**Astronomy
&
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The Type Ia Supernova 2001V in NGC 3987[*]

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Abstract. CCD photometry is presented of the type Ia SN 2001V occurred in the edge-on spiral galaxy NGC 3987. The observations made through Johnson-Cousins *BVRI* filters were collected from Feb. 24 ($t = -8$ days, with respect to B-maximum), up to May 5 ($t = +62$ days). The light curves are analyzed with the revised Multi-Colour Light Curve Shape (MLCS) method (Riess et al. 1998) by fitting template vectors to the observed light curves simultaneously. The reddening of SN 2001V is estimated to be $E(B - V) = 0.05$ mag, while the galactic component is $E(B - V) = 0.02$ mag (Schlegel et al. 1998), suggesting that part of the reddening may be due to the ISM in the host galaxy. The Δ parameter in MLCS converged to -0.47 mag, indicating that this SN was overluminous relative to the majority of Type Ia SNe. The inferred distance to its host galaxy, NGC 3987, is 74.5 ± 5 Mpc, which is in good agreement with recently determined kinematic distances, based on radial velocity corrected for Virgo-infall and Hubble constant $H_0 = 65$ km s^{-1}Mpc^{-1}.

Key words. stars: supernovae: individual: SN 2001V

1. Introduction

SN 2001V was discovered spectroscopically by P. Berlind at the F. L. Whipple Observatory on Feb. 19, 2001 (Jha et al. 2001). The supernova was immediately classified as of Type Ia based on the Si II absorption trough at 6150 Å. The blue continuum suggested that this SN was discovered before maximum light. This was also strengthened by the high expansion velocity (14 000 km s^{-1}) derived from the center of the Si II line. Because the light curves of Type Ia SNe are now frequently used to infer distances to the host galaxies, such SNe that are identified before maximum are very important, because i) the light curve can be sampled more effectively, ii) the inferred distances are better constrained by the light variation around maximum than at later phases.

The host galaxy, NGC 3987 belongs to the small group centered on NGC 4005 (Nilson 1973; Gregory & Thompson 1978). This group is located within the medium-sized cluster Zw 127-10 (Zwicky et al. 1961). NGC 3987 is an edge-on, Sbc-type galaxy with remarkable central dust lane. The IRAS point source 11547+2528 is located close to the optical center of this galaxy, which was also detected in radio (Condon & Broderick 1986).

SN 2001V is the first supernova discovered in this galaxy. The SN occurred in the outskirts, almost at the visible edge of the host (Fig. 1). The position of the SN as well as its blue colour at maximum suggest that the effect of interstellar extinction is probably not very high for SN 2001V. Indeed, the galactic component of the reddening in this direction is only $E(B - V) = 0.02$ mag, according to Schlegel et al. (1998).

There are two recent distance estimates for NGC 3987: Mould et al. (1993) lists $\mu_0 = 33.82$ mag (58.1 Mpc) based on near-IR Tully-Fisher relation, while van Driel et al. (2001) gives $v = 4361$ km s^{-1} as a group-averaged radial velocity corrected for Virgo-infall that results in $d = 67.1$ Mpc (adopting $H_0 = 65$ km s^{-1} Mpc^{-1}). Based on the average of these distance estimates, the expected maximum brightness of a Type Ia SN is about 14.6 mag. According to the NASA/IPAC Extragalactic Database, the redshift of NGC 3987 is $z = 0.015$. Thus, SN 2001V is a relatively nearby, low-redshift SN.

