arising in our Galaxy, in NGC 4526 and in high-velocity clouds located in between have been identified in a high-resolution spectrum. The total amount of reddening related to these features has been estimated as $E(B - V) = 0.06$.

The light curve shapes are similar, but not identical, to those of SN 1992A. The onset of the secondary maximum in the *I* band occurs around day +20. The SN reached at maximum $B = 11.84$ and showed a distinctly blue colour [$(B - V) = -0.08$]. SN 1994D is therefore the bluest SN Ia observed to date. SN 1994D appears to depart from the previously reported correlation between maximum brightness and rate of decay. The implications of this for the absolute magnitudes and colour dispersion of type Ia SNe are discussed.

The spectroscopic evolution of SN 1994D followed that of standard objects like SN 1992A. The excellent time coverage allowed us to show a sudden break in the decline rate of the expansion velocity deduced from the Si II $\lambda 6355$ line at around day -6, probably indicating that after this phase this strong feature originates well above the photosphere. Finally, physical parameters and line identifications have been obtained modelling the day -4 spectrum by means of a spectrum synthesis code. Overall, the spectrum is successfully fitted as a normal SN Ia, although the very blue colour cannot be reproduced. The observed weakness of the Co II absorption around 3350 Å and its possible bearing on the amount of radioactive Ni produced during the explosion are discussed.

Key words: supernovae: general – supernovae: individual: SN 1994D – supernova remnants.

1 INTRODUCTION

SN 1994D ($\alpha = 12^{\text{h}} 34^{\text{m}} 02^{\text{s}}.37$, $\delta = +7^{\circ} 42' 04''.7$, 2000.0) was discovered on 1994 March 7 in NGC 4526 9 arcsec west and 7 arcsec north of the galaxy nucleus, during the Leuschner Observatory Supernova Search (Treffers, Filippenko & Van Dyk 1994). On the basis of a spectrum taken two days later, and showing a very blue continuum and

the characteristic Si II $\lambda 6355$ feature, this supernova (SN) was classified as type Ia well in advance of maximum brightness (Martel & Goodrich 1994).

Three reasons provided the motivation for a special effort in the observational coverage of this SN: (i) the parent galaxy belongs to the Virgo cluster, which represents a crucial step in the distance ladder; (ii) the absence of spectral peculiarities of the kind shown by two recent Virgo SNe Ia, 1991T

and 1991bg, indicated SN 1994D as a good example of the *standard Ia* class; (iii) an accurate coverage of the maximum phase could be secured because of the early discovery.

The goal of obtaining a daily coverage of the spectroscopic and photometric behaviour of SN 1994D was accomplished by electing this SN as a *target of opportunity* at the ESO, La Silla. Observations made at other observatories were also useful in obtaining a complete coverage.

In this paper we give a detailed account of the results of these observations, along with a preliminary spectroscopic analysis using the synthetic spectrum technique.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Photometry

Table 1 shows the journal of the photometric observations, most of which were obtained with the Dutch 0.9-m telescope, equipped with a TK coated 512×512 pixel CCD ($0.44 \text{ arcsec pixel}^{-1}$). Typical exposure times span from 1 min for the *I* band up to 5 min for *U*. Additional photometry was collected at the 3.6-m + EFOSC1 and 2.2-m + EFOSC2 telescopes at La Silla, and at the 1.8-m telescope of the Asiago Astrophysical Observatory. Also included are the

Table 1. Photometric observations of SN 1994D.

Date	J.D. 2400000+	Phase ^a (days)	U	B	V	R	I	Seeing (arcsec)	Telescope
11/3/94	49422.7	-10	12.89	13.26	13.27	13.11	13.24	1.5	ESO-0.9
12/3/94	49423.8	-9	12.44	12.91	12.93	12.70	12.84	1.4	ESO-0.9
13/3/94	49424.7	-8	12.11	12.67	12.67	12.43	12.60	1.3	ESO-0.9
14/3/94	49425.7	-7	11.84	12.41	12.47	12.31	12.41	1.5	ESO-0.9
15/3/94	49426.7	-6	11.64	12.26	12.29	12.15	12.27	1.4	ESO-0.9
16/3/94	49427.7	-5	11.50	12.10	12.17	12.04	12.18	1.6	ESO-0.9
17/3/94	49428.7	-4	11.41	11.99	12.08	11.98	12.15	1.8	ESO-0.9
18/3/94	49429.7	-3	11.31	11.89	11.98	11.92	12.18	1.9	ESO-0.9
19/3/94	49430.7	-2	11.30	11.86	11.93	11.90	12.21	1.5	ESO-0.9
20/3/94	49431.7	-1	11.33	11.84	11.92	11.91	12.22	1.3	ESO-0.9
22/3/94	49433.7	+1	11.40	11.84	11.91	11.89	12.24	1.3	ESO-0.9
23/3/94	49434.7	+2	11.42	11.89	11.90	11.86	-	1.3	ESO-0.9
24/3/94	49435.7	+3	11.52	11.91	11.92	11.87	12.26	1.5	ESO-0.9
25/3/94	49436.7	+4	-	11.99	11.96	11.91	-	1.9	ESO-0.9
	49436.7	-	-	-	11.93	11.96	12.24	-	NF-0.5
26/3/94	49437.7	+5	-	12.02	11.97	11.96	-	2.4	ESO-0.9
	49437.7	-	-	-	11.98	12.04	12.42	-	NF-0.5
27/3/94	49438.7	+6	-	12.13	12.03	12.03	-	1.6	ESO-0.9
28/3/94	49439.7	+7	-	12.25	12.10	12.15	-	1.7	ESO-0.9
	49439.7	-	-	-	12.12	12.18	12.53	-	NF-0.5
29/3/94	49440.7	+8	12.12	12.33	12.21	12.33	12.76	1.4	ESO-0.9
	49440.7	-	-	-	12.20	12.31	12.68	-	NF-0.5
30/3/94	49441.7	+9	12.24	12.44	12.29	12.43	12.81	2.0	ESO-0.9
31/3/94	49442.7	+10	-	-	-	12.45	12.82	-	NF-0.5
01/4/94	49443.7	+11	-	-	12.39	-	-	-	NF-0.5
02/4/94	49444.7	+12	12.75	12.80	12.53	-	-	1.4	ESO-0.9
03/4/94	49445.7	+13	12.94	12.95	12.59	-	-	1.6	ESO-0.9
04/4/94	49446.7	+14	13.10	13.10	12.64	-	-	1.4	ESO-0.9
07/4/94	49449.7	+17	-	-	12.73	12.71	12.56	-	NF-0.5
09/4/94	49451.7	+19	-	-	-	-	12.52	-	NF-0.5
13/4/94	49455.7	+23	14.48	14.28	13.25	12.89	12.60	1.3	ESO-0.9
15/4/94	49457.7	+25	14.63	14.46	13.42	13.05	12.78	1.6	ESO-0.9
16/4/94	49458.7	+26	-	-	-	13.07	-	-	NF-0.5
17/4/94	49459.7	+27	-	14.60	13.57	13.21	-	1.5	ESO-0.9
18/4/94	49460.7	+28	-	-	-	13.22	-	-	NF-0.5
01/5/94	49473.7	+41	-	-	-	13.88	13.84	-	NF-0.5
06/5/94	49478.7	+46	15.43	15.27	14.20	14.05	14.13	1.6	ESO-0.9
14/5/94	49486.7	+54	-	15.36	14.56	14.38	14.37	1.6	MPI-2.2
25/5/94	49497.7	+65	-	15.45	14.85	14.65	-	1.7	ESO-0.9
27/5/94	49499.7	+67	-	-	14.87	-	-	-	NF-0.5
07/6/94	49510.7	+78	-	15.61	15.22	15.03	15.28	2.9	AS-1.8

^aRelative to maximum *B* (JD = 2449432.5).
 ESO-0.9 = 0.92-m ESO-Dutch + CCD TK512.
 MPI-2.2 = ESO-MPI 2.2-m + EFOSC2 + TH1024.
 AS-1.8m = Asiago 1.8-m + CCD TK512.
 NF-0.5 = NF/0.45-m + Craft-Cassini 1024.

observations by W. Neely at the 0.45-m telescope equipped with a 1024×1024 pixel CCD of the NF/Observatory (New Mexico).

In Fig. 1 the positions of SN 1994D and of the two reference stars (A and B) are indicated. The SN is located on the edge of the dust lane of NGC 4526, which makes it impossible to measure the SN magnitude by means of plain aperture photometry. Therefore, after the usual bias and flat-field corrections, magnitude measurements have been obtained by means of point-spread function fitting using the ROMAFOT package in the ESO-MIDAS environment.

Colour terms for each instrument have been computed using standard field observations (Landolt 1992). The SN magnitudes have been calibrated by means of relative photometry with respect to star A (see Fig. 1), whose *UBVRI* magnitudes were given by Kilkenny & Malcom (1984). A calibration of this star has been checked on two photometric nights (1994 March 10 and 12) giving values ($U=14.58$, $B=13.59$, $V=12.54$, $R=12.01$ and $I=11.50$) in good agreement with those reported by Kilkenny & Malcom (1984). To estimate the internal errors we used star B. The magnitudes of this star, averaged over 18 nights, are $U=16.74$ ($\sigma=0.06$), $B=16.78$ ($\sigma=0.04$), $V=16.19$ ($\sigma=0.02$), $R=15.81$ ($\sigma=0.04$) and $I=15.49$ ($\sigma=0.03$). Since this star is also projected on to NGC 4526, but is ~ 4 mag fainter than the SN, the internal errors of the SN photometry in the early phases described in this paper are significantly smaller than the rms errors quoted above.

