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Research Note

The Type Ia SN 1999by in NGC 2841: near-maximum BV(RI)$_c$ photometry and the multicolor light–curve shape (MLCS) method

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Abstract. Results of $BV(RI)_c$ CCD photometry of the bright supernova SN 1999by in the flocculent galaxy NGC 2841 are presented. The Multicolor Light-Curve Shape (MLCS) method is applied to fit the observed V lightcurve around its maximum-light period. The reddening and the luminosity correction parameters were estimated.

Key words: stars: supernovae: individual: SN 1999by – stars: supernovae: general – galaxies: individual: NGC 2841 – techniques: photometric

1. Introduction

Independent discoverers reported the explosion of a potentially bright supernova 1999by in a disk galaxy NGC 2841: an English amateur astronomer (Arbour 1999; coordinate measurer: M. Armstrong); Papenkova et al. (1999) on behalf of LOSS (Lick Observatory Supernova Search), and confirmed by the Katzman Automatic Imaging Telescope (KAIT); as well as a Hungarian amateur astronomer (Berkó 1999). Chronology and other observational details are described in IAU Circulars 7156 and 7157.

An interesting circumstance is that this relatively bright supernova 1999by exploded in a flocculent disk galaxy NGC 2841 (UGC 4966, PGC 26512; type is SA(R)3 as given in RC3 by de Vaucouleurs et al. 1991), which is a well known Sb galaxy and the host of three past supernovae (Papenkova et al. 1999). RC3 galactic ccordinates of the host galaxy are l^{II}=166$.^{\circ}$94, b^{II}=+44$.^{\circ}$15. The dark spiral arm structure of the prototype flocculent galaxy NGC 2841 was studied by Block et al. (1995).

The CCD spectra made by Gerardy & Fesen (1999) on May 02.2 UT show it to be a subluminous Type Ia supernova about 10 days before its maximum-light. The spectra obtained on May 06.2 confirm that SN 1999by is a Type Ia event, but the spectrum is peculiar (Garnavich et al. 1999).

The analysis of their photometric and spectroscopic observations by Bonanos et al. (1999) suggested that SN 1999by reached its B maximum on UT 1999 May 10 (JD 24501308.5 $\pm$ 1 day) with B=13.80$\pm$0.02 and V=13.36$\pm$0.02, as indicated by their photometric observations. They compared the lightcurve to the templates of the subluminous Type Ia supernova SN 1991bg and concluded that the SN 1999by is one of the most subluminous Type Ia supernova ever observed. The ratio of the spectral lines 580 and 615 nm is small, consistent with it being an under-luminous case (Bonanos et al. 1999).

Type Ia supernovae have been known as representative standard candles in the Universe and used in measurements of cosmological parameters. Extensive details and reviews of this subject are given by Baade (1938), Leibungut (1991), Branch & Tammann (1992). Recently Riess et al. (1996) developed an empirical method that uses *Multicolor Light-curve Shapes* (MLCSs) to estimate the luminosity, distance, and total line-of-sight extinction of Type Ia supernovae and gave tabulated template vectors for the temporal evolution of the lightcurve parameters in the $BVRI$ photometric system for the actual calculations. Very recent examples of the interesting applications connecting the MLCS and spectroscopic methods based on works by Nugent et al. (1995); Riess et al. (1996, 1998) have been reported by Jha et al. (1999) and Vinkó et al. (1999).

Thus, the broad-band $BVRI$ photometric observations are important in studies of the Type Ia supernovae, to estimate the total line-of-sight extinction and cosmological parameters. The principal goal of this paper is to report the results of our photometric observations supplementing the data set with other photometric observations available now and studying their matching to the synthetic lightcurves derived by applying the MLCS method. There are outcoming by-products of this work as conclusions on the values of reddening and "luminosity correction" Δ (Riess et al. 1996) as well as checking the extinction-free distance modulus derived from the recent observations comparing it with the earlier values (e.g.: in RC3 by de Vaucouleurs et al. 1991; Block et al. 1995).