In the following, details of the observations and data reductions are given, then the results of the photometric analysis are presented and discussed.
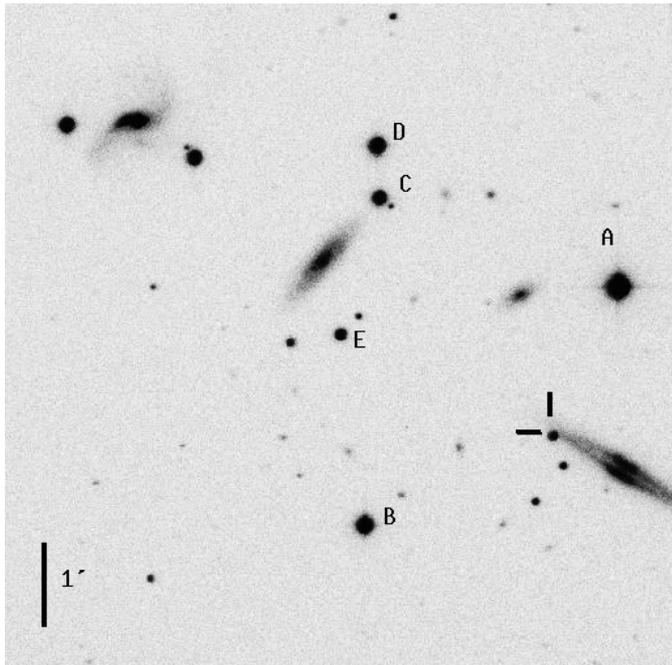
Fig. 1. The central $7' \times 7'$ of the observed field of NGC 3987 taken with the Schmidt telescope of Konkoly Observatory on Feb. 29, 2001. The position of SN 2001V is marked. The comparison stars are labeled. North is up and east is to the left.
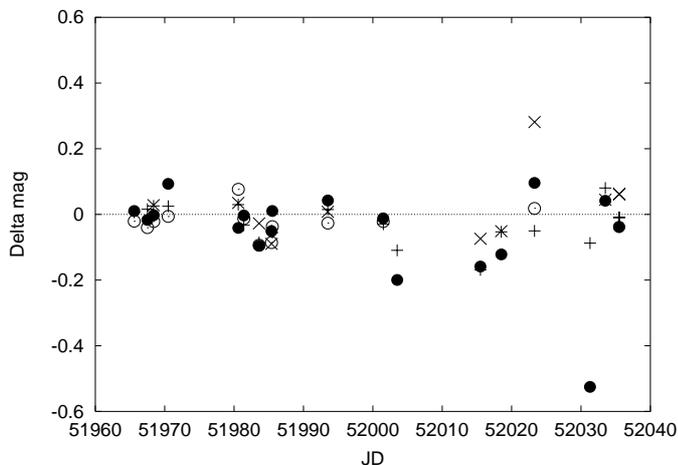
Fig. 2. The difference of magnitudes of SN 2001V obtained from aperture- and PSF-photometry. Open circles: *B*-filter, filled circles: *V*-filter, plus signs: *R*-filter, crosses: *I*-filter.

2. Observations and data reduction

The light variation of SN 2001V was followed on 18 nights, starting from $t = -8$ days (with respect to B−maximum), extending up to $t = +62$ days. The telescopes and detectors used are listed in Table 1. All data were collected through standard Johnson-Cousins *BVRI* filters.

The CCD-frames have been reduced in *IRAF*[1]. First, the instrumental magnitudes of the SN and the selected comparison

stars (Fig. 1) were derived with aperture photometry using the task *digiphot/apphot*. The radius of the aperture was 6 pixels (about $2 \times FWHM$, see Table 1), while the sky level was determined in a 5 pixel-wide annulus with inner radius of 10 pixels. Because the SN is located close to the "tip" of NGC 3987, most of the pixels in the annulus were not affected significantly by the light from the host galaxy. The sky level was determined by calculating the modal average ($3 \times$ median $- 2 \times$ mean) of the intensities in the annulus. The calculations were done interactively, and the results were plotted on the screen and inspected visually in order to detect any obvious systematic errors. The average sky level around the SN was always very close to the background around the comparison stars, no clear systematic effect could be found.