2.2 Spectroscopy

The spectroscopic observations were obtained mostly at the ESO 1.5-m telescope using the Boller & Chivens spectrograph equipped with a FORD 2048×2048 pixel CCD. Typical exposure times were 30 min. Other spectra were obtained with the NTT, the ESO MPI 2.2-m telescope, the ESO 3.6-m telescope and with the 1.8-m telescope of Asiago Astrophysical Observatory. The journal of spectroscopic observations is shown in Table 2.

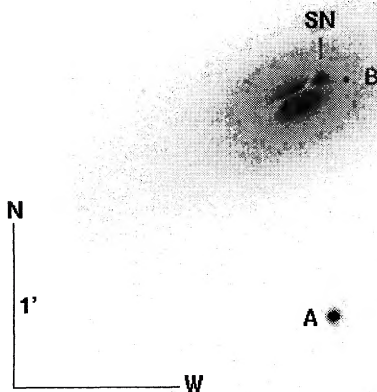


Figure 1. SN 1994D in NGC 4526. The frame was obtained on March 22 in the *V* band with the ESO Dutch 0.9-m telescope. The reference stars A and B used for the relative photometry are indicated.

Spectroscopic observations have been reduced by means of MIDAS procedures; particular care has been devoted to the extraction of the SN spectra in order to avoid contamination from the parent galaxy background. The wavelength calibration has been derived from exposures of He- Ar lamps, while the response curves have been obtained via observations of spectrophotometric standard stars. Finally, the absolute flux calibration has been checked against the broad-band photometry and, if necessary, slightly adjusted.

On March 18 two high-resolution spectra of SN 1994D, covering the region $4100\text{--}6650 \text{ \AA}$, were obtained (15 and 30 min exposures, respectively) at the ESO NTT telescope using the ESO Multi Mode Instrument (EMMI) in the Echelle mode, with a slit 25 arcsec long and 1.5 arcsec wide (resolution of $0.2 \text{ \AA}$ FWHM at $5900 \text{ \AA}$, i.e. 10 km s^{-1}). The long slit allowed the accurate subtraction of the sky contribution. Order definition and extraction, wavelength rebinning and sky subtraction were performed by means of MIDAS routines. In this case, flux calibration was achieved by comparison with a medium-resolution spectrum of the SN taken the previous day (see Table 2). Finally, the orders were merged and the two exposures combined to a weighted mean to give the final spectrum. A signal-to-noise ratio of about 60 in the region of the Na I D doublet was thus achieved.

Table 2. Journal of spectroscopic observations.

Date	J.D. 2400000+	Phase ^a (days)	range $\text{\AA}$	resolution ^b FWHM ($\text{\AA}$)	equipment
10/03/94	49421.7	-11	3200-7200	10	ESO-1.5
11/03/94	49422.7	-10	3500-7200	3	MPI-2.2
12/03/94	49423.7	-9	3700-8600	18	ESO-3.6
13/03/94	49424.7	-8	3800-7200	5	ESO-1.5
16/03/94	49427.7	-5	3500-10000	10	ESO-1.5
17/03/94	49428.7	-4	3000-10500	10	NTT
18/03/94	49429.7	-3	4100-6650	0.2	NTT-ECH
19/03/94	49430.7	-2	3500-9000	8	ESO-1.5
23/03/94	49434.7	+2	3500-9000	8	ESO-1.5
	49434.7		4500-7000	6	ESO-1.5
24/03/94	49435.7	+3	3500-9200	10	AS-1.8
	49435.7		4400-7000	6	ESO-1.5
	49436.7	+4	4400-7000	6	ESO-1.5
26/03/94	49437.7	+5	4400-7000	6	ESO-1.5
28/03/94	49439.7	+7	4400-7000	6	ESO-1.5
31/03/94	49442.7	+10	3800-10000	10	AS-1.8
	49442.7		5800-9200	12	ESO-1.5
01/04/94	49443.7	+11	3800-10000	10	AS-1.8
	49443.7		5800-9200	12	ESO-1.5
02/04/94	49444.7	+12	3800-7200	5	ESO-1.5
03/04/94	49445.7	+13	3800-7200	5	ESO-1.5
05/04/94	49447.7	+15	3800-7200	5	ESO-1.5
07/04/94	49449.7	+17	3800-7200	5	ESO-1.5
09/04/94	49451.7	+19	3800-7200	5	ESO-1.5
14/04/94	49456.7	+24	3800-10000	28	ESO-1.5
16/04/94	49458.7	+26	4500-10500	12	ESO-1.5
10/05/94	49482.7	+50	3600-9600	18	ESO-3.6
14/05/94	49486.7	+54	3500-7200	8	MPI-2.2

^aRelative to maximum *B* (JD = 244 9432.5).

^bFWHM of night-sky lines.

ESO-1.5 = ESO 1.5-m + B&C + Ford2048.

MPI-2.2 = ESO-MPI 2.2-m + EFOSC2 + TH1024.

ESO-3.6 = ESO 3.6-m + EFOSC1 + TK512.

NTT = NTT + EMMI + TK2048 (red arm) or TH1024 (blue arm).

NTT-ECH = NTT + EMMI echelle mode + TK2048.

AS-1.8 = Asiago 1.8-m + B&C + TH7882.

3 INTERSTELLAR ABSORPTION TOWARDS SN 1994D

Since SN 1994D is seen projected on to dust lane of the parent galaxy NGC 4526 (see Fig. 1), the presence of interstellar extinction is not unexpected. Indeed, as shown in Fig. 2, in the high-resolution spectrum of SN 1994D we detected a number of unresolved components of the Na I D doublet at velocities $v_{\text{LSR}} = -9.9, 212.3, 227.7, 249.5$ and 708.9 km s^{-1} , in good agreement with the similar report by King et al. (1995). Another component, barely resolved from that at 212.3 km s^{-1} , is visible at $v_{\text{LSR}} = 203.5 \text{ km s}^{-1}$, at a velocity coincident with that of one component of the Ca II H and K doublet observed by King et al. (1995). While the lower velocity component is associated with the Galaxy and the higher velocity component with NGC 4526, the intermediate components have been attributed to high-velocity clouds (HVC) located at distances between 1 and 10 kpc (King et al. 1995).

The total equivalent widths (EW) of the Na I D lines are 39 mÅ for the galactic component, 89 mÅ for the HVCs, and 76 mÅ for the interstellar gas in NGC 4526. The total EW (Na I D) is 0.20 Å . The empirical relation between EW (Na I D) and reddening given by Richmond et al. (1994) gives $E(B-V) \sim 0.08$, while the relation given by Barbon et al. (1990) gives $E(B-V) \sim 0.05$, in excellent agreement with the estimates of King et al. (1995), $E(B-V) \sim 0.05$, obtained from the neutral hydrogen column density. Therefore we adopt as a best estimate of the reddening towards SN 1994D a value of $E(B-V) \sim 0.06 \pm 0.02$.

No other absorptions have been detected, with the exception of a very faint feature at about 6446 Å , which can be identified with the diffuse interstellar band (DIB) 6445 Å

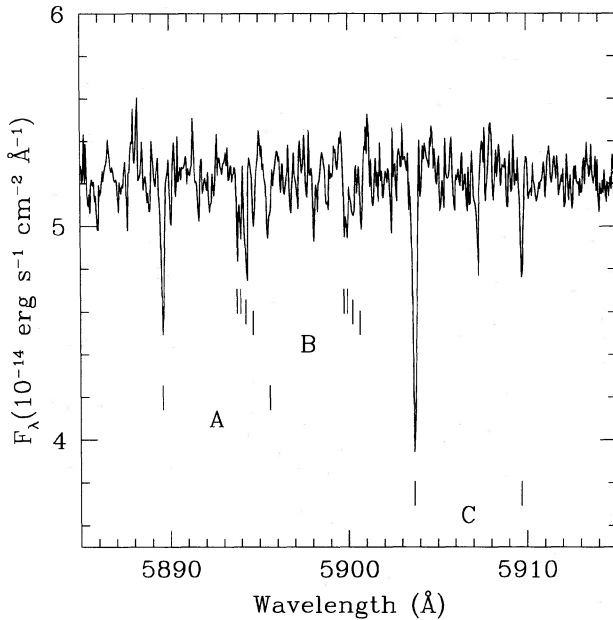


Figure 2. High-resolution spectrum of SN 1994D taken on 1994 March 18, in the region of the Na I D doublet. The ticks mark the Milky Way (A), the high-velocity clouds (B) and the parent galaxy components (C). The S/N ratio is about 60, and the resolution is 0.2 Å (FWHM).

(Herbig 1993). In particular, no signature of the usually most prominent DIBs, centred on 5780 and 5797 Å , has been found, similar to the case of SN 1993J in M 81 (Benetti et al. 1994). Finally, there are no emission features present in the spectral range covered by our spectrum, confirming the analogous report by Smith et al. (1994).

