SN2011by: Rozhen photometry and spectra

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Abstract. We present $BVRI$ photometric data and several low-resolution spectra covering 4-month period after the explosion of SN2011by. The maximum light in I band occurs 2.25 d earlier than that in B band. The photometric data clearly exhibit presence of secondary peak in R and I filter. The measured declined rates in $BVRI$ bands during the initial fading and late-time weakening and the absolute magnitude at maximum light of SN2011by are typical for SN Ia stars. Our data were well reproduced by the 92al model. The measured time gradient of the expansion velocity of the SiII 6355 feature and its EW are appropriate for "Normal" subtype of SNe Ia. We found two trends in August: gradually decreasing of the SiII 6355 feature and fast strengthening of 5720 Å.
Key words: galaxies: individual (NGC 3972) – stars: evolution – stars: Supernovae: fundamental parameters – stars; individual – SN 2011by

1. Introduction

All types of Supernovae are important for modern astrophysics due to their role in our understanding of the stellar evolution and galactic nucleosynthesis as main producers of heavy elements.

The empirical studies until last decade showed that the Type Ia supernovae (SN Ia's) formed a homogeneous set due to their almost equal maximum absolute magnitude of about -19.3^m. That is why they were accepted as precise indicators of astronomical distances. The hypothesis of SN Ia's as standard candles was explained from the models suggesting that these explosions occur when the degenerate carbon-oxygen white dwarf (WD) approaches the Chandrasekhar mass (M_{Ch}) and the carbon near its center ignites (Hillebrandt & Niemeyer 2000). This scenario provided a natural explanation for the observed homogeneity among the SNe Ia.

There are two models proposed to explain how a white dwarf can approach the Chandrasekhar mass. In the single degenerate (SD) model (Whelan & Iben 1973), a WD accretes mass from its hydrogen-rich star companion. In the double degenerate (DD) model, a supernova results from the merger of two WDs (Webbink 1984; Yungelson & Livio 2000). Early radio and X-ray observations would probe the circumstellar medium of nearby SNe Ia and would discriminate between the SD and DD models (Horesh et al. 2012).

In the meantime a handful of objects were discovered whose properties (light curve shapes, luminosities, evolution of spectral lines and expansion velocities) cannot readily be explained within the M_{Ch} framework (Howell et al. 2006, Hicken et al. 2007, Yamanaka et al. 2009, Taubenberger et al. 2011) and the diversity of SNe Ia appeared.

Recently the supernovae of SN Ia type became interesting not only for astrophysics but also for cosmology (Riess et al. 1998, Perlmutter et al. 1999). It was supposed that the relation between the shape of the light curve and its peak luminosity can be used to constrain the equation-of-state parameter for dark energy (Phillips 1993, Miknaitis et al. 2007, etc.). Moreover, observations of SNe Ia at low and high redshift could serve as probe for time evolution of dark energy and for the expansion history of the Universe (Riess et al. 2007). For that purpose empirical and theoretical comparison of both light curve shape luminosity indicators (Phillips 1993, Goldhaber et al. 2001, etc.) and spectral indicators (Nugent et al. 1995, Bronder et al. 2008, Maguire et al. 2012, etc.) is necessary.

Our *BVRI* photometric and low-dispersion spectral observations of SN-2011by aimed to provide additional empirical data about the SNe Ia type explosions.

The target was discovered around the center of the Sc galaxy NGC 3972 on April 26 2011 at magnitude of 14.2^m (Jin & Gao 2011) and confirmed on April 27.3 (Brimacombe et al. 2011, Green 2011). Its first optical spectrum on April 27.5 was consistent with that of a SN Ia subtype which absorption minimum of SiII 6355 was blue-shifted by about 12000 km/s (Green 2011, Zhang et al. 2011). The spectrum taken about six months after the maximum light corresponded to the age of SN2011by (Marion et al. 2011).