Second, the whole dataset has been re-reduced using PSF-photometry (*digiphot/daophot*), as also advised by the referee of this paper. PSF-photometry is a superior photometric method if the background strongly varies around the objects, and its removal is complicated. Since SN 2001V is somewhat contaminated by its host, the use of PSF-photometry may be useful to separate the light of the SN from that of the galaxy. This method requires bright stars with high S/N to construct a good PSF. Because there are only a few of such stars in the field of NGC 3987, and also the field of view of most of the telescopes used in this study was quite small, a lot of frames contained only 4–5 stars around the SN. Nevertheless, the PSF of each frame was determined interactively. The analytic component of the PSF was approximated by the built-in *penny2* function in *daophot*, but in most cases it was based on only 2–3 stars. The frames made with the Schmidt-telescope (Table 1) contained many more field objects, but the PSF on these frames showed significant positional dependence. Therefore, a second-order variable PSF model has been constructed for these pictures, while constant PSF was determined for all other frames. Individual sky levels were calculated for all objects, and the background was subtracted iteratively during the fitting of the PSF in *daophot/allstar*. Then the residuals were examined visually on the subtracted frames. The stars as well as the SN were adequately removed from most frames, but slight residuals were present at the position of the brightest stars on some frames. This was probably caused by the uncertainty of the PSF due to the small number of PSF-stars.

Differential magnitudes of SN 2001V have been computed using the comparison stars labeled in Fig. 1 (see also Table 2 below). After transforming them to the standard system (Vinkó et al. 2001), the brightness of the SN was calculated from the calibrated *BVRI* magnitudes of each comparison star (see below). Then the SN magnitudes belonging to the same frame were averaged.

In order to search for any systematic effect caused by the reduction procedure, we have compared the SN magnitudes from the aperture- and PSF-photometry. Figure 2 presents the aperture minus PSF-magnitudes in all filters as a function of time. It is apparent that most of the differences are within ±0.1 mag. Naturally, the differences are higher at later phases, when the SN became fainter, but there is no visible systematic trend in the data. We conclude that both the aperture- and PSF-photometry of SN 2001V presented here are affected by

Table 1. Parameters of telescopes and detectors. The columns give the name of the observatory, the telescope, the type of the CCD, the readout noise (in electrons), the number of pixels, the pixel scale (in arcsec/pixels), the total field of view (in arcmins), and the typical *FWHM* of the images (in pixels). An asterisk in the *FWHM* column denotes 2×2 binning.

Code	Obs.	Tel.	CCD	RDN	Pixels	Scale	FoV	*FWHM*
A	Konkoly Obs.	60 cm Schmidt	Photometrics	14 e^-	1536×1024	1.00"	$25.5 \times 17'$	3.3
B	Konkoly Obs.	100 cm RCC	Photometrics	6 e^-	1024×1024	0.29"	$5 \times 5'$	3.1*
C	Konkoly Obs.	100 cm RCC	Wright EEV	10 e^-	1200×800	0.36"	$7 \times 5'$	3.2*
D	Szeged Obs.	40 cm Cass	SBIG ST-9	13 e^-	512×512	0.70"	$6 \times 6'$	3.0*
E	Baja Obs.	50 cm RCC	Apogee AP7	18 e^-	512×512	1.29"	$11 \times 11'$	3.3

Table 2. Comparison stars in the field of NGC 3987.

Star	V	$B - V$	$V - R$	$V - I$
A	10.67 (0.01)	0.59 (0.02)	0.44 (0.02)	0.71 (0.02)
B	12.23 (0.02)	0.84 (0.02)	0.48 (0.02)	0.95 (0.02)
C	13.00 (0.02)	0.59 (0.03)	0.36 (0.02)	0.69 (0.03)
D	12.25 (0.02)	0.43 (0.05)	0.28 (0.02)	0.57 (0.02)
E	14.77 (0.03)	0.85 (0.06)	0.49 (0.04)	0.89 (0.05)

approximately the same amount of random errors at the ±0.1 mag level, mainly due to the technical limitations of the applied instruments (lower S/N, small field of view, very few PSF-stars). In order to reduce the uncertainties introduced by the reduction method, the SN magnitudes resulting from both aperture- and PSF-photometry were averaged, and these magnitudes were accepted as the final result.