4 THE LIGHT AND COLOUR CURVES

The *UBVRI* light curves of SN 1994D are presented in Fig. 3, and the main photometric parameters are listed in Table 3. The light curves of SN 1992A (Suntzeff 1995), which is assumed to be a standard SN Ia (Kirschner et al. 1993), are also sketched in Fig. 3 for comparison.

With the exception of the *U* band, the light curves of the two SNe are rather similar: the widths of the principal maxima increase going from band *U* to *I*, and a secondary

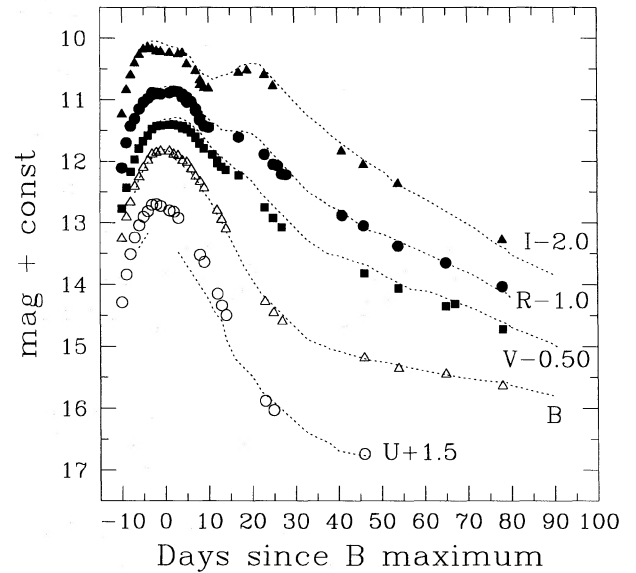


Figure 3. *UBVRI* broad-band light curves of SN 1994D. The abscissa refers to the B light curve. The dotted lines represent the corresponding light curves of SN 1992A (from Suntzeff 1995). They have been shifted in unison by a constant value to allow the B light curves of the two SNe to overlap and to show differences in the colours of the two SNe.

Table 3. Photometric parameters of SN 1994D.

Data	U	B	V	R	I
epoch * of max.	430.5	432.5	434.5	434.5	428.5
of second max.	-	-	-	449.5	451.5
magnitude at max.	11.30	11.84	11.90	11.86	12.15
at second max.	-	-	-	12.71	12.52
early decl. rate †	15.1	12.5	7.2	-	-
Δm_{15}		1.26			
colours at B max.	U-B	B-V	V-R	V-I	
	-0.51	-0.08	0.00	-0.30	

*JD 244 9000.0.

†mag $(100^{\circ})^{-1}$.

maximum is visible in the redder wavelengths about 20 days after the first one.

Maximum brightness is reached on March 19 in U and two days later (i.e. on March 21, JD 244432.5) in B . This will be used in the following as a reference date for the computation of epochs. As usual for SNe Ia, the V maximum was reached two days after the B maximum, but the detailed photometric coverage allows one to see that the V magnitude remained nearly constant for about two days. A similar behaviour is seen in the R band. The effect is extreme in the I band, where peak brightness is actually attained before the U maximum: the magnitude in that band remained nearly constant for over a week. Then, after a short post-maximum decline, the I -band light curve shows a well-defined secondary maximum, about 0.4 mag fainter than the principal maximum, analogously to SN 1992A. A corresponding halt in the luminosity decline, reminiscent of the Plateau in SNe II-P, is visible in the R band and, although much less markedly, in V . Epochs and dates of the maxima along with decline rates are listed in Table 3.

The colour curves of SN 1994D are compared in Fig. 4 with those of SN 1992A. The $(B-V)$ colour index of SN 1994D 10 days before the B maximum is $(B-V)=0$; it then becomes progressively bluer, reaching a minimum value of -0.09 at phase -4 , and becomes redder again after this. At this phase SN 1994D was 0.2–0.3 mag bluer than SN 1992A but, because of a different colour evolution, the two SNe eventually reached about the same $(B-V)$ colour, ~ 1.1 , about 25 days after maximum. Subsequently, the $(B-V)$ colour turned slowly to the blue again, reaching a value 0.4 on day 80.

A similar behaviour is shown by the $(U-B)$ colour index. We see that $(U-B)=-0.37$ on day -10 and it reached a minimum value -0.63 four days later; this corresponds to the phase when the velocity curve for Si II changed slope (cf.

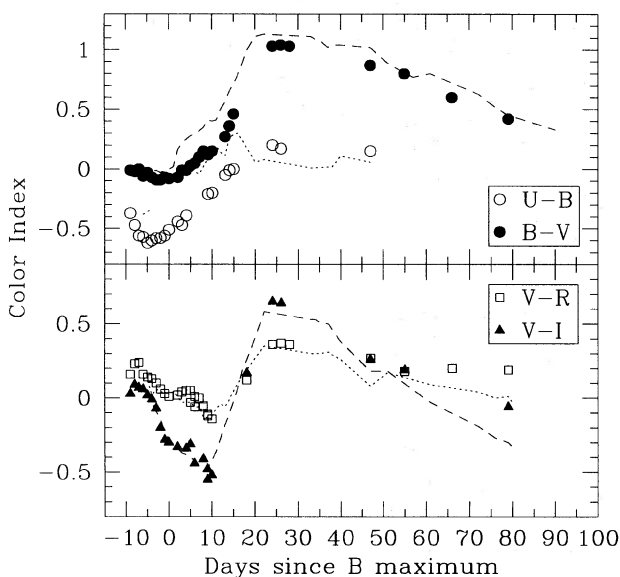


Figure 4. Colour curves for SN 1994D. Upper panel: $(B-V)$ and $(U-B)$; lower panel: $(V-R)$ and $(V-I)$. The dotted and dashed lines are the colour curves of SN 1992A (from Suntzeff 1995). No shift has been applied to the data.

Section 6). Afterwards, $(U-B)$ turns redder, reaching a maximum value $(+0.20)$ in coincidence with the $(B-V)$ maximum. At later epochs we have only one point, which suggests that $(U-B)$ remained almost constant until 50 days after maximum, at a value ~ 0.1 mag redder than that of SN 1992A.

The above mentioned differences in the colour curves of SNe 1994D and 1992A appear clearly in Fig. 3, where the light curves in different bands have been shifted so that the two B maxima coincide.

Few other SNe Ia have been observed with a comparable temporal coverage and photometric accuracy. Among these we note that, concerning the $(B-V)$ colour evolution, SN 1980N appears similar to SN 1992A, whereas SN 1990N is similar to SN 1994D, although the latter was bluer at maximum. It appears, therefore, that even among *standard* SNe Ia small differences can be found both in the light and colour curves. At present, these differences have not found a convincing physical explanation, but their existence suggests a need for caution in the use of SNe Ia as distance indicators.

The shapes of the $(V-R)$ and $(V-I)$ colour curves are more complex, with the hint of a first maximum at about days -9 , a minimum on days 8–10 and a second maximum around day $+25$, i.e. at the same epoch as the $(B-V)$ and $(U-B)$ maxima. This phase corresponds roughly to the secondary maxima in the R and I bands. Until day 50 there are no significant differences from SN 1992A, but later on both $(V-I)$ and $(V-R)$ in SN 1994D are redder (~ 0.25 mag on day 80).

As reported in Table 3, at the epoch of the B maximum the observed colour is $(B-V)=-0.08$. After correcting for the reddening derived in the previous section, we obtain $(B-V)_0^{\max}=-0.14$. In the past it was believed that all SNe Ia had the same $(B-V)$ colour at maximum, and that the observed differences were caused only by reddening. $(B-V)_0^{\max}=-0.15$ was typically adopted as a reference colour at B maximum (e.g. Della Valle & Panagia 1992; Branch & Tammann 1993). Recently a somewhat redder reference colour has become more fashionable [as red as $(B-V)=+0.09\pm 0.04$; Sandage & Tammann 1993]. Therefore, the observed $(B-V)$ colour of SN 1994D appears to lend support to the bluer estimates. Even if extinction within the parent galaxy can be very important in particular cases (e.g. SNe 1986G or 1989B), however, there is now convincing evidence that the $(B-V)$ colour at maximum has an intrinsic dispersion (cf. Phillips 1993; Vaughan et al. 1995). A good example is given by the four SNe, SN 1994D ($B-V=-0.14$), SN 1992bc ($B-V=-0.07$; Maza et al. 1994), SN 1992A ($B-V=0.0$; Suntzeff 1995) and SN 1990N ($B-V=+0.02$; Leibundgut et al. 1991), none of which is thought to have suffered significant reddening within the parent galaxy.

5 DISTANCE AND ABSOLUTE MAGNITUDE

NGC 4526, the parent galaxy of SN 1994D, is a member of the Virgo Cluster (Tully 1988). It is interesting to compare the luminosity of this SN with those of other well-studied SNe Ia that exploded in the Virgo Cluster. Table 4 shows the basic data for 10 SNe Ia (including SN 1994D) selected from an updated version of the Asiago Supernova Catalogue (Barbon et al. 1989) on the basis of Virgo membership,

Table 4. Type Ia SNe with reliable photometry in the Virgo Cluster. The Virgo subgroup membership is from Tully (1988).

