

THE PECULIAR TYPE Ia SUPERNOVA 1999by: SPECTROSCOPY AT EARLY EPOCHS¹

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ABSTRACT

We present medium-resolution ($\lambda/\Delta\lambda \approx 2500$) optical spectroscopy of SN 1999by in NGC 2841 made around its light maximum. That the depth ratio of the two Si II features at 5800 and 6150 Å are $R(\text{Si II}) \approx 0.63$ at maximum indicates that this SN belongs to the peculiar subluminescent Type SNe Ia. Radial velocities inferred from the minimum of the 6150 Å trough reveal a steeper decline of the velocity curve than expected for normal SNe Ia, consistent with the behavior of published *VRI* light curves. A revised absolute magnitude of SN 1999by and distance to its host galaxy NGC 2841 are estimated based on the multicolor light-curve shape (MLCS) method, resulting in $M_V(\text{max}) = -18.06 \pm 0.1$ mag and $d = 17.1 \pm 1.2$ Mpc, respectively. An approximate linear dependence of the luminosity parameter Δ on $R(\text{Si II})$ is presented.

Key words: stars: distances — supernovae: general — supernovae: individual (SN 1999by)

1. INTRODUCTION

In the last decade it became evident that some of the observed Type Ia supernovae are intrinsically subluminescent compared with the majority of so-called normal SNe Ia. SN 1991bg (Filippenko et al. 1992) is now considered their prototype, and the sample of well-observed events includes SN 1992K (Hamuy et al. 1994), SN 1997cn (Turatto et al. 1998), and SN 1998de (Modjaz et al. 2001). Besides being about 1 mag fainter than normal SNe Ia at maximum, subluminescent SNe Ia also exhibit peculiar colors and spectra. For example, the intrinsic (unreddened) $(B-V)_0$ color around maximum is 0.7–0.8 mag redder than normal SNe Ia, reaching $(B-V)_0 = 1.5$ mag at 10 days after maximum light. The spectroscopic peculiarity is represented by (1) the appearance of a strong Ti II band in the blue region and (2) the increase of the ratio of the depths of Si II absorption troughs at 5800 and 6150 Å [$R(\text{Si II})$] (e.g., Nugent et al. 1995). Moreover, subluminescent SNe Ia have steeply declining light curves. Their decline rate parameter is $\Delta m_{15}(B) > 1.9$ instead of 1.0–1.5, as for normal SNe Ia (e.g., Phillips et al. 1999). Because both $R(\text{Si II})$ and $\Delta m_{15}(B)$ correlate with the peak luminosity, the observational data indicate that subluminescent SNe Ia have less energetic explosions and less ejected N I mass than normal SNe Ia, although the correlation between the different quantities cannot be described with a single parameter (Hamuy et al. 1996; Hatano et al. 2000).

In this paper we present medium-resolution spectra of the subluminescent Type Ia SN 1999by that occurred in NGC

2841. Chronicles of the discovery and the earliest observations can be found in IAU Circular 7156–7159. Gerardy & Fesen (1999) pointed out very soon that the spectrum of SN 1999by is Type Ia, while Garnavich, Jha, & Kirshner (1999) noted that SN 1999by belongs to the group of subluminescent SNe Ia, based on the $R(\text{Si II})$ line depth ratio. Early-phase spectra of such SNe are available only for SN 1991bg and SN 1997cn. Thus, the spectroscopic observations made around maximum light may supply interesting details about peculiar SNe Ia. Very recently Howell et al. (2001) presented spectropolarimetric evidence for the strong ($\approx 20\%$) asphericity of the ejecta of SN 1999by, suggesting a connection between the observed asymmetry and the mechanism producing subluminescent SNe Ia.

Our new observations are described in § 2, while their interpretation is given in § 3. Section 4 summarizes the results of this paper.

2. SPECTROSCOPIC OBSERVATIONS

SN 1999by was observed with the 1.88 m telescope and Cassegrain spectrograph of the David Dunlap Observatory on three nights between 1999 May 10 and 1999 May 21. The 150A grating in second order with an order separation filter in the stellar beam was applied, resulting in a reciprocal dispersion of $1.22 \text{ Å pixel}^{-1}$ on the CCD detector. The recorded spectra cover about 1250 Å , centered on 6000 Å .