At first, the magnitudes of the comparison stars were calibrated via Landolt standards, observed at Calar Alto Observatory with the 1.2 m Cassegrain, under photometric conditions on Aug. 11, 2001. The reliability of this dataset as been checked by using the calibrated photometry of some of the field stars made by the CfA Supernova Group at the F. L. Whipple Observatory. Because the comparison stars used in this study and those adopted by the CfA-group were different, we have re-computed the magnitudes of our comparison stars using the CfA-dataset as secondary standards on a set of *BVRI* frames collected with the Schmidt telescope of Konkoly Observatory on March 14, 2001. After performing aperture photometry (with the same parameters described above) and standard transformation, the "Calar Alto" calibration and the "CfA/Konkoly" calibration was found to be fully consistent. The differences between the two datasets were within ±0.02–0.03 mag. Finally, the results from the CfA/Konkoly calibration were adopted, in order to keep maximal consistency with data of SN 2001V from other observatories. The final standard magnitudes of the comparison stars are collected in Table 2. The uncertainties reflect the statistical errors given by *daophot* and also the magnitude differences between the two calibrating datasets.

The calibrated standard magnitudes of SN 2001V are listed in Table 3. The estimated errors of each point are given in parentheses. These uncertainties were calculated as $\sigma^2 = \sigma_p^2 + \sigma_m^2 + \sigma_t^2$, where σ_p is the statistical error given by *daophot*, σ_m is the error due to the photometric method (assumed to be equal to the difference between the aperture- and PSF-photometry, plotted in Fig. 2) and σ_t is the error introduced by the standard transformation (adopted as 0.03 mag for each data point).
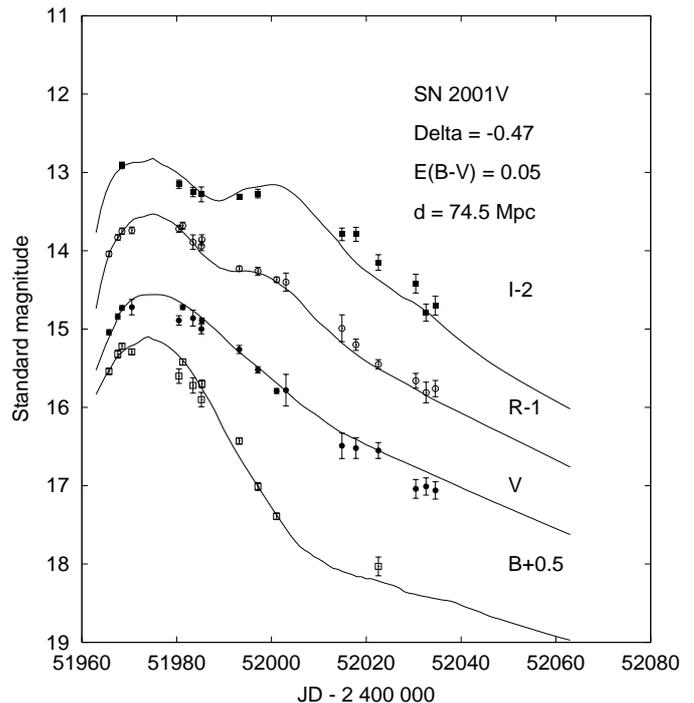
Fig. 3. Light curves of SN 2001V in *B, V, R, I* filters (the *B, R, I* data were shifted for better visibility). The lines are the template light curves fitted by the MLCS method (see text).

The observations listed in Table 3 were compared with the *R*−band CCD photometric data of K. Hornoch (Hornoch 2001) and found in reasonable agreement within ±0.1 mag. More recently Mandel et al. (2002) published $B_{max} = 14.64 \pm 0.03$ mag based on a more extensive photometric dataset. This agrees very well with our template fitting (see next section) resulting in $B_{max} = 14.60 \pm 0.16$ (the larger uncertainty is due to the lack of data around maximum in our photometry). This agreement may give some support to our belief that the data in Table 3 probably do not suffer from large systematic errors.

3. Results

The *BVRI* light curves were analyzed by the Multi-Colour Light Curve Shape (MLCS) method of Riess et al. 1998 (the SN template vectors were kindly provided by A. Riess). The timescale of the observations was divided by $1 + z = 1.015$ to remove the effect of time dilation. The value of *K*-correction in the *V* band at this redshift varies between −0.01 and 0.03 mag (Hamuy et al. 1993), which is definitely smaller than the

Table 3. Photometry of SN 2001V. The uncertainties are given in parentheses. See Table 1 for telescope codes.