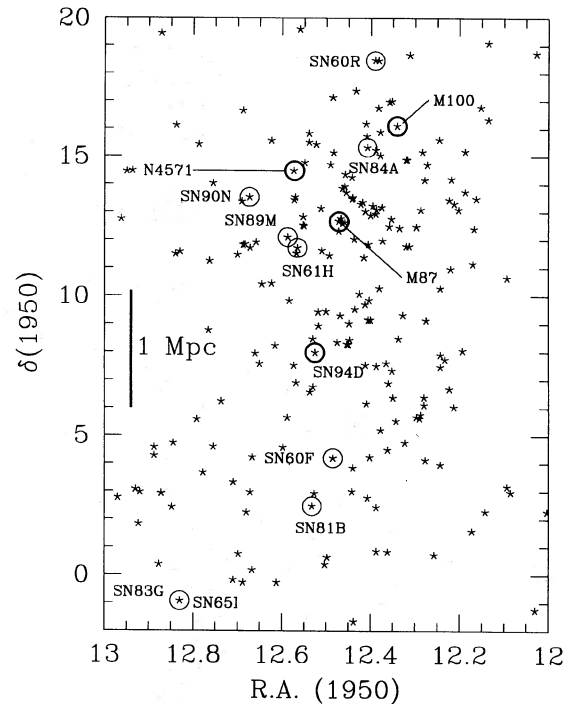
SN	Gal.	V_r km s ⁻¹	Group	μ	m_B	$(B - V)_{max}$	Δm	$\Delta \mu$
1960F	N4496	1738	11-4+1	30.40	11.69	-	-0.15	-0.28
1960R	N4382	773	11-1	30.80	11.87	-	+0.03	+0.12
1961H	N4564	1020	11-1	-	11.80	-	-0.04	-
1965I	N4753	1221	11+9+1	31.30	12.37	0.10	+0.53	+0.62
1981B	N4536	1866	11-4+1	30.50	12.00	0.00	+0.16	-0.18
1983G	N4753	1221	11+9+1	31.30	12.97	0.19	+1.13	+0.62
1984A	N4419	-273	11-1	30.30	12.47	0.29	+0.63	-0.38
1989M	N4579	1805	11-1	31.10	12.56	0.26	+0.72	+0.42
1990N	N4639	983	11-1	31.40	12.65	0.09	+0.81	+0.72
1994D	N4526	450	11-1	30.68	11.84	-0.08	-	-
$\langle m_B \rangle = 12.22 \sigma = 0.44$				$\langle \mu \rangle = 30.86 \sigma = 0.42$				

reliable classification (type Ia or type I in elliptical galaxies) and good photometric coverage in the B and V bands (the peculiar SNe Ia 1991T and 1991bg have been excluded). Radial velocities (column 3) and group membership (column 4) are from Tully (1988), whereas the distance moduli (column 5) estimated with the Tully-Fisher (TF), surface brightness fluctuations (SBF) and planetary nebulae luminosity function (PNLF) methods, are from the compilation by Vaughan et al. (1995), with the exception of NGC 4564, for which the distance modulus is from Tully (1988). Observed magnitudes and colours of the SNe (columns 6 and 7 respectively) are from Vaughan et al. (1995) with the exception of SN 1961H, for which we used the values reported in Barbon et al. (1989), and SN 1965I (data from Capaccioli et al. 1990). Also included in columns 8 and 9 are the differences in magnitudes and distance moduli with respect to SN 1994D.

As can be seen in Table 4, the observed SN magnitudes at maximum light of Virgo SNe Ia vary over a range of ~ 1.3 mag ($\sigma \sim 0.4$ mag). This arises for several reasons, namely reddening within the parent galaxies (not accounted for in Table 4), intrinsic spread of SN luminosities, and distance dispersion within the cluster. In fact, the distance moduli to the SN parent galaxies span over ~ 1 mag ($\sigma \sim 0.4$ mag), which is similar to what is found for the SN apparent magnitudes. A different way to illustrate this point is to look at the sky map in Fig. 5, where the positions of Virgo galaxies from Tully (1988) are reported and SN Ia parent galaxies from Table 4 are indicated. The SN parent galaxy distribution reflects the overall galaxy distribution, with a spread of the plane of the sky which corresponds closely to the spread in the radial direction (about 5 Mpc). Therefore the dispersion in the apparent magnitudes is fully consistent with the dispersion in the distances to the parent galaxies.

The absolute magnitude of SN 1994D depends on the adopted distance to the parent galaxy. If we adopt $\mu = 30.68$ from Tonry (1995), which was obtained with the SBF method, we get for SN 1994D, after correction for extinction, $M_{B,0}^{\max} = -19.08$ and $M_{V,0}^{\max} = -18.96$, while if we adopt the mean of the nine distances to Virgo galaxies listed in Table 4 ($\mu = 30.86$), we get $M_{B,0}^{\max} = -19.26$ and $M_{V,0}^{\max} = -19.14$. Both values are brighter than typical values for normal SN Ia (e.g. Phillips 1993; Branch & Miller 1993; Vaughan et al. 1995).

Recently, the distances to two Virgo cluster members have been derived from observations of Cepheids. Ground-based

**Figure 5.** Positions of the parent galaxies of the most extensively studied SN Ia in the Virgo Cluster and of other cluster members from Tully (1988). The positions of M87, M100, NGC 4571 and 4526 are marked. The projected scale has been computed adopting a distance modulus $\mu = 30.86$.

observations have given for NGC 4571 a distance modulus $\mu = 30.87 \pm 0.15$ (Pierce et al. 1994), while *HST* observations have yielded for M100 $\mu = 31.16 \pm 0.20$ (Freedman et al. 1994). Both galaxies are bona fide cluster members even if they have different recession velocities (282 and 1522 km s⁻¹, respectively). Both distance values are compatible with the distance dispersion found for the SN parent galaxies in Virgo.

The nearby SNe Ia 1937C, 1895B and 1972E have also been calibrated by means of the Cepheids observed in their parent galaxies using *HST*. The resulting mean absolute magnitudes are $M_B = -19.65 \pm 0.13$ and $M_V = -19.60 \pm 0.11$ (Saha et al. 1995). This is much more luminous than SN

1994D. We remark, however, that if the TF or SBF distances were used, the three SNe would be about one magnitude fainter than reported above, and thus fainter than SN 1994D (cf. Table 5).

These discrepancies could have their origin both in the existence of systematic errors affecting the distance measurements to each parent galaxy and in the scatter of the absolute magnitudes at maximum of type Ia SNe. It should be noted that a number of recent observations suggest that type Ia SNe form a class of objects less homogeneous than was believed in the past (Della Valle & Livio 1994 and references therein). In particular, the recent discovery of some SNe with many of the properties of SNe Ia, but with distinct spectral peculiarities, such as 1991bg and 1991T, cast some doubts on the homogeneity of SNe Ia.

Vaughan et al. (1995) have demonstrated that with currently available data, a homogeneous sample (i.e. one with a small spread in absolute magnitude) can be isolated by selecting only those SNe with an intrinsic $(B - V) \sim 0.0$ at maximum light. This is also implicit in the new data of Hamuy et al. (1995). However, it is worthwhile to note that some problems still remain.

Compare for instance SN 1994D with 1992A (exploded in NGC 1380 in the Fornax cluster: Kirshner et al. 1993; Suntzeff 1995). The two SNe have reasonably similar light and colour curves and spectral evolution, and may be expected also to have similar absolute luminosities at maximum. Instead, although the distance moduli of the Virgo and Fornax clusters are thought to be similar (see for example McMillan, Ciardullo & Jacoby 1993, Richtler et al. 1992 or Tully 1988) the apparent magnitude of SN 1994D was about 0.7 mag brighter than that of SN 1992A, even not accounting for the estimated reddening of SN 1994D. A similar difference is found with respect to the B magnitude of the type Ia SN 1980N, which also exploded in Fornax (NGC 1316) (Hamuy et al. 1991). Only additional accurate measurements of the distances to Virgo and Fornax may show whether the difference in absolute magnitudes quoted above is a result of intrinsic differences between the SNe or to a distance dispersion within the clusters.

We finally note that SN 1994D does not conform to the luminosity versus decline rate relation suggested by Phillips (1993) if the SBF distance modulus is adopted for NGC 4526 ($\mu = 30.68$). Its decline parameter is, in fact, $\Delta m_{15}(B) = 1.26$ mag (see Table 3). This is close to the values measured for SNe 1980N (1.28), 1989B (1.31) and 1992A (1.33), all of which were fainter than SN 1994D at maximum. The adoption of the other distance moduli discussed above would make SN 1994D even brighter. We note that the

calibration of this SN using the relation found by Phillips (1993) gives $\mu = 29.93$, and would make NGC 4526 a foreground cluster galaxy. We also remark that the brightness of SN 1994D and the morphological type of its parent galaxy (S0) do not fit into the relation proposed by Hamuy et al. (1995), who found that the intrinsically brightest SNe appear in the galaxies with the younger stellar populations. This in itself would not contradict the emerging pattern of correlations if there were evidence of an episode of more recent star formation in NGC 4526.

6 THE SPECTROSCOPIC EVOLUTION

The spectral evolution of SN 1994D from day -11 to day $+50$ is shown in Figs 6 and 7, where a selection of the whole data base is presented. For time coverage and quality of the spectroscopic data SN 1994D is possibly the best-studied SN Ia to date. Owing to the high time resolution of the observations, the spectral evolution of SN 1994D can be followed in great detail by observing the day-to-day variations of single features.