Reduction was performed by standard routines in IRAF.³ The wavelength scale was calibrated with FeAr spectral lamp exposures. The background light due to the host galaxy was approximated with a quadratic polynomial

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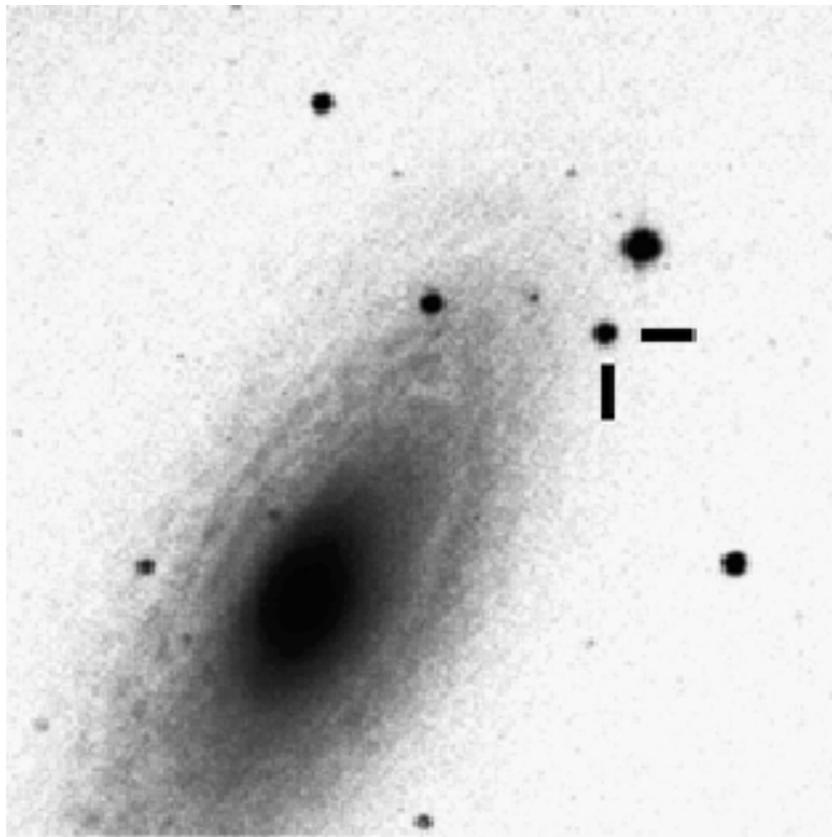
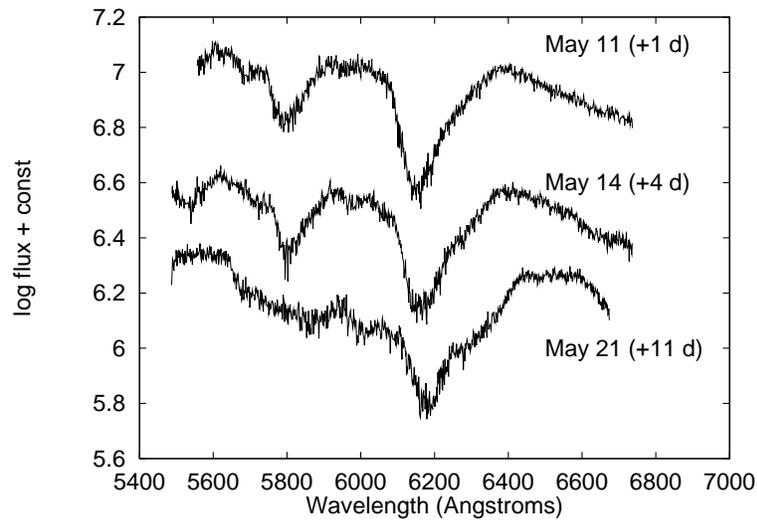


FIG. 1.—*Top*: Spectra of SN 1999by, shifted vertically for better visibility. Epochs are indicated at the right each spectrum. *Bottom*: CCD image of SN 1999by (*marked*) taken with the 1 m RCC telescope at Piskéstető station of the Konkoly Observatory on 1999 May 21. North is up, and east is to the left.

perpendicular to the dispersion axis and subtracted from the SN aperture at each wavelength.