Silverman et al. (2013) conclude that SN2011by is photometrically and spectroscopically normal on the basis of early *BVRI* photometry as well as its 7 near-maximum-brightness spectra and 2 late-time spectra. They determined 2011 May 9.9 UT as *B*-band maximum brightness of SN2011by.

The detected X-Ray point-source at the position of SN2011by during April – June 2011 by the Swift X-Ray Telescope (Immler & Russell 2011) was not confirmed by the Chandra observations (Pooley 2011).

Johansson et al. (2013) measured no significant excess far-IR emission with respect to the estimated host galaxy background at the location of SN2011by.

2. Rozhen observations and data reduction

Our observations were carried out with the three telescopes of the Rozhen National Astronomical Observatory (hereinafter briefly Rozhen data/spectra/observations/etc.). The CCD photometric observations by using standard Bessell *BVRI* filters cover totally 44 nights. Most of them were obtained with the 60-cm Cassegrain telescope using the FLI PL09000 CCD camera (3056 × 3056 pixels, 12 μm/pixel, FoV 27.0 × 27.0 arcmin with focal reducer). Three observations were obtained with the 50/70-cm Schmidt telescope equipped by the CCD camera FLI PL16803 (4096 × 4096 pixels, 9 μm/pixel, FoV 1.2 × 1.2 degree) and 2 observations by the 2-m RCC telescope with the CCD camera VersArray 1300B (1340 × 1300 pixels, 20 μm/pixel, FoV 5.7 × 5.6 arcmin).

The standard IDL procedures (adapted from DAOPHOT) were used for reduction of the photometric data. The comparison stars in the observed field (Fig. 1) were chosen by the criterion to be constant in the framework of the precision of the corresponding equipment and filters during the 4-month observations. Information about the comparison stars was taken from the GSC2.3 catalogue (Lasker et al. 2008). It was used as a base for determination of their magnitudes and colors by our observations (Table 1).

All data are corrected for interstellar absorption and reddening appropriate to the SN2011by direction (data from NASA/IPAC Extra-galactic Database

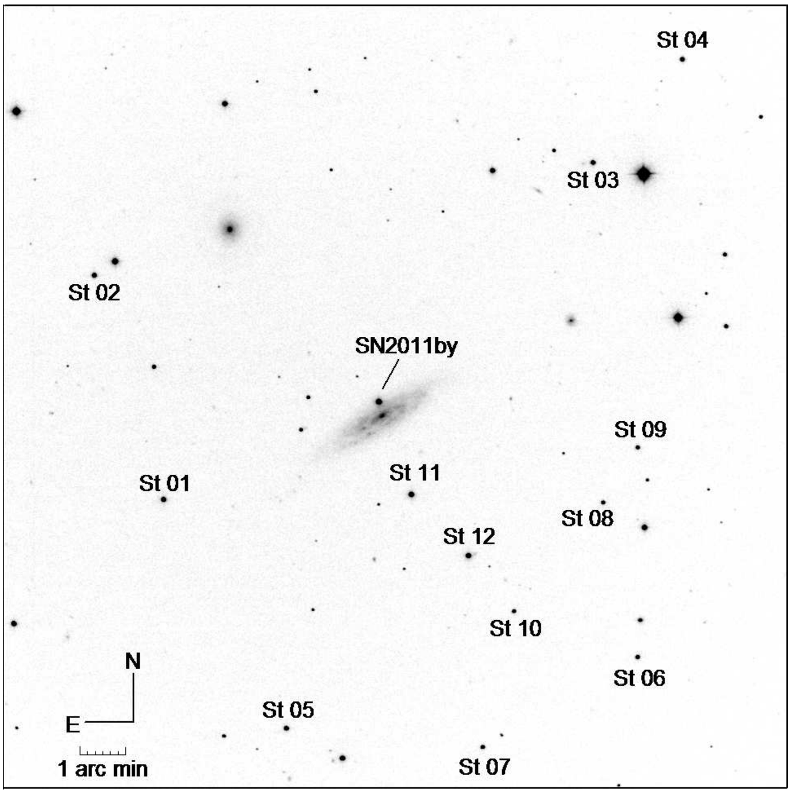

Fig. 1. The observed field with designed comparison stars

and Schlafly & Finkbeiner 2011). Table 2 presents the observed $BVRI$ magnitudes of the target which values and errors are calculated by averaging of 3-5 photometric observations per night.