The spectral evolution follows the typical path defined by *normal* SNe Ia such as SN 1981B (Branch et al. 1983), SN 1989B (Barbon et al. 1990; Wells et al. 1994), SN 1990N (Leibundgut et al. 1991; Mazzali et al. 1993) and SN 1992A (Kirshner et al. 1993). This is shown in Fig. 8, where the spectra of SN 1994D and 1992A (data from the ESO Key Programme on SNe) are compared at three different phases. We said earlier that SN 1992A at maximum had $(B - V)_0 = 0.0$, i.e. it was about 0.1 mag redder than SN

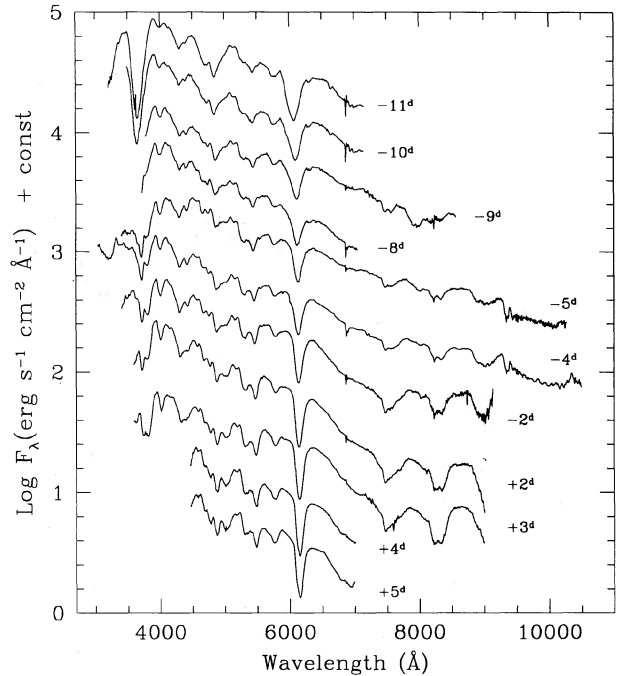


Figure 6. Spectroscopic evolution of SN 1994D from day -11 to day $+5$. The phase is computed from the B maximum (March 21). For presentation the spectra have been shifted by an arbitrary amount: -11^d ($+18.3$ ($\log F_\lambda$)), -10^d ($+17.9$), -9^d ($+17.4$), -8^d ($+17.0$), -5^d ($+16.4$), -4^d ($+16.0$), -2^d ($+15.6$), $+2^d$ ($+15.1$), $+3^d$ ($+14.7$), $+4^d$ ($+14.3$) and $+5^d$ ($+13.9$).

Table 5. Comparison between the absolute magnitudes obtained for SNe 1895B, 1937C and 1972E using the Cepheids PL relation (Saha et al. 1995) or the SBF-TF methods (Vaughan et al. 1995).

SN	m_B	μ_{Cep}	μ_{SBF-TF}	$M_B(Cep)$	$M_B(SBF-TF)$
1895B	8.33	28.13	27.10	-19.80	-18.89
1937C	8.71	28.47	26.90	-19.65	-18.19
1972E	8.58	28.13	27.10	-19.55	-18.63
1994D	11.84	-	30.68	-	-19.08
$\langle M_B \rangle$				-19.65	-18.70

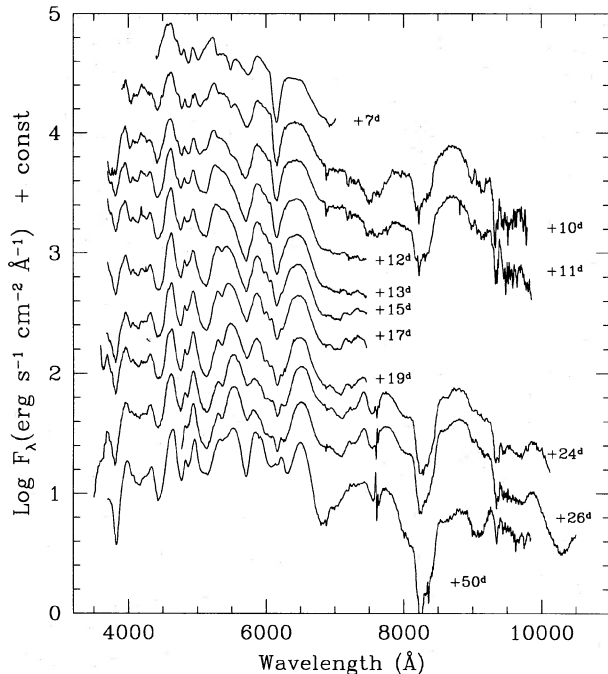


Figure 7. The same as in Fig. 6 for day +7 to day +50. For presentation the spectra have been shifted by an arbitrary amount: +7^d (+17.9), +10^d (+17.6), +11^d (+17.3), +12^d (+17.0), +13^d (+16.7), +15^d (+16.4), +17^d (+16.2), +19^d (+15.9), +24^d (+15.8), +26^d (+15.7) and +50^d (+15.6).

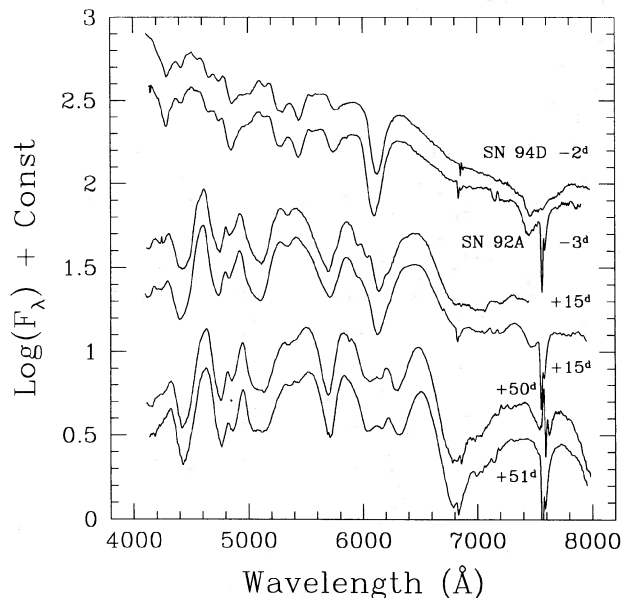


Figure 8. Comparison between the observed spectra of SN 1994D (upper) and SN 1992A (lower) at three different phases. The spectra of SN 1992A have been taken at ESO La Silla on 16/01/92 (NTT+EMMI), 4/02/92 (3.6-m+EFOSC1) and 11/03/92 (NTT+EMMI). Flux units are arbitrary, and the wavelengths have been reported to the rest frames.

1994D, but altogether the spectra of the two SNe are almost identical, with only very minor differences. This fact might make one wary of the derived reddening for SN 1994D.

Of particular interest is the evolution of Si II $\lambda 6355$, which is the most prominent feature in SNe Ia near maximum. This is shown in Fig. 9. Starting already with the first spectrum (day -11), the line appears as a well-developed P Cygni profile, showing a very broad absorption (FWHM $\sim 11\,300\text{ km s}^{-1}$) centred at about 6070 Å and with the blue edge corresponding to a velocity of $\sim 21\,600\text{ km s}^{-1}$, a value consistent with that measured in SN 1990N on day -14 ($\sim 25\,000\text{ km s}^{-1}$; Leibundgut et al. 1991). This indicates that the Si synthesized during the explosion extends well beyond the limit fixed by the unmixed W7 model ($15\,000\text{ km s}^{-1}$; Nomoto, Thielemann & Yokoi 1984) as pointed out already by Mazzali et al. (1993) for 1990N and by Kirshner et al. (1993) when discussing the earliest spectrum of SN 1992A.

The absorption component of the Si II line becomes narrower and moves redwards as the photosphere recedes, and it is barely visible in the spectrum of day +50, with the SN entering the nebular phase. The emission component also evolves with time. Starting from day -11, the flat red wing of the emission profile becomes increasingly steep until day -2; afterwards it begins to flatten out again until day +7. At this epoch another feature, centred near 6520 Å and probably owing to some Ni III emission line (cf. SN 1991bg, Mazzali et al. 1995, in preparation) becomes increasingly important as the Si II emission gradually fades. The rapid variation of the blue wing of the Si II absorption trough can

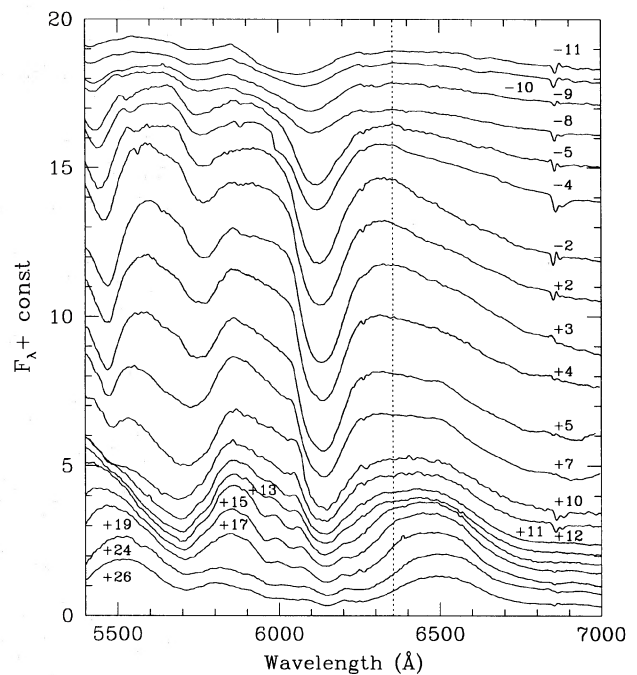


Figure 9. Evolution of the Si II $\lambda 6355$ region from day -11 (top) to day +26 (bottom) for all spectra shown in Figs 6 and 7. The spectra have been corrected for the recession velocity of the parent galaxy. The dotted line is placed at the rest frame position of the feature.