Because of the rarity of photometric nights at the DDO site (in the proximity of Toronto), precise flux calibration of the spectra was not possible. However, an approximate correction for the CCD spectral response has been determined by obtaining the spectra of three nearby field stars (numbers 2, 3, and 4 of Skiff⁴ 1999a, 1999b, 1999c; see Fig. 1 of Tóth

& Szabó 2000). Their $B-V$ indices (0.59, 0.75, and 0.60 mag, respectively) correspond to $T_{\text{eff}} \approx 5500\text{--}6000$ K, according to the tables of Schmidt-Kaler (e.g., Carroll & Ostlie 1996). The measured continua of these stars could be approximated by a smooth polynomial. The real continuum fluxes (assuming $\log g = 4$) were estimated from model spectra of Buser & Kurucz (1992). Then, the wavelength-dependent sensitivity of the CCD spectrograph used was calculated by dividing the measured continua by the chosen model continuum flux values. The resulting function turned out to be smooth and slightly decreasing to the red. We

⁴ See also <ftp://ftp.lowell.edu/pub/bas/starcats/loneos.phot>.

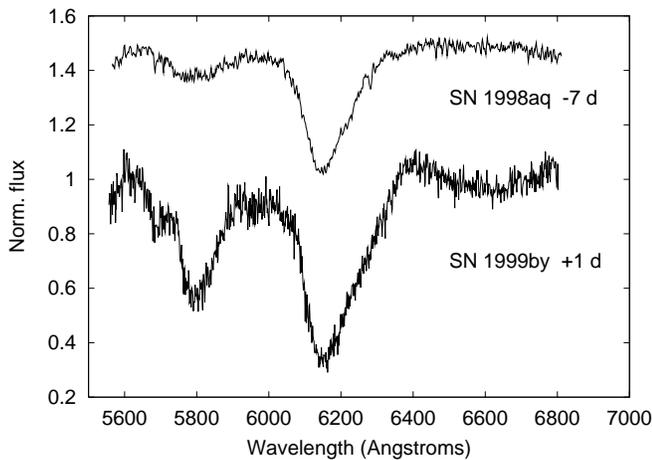


FIG. 2.—Comparison of spectra of SN 1999by (*bottom*) and SN 1998aq (*top*) around maximum light. The latter spectrum was shifted by 0.5. The relative strength of the 5800 Å Si II trough in SN 1999by is apparent.

have looked for any sudden drop in the sensitivity function that might distort the depths of spectral lines and found none.

The SN spectra were then corrected by dividing the measured spectra by the approximate sensitivity function described above. Because the comparison stars used were not spectroscopic standards, the corrected “continuum” slopes of the SN spectra may still be slightly distorted. Nevertheless, SN spectra calibrated in such a way are acceptable for a comparative analysis as described in § 3.1.

The reduced spectra are collected and plotted in Figure 1. The epochs of the observations are indicated at the right of each spectrum. The phases relative to B -maximum were determined by adopting the result of Bonanos et al. (1999) that the maximum in B occurred on JD 2,451,308.5 (1999 May 9/10), which was also confirmed by photometry of Tóth & Szabó (2000) (note that the Julian date of maximum light was misprinted in both papers).

Although the spectral coverage is rather small, the appearance of the strong Si II line around 6150 Å unambiguously identifies the type as Ia SN. The other strong feature, the absorption trough at 5800 Å, is also attributed to Si II. The relative strength of this line to that of the 6150 Å line $R(\text{Si II})$ (Nugent et al. 1995) suggests that SN 1999by is a subluminal event, as mentioned in § 1. This is illustrated in Figure 2, in which the maximum-light spectrum of SN 1999by is plotted together with a premaximum spectrum of SN 1998aq (Vinkó et al. 1999) obtained with the same instrument and setup (unfortunately, no spectrum of SN 1998aq closer to its maximum light was available to us). The spectra in Figure 2 were normalized to the local “continuum” for illustrative purpose. It is easily seen that the 5800 Å line is much weaker in SN 1998aq than in SN 1999by. This line gets stronger in premaximum spectra of SNe Ia when approaching the maximum; however, in normal SNe the increase of $R(\text{Si II})$ is only 0.04–0.06 (Riess et al. 1998b). Thus, the 5800 Å feature was not much stronger in the spectrum of SN 1998aq at maximum.