Six low-dispersion spectra of the target were obtained during May 21, 23, 24, 25, August 3, and 8 2011 by the 2-m RCC telescope equipped with VersArray 512 CCD camera (512 × 512 pixels, 24μm/pixel) and focal reducer FoReRo-2 using a grism with 300 lines/mm. The resolution of our spectra is about 10.4 Å(FWHM of two pixels) and they cover the range 5100 – 7700 Å.

The reduction of the spectra of SN2011by was performed using IRAF packages by bias subtraction, flat fielding, cosmic ray removal, one-dimensional spectrum extraction and wavelength calibration. The spectra were normalized at the region around 6500 Å.

Table 1. Coordinates, magnitudes and colors of the comparison stars

Star	ID GSC1.2(2.3)	RA [2000]	DEC [2000]	V [mag]	$B-V$ [mag]	$V-R$ [mag]	$V-I$ [mag]
St01	3836-0119	11 56 19.07	55 17 37.7	14.019±0.015	1.069±0.022	0.519±0.014	0.987±0.012
St02	3836-0146	11 56 28.31	55 22 34.2	14.085±0.015	0.827±0.023	0.357±0.013	0.732±0.013
St03	3836-0170	11 55 11.19	55 24 33.5	14.123±0.013	1.125±0.025	0.596±0.010	1.198±0.009
St04	3836-0173	11 54 56.74	55 26 42.5	14.171±0.014	0.892±0.021	0.385±0.014	0.772±0.014
St05	N7IR005065	11 56 01.72	55 12 32.6	14.371±0.013	0.790±0.025	0.332±0.011	0.669±0.011
St06	3836-0100	11 55 07.78	55 13 45.9	14.677±0.014	1.072±0.036	0.524±0.007	1.004±0.008
St07	N7IR005008	11 55 32.01	55 11 57.5	14.924±0.015	0.822±0.029	0.340±0.012	0.671±0.010
St08	N7IR005594	11 55 11.95	55 17 09.5	15.005±0.015	0.752±0.033	0.317±0.011	0.651±0.009
St09	N7IR005742	11 55 06.20	55 18 19.5	14.965±0.017	0.931±0.035	0.436±0.016	0.874±0.017
St10	N7IR005363	11 55 26.33	55 14 52.8	15.129±0.015	0.825±0.033	0.352±0.010	0.710±0.011
St11*	3836-0118	11 55 41.13	55 17 31.5	13.540±0.012	0.820±0.019	0.349±0.010	0.701±0.011
St12*	3836-0111	11 55 32.79	55 16 09.0	13.643±0.009	0.783±0.018	0.329±0.009	0.664±0.009

The sign "*" is for the comparison stars of the observations with the 2-m telescope

3. Analysis of the results

3.1. Photometric data

In order to determine the characteristic times of the explosion we approximated the corresponding parts of both the AAVSO and Rozhen photometric curves of SN2011by by the same polynomial functions (Fig. 2, dashed lines).

Table 3 shows the values of the characteristic parameters describing the SNe Ia light curves (Hamuy et al. 1996a) corresponding to our target: t_1^k and $m_{t_1}^k$ are the time and magnitude of the "inflection" point where the curvature of the "k"-th light curve changes sign; t_2^k and $m_{t_2}^k$ are the time and magnitude of the intersection of the straight line that fits the exponential tail and the straight line that fits the initial decline phase of the "k" light curve; Δm_T^k is the magnitude decay of the "k"-th light curve in the first "T" days after the "k"-th maximum light (as usually the time of the B maximum is assumed as a zero moment).