JD	B	V	R	I	Tel.
51965.6	15.04(0.037)	15.04(0.033)	15.04(0.033)	–	A
51967.5	14.82(0.051)	14.84(0.035)	14.83(0.036)	–	A
51968.4	14.72(0.037)	14.73(0.030)	14.75(0.041)	14.91(0.042)	A
51970.5	14.79(0.035)	14.72(0.098)	14.74(0.043)	–	E
51980.6	15.10(0.093)	14.89(0.061)	14.72(0.046)	15.15(0.052)	D
51981.4	14.92(0.040)	14.72(0.030)	14.68(0.045)	–	E
51983.6	15.22(0.098)	14.86(0.102)	14.89(0.093)	15.25(0.060)	D
51985.4	15.40(0.092)	15.00(0.060)	14.94(0.058)	15.28(0.095)	D
51985.5	15.20(0.050)	14.89(0.032)	14.86(0.064)	–	C
51993.5	15.93(0.040)	15.26(0.052)	15.23(0.034)	15.31(0.031)	A
51997.5	16.51(0.050)	15.52(0.040)	15.26(0.050)	15.27(0.055)	C
52001.5	16.89(0.043)	15.79(0.032)	15.37(0.034)	–	E
52003.5	–	15.78(0.202)	15.40(0.115)	–	E
52015.5	–	16.49(0.163)	15.99(0.172)	15.79(0.080)	D
52018.5	–	16.52(0.132)	16.20(0.072)	15.79(0.090)	D
52023.3	17.53(0.036)	16.55(0.101)	16.45(0.060)	16.15(0.100)	A
52031.3	–	17.04(0.120)	16.66(0.095)	16.42(0.120)	D
52033.5	–	17.01(0.110)	16.81(0.132)	16.79(0.110)	B
52035.5	–	17.06(0.111)	16.76(0.104)	16.70(0.121)	B

uncertainty of our measurements, thus it was not taken into account. The maximum absolute magnitude of the fiducial light curve was adopted as $M_V^{\max} = -19.46$ mag (Richardson et al. 2002). The fitting was computed simultaneously to all light curves. Details of the procedure are described in Vinkó et al. (2001). The minimum of the χ^2 was found at the following parameters: $T_0(B) = $ JD 2451973.0 ± 0.2 (fiducial B-maximum), $E(B - V) = 0.05 \pm 0.02$ mag, $\mu_0 = 34.36 \pm 0.14$ mag and $\Delta = -0.47 \pm 0.04$ mag. The given uncertainties are formal errors corresponding to the geometry of the χ^2 function around minimum. The fitted light curves are shown in Fig. 3. Note, that the $T_0(B)$ parameter given here corresponds to the maximum of the *fiducial* light curve (with $\Delta = 0.0$), the actual maximum of SN 2001V in B occurred one day later, at JD 2451974.

The parameters above imply some interesting properties of SN 2001V. Comparing the $E(B - V)$ colour excess with the reddening due to Milky Way dust ($E(B - V)_{\rm gal} = 0.02$, Schlegel et al. 1998), it can be seen that the ISM in the host galaxy contributes to the dust absorption. Since NGC 3987 is an edge-on galaxy with strong central dust lane, this is not an unexpected result. The host-galaxy reddening could have been even more severe if the SN had occurred closer to the central plane of NGC 3987, like e.g. in the case of SN 1986G (Phillips et al. 1987), or, more recently SN 2002cv in NGC 3190 (Meikle & Mattila 2002).