2. Observations

2.1. Photometry at the Konkoly Observatory

CCD imaging and photometric monitoring observations were performed in the Cousins $BV(RI)_c$ photometric system. The

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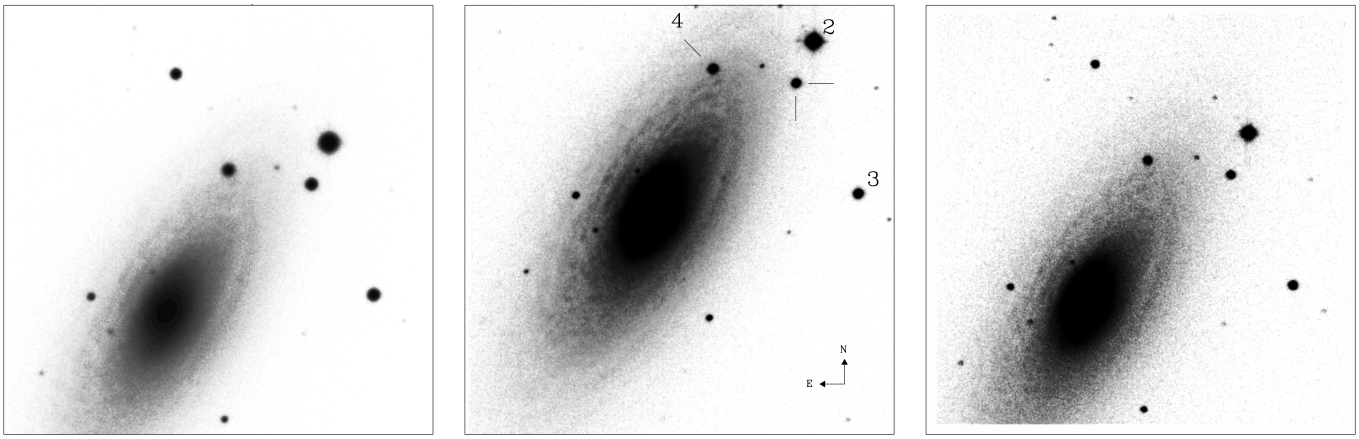

Fig. 1. Selected observational images of the supernova 1999by in NGC 2841. *Left-panel:* Observed I filtered image (#1 in Table 1.). *Mid-panel:* Finding chart of comparison stars: the numbers 2, 3, and 4 correspond to the numbered stars given by Skiff (1999); the supernova is marked by the two lines at the edge of the galaxy. The observed I filtered image is selected from the collection made on the night of #4 observational data set (Table 1). *Right-panel:* Observed I filtered image (#5 in Table 1). The exposures of the displayed images were 200, 300 and 80 seconds, respectively, and were normalized to ADU/s unit. Each side of these images is $5\farcm1\times5\farcm1$. The celestial equatorial North and East directions are indicated by arrows.

camera is attached to the Cassegrain focus of the 1 metre Ritchey-Chrètien-Coudé (RCC) telescope at Piszkéstető station of the Konkoly Observatory. The CCD camera is an S300:7896 series standard cooled system made by the Photometrics Ltd. The detector chip is a TH 7896, which has been coated for extended UV response with 1024×1024 19×19 micron sized imaging pixels. The observational span began just a few days after the optical maximum-light of the supernova in a ten day interval and it was limited by both the scheduled telescope time and the changeable weather conditions (Table 1). As a characterization of the seeing the FWHM of the brightness profiles of stars had a range between 2.5 and 4.0 arc seconds both for the comparison stars Nos. 3, 4 and the supernova in the whole observational period.

Standard reduction procedures were applied for the CCD images including bias corrections, flat-fielding and dark current, which is negligible with this CCD chip for exposure times less than five minutes. Temporal evolution of appearence of the supernova is displayed in Fig. 1 marking the adequate comparison stars and the supernova. The comparison stars were selected from the collection of reliable photometric comparison stars given by Skiff (1999) around the galaxy NGC 2841.

PSF fitting photometry was applied to determine the magnitudes and to perform differential photometry between a comparison star and the supernova. The sky background due to the host galaxy is negligible at the position of the supernova, even at the foreground star No. 4, which is apparently on the disk of the host galaxy. Moreover, the location of the star No. 3 is far enough from the galaxy and the background level is very close to the sky value. Typical background values with the I filter were about 1–2 ADU/s/pixel both at the comparison stars and the supernova, while the peak values of these objects were 40–50 ADU/s/pixel. Therefore, contribution of the light due to the surface brightness of the disk of the parent galaxy does not contaminate the generation of the PSFs and the magnitude determinations.