3. DATA ANALYSIS AND INTERPRETATION

3.1. Line Depths and Radial Velocities

We have calculated the value of $R(\text{Si II})$ for SN 1999by following the definition of Nugent et al. (1995). $R(\text{Si II}) =$

0.63 was obtained for the May 11 spectrum, while $R = 0.66$ was determined for the May 14 one, in accord with the result of Garnavich et al. (1999; see also Hatano et al. 2000). This is more than a factor of 2 larger than its usual value of $R = 0.25 \pm 0.1$ for normal SNe Ia (Riess et al. 1998b; Hatano et al. 2000).

Very recently Howell et al. (2001) published three spectra of SN 1999by made just before our observations. From their Figure 1 we estimated $R(\text{Si II}) = 0.68, 0.70, 0.66$ at epochs $\tau = -2, -1, \text{ and } 0$, respectively. These agree very well (within a few hundredths) with the results derived from our spectra, suggesting that our observations probably do not contain wavelength-dependent systematic errors distorting the line-depth ratio.

$R(\text{Si II})$ correlates with the luminosity parameter Δ introduced by Riess, Press, & Kirshner (1996) in the multicolor light-curve shape (MLCS) method. A calibration of the linear dependence of $R(\text{Si II})$ on Δ was given by Riess et al. (1998b), resulting in $\Delta = 2.33R - 0.55 (\pm 0.22)$ at +1 day phase, while at +4 days the slope and zero point changes to 2.06 and -0.46 , respectively. By substituting the $R(\text{Si II})$ values given above one can get $\Delta = 0.90 \pm 0.23$ for the luminosity parameter of SN 1999by (the given error takes into account the quoted uncertainty of the R – Δ calibration). For normal SNe Ia $\Delta \approx 0$ therefore this high value suggests that SN 1999by is one of the most subluminal SNe Ia (Bonanos et al. 1999). Note that this spectroscopic Δ is not suitable for describing the multicolor light curve of SN 1999by, which requires $\Delta > 1.0$. The light-curve decline parameter, $\Delta m_{15}(B) = 1.87$, is also indicative of the low luminosity (Bonanos et al. 1999).

Radial velocities were inferred from the absorption minima of the 6150 Å Si II trough (fitted by a low-order polynomial around minimum). Table 1 lists the resulting radial velocities, corrected for the host galaxy center recession velocity $v_{\text{gx}} = 638 \text{ km s}^{-1}$ (as given in the NASA/IPAC Extragalactic Database). As the anonymous referee pointed out, SN 1999by was close to the edge of NGC 2841 and could have significant orbital velocity in addition to the center-of-galaxy radial velocity. The rotation velocity of NGC 2841 at distances greater than 10 kpc from its center is $\approx 300 \text{ km s}^{-1}$ (Sofue et al. 1999). Thus, the uncertainty of the radial velocities is at least $\pm 300 \text{ km s}^{-1}$ because of the possible orbital velocity, as well as the large width of the Si II line. Nevertheless, this uncertainty is only a few percent of the Si II expansion velocity.

Figure 3 compares the radial velocities of SN 1999by with those of SN 1998aq (Vinkó et al. 1999) and SN 1994D (Patat et al. 1996). The decline of the radial velocities of SN 1999by is much stronger than in the other two cases. SN

TABLE 1

RADIAL VELOCITIES OF SN 1999by
FROM THE MINIMUM OF THE Si II LINE

JD (–2,400,000)	τ (days)	v_r (km s^{-1})
51309.6.....	+1	10,174
51312.5.....	+4	9560
51319.6.....	+11	8946

NOTE.—The velocity of NGC 2841 ($v_{\text{gx}} = 638 \text{ km s}^{-1}$) has been added to get rest-frame radial velocities of the supernova.

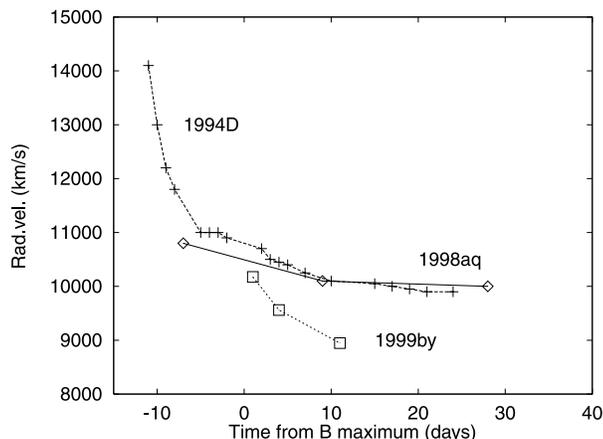


FIG. 3.—Radial velocity curve of SN 1999by, computed from the minimum of the Si II 6150 Å line (squares) and compared with those of SN 1998aq (diamonds) and SN 1994D (plus signs). See text for references.