The transition between the rapid decline after the maximum (photospheric phase) and the much slower decline (nebular phase) of SN2011by is best visible in B and V bands (Fig. 2) and occurs around 40 days after the B maximum.

The light decline during the fast phase is biggest in B filter and decreases to the longer wavelengths (up to 2.7 times in I band). The light decline during the slow phase is biggest in I filter and decreases to the shorter wavelengths (up to 1.5 times in B band). Our value of Δm_{15}^B (Table 3) coincides within the errors with that of Silverman et al. (2013) $\Delta m_{15}^B = 1.14 \pm 0.03$ mag.

The multicolor observations of SN2011by shown that the maximum light in I band occurs 2.25 d earlier than that in B band (Table 3).

The color curves of SN2011by (Fig. 3) have the same course. They show that around the light maximum the target color becomes more blue, between day 10 and day 40 (K-point) it becomes redder and after that the color turns blue gradually.

A secondary light peak is well visible on the R and I light curves of SN2011by and scarcely in V band (Fig. 2).

Table 2. Rozhen photometry of SN 2011by

JD	B	σ_B	V	σ_V	R	σ_R	I	σ_I	Telescope
2455681.395	14.081	0.004	13.928	0.005	13.774	0.005	13.777	0.005	60-cm
2455681.582	14.066	0.024	13.880	0.009	13.726	0.006	13.715	0.012	60-cm
2455688.294	13.101	0.012	12.924	0.003	12.840	0.005	12.989	0.009	60-cm
2455688.574	13.124	0.013	12.918	0.003	12.838	0.006	12.982	0.002	60-cm
2455689.345	13.061	0.016	12.881	0.008	12.810	0.004	13.000	0.003	60-cm
2455702.446	13.703	0.014	13.176	0.003	13.263	0.010	13.698	0.002	60-cm
2455703.286	13.779	0.018	13.232	0.006	13.330	0.003	13.734	0.009	60-cm
2455704.378	13.916	0.012	13.305	0.004	13.396	0.005	13.751	0.003	60-cm
2455705.292	14.006	0.011	13.362	0.004	13.436	0.003	13.763	0.012	60-cm
2455706.294	14.128	0.010	13.430	0.006	13.472	0.006	13.758	0.002	60-cm
2455707.282	14.251	0.006	13.497	0.008	13.516	0.006	13.731	0.010	60-cm
2455710.308	14.578	0.009	13.628	0.009	13.536	0.018	13.674	0.016	Shmidt
2455715.409	15.102	0.017	13.921	0.004	13.656	0.007	13.539	0.007	60-cm
2455717.464	15.304	0.049	14.045	0.010	13.714	0.005	13.496	0.002	60-cm