The reddening was also estimated using the "Lira-Phillips law" (Phillips et al. 1999) as an independent check of the value given by the MLCS method. This method uses the apparent homogeneity of the unreddened $(B - V)_0$ colours of SNe Ia in the $30 < t_V < 90$ phase interval (t_V is the phase measured from V−maximum). Unfortunately, there is only one observed $(B - V)$ data point in Table 3 that can be used for this purpose ($(B - V) = 0.98 \pm 0.10$ mag). The moment of V−maximum was estimated from the template light curves fitted by the MLCS

SN 2001V + Hamuy template 91T
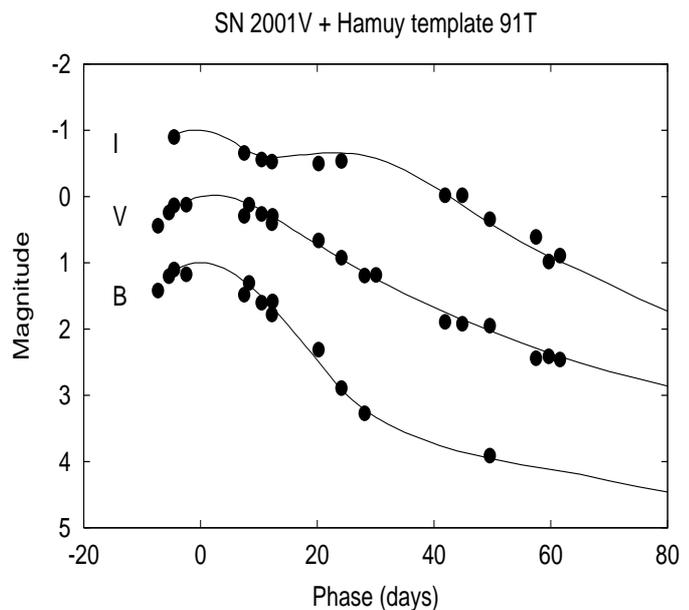
Fig. 4. Comparison of light curves of SN 2001V (symbols) and SN 1991T (continuous lines).

method. It occurred at $T_0(V) = 2451976 \pm 1$ JD. After correcting for time dilation, the phase of the observed $(B - V)$ point was found to be $t_V = 46.3 \pm 1$ days. The relation

$$(B - V)_0 = 0.725 - 0.0118(t_V - 60)$$

given by Phillips et al. (1999) resulted in $(B - V)_0 = 0.89 \pm 0.02$. This implies $E(B - V) = 0.09$ mag, which is not too far from the value given by MLCS. However, its uncertainty is probably higher, because this estimate is based on a single observation, and the "Lira-Phillips law" itself may have an intrinsic uncertainty at the 0.1 mag level (Li et al. 2001a). On the other hand,

the similarity of the reddening values given by two independent methods may mean that the estimated $E(B-V)$ is close to the real value.

Adopting $E(B-V) = 0.05$ mag, the total absorption in the B, V, R and I bands is $A_B = 0.21$, $A_V = 0.16$, $A_R = 0.13$, $A_I = 0.09$ mag, respectively, using the galactic reddening law given by Schlegel et al. 1998.

The luminosity parameter $\Delta = -0.47$ implies that SN 2001V is a super-luminous Type Ia SN, relative to the majority of such SNe. Super-luminous SNe are often referred as SN 1991T-, or SN 1999aa-like events (see Li et al. 2001b). The distinction between different subtypes of SNe Ia is usually based on spectroscopic properties, e.g. the strength of the Si II trough at 6150 Å. Overluminous SNe Ia have a weaker Si II 6150 Å line, and the Fe III lines are strong. In addition, SN 1999aa-like events usually show strong Ca II H & K lines, which are weak in SN 1991T-like SNe. These spectroscopic characteristics correlate with photometric properties: the light curves of SN 1991T-like SNe decline more slowly, and they are bluer in maximum than normal SNe Ia. Thus, overluminous SNe may be recognizable from photometry, e.g. via the MLCS-method.

We do not have spectroscopic data of SN 2001V at our disposal, but two spectra of SN 2001V, obtained around maximum, are available in graphical form from the CfA-website[2]. As the referee of this paper, Dr. Weidong Li, pointed out, these spectra are very similar to that of SN 1999aa: broad, but less prominent Si II 6150 Å line, strong Fe III and Ca II H & K lines. These spectral features fully support our conclusion (based on photometry), that SN 2001V is an overluminous SN Ia.