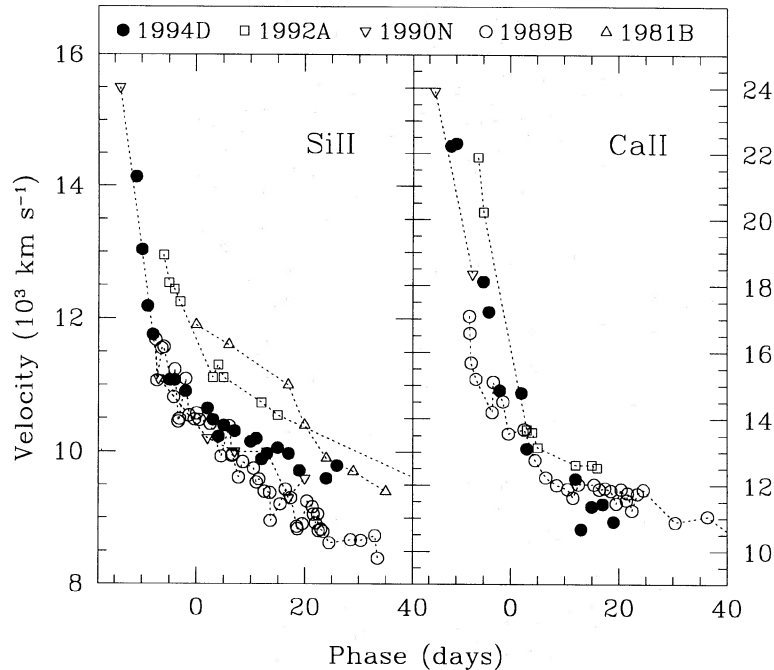


Figure 10. Evolution of the expansion velocity as deduced from the minima of the Si II $\lambda 6355$ absorptions (left panel) and Ca II H and K (right panel) for SN 1994D, SN 1992A (ESO KP, unpublished; Kirshner et al. 1993), SN 1990N (Leibundgut et al. 1991), SN 1989B (Barbon et al. 1990; Wells et al. 1994) and SN 1981B (Branch et al. 1983). The adopted recession velocity of NGC 4526 is $+709 \text{ km s}^{-1}$ (King et al. 1995).

be used to assess the phase of a given spectrum with an accuracy of ± 2 d. It should also be noted that SN Ia models (Mazzali et al. 1993) showed that Fe II absorption lines blend in the blue wing of the Si II absorption well after the maximum.

The velocity evolution deduced from the positions of the absorption minima of Si II $\lambda 6355$ is presented in Fig. 10, (left panel) along with those of SNe 1992A, 1990N, 1989B and 1981B. The decline rates are similar for all objects, with good agreement between 1994D, 1990N and 1989B (maximum differences being $\sim 500 \text{ km s}^{-1}$), while SNe 1992A and 1981B show higher velocities. The velocities derived from the Ca II H and K lines show the same differences among the various SNe (Fig. 10, right panel).

The behaviour of the Si II line velocity shows a definite change in the decline rate around day -6 , in good agreement with 1990N, the only other SN Ia observed at such early phases. Pearce, Colgate & Petschek (1988) and Branch, Drucker & Jeffery (1988) suggested that this trend can be approximated by a power law $v \propto t^{-\alpha}$, with two indices. Such a fit applied to SN 1994D gives $\alpha = 0.67$ for $-11 \leq t \leq -8$ d and $\alpha = 0.12$ for $-5 \leq t \leq 26$ d. Since $\alpha = 2/(n-1)$ (Branch et al. 1988), where n is the exponent of the power-law density profile $\rho \propto r^{-n}$, these two values imply $n \sim 4$ and ~ 17 , respectively. While the former result is consistent with the canonical $n=7$ value, the latter is unquestionably different, but may be understood as follows.

At very early phases, when the photosphere is located at rather large velocities ($\sim 10000 \text{ km s}^{-1}$), the amount of material above the photosphere is small ($< 0.5 M_{\odot}$). Thus, the lines are formed very close to the photosphere, and the

velocity corresponding to the Si II minimum is very close to that of the photosphere. So, the rate of change of the Si II line velocity with time follows that of the position of the photosphere in velocity coordinates, and indicates a density index close to $n=7$ (which implies $\alpha=2/3$). After maximum, the photospheric velocity becomes less than 10^4 km s^{-1} and drops very rapidly, and thus the photosphere falls in the region where the density gradient in the explosion model is flatter ($n=2$). Thus the absorbing layers become larger and larger. For this reason, strong lines such as Si II $\lambda 6355$ are formed over a large velocity range, and the velocity derived from the position of the absorption is significantly larger than that of the photosphere.

This is illustrated quantitatively in Fig. 11, where the observed SN 1994D data are compared with the photospheric velocities deduced from the spectrum synthesis model for SN 1990N of Mazzali et al. (1993) and with the velocity of the spectrum discussed in Section 7. It is clear that, while before maximum the Si II absorption velocity is close to that of the photosphere, after maximum the photospheric velocity continues to decrease at an almost constant rate, and the velocity of the Si II absorption becomes increasingly different. In the same figure the velocities computed from the minima of the weak Si II $\lambda 5640$ feature are also shown (see Fig. 12 for the identification). Since these lines are weak, they are always formed close to the photosphere. The velocity of these lines is therefore a better diagnostic for the photospheric velocity. On the other hand, the Ca II H and K doublet, which has a much larger optical depth than the Si II one owing to the large gf values of the lines, is always faster than even the Si II feature, because it forms over a

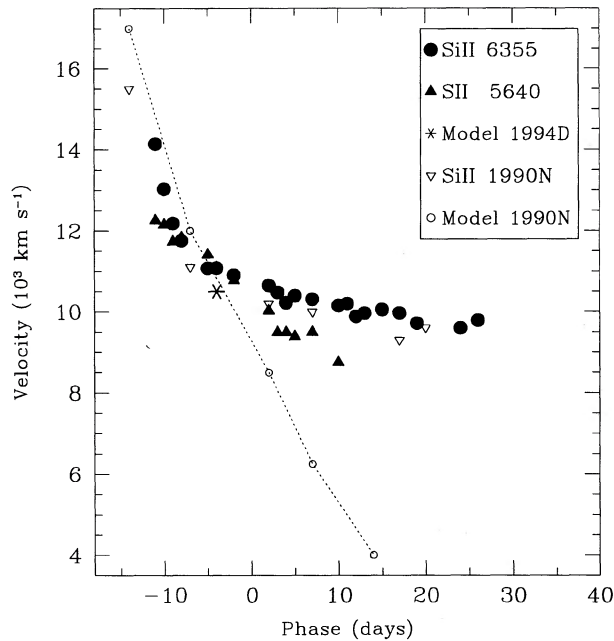


Figure 11. Comparison of the expansion velocities of the photosphere as deduced from observations and spectral synthesis models for SNe 1994D and 1990N. Measurements of the absorption minima of Si II $\lambda 6355$ and Si II $\lambda 5640$ and models from Mazzali et al. (1993) and Section 7 are shown.

larger velocity range at all epochs. So, for the Ca II doublet, the change of slope after maximum is also observed, as the result of the larger mass above the photosphere, but is less extreme than in the Si II line because even well before maximum the Ca II line velocity was greater than the photospheric velocity. This is an additional demonstration that weak lines should be used in order to estimate v_{ph} , especially after maximum, as pointed out by Mazzali et al. (1993). This remark has reference to the expanding photospheric methods for determining SN luminosities.

The epoch when the decline rate of the Si II line velocity changes coincides with the minimum of the $(U-B)$ colour curve (cf. Section 4). This may not be a coincidence, since if the line opacities grow faster after this epoch, as shown by the Si II line, then the Fe II and Co II lines in the U region become more effective absorbers, and the $(U-B)$ index turns redder. Another contribution to this effect is the fact that the effective temperature reaches a maximum around 10 days before the B maximum (Mazzali et al. 1993).