In order to determine the transformation coefficients between the instrumental magnitudes and the international photometric system the standard stars in the Dipper Asterism of the M67 were used (Schild 1983; Joner & Taylor 1990). Following the notations of Henden & Kaitchuk (1982) and Benson (1998), the resulting transformation coefficients are for V ε=–0.003, as well as μ_{BV}=1.209, μ_{VR}=0.990, and μ_{VI}=0.950. CCD $UBVRI$ photometric standard areas PG1323$-$086 and PG1657+078 around the celestial equator (Landolt 1992) were also observed in order to check the photometric performance. However, it should be mentioned that since the broad-band photometric system is standardized using normal standard stars, the colors derived from the broad-band photometry for supernovae could therefore generally differ from those for normal stars due to the peculiar spectral features of the supernovae. Our goal is to apply the MLCS method to fit the synthetic lightcurve to the observations. Note here that the MLCS method was extensively tested (Riess et al. 1996, 1998; Jha et al. 1999) and finally, it can efficiently be applied for the empirical $BVRI$ photometric data.

2.2. Other selected photometric data

In order to extend our measurements and to compare them to other data only filtered photometric observations were selected from the available data sets: i) Hanzl (1999a, b, c, d) who consequently reported the error bars (1 σ) of his magnitude data; and ii) only the filtered data from collection of the *Variable Star Observers' Network* (VSNET). In cases of the selected filtered observations where the error bars were not reported the probable errors in V can be guessed as $\pm$0.05 mag for the bright state and about 0.1–0.2 mag for the faint state of the object, when

Table 1. Post-maximum photometry of SN 1999by (Konkoly Observatory)

#	UT 1999 May	V	σ_V	$(B-V)$	σ_{B-V}	$(V-R)$	σ_{V-R}	$(V-I)$	σ_{V-I}
1	15.932	13.23	0.02	1.12	0.03	0.38	0.02	0.24	0.01
2	16.854	13.31	0.01	1.29	0.04	0.31	0.01	0.48	0.01
3	18.855	13.54	0.01	1.73	0.06	0.36	0.01	0.50	0.01
4	19.837	13.63	0.01	1.60	0.02	0.40	0.01	0.49	0.01
5	21.846	13.91	0.05	1.41	0.04	0.45	0.04	0.74	0.04

Observers #1–4: I. Toth; #5: R. Szabó

the brightness was close to the limiting magnitude of a small telescope with a CCD or a photometer.

3. Results and discussion

The resulting and selected photometric V magnitude observations are shown in Fig. 2 with different symbols. For the chronology we have two values for the time of the maximum-light in the optical: i) given by Bonanos et al. (1999) derived from their photometric observations with an error bar of one day (their suggested maximum-light with error bars JD 24501308.5 $\pm$ 1 day is shown in Fig. 2); ii) our and other observations suggest a time of the maximum of JD 2451309.75 (UT 1999 May 11.25). It is assumed that times of the maximum light in B and V do not differ significantly if say, they occured within few days. Inspecting Fig. 2 it is obvious that i) the post-maximum observations are mainly based on the photometry with the 1 metre RCC telescope; and ii) pre-maximum data – mainly covering the ascending branch of the lightcurve are VSNET data. The observed $(B-V)$ colors correspond to a subluminous supernova (cf. Fig. 1 of Riess et al. 1996).

3.1. Applications of the MLCS method

Our principal goal is to recover the observed lightcurve applying the MLCS method. Rearranging the MLCS formulation by Riess et al. (1996) (cf. Vinkó et al. 1999), for any time instant, the observed V magnitude can be expressed as follows

$$V_{obs}(\tau) = \mu_0 + M_V(\tau) + R_V(\tau)\Delta + 3.1E(B-V) \qquad (1)$$

where $V_{obs}(\tau)$ is the observed V magnitude at τ, which is the time relative to the actual maximum-light of the supernova, μ_0 is the extinction-free distance modulus, we adopted the RC3 distance of 14.0 Mpc (μ_0=30.73 mag) in the calculations below. M_V and R_V are time-dependent parameters of the MLCS method (Table 2 of Riess et al. 1996), Δ is the "luminosity correction", which gives the magnitude difference between the observed and the template supernova, $E(B-V)$ is the color excess in $(B-V)$, and the standard value 3.1 of the coefficient of the ratio of the total to the selective V absorption is assumed for the Milky Way Galaxy.