2455718.406	15.349	0.033	14.100	0.010	13.753	0.006	13.498	0.007	60-cm
2455727.356	15.931	0.031	14.680	0.009	14.332	0.003	13.992	0.010	Shmidt
2455727.383	15.923	0.051	14.664	0.016	14.322	0.011	13.955	0.004	60-cm
2455728.412	16.020	0.055	14.746	0.032	14.387	0.018	14.083	0.004	Shmidt
2455735.305	16.205	0.048	14.968	0.008	14.686	0.006	14.427	0.016	60-cm
2455736.307	16.193	0.064	14.984	0.003	14.716	0.008	14.463	0.013	60-cm
2455737.306	16.220	0.156	15.047	0.003	14.764	0.027	14.506	0.023	60-cm
2455739.361	16.262	0.049	15.078	0.004	14.829	0.016	14.621	0.017	60-cm
2455740.318	16.276	0.010	15.113	0.003	14.870	0.002	14.670	0.007	60-cm
2455751.300	16.626	0.097	15.448	0.048	15.242	0.026	15.177	0.017	60-cm
2455752.299	16.508	0.069	15.443	0.029	15.270	0.016	15.238	0.031	60-cm
2455753.299	16.464	0.077	15.459	0.006	15.328	0.033	15.272	0.025	60-cm
2455754.299	16.560	0.089	15.492	0.031	15.306	0.007	15.287	0.026	60-cm
2455755.317	16.552	0.040	15.552	0.024	15.387	0.026	15.388	0.017	60-cm
2455756.315	16.667	0.143	15.605	0.009	15.395	0.022	15.422	0.094	60-cm
2455757.338	16.694	0.170	15.570	0.067	15.434	0.004	15.466	0.012	60-cm
2455758.303	16.548	0.057	15.686	0.029	15.468	0.029	15.494	0.024	60-cm
2455759.343	16.621	0.021	15.630	0.015	15.497	0.013	15.548	0.056	60-cm
2455761.357	16.659	0.024	15.681	0.043	15.525	0.022	15.669	0.005	60-cm
2455763.318	16.631	0.027	15.764	0.030	15.635	0.034	15.737	0.015	60-cm
2455765.325	16.672	0.033	15.766	0.029	15.672	0.023	15.799	0.041	60-cm
2455767.318	16.641	0.034	15.854	0.070	15.737	0.015	15.818	0.005	60-cm
2455768.310	16.756	0.026	15.862	0.018	15.771	0.010	15.939	0.029	60-cm
2455769.333	16.749	0.089	15.914	0.055	15.829	0.009	16.010	0.007	60-cm
2455771.337	16.739	0.022	15.943	0.004	15.861	0.004	16.036	0.008	2-m
2455776.302	16.834	0.004	16.091	0.008	16.015	0.003	16.194	0.009	2-m
2455777.286	16.943	0.020	16.106	0.054	15.996	0.060	16.275	0.033	60-cm
2455780.321	16.869	0.244	16.092	0.040	16.175	0.025	16.429	0.046	60-cm
2455785.300	16.905	0.155	16.263	0.067	16.333	0.056	16.576	0.039	60-cm
2455789.280	17.306	0.053	16.449	0.029	16.444	0.138	16.740	0.061	60-cm
2455792.282	16.705	0.064	16.376	0.101	16.547	0.082	16.813	0.046	60-cm
2455795.281	17.322	0.088	16.557	0.080	16.653	0.082	16.875	0.081	60-cm