Branch & van den Bergh (1993) suggested that the expansion velocity deduced from the Si II $\lambda 6355$ line 10 days after the maximum is correlated with the morphological type of the parent galaxy. According to their findings, the slower SNe arise in the early-type galaxies. For SN 1994D, which exploded in an S0 galaxy, this velocity is about $10\,000\text{ km s}^{-1}$, and is similar to those shown by SNe 1989B and 1990N (see Fig. 10), which exploded in Sb and SBb galaxies, respectively. On the other hand, SN 1992A, which

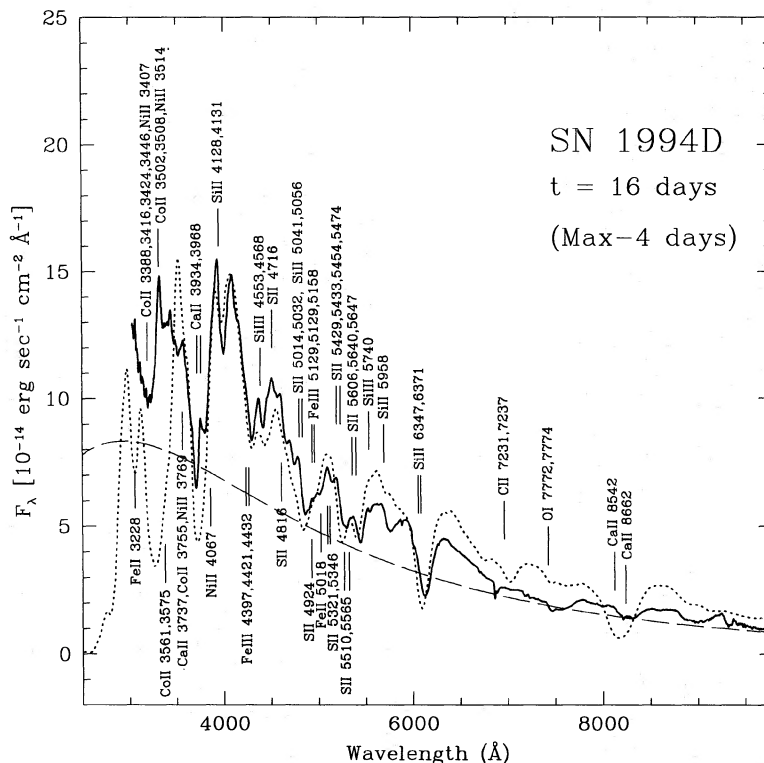


Figure 12. Synthetic spectrum (dotted) and observed spectrum for March 17 (max - 4 days). The latter has been corrected for parent galaxy recession velocity ($+709\text{ km s}^{-1}$). The long-dashed line is the photospheric blackbody spectrum. Main-line identifications are positioned according to Mazzali et al. (1993).

occurred in a S0/Sa galaxy, appears to be significantly faster than SN 1994D and comparable to SN 1981B, whose parent galaxy is of type Sc. Thus, if a relation between expansion velocity and galaxy type exists, it is certainly affected by a strong dispersion.

7 A SYNTHETIC SPECTRUM

We have modelled the March 17 spectrum of SN 1994D using the Monte Carlo code described by Mazzali & Lucy (1993), which was already successfully used to model the SNe Ia 1990N (Mazzali et al. 1993) and 1991T (Mazzali, Danziger & Turatto 1995).

The spectrum corresponds to an epoch 4 days before B maximum, which can be considered as a typical representation of an SN Ia photospheric epoch spectrum. At this epoch SN 1994D had magnitudes $U = 11.41$, $B = 11.99$, $V = 12.08$, i.e. $(B - V) = -0.09$. For our models, we assumed a rise time to B maximum of 20 days, so that on March 17 the epoch from the explosion is $t = 16$ d. We used the reddening estimated in Section 3 [$E(B - V) = 0.06$] and we have adopted as distance modulus the value $\mu = 30.68$ mag (i.e. 13.7 Mpc), measured with the SBF method (Tonry 1995).

The similarity between SNe 1994D and 1990N leads us rather straightforwardly to the determination of the other input parameters for the synthetic spectrum. These are: $L = 1.10 \times 10^{43}$ erg s $^{-1}$ (i.e. $\log L/L_{\odot} = 9.46$, $M_{\text{Bol}} = -18.9$) and $v_{\text{ph}} = 10\,500$ km s $^{-1}$, i.e. $R_{\text{ph}} = 1.45 \times 10^{15}$ cm (or $R_{\text{ph}} = 20\,750 R_{\odot}$), and are similar to those for SN 1990N at a similar epoch. These values lead to the best fit to the spectrum given the adopted values of distance, reddening and epoch. In the model, we adopted a W7 density structure. The composition was that of W7 with full mixing for $v > 6000$ km s $^{-1}$. The relative abundances of Fe, Co and Ni were varied according to the epoch.

With this input, the model has a photospheric density $\log \rho_{\text{ph}} (\text{g cm}^{-3}) = -13.34$, and the mass above the photosphere is $0.47 M_{\odot}$. The effective temperature at the photosphere derived from L and R_{ph} is 9300 K. Photon backscattering owing to line blocking in the atmosphere leads to a net heating of the near-photospheric layers, so that the equivalent blackbody temperature at the photosphere is $T_{\text{B}} = 10\,700$ K.

The synthetic spectrum we obtained is shown in Fig. 12, compared to the observed one. It has magnitudes $U = 11.64$, $B = 12.04$ and $V = 12.00$. The observed spectrum is reasonably well reproduced by the synthetic one. In particular, features like the Si II lines, the presence of the Si III absorption near 4400 Å, and the importance of the Fe III lines both in the absorption near 4300 Å and in the region 4800 – 5000 Å, which is well fitted, confirm that the temperature in the atmosphere is rather high at this epoch.

The model Ca II IR triplet is stronger than the observed one, as is the H and K doublet, although much less so. Since only a small fraction ($\sim 10^{-6}$) of all Ca atoms are Ca II in our model (Ca III dominates), it is possible that this fraction is somewhat overestimated.

The real puzzle is provided by the poor fit of the predominantly Co II feature near 3250 Å. In the observed spectrum of SN 1994D, the absorption is much weaker than in SN 1990N at day -7 , which was well matched by the model (Mazzali et al. 1993). A deep Co II feature was observed also

in SN 1981B near maximum (Branch et al. 1983), and in SN 1987N about one week after maximum (Branch & Tammann 1992). A similar discrepancy, although less pronounced, is seen when comparing the spectrum of SN 1994D with that of SN 1992A on days $-7/-6$ (Kirshner et al. 1993). We note, however, that slightly different epochs may play an important role.

The weakness or absence of this feature in the observed spectrum of SN 1994D again raises the continuing problem of the lack of a certain identification of the cobalt synthesized in the explosion. In this respect it should be noted that, unlike the situation in SN 1987A, the light curves of SNe Ia are not followed for long enough, so that the time when they reproduce the ^{56}Co decay rate is not reached. Unequivocal support for the presence of this radioactive nuclide from this independent method is thus lacking (Suntzeff 1995). Since we have no reason to doubt the wavelength or flux calibration of our spectra, and since the weakness of this feature occurs in spectra of at least one of four other observed SNe Ia (SN 1992A, Kirshner et al. 1993), we must seek other explanations. One possibility is that the radioactive nuclides in SN 1994D are not mixed out to the photosphere and beyond at phase -4 days, so that Co is more concentrated in the innermost layers that are not yet visible at this epoch. Since the iron produced in the explosion should be closely coupled to the cobalt, one should try to answer the question of whether or not the amount of iron in the envelope modelled through the various Fe II and Fe III transitions can be made compatible with the (small) amount of cobalt required to fit the Co II feature. Since this is not the case, the lines of Fe can only be well reproduced if it is assumed that the fraction of ^{54}Fe is enhanced with respect to the W7 model. Then one is still left with the question of why there is mixing in some supernovae and not in others, a matter to be addressed with better understood models of the explosion and its immediate aftermath. Another possibility is that at the moment we have not adequately accounted for all the line opacity in these objects particularly at UV wavelengths. The fact that the UV spectra of SN 1990N at early phases differ quite strongly from those of SN 1992A (Kirshner et al. 1993) suggests there is still much that is unaccounted for in the models with respect to the sources of line opacity. Most of the problem may lie with the necessity for a correct treatment of ionization and excitation in the part of the UV which is optically thin in the continuum, but thick in the lines due to line blocking.

Although we computed several other models that had somewhat different input parameters for the adopted distance, reddening and epoch, none of them fitted the observed spectrum much better than the one we show here, and none had colours bluer than $(B - V) = 0.0$. In practice, at higher temperatures (i.e. higher L 's or smaller v_{ph} 's), the continuum becomes bluer, but the Fe III lines get stronger, and since they fall mostly in the region of the B filter the $(B - V)$ colour remains practically constant. This is exactly what happens in the hot SN 1991T (Mazzali et al. 1995). Perhaps it is the somewhat high flux in the red part of the model which keeps the colours too red. Since this flux is the result of photon blocking in the UV, this may signal that we are overestimating that effect, although it is not easy to see how less blocking could result in a smaller V flux but leave U and B unaffected. In any case, given that all line features are well

reproduced in the model, we do not expect that very different input parameters can yield a good fit to both the colours and the lines, since then the temperature would probably differ significantly from that of our current best fitting model, and different lines would probably be present in the synthetic spectrum.

One obvious problem with the model shown in Fig. 12 is that the lines of Si II and Ca II are too strong. In models with the same L but somewhat lower v_{ph} , the temperature is higher, and so is the ionization. This causes the Si II and Ca II lines to be a bit weaker, but the Fe III lines are then too strong. Also, if the temperature is too high, the Si III lines $\lambda 4379 + 4395 \text{ \AA}$ and $5740 \text{ \AA}$ become far too strong. The acceptable range of v_{ph} 's for the chosen distance and reddening, and the resulting luminosity, is between 9000 and 11000 km s^{-1} . The fact that not all lines can be simultaneously fitted may indicate that the adopted distance, reddening and epoch may be incorrect. The epoch can be checked by modelling the earliest spectra, where even a small error in t may be significant. Distance and reddening, on the other hand, must be investigated by computing grids of models, changing these values from grid to grid. Although such a detailed analysis is beyond the scope of the present paper, in the following we briefly discuss some preliminary results concerning the distance.