To calculate the MLCS lightcurve the quantities of the Δ and $E(B-V)$ should be determined. The computation of Δ is related to the adopted value of the reddening for any instant τ for *discrete* observational points

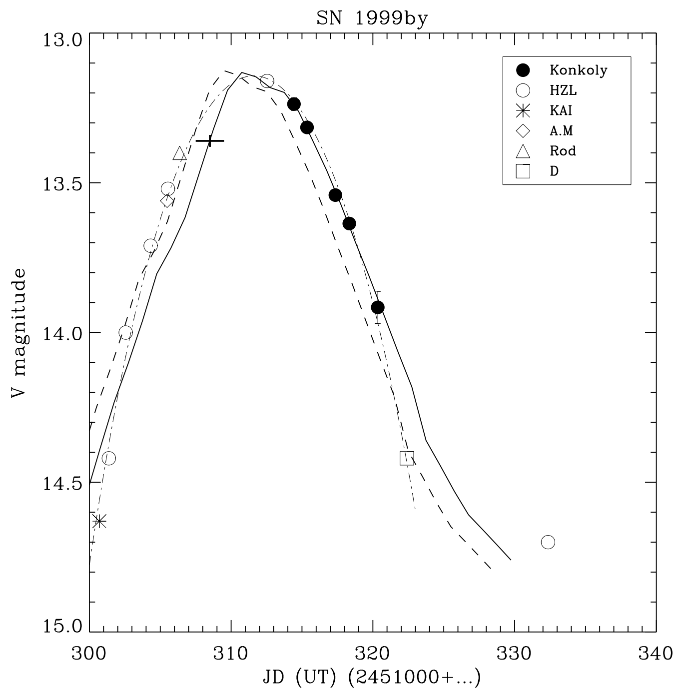

Fig. 2. Near-maximum time V lightcurve of the SN 1999by. The symbols represent the different observations by corresponding observers (legend is the following: Konkoly - our data; HZL - Hanzl (1999a, b, c, d); VSNET data: KAI - Katzman Automatic Imaging Telescope; Rod; A.M; and D). The 1 σ error bars of the observed magnitudes are usually within the dots of the symbols (few hundreths of magnitude). The thick solid line is the synthetic lightcurve calculated applying the MLCS method assuming the time of the V maximum determined by our search; the dashed line is the MLCS lightcurve computed for the maximum given by Bonanos et al. (1999); the dash-dot-dash line is a heuristic "skew parabola" with the form of $V_{obs}(t) = t/(a+bt+ct^2)$ curve fit for the shorter interval as $\pm$10 days around the maximum.

$$\Delta = \frac{V_{obs} - \mu_0 - M_V(\tau) - 3.1E(B-V)}{R_V(\tau)}. \qquad (2)$$

The mean of these Δ values are used to calculate the MLCS lightcurve. We adopt the value of $E(B-V)$ in two ways: i) computing from our *discrete* observed points close to the maximum-light; ii) using the reddening map of the Milky Way Galaxy.

In the first case the reddening $E(B-V)$ are directly estimated from the observations. We have adopted the observed color $(B-V)_{obs}$ and the expression of Δ in Eq. (2) as follows. The total line-of-sight reddening can be estimated using the relation by Riess et al. (1996)

$$E(B-V) = (B-V)_{obs} - (B-V)_0 - R_{B-V}(\tau)\Delta \qquad (3)$$

where $(B-V)_0$=–0.244, and R_{B-V} are taken from Riess et al. (1996). Inspecting the value of the distance modulus while keeping it close to its reference value (RC3) and using trial values of the reddening the distance modulus μ_0 (Eq. 1) is obtained from

$$\mu_0 = V_{obs} - M_V(\tau) - R_V(\tau)\Delta - 3.1E(B-V). \qquad (4)$$

We have performed a grid search interactively using our observed $(B-V)_{obs}$ colors taking trial $E(B-V)$ values monitoring both the values of μ_0 corresponding to the *discrete* observations and the quality of fit of the resulted MLCS curves to the observations. The acceptable range for the $E(B-V)$=0.0÷0.10 mag which is consistent with both the observations and which keeps the distance modulus within a narrow range around its adopted reference value, with extremal values of 30.51 (12.64 Mpc) and 30.97 (15.63 Mpc) within 20% relative variation in the distance. The extremal values are unrealistic perhaps because these are influenced by the larger error bars due to the limiting magnitude of small telescopes when the supernova was very faint emerging on its ascending branch; however, the smaller values are closer to the 9.5 Mpc mentioned by Block et al. (1995). The determined value of $E(B-V)$ is 0.05±0.02, which is used to compute the value of Δ relating to our observations (Eq. 2) and these parameters are by-products of our calculations. The mean value of Δ is 1.62±0.04. This large value agrees with a subluminous Type Ia supernova 1999by as revealed by Bonanos et al. (1999), Garnavich, Jha & Kirshner (1999). Using this global value for the observations the two MLCS curves are calculated corresponding to the two adopted values of the maximum-light (Fig. 2). The rising branch can be matched well by the computed curve adopting the time of maximum-light given by Bonanos et al. (1999), while the maximum-plato and declining branch can be perfectly fitted by the calculated curve using our suggested time of the maximum-light. The value of V *maximum light* magnitude by Bonanos et al. (1999) is inconsistent with all other observed data sets collected, although their maximum point is incidentally well fitted by the MLCS curve derived using our time of maximum-light. These discrepancies could be explained by the differences between the photometric system realizations by the observers rather than by any intrinsic property of the supernova.