1991bg showed similar behavior (Filippenko et al. 1992), while the other subluminous SNe Ia were not well covered spectroscopically around maximum. The stronger velocity decline is also in good agreement with the recent result of Hatano et al. (2000) that subluminous events have lower velocities at 10 days after maximum than do normal SNe Ia. This may support the hypothesis that subluminous SNe Ia arise from sub-Chandrasekhar mass progenitors and thus have less energetic explosions than normal Type Ia events (see Modjaz et al. 2001 for recent review of explosion models).

3.2. Absolute Magnitude and Distance

Application of the multicolor light-curve shape (MLCS) method for SN 1999by has been published very recently by Tóth & Szabó (2000). They used only the V light curve for template fitting and $B-V$ data for the reddening determination, and they revealed $\Delta > 1.6$ mag. This may indicate that SN 1999by is extremely subluminous. For example, SN 1991bg, the prototype, which is known as one of the least luminous SNe Ia to date, had $\Delta = 1.44 \pm 0.1$ (Riess et al. 1996).

We reanalyzed the BVR photometric data set published by Tóth & Szabó (2000) and supplemented by the data of Hanzl (1999a, 1999b, 1999c, 1999d), using the original MLCS template curves of Riess et al. (1996). Because the photometric data are inhomogeneous, systematic errors may distort the parameters derived from them. Thus, the results below can be considered only crude estimates.

Although Riess et al. (1998a) developed a second version of MLCS (MLCS-2, based on an extended list of calibrated SNe), the updated template vectors have not been published yet. However, recently Vinkó et al. (2001) demonstrated that for nearby SNe even with moderate reddening the MLCS-1 and MLCS-2 methods produce consistent results if the maximum magnitude of the fiducial ($\Delta = 0$) light curve is set properly. We adopted $M_V^{\max} = -19.46$ mag for the fiducial V light curve (A. G. Riess 2001, private communication), while the original MLCS-1 method was based on $M_V^{\max} = -19.36$ mag. The difference has been taken into account by adding $+0.1$ mag to the distance modulus computed with MLCS-1.

For SN 1999by, $E(B-V) = 0.01$ was adopted, consistent with the all-sky reddening map of Schlegel, Finkbeiner, &

Davis [1998; Tóth & Szabó derived $E(B-V) = 0.05 \pm 0.02$ from their SN photometry]. The template vectors were fitted simultaneously to all BVR data; i.e., the residuals of all data were combined in a single χ^2 function. The fitting was restricted for $\tau > -2$ days, because the available premaximum data of SN 1999by could not be adequately fitted together with the postmaximum data (see also Tóth & Szabó 2000). Also, the minimum photometric error was increased to ± 0.15 mag by taking into account some possible systematic uncertainties in the data set used (e.g., due to errors in the standard transformation).

The simultaneous fitting of the template curves resulted in $\Delta = 1.4 \pm 0.1$ and $\mu_0 = 31.16 \pm 0.15$ mag for the luminosity parameter and the reddening-free distance modulus, respectively. The given uncertainty of the distance modulus is only the rms error of the fitting, disregarding the possible systematic errors in the absolute magnitudes of the template light curves. The quality of the fit can be judged from Figure 4. It is seen that the fitting is not perfect; however, we believe that this is as close to the optimal result as can be achieved from the present data sets. The minimum of the reduced χ^2 that could be reached was $\chi^2 \approx 1.5$. Still, the solution may be systematically incorrect, because for such underluminous SNe the template vectors in MLCS-1 are based only on the light curves of SN 1991bg, and the light variation of SN 1999by may differ substantially from that. The large deviation of the premaximum points may be due to such inconsistency. Also, photometric errors higher than we adopted (± 0.15 mag) cannot be ruled out.