In this paper we adopted for our models distance and reddening as discussed in Section 5, and for the epoch a typical SN Ia risetime. Thus the input parameters L and v_{ph} were close to the typical SN Ia parameters, which gave satisfactory results with SN 1990N. Other values of the distance discussed in Section 5 do not greatly differ from the one we chose ($\mu = 30.68$), so we should not expect that adopting any of them would lead to drastic changes in our model results, other than small changes in L and v_{ph} , which our model would probably not be able to discriminate among.

We have computed some models for $\mu = 31.13$, which is the value in Tully's Catalogue (1988). This is sufficiently different from $\mu = 30.68$ that noticeable differences in the synthetic spectra might be expected. We found that a satisfactory fit can be obtained for $\log L/L_{\odot} = 9.65$ (i.e. $L = 1.72 \times 10^{43} \text{ erg s}^{-1}$, $M_{\text{bol}} = -19.38$) and $v_{\text{ph}} = 11500 \text{ km s}^{-1}$. The model has a similar temperature to that of Fig. 12, but the mass above the photosphere is smaller, and so lines are not as deep. The line velocity is apparently somewhat too large, so a correct estimate for the distance may lie between 30.68 and 31.13, and SN 1994D may be somewhat brighter than normal SNe Ia.

In order to test whether the 'long' distance scale to Virgo is compatible with the observations, we computed models for $\mu = 31.5$ and 32.0. The large distances result in the need for a large luminosity, $\log L/L_{\odot} = 9.80$ (i.e. $L = 2.4 \times 10^{43} \text{ erg s}^{-1}$, $M_{\text{bol}} = -20.25$) and 10.0, (i.e. $L = 3.8 \times 10^{43} \text{ erg s}^{-1}$, $M_{\text{bol}} = -19.75$), respectively. In both cases, L is so large that very high v_{ph} 's ($> 12000 \text{ km s}^{-1}$) are required to obtain a reasonable temperature ($\sim 10000\text{--}12000 \text{ K}$). In all such cases, though, with a W7 density structure, either the temperature is too high and the observed lines do not form because of ionization, or v_{ph} is too large, there is not enough mass above the photosphere and no strong lines are seen in the synthetic spectrum. Thus, if a W7 density structure is used, a very large distance to Virgo is incompatible with the observed spectrum of SN 1994D.

8 DISCUSSION AND CONCLUSIONS

In this paper we presented the optical observations of SN 1994D collected at ESO and Asiago, which provide an almost daily coverage and constitute one of the largest set of observations of a SN Ia near maximum light.

High-resolution ($0.2 \text{ \AA}$ FWHM at $5900 \text{ \AA}$) spectroscopy allowed the detection of three components in the Na I D doublet owing to clouds in the Galaxy, to HVCs and to interstellar matter within the parent galaxy (Section 3). Although the parent galaxy, NGC 4526, is of early type (S0), this is not surprising, since the SN exploded on the edge of a dust lane. Empirical relations $\text{EW}(\text{Na I D})$ versus $E(B - V)$ give a reddening $E(B - V) = 0.06$ in good agreement with an analogous finding by King et al. (1995) based on the H I column density.

The frequent and accurate *UBVRI* photometric coverage allows a detailed study of the photometric evolution. In the U band the peak of the light curve was narrow. B maximum, which has been assumed as reference for the computation of the epochs, was reached 2 days later. In these bands maximum light was followed by a normal luminosity decline. V maximum, which was reached 2 days after B maximum, as is normal for SNe Ia, is less well defined, and the luminosity declines more slowly. This effect is even more pronounced at redder wavelengths (R and I), where the peaks are flat topped and secondary maxima (perhaps hinted also in V) are visible about 20 days past the principal maxima. The photometric data of SN 1994D are summarized in Table 3.

The presence of secondary maxima in the *JHK* light curves of normal SNe Ia had already been noticed earlier by Elias et al. (1981) who also noted a similar behaviour in the I (and possibly R) band of SN 1972E. Our new data on SN 1994D, along with other recently published observations of SN 1989B (Wells et al. 1994) and SN 1992A (Suntzeff 1995) confirm previous findings based on poorer quality material.

It seems clear from the evidence adduced by Suntzeff (1995), and from our *VRI* photometry for SN 1994D and associated spectrophotometry, that the double-peaked light curves have little to do with the presence of absorption features, or the lack of emission features. Rather, they appear to result from a redistribution of energy over a considerable wavelength range as a result of which longer wavelength radiation is enhanced at the expense of shorter wavelength radiation. The physical reason for this at a phase 20 days after maximum light remains to be elucidated. Höflich (1995) has been able, with some classes of models, to reproduce this secondary maximum as a result of significant expansion of the photospheric radius after primary maximum. Clearly, closely spaced observations of SN Ia light curves over the complete accessible wavelength range are desirable.

With the available photometry, the colour evolution can also be followed in great detail. The comparison with SN 1992A, an object in many respects very similar to SN 1994D, shows real differences at maximum light, which cannot be attributed to uncertainties in the measurements. We stress also that the intrinsic colour of the SN is considerably blue, $(B - V)_{\text{max}}^{\text{int}} = -0.14$. This value, compared with those of other well-studied SNe Ia, confirms the colour dispersion within this class of objects.

SN 1994D is among the brightest SNe observed in the Virgo cluster (cf. Table 4). Whether this is a result of the

location of the parent galaxy on the near side of the cluster or of an intrinsically high luminosity of the SN cannot be assessed with certainty without further modelling work. The SBF method gives, for NGC 4526, a distance modulus $\mu = 30.68$ (Tonry 1995), which is within a few tenths of a magnitude from the average for the whole Virgo cluster, and not dissimilar to the recent determinations of the distance of two members of the cluster, obtained using observations of Cepheids ($\mu = 30.87 \pm 0.15$ for NGC 4571, Pierce et al. 1994, and $\mu = 31.16 \pm 0.20$ for M 100, Freedman et al. 1994). With the SBF distance modulus, $\mu = 30.68$, SN 1994D becomes as bright as $M_{B,0}^{\max} = -19.08$ and $M_{V,0}^{\max} = -18.96$. These are rather bright values, although not exceptional (cf. Phillips 1993; Vaughan et al. 1995; Branch & Miller 1993), and are compatible with the results of the spectral synthesis models. SN 1994D is about 0.6 mag fainter than the mean calibration of SN Ia using the Cepheid method, but brighter than the same objects calibrated with the SBF-TF method. With its relatively high luminosity and normal luminosity decline, SN 1994D does not fit the empirical relation $M_B^{\max}$ versus Δm_{15} by Phillips (1993).

The spectral evolution in the photospheric epochs described here follows the path of normal SNe Ia, such as SN 1992A (cf. Fig. 8). The coverage starts very early, spanning from day -11 to day $+55$; this allowed a detailed study of the line position and profile variations. In particular, we analysed the behaviour of the Si II $\lambda 6355$ line. The evolution of the expansion velocity deduced from the absorption minimum of this feature is similar to those shown by SNe 1990N and 1989B, while it is slightly different from SNe 1981B and 1992A, SN 1994D being $\sim 1000 \text{ km s}^{-1}$ slower. It shows a sudden break in the decline slope at around day -6 , which is observed also in the Ca II H and K lines. This is probably a common feature for all the strong lines, which are formed with the contribution of envelope layers even well above the photosphere, spanning a large range of velocities. This is not the case for weaker lines, which form close to the photosphere. For this reason such weak lines should be used to estimate the photospheric velocity. This is an important point concerning the use of the expanding photosphere method in estimating SN distances. The comparison between the observed values of the velocity and those derived from spectral modelling (cf. Fig. 11) confirms this behaviour.

We modelled the day -4 spectrum of SN 1994D using a Monte Carlo spectral synthesis code. The adopted density structure and abundances are drawn from a classical mixed W7 model. Most features are well reproduced assuming that the burst occurred 20 days before B maximum, and had a photospheric velocity of $10\,500 \text{ km s}^{-1}$ and an effective temperature of 9300 K , in fair agreement with the analogous values found for SN 1990N at a similar epoch. In particular, the positions and intensities of the Si II, S II, Fe II and Fe III lines are satisfactorily matched. The model does not succeed in reproducing the observed colours and the spectral feature at $3300 \text{ \AA}$, which is a good diagnostic for the Co abundance. We note that other objects which are otherwise similar to SN 1994D (SNe 1990N and 1992A) show at this epoch different profiles for these lines. Further spectral modelling of the whole data set is mandatory in order to assess if this is caused by an overall underabundance of Ni in SN 1994D (which is in conflict with the apparently normal luminosity and the blue colour) or by a deviation from the standard W7 abun-

dance structure. Finally, models suggest that a slightly larger distance than the SBF value may result in better fits to the spectrum. In this case SN 1994D would be somewhat brighter than normal SNe Ia. This must be further verified with models of spectra at different epochs.

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