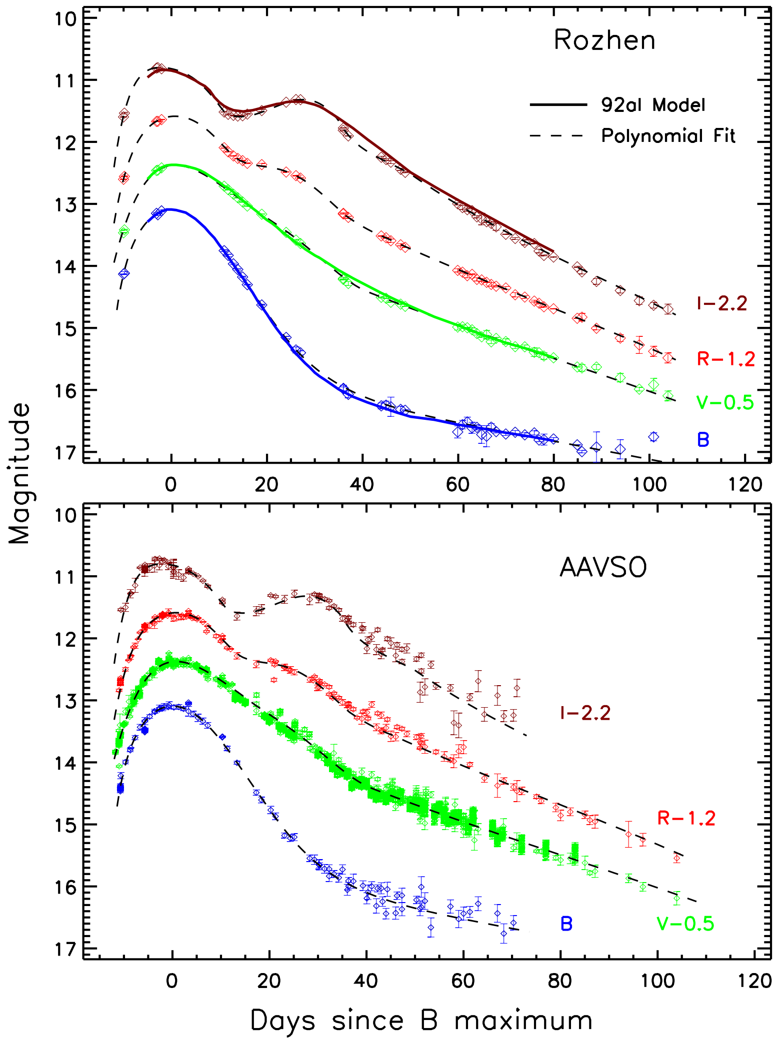

Fig. 2. *Top:* Rozhen light curves of SN2011by; *bottom:* AAVSO data

Secondary light peaks were seen firstly in the NIR bands J, H, and K of some SNe Ia. Recently they were observed in I filter of the most SNe Ia and are very seldom in R band. But the peculiar SNe Ia (SN1991bg-like) do not reveal secondary light peak.

The most recent estimate of the distance to NGC 3972 (Cappellari et al. 2011) is 22 Mpc that means distance modulus to SN2011by of $m - M = 31.71$ mag. Using the visual magnitudes $m_{\rm max}$ of SN2011by in the different colors at the maximum light and the extinction in this direction (NED and Schlafly & Finkbeiner 2011), we determined its absolute magnitudes $M_{\rm max}$ at the peak luminosity (Table 3, third raw). The obtained values of $M_{\rm max}$ in B and V

Table 3. Light curve parameters

Parameter		B	V	R	I
JD(max)	[days]	0.000	0.796	0.771	-2.255
$m_{\max}$	[mag]	13.093	12.874	12.787	12.999
$M_{\max}$	[mag]	-18.62	-18.84	-18.92	-18.71
t_1^k	[days]	15.47	19.70	10.61	14.421
t_2^k	[days]	32.56	40.79	47.30	27.597
$m_{t_1}^k$	[mag]	14.103	13.714	13.243	13.793
$m_{t_2}^k$	[mag]	15.790	14.909	14.831	13.519
Δm_{15}^k	[mag]	1.101	0.582	0.735	0.792
Δm_{20}^k	[mag]	1.664	0.855	0.817	0.689
Δm_{60}^k	[mag]	3.434	2.586	2.472	2.216
$\frac{\Delta m}{\Delta t}(fast)$	[mag/day]	0.110	0.057	0.041	
$\frac{\Delta m}{\Delta t}(slow)$	[mag/day]	0.015	0.027	0.032	0.038