Note, however, that it is not clear whether the higher luminosity is necessarily connected with the spectroscopic peculiarities. There are examples, such as SN 1992bc (Riess et al. 1998), that were super-luminous, but otherwise showed normal spectra around maximum. Thus, the overluminosity of some Type Ia SNe might be due to e.g. statistical fluctuation of the ejected ^{56}Ni mass that powers the light curve, rather than a difference in the explosion mechanism or the physical state of the progenitor. Recently Richardson et al. (2002) found that the maximum brightness M_B of SNe Ia has a Gaussian distribution with $\sigma = 0.56$ mag (corrected for the effect of extinction).

From yet unpublished photometry, recently Mandel et al. (2002) concluded that SN 2001V was a "normal" Type Ia event, with light and colour curves very similar to SN 1990N. On the other hand, they also determined the initial decline rate, and found $\Delta m_{15}(B) = 0.99 \pm 0.05$. This decline rate may suggest an overluminous, rather than a "normal" SN Ia (e.g. Hamuy et al. 1996). Although our photometry has less accuracy and phase coverage, we also attempted to estimate this parameter and found $\Delta m_{15}(B) = 0.9 \pm 0.1$. According to the correlation between $\Delta m_{15}(B)$ and Δ (e.g. Riess et al. 1998), this is consistent with the Δ parameter given by the MLCS-method. Furthermore, Fig. 4 shows the essential similarity of the light

curves of SN 2001V with that of SN 1991T ($\Delta m_{15}(B) = 0.94$, Hamuy et al. 1996).

Thus, all available data consistently support the conclusion that SN 2001V was an intrinsically bright SN Ia. At maximum, it was brighter than the fiducial Type Ia SN by about 0.5 mag. Adopting the parameters given by the MLCS-method, the inferred absolute magnitudes of SN 2001V at maximum are

$$M_B^{\mathrm{max}} = -19.97 \pm 0.15 \text{ mag}$$
$$M_V^{\mathrm{max}} = -19.96 \pm 0.15 \text{ mag}$$
$$M_R^{\mathrm{max}} = -19.96 \pm 0.15 \text{ mag}$$
$$M_I^{\mathrm{max}} = -19.63 \pm 0.15 \text{ mag.}$$

The true distance modulus, $\mu_0 = 34.36 \pm 0.14$ mag, corresponds to 74.5 ± 5 Mpc. The uncertainty given here is the formal error of the fitting, and does not include possible systematic effects, such as the zero-point of the SN distance scale. The MLCS distance marginally agrees with the kinematic distance of NGC 3987 corrected for Virgo-infall (67 Mpc, see Sect. 1), the difference is about $1.5\,\sigma$. The Tully-Fisher distance (58 Mpc, Sect. 1) is about 20 percent lower. The TF distance modulus ($\mu_0(TF) = 33.82$, Mould et al. 1993) can be brought into agreement with the MLCS distance by adding 0.54 mag to the previous one, in agreement with the suggestion by Shanks (1997) for matching the TF and SN distance scales.

4. Summary

The results of this paper can be summarized as follows.

1. We presented *BVRI* photometry of SN 2001V starting from 8 days before maximum light and extending up to 60 days past maximum.
2. The reddening was estimated by applying the MLCS template fitting method for all light curves. This resulted in $E(B-V) = 0.05 \pm 0.02$ mag, indicating that there was significant extinction in the host galaxy affecting the light from SN 2001V. The empirical "Lira-Phillips law" gave similar, but slightly higher colour excess ($E(B-V) = 0.09$ mag). Its uncertainty is probably higher, because it is based on only a single observation. Therefore, the result from the MLCS-method was accepted as final.
3. The light curve analysis indicates that SN 2001V was an over-luminous SN by about 0.5 mag relative to the fiducial SN Type Ia. This is consistently supported by the overall similarity of the light curves and the $\Delta m_{15}(B)$ decline rate with those of SN 1991T, and also the publicly available spectra of SN 2001V. The spectral features suggest that SN 2001V may be a SN 1999aa-like object (Li et al. 2001b).
4. The SN distance was inferred from the MLCS method and found to be 74.5 ± 5 Mpc. This marginally agrees with the previous kinematic distance, but 15 about 20 percent higher than the Tully-Fisher distance of NGC 3987.

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[2] http://cfa-www.harvard.edu/cfa/oir/Research/ supernova

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