The photometric Δ is significantly higher than the value found from spectroscopy ($\Delta = 0.90$; § 3). It was not possible to achieve an adequate fit with $\Delta = 0.9$ given by spectroscopy. Thus, the current spectroscopic determination of Δ does not give a suitable result for SN 1999by, which is probably true for other extremely subluminous SNe Ia as well. An improved $R(\text{Si II}) - \Delta$ calibration is presented in the next section.

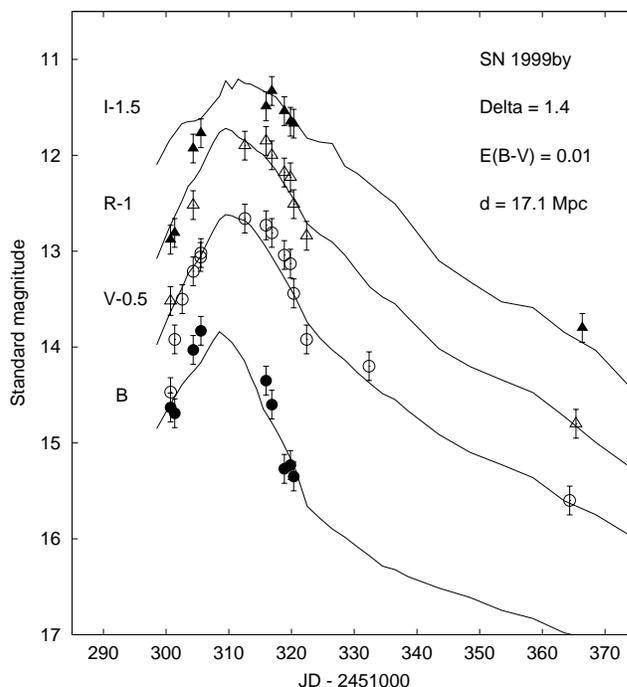


FIG. 4.—MLCS fit to published BVR data of SN 1999by

Although subluminescent SNe Ia are usually eliminated from the sample of “good” distance indicators, the MLCS method gives information on their distances as well. The new distance modulus of SN 1999by given above corresponds to a geometric distance of 17.1 ± 1.2 Mpc, which is significantly higher than $d = 10\text{--}12$ Mpc, given by Tóth & Szabó (2000) and Tully (1988). Note that the template vectors of the MLCS-1 method were calibrated from a training set of SNe that adopts Tully-Fisher and surface brightness-fluctuation distances but the final absolute magnitudes were shifted to match the Cepheid-based distance scale (Riess et al. 1996). Thus, the higher distance given above simply reflects the difference between various distance scales and may still contain a systematic error. Both Cepheid and Tully-Fisher distances undergo significant revisions nowadays (e.g., Gibson et al. 2000; Sakai et al. 2000), so this question can be answered only when the problems of the different distance scales are solved.

3.3. Comparison with Other SNe Ia

The absolute magnitudes of SNe Ia correlate with $R(\text{Si II})$, as was presented very clearly by Nugent et al. (1995). Although Hatano et al. (2000) demonstrated that this correlation is not a one-parameter sequence, the dependence of M_V^{max} on $R(\text{Si II})$ may still be a somewhat useful relation for predicting SNe luminosities from spectra observed around maximum (at least as a first approximation). Now the correlation can be slightly improved using the new data of subluminescent SNe Ia.

We have collected values of the light-curve parameter Δ that were derived via the MLCS method and the values of $R(\text{Si II})$, both at V maximum. These are listed in Table 2. Because Δ measures the deviation of the V light curve of a particular SN from the fiducial SN Ia light curve at maximum, it is also directly proportional to the maximum absolute magnitude M_V^{max} . However, at present, Δ seems to be a more useful parameter than M_V^{max} because it is determined directly from the shape of the (multicolor) light curves; therefore it is not affected by the adopted zero point of the distance scale.