In the second case the reddening was determined in the galactic direction of the supernova of l^{II}=166°.91, b^{II}=+44°.12. The reddening maps by Burstein & Heiles (1982) (BH) show an optically thin small absorbing ISM clump of our galaxy. Using the digitized BH maps available from Berkeley, its reddening is negligible. The very recently published (Schlegel et al. 1998) all-sky maps of dust infrared emissions for the estimation of reddening foregrounds determined by COBE/DIRBE and IRAS space observatories yield the value of $E(B-V)$=0.015 mag toward the supernova direction. This value is almost in the order of the magnitude determination of the photometric measurements (Table 1). Taking into account the probable error level of the reddening derived from these maps as a few hundredths in magnitude the galactic $E(B-V)$ is very low. The computations yield the mean value of Δ as 1.71±0.04 from the discrete observations using Eq. (2). This large value also refers to a subluminous Type Ia supernova similarly as it was obtained using our observed reddening calculations. The MLCS curves associating the two different times of maximum-light are practically the same for both approximations of the $E(B-V)$. If we use the value of $E(B-V)$ derived from DIRBE maps using the Δ=1.62 and recompute the distance modulus for each observation the scatter in the distance modulus is much smaller: μ_0 ranges from 30.62 to 31.07 mag (13.30 and 16.36 Mpc), respectively. Note that these values of Δ are larger than that plotted on Fig. 2 of Riess et al. (1996) (1.25). Our Δs were derived from photometric data. The reddening is small for the SN 1999by.

3.2. Absolute magnitude and distance estimations

How can the resulting value of $\Delta = 1.62$ at the maximum light be recovered knowing the determined value of $V_{max} = 13.10 \pm 0.05$ mag (cf. Fig. 2)? Applying the relations $\Delta = M_V - (-18.54)$ and $\mu_0 = V_{max} - M_V$ these yield a control formula as $\Delta = V_{max} - \mu_0 + 18.54$. Adopting different values of the distance and inspecting the calculated absolute magnitudes then the adequate distance range should be around 10–12 Mpc with μ_0 30.0–30.40 mag. The distance of 11 Mpc corresponds to $\Delta = 1.62$. Using the possible lower and upper bounds for the V_{max} the resulting distance range is unchanged: the estimated absolute magnitudes are between –16.87 and –16.97 mag at the maximum light as derived from the available photometric data.

4. Conclusions

Our recent note addresses initial issues for further studies. A preliminary set of conclusions are as follows.

The fitting of MLCS curves prefers the date of maximum-light in V of JD 2451309.75 (UT 1999 May 11.25) with the value of the apparent extra-atmospheric V magnitude of 13.10±0.05 (it is not corrected to the galactic and extragalactic sources of extinction). The large values of the "luminosity correction" correspond to a subluminous Type Ia supernova, computed both from the observed values of the reddening and determined using the reddening map. The reddening value derived by our observations is slightly larger than those determined from the COBE/DIRBE all-sky survey reddening map but the error bars in the $E(B-V)$ determinations amounts to a few hundredths in magnitude. The estimated radial distance of the supernova in the principal plane of the parent galaxy is about 10 kpc, moreover the Type Ia supernovae do not concentrate necessarily in the principal disk. In a general case the SN 1999by could be far from the principal plane of its host galaxy, thus the effect of extinction due to overall distribution of the ISM in NGC 2841 can be negligible.

Distance of the NGC 2841 is still uncertain: different values were reported in the literature (e.g. in RC3 by de Vaucouleurs et al. 1991; Block et al. 1995). We also encountered this problem (cf. Sect. 3.1) applying the fitting procedure which is based on broad-band photometric data of this supernova: we prefer the smaller distance which ranges from 10–12 Mpc which is slightly larger than that given by Block et al. (1995) and smaller than the value in RC3. So, due to these discrepancies the distance should be determined more accurately in the future either by using the available spectroscopic data for this supernova or via Cepheids applying large optical telescopes.

The available spectroscopic observations (L.L. Kiss private communication) together with the $BVRI$ photometric results can improve the determination of the value of the "luminosity correction" Δ as well as allow us to refine the extinction-free distance modulus and the distance of the host galaxy.

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