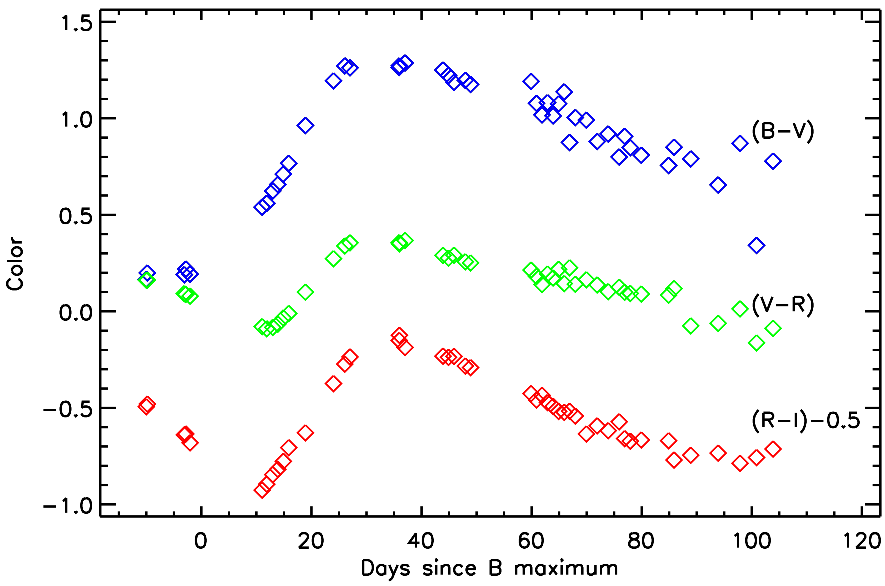

Fig. 3. Color curves $B-V$, $V-R$, and $R-I$ of SN2011by

almost coincide with those obtained by the empirical relations of Phillips (1993) (between the absolute magnitudes of SNe and their $\Delta m_{15}(B)$) while that in I color (Table 3) is slightly bigger (by 0.3 mag).

The Rozhen data were well reproduced (Fig. 2, solid lines) by the model 92al of Hamuy et al. (1996a) that is another confirmation that the light curve of SN2011by is normal.

3.2. Spectral data

The Rozhen spectra of SN2011by (Fig. 4) might be separated in two types: "early" from May and "late" from August. Their qualitative analysis led to the following results.

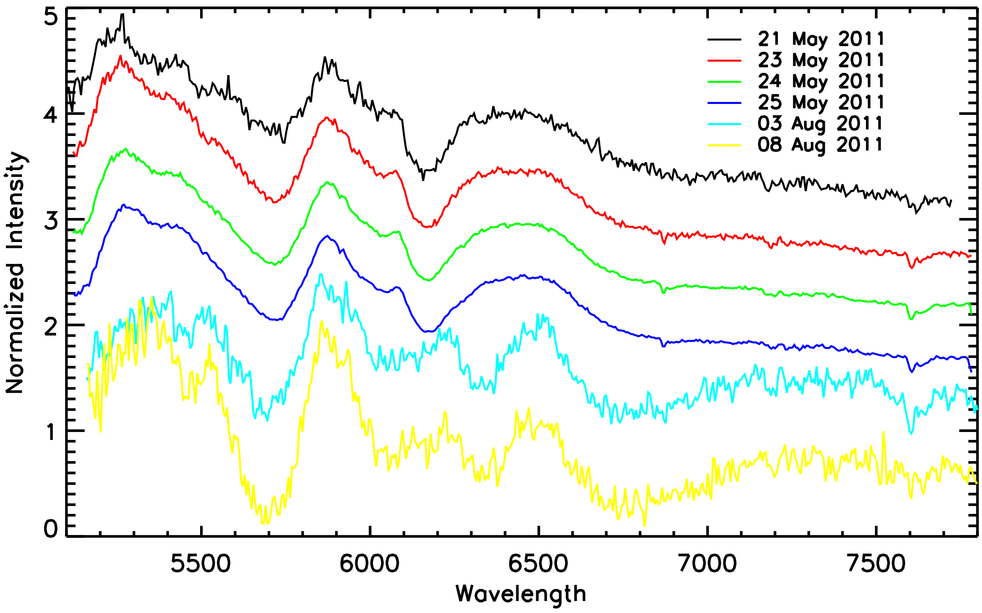

Fig. 4. The low-resolution spectra of SN 2011by

The "early" four Rozhen spectra from May (10 – 15 days after the light maximum) are almost the same, with two wide, asymmetric absorption troughs. The SN2011by "early" spectra resemble (but are not the same) those of normal SNe Ia, e.g. that of SN1998aq 20 days after its explosion (fig. 1b of Branch et al. 2003) and that of SN1994D (Patat et al. 1996). Moreover, the time of the last near-maximum-brightness spectrum of Silverman et al. (2013, fig. A2) almost coincides with that of the early Rozhen spectra and they seem to be almost identical.