The result is plotted in Figure 5, where the solid line represents the approximate relation

$$\Delta = 3.5 \pm 0.44R(\text{Si II}) - 0.8 \pm 0.17, \quad (1)$$

while the dashed line shows the relation given by Riess et al. (1998b; see § 3.1). It is seen that the Riess et al. calibration

TABLE 2

$R(\text{Si II})$ AND Δ PARAMETERS OF SNE IA AT MAXIMUM

SN	$R(\text{Si II})$	Δ	σ_Δ	Ref.
1994ae	0.12	-0.13	0.05	N, R
1991T	0.14	-0.56	0.31	N, R
1981R	0.16	0.00	0.32	N, R
1990N	0.16	-0.28	0.31	N, R
1998bu	0.23	0.02	0.05	J, H
1989B	0.29	0.04	0.31	N, R
1992A	0.38	0.44	0.13	N, R
1986G	0.53	0.41	0.31	N, R
1991bg	0.62	1.44	0.10	N, R
1997cn	0.63	1.50	0.05	T
1999by	0.63	1.40	0.10	P

REFERENCES.—(N) Nugent et al. 1995; (R) Riess et al. 1996; (J) Jha et al. 1999; (H) Hatano et al. 2000; (T) Turatto et al. 1998; (P) present paper.

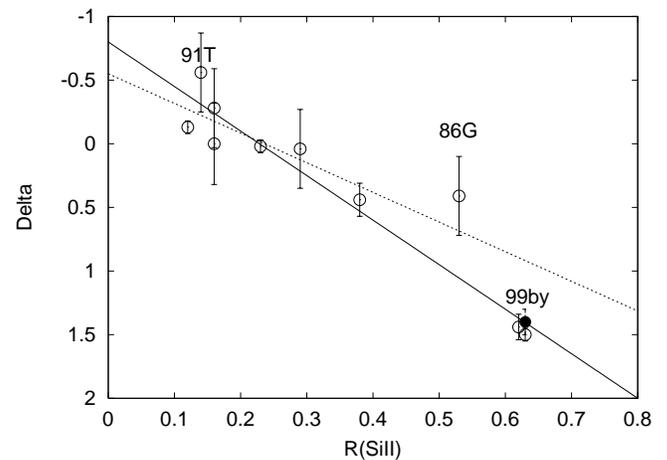


FIG. 5.—Dependence of the light-curve parameter Δ on $R(\text{Si II})$, using data of well-observed SNe Ia (see Table 2 for references). The dashed line represents the relation given by Riess et al. (1998b), while the solid line shows our new calibration (see text).

yields systematically lower Δ for the most subluminescent SNe Ia. The new relation fits these SNe better; thus it may be used to predict Δ from the measurement of $R(\text{Si II})$ around maximum. Such prediction may be useful, for example, in the “snapshot” distance estimate method (Riess et al. 1998b) when only a few nights’ data are available for a particular SN.

In Figure 5 it may also be interesting that the most subluminescent supernovae, SN 1991bg, SN 1997cn, and SN 1999by, represent a small group with a very consistent line-depth ratio and Δ (or absolute magnitude). It may mean that subluminescent SNe Ia might be better distance indicators than previously thought, if their subluminescent status is properly identified from spectroscopy and their difference from normal SNe Ia is taken into account. It is known (e.g., Hamuy et al. 1994) that such subluminescent SNe Ia may be more frequent events than their discovery rate suggests; thus, it is possible that many more such objects will be detected in the extensive supernova search programs. However, the present sample is obviously too small to draw a certain conclusion.

4. SUMMARY

The results of this paper can be summarized as follows:

1. Three spectra of the subluminescent Type Ia SN 1999by around maximum were obtained at DDO, centered on the Si II trough at 6150 \AA . The $R(\text{Si II})$ line depth ratio (Nugent et al. 1995) is determined to be 0.63 at maximum, indicative of an intrinsically subluminescent SNe Ia.

2. Radial velocities of the 6150 \AA Si II line were determined by measuring the Doppler shift of the line core. It is shown that SN 1999by exhibited stronger a decline of its radial velocity curve than other spectroscopically normal SNe Ia. This may support the low-energy, sub-Chandrasekhar mass explosion proposed for such SNe.

3. Absolute magnitude and distance of SN 1999by have been derived via the MLCS method. The assumption that the reddening is $E(B-V) = 0.01$ led to $M_V^{\text{max}} = -18.06 \pm 0.1$ mag and $d = 17.1 \pm 1.2$ Mpc. The maximum absolute magnitude, as well as the line depth ratio $R(\text{Si II})$, of SN 1999by are in very good agreement with those of other extreme subluminescent SNe Ia, such as SN 1991bg and SN

1997cn. An approximate linear relation has been determined to predict the light-curve parameter Δ of SNe Ia over a wide range of observed $R(\text{Si } \pi)$.

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