The first prominent feature of our "early" spectra is a wide (FWMH = 140 Å), asymmetric absorption around 6170 Å that is attributed to blue-shifted SiII 6347, 6371 (collectively called 6355). Its depth and width are almost the same within our 4-day spectral run in May. Table 4 presents the measured wavelengths and EW of the SiII 6355 feature from all Rozhen spectra.

The second prominent feature of our "early" spectra is wide (FWMH above 150 Å), asymmetric trough around 5720 Å. It slightly strengthens during our spectral run in May.

Table 4. Parameters of SiII 6355

	May 21	May 23	May 24	May 25	Aug 03	Aug 08
λ [Å]	6159	6174	6172	6170	6332	6343
EW [Å]	71	75	71	69	70	52

The Rozhen "late" spectra of SN2011by differ from the "early" ones (Fig. 4) but are very similar to the spectra of normal SNe Ia, e.g. those of SN1998aq taken 2 months after its explosion (fig. 1c of Branch et al. 2003).

The depth and width of SiII 6355 in the "late" spectra were close to those of May but the feature was shifted almost to its laboratory wavelength (Table 4). In contrast, the depth of 5720 Å in August is considerably bigger than that in May but without noticeable wavelength shift. Moreover, its depth increases around 2 times within only 5 days at the beginning of August (Fig. 4) and its profile is yet almost symmetrical. This is the main difference between the two "late" Rozhen spectra.

In fact, the 5720 Å feature began to strengthen gradually from day -11 (spectra of Silverman et al. 2013), this trend continued in May and it became the most prominent feature at the beginning of August (Fig. 4). In contrast, the SiII 6355 Å feature gradually decreases that is visible in our "late" spectra (Table 4) as well as in true late spectra (200 – 300 days after explosion) of Silverman et al. (2013).

There are still several differences between the "early" and "late" spectra of SN2011by (Fig. 4): the change of the intensity of the wide, asymmetric structure covering the range 5150–5600 Å; appearing of wide, highly asymmetric absorption trough centered at 6750 Å; appearing of well-pronounced absorption at 5450 Å.

On the basis of Doppler shift of the SiII 6355 feature between May 21 and August 8 (Table 4) we calculated average velocity gradient of $\dot{v} = 109$ km/s per day. Silverman et al. (2013) determined considerable smaller value $\dot{v} = 53$ km/s per day but it refers to epoch near maximum brightness.

Benetti et al. (2005) divided the SNe Ia into three subtypes (FAINT, HVG and LVG) which differ not only by expansion velocity v and velocity gradient $\dot{v}$ but also in their luminosity at maximum light M_B and light decrease decline $\Delta m_{15}(B)$. The obtained by us values of M_B, $\Delta m_{15}(B)$, and $\dot{v}$ together with the expansion velocity of 10350 km/s at maximum luminosity determined by Silverman et al. (2013), allow to classify the target as rather LVG member.

Moreover, the values of the foregoing parameters as well as the measured value of $EW \simeq 70$ Å of the SiII 6355 feature in our spectra and the $B - V$ value at maximum light are appropriate for the "Normal" SNe Ia according to the subdivision of Wang et al. (2009).

4. Conclusion

The main results from the analysis of the observational data of the new SN Ia-type star SN2011by are:

1. The measured declined rates in $BVRI$ colors during the initial fading and late-time decline are typical for a normal SN Ia. Our data were well reproduced by the 92al model.
2. The maximum light in I band occurs 2.25 d earlier than that in B band.
3. There is well-pronounced secondary light peak in R and I filter of SN-2011by.
4. The absolute magnitudes of SN2011by at maximum light are typical for SN Ia stars.
5. The time gradient of the expansion velocity of the SiII 6355 feature and its EW are typical for the "Normal" group according to the division of Wang et al. (2009).
6. We found two trends in August: gradually decreasing of the SiII 6355 feature and fast strengthening of 5720 Å.

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