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Optical observations of SN 2011fe

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Abstract. We present *UBVRI* photometry of the supernova 2011fe in M101, obtained in the interval of 1 – 652 days after its discovery, as well as one spectrum, taken 105 days after the brightness maximum in the *B* band. We derived parameters of the light curves, constructed the colour curves and a "quasi–bolometric" light curve. The light curves, colour evolution and spectrum of the object indicate that SN 2011fe belongs to the "normal" subset of type Ia supernovae. It is practically identical to a well-studied "normal" SN Ia 2003du.

Key words: supernovae: individual (SN 2011fe)

1. Introduction

Supernova (SN) 2011fe, located at $\alpha = 14^{\rm h}03^{\rm m}05^{\rm s}.81, \delta = +54^{\circ}16'25''.4$ (2000.0) in the galaxy M101 (NGC 5457), was discovered by the Palomar Transient Factory on UT 2011 Aug 24.2, less than one day after its explosion (Nugent *et al.*, 2011). It is the closest and brightest type Ia SN since SN 1972E, so it provides an unprecedented opportunity for numerous follow-up studies.

Li *et al.* (2011) checked the archival HST images of the site and found out that a luminous red giant cannot be the companion to the SN progenitor. This conclusion was confirmed by early X-ray and radio observations (Horesh *et al.*, 2012; Chomiuk *et al.*, 2012). The results of photometric monitoring were presented by Vinko *et al.* (2012, hereafter V12), Richmond and Smith (2012, hereafter RS12) and Munari *et al.* (2013, hereafter M13). Pereira *et al.* (2013, hereafter P13) reported spectrophotomeric observations and derived synthetic *UBVRI* magnitudes based on these data. Infrared photometry was presented by Matheson *et al.* (2012). Optical spectral evolution was investigated by Parrent *et al.* (2012), Smith *et al.* (2011), Patat *et al.* (2013) and Shappee *et al.* (2013). This bright nearby event should provide a wealth of information on the nature of thermonuclear supernovae.

2. Observations

We present here photometry of SN 2011fe in the *UBVRI* passbands obtained at five sites, starting one day after the discovery and continuing for a period of 652 days. Most of the data were obtained at the Stará Lesná Observatory of the Astronomical Institute of the Slovak Academy of Sciences. The other observing sites were the Crimean Laboratory of the Sternberg Astronomical Institute (SAI)(Nauchniy, Crimea, Ukraine); the Simeiz Observatory of the Crimean Astrophysical Observatory (Simeiz, Crimea, Ukraine); the Moscow Observatory of SAI (Moscow, Russia); the Special Astrophysical Observatory of RAS (Nizhniy Arkhyz, Russia). A list of the observing facilities is given in Table 1.

Table 1. Telescopes and detectors employed for the observations.

Telescope code	Location	Aperture [m]	CCD camera	Filters	Scale [arcsec pixel^{-1}]	FoV [arcmin]
T50	Stará Lesná, Slovakia	0.5	SBIG ST-10 XME	$UBVR_CI_C$	1.12	20.4x13.7
T15	-"-	0.15	-"-	BVR_CI_C	1.26	22.9x15.5
T60	-"-	0.6	VersArray F512	$UBVR_CI_J$	1.38	5.9
C60	Nauchniy, Crimea, Ukraine	0.6	Apogee AP-47p	$UBVR_CI_J$	0.71	6.1
S100	Simeiz, Crimea, Ukraine	1.0	VersArray B1300	$UBVR_CI_J$	0.65	7.2
M70	Moscow, Russia	0.7	Apogee AP-7p	$UBVR_CI_J$	0.64	5.5
N100	Nizhniy Arkhyz, Russia	1.0	EEV 42-40	$UBVR_CI_C$	0.48	8.3
N600	-"-	6.0	-"-	V	0.36	6.3

The standard image reductions and photometry were made using the IRAF[1]. The magnitudes of the SN were derived by an aperture photometry or a PSF-fitting relatively to a sequence of local standard stars. The CCD image of SN 2011fe and local standard stars is presented in Fig. 1.

[1]IRAF is distributed by the National Optical Astronomy Observatory, which is operated by AURA under cooperative agreement with the National Science Foundation.

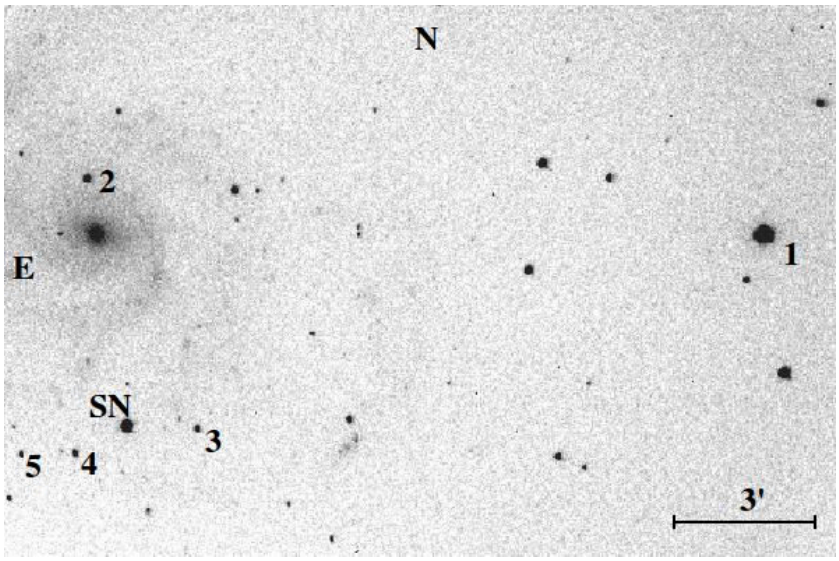

Figure 1. The image of SN2011fe and local standard stars, obtained by the T50 telescope in the R band.

The $BVRI$ magnitudes of stars No.2-5 were taken from Henden *et al.* (2012). Star No.1 (HD 122601) was calibrated on 5 photometric nights using the telescopes C60 and M70. The resulting magnitudes are $U = 9.44 \pm 0.03; B = 9.44 \pm 0.02; V = 9.02 \pm 0.01; R = 8.76 \pm 0.01$; and $I = 8.52 \pm 0.02$. The U-band magnitudes of the stars No 2, 3 and 4, measured relatively to the star No.1, are 13.44±0.04, 14.68±0.05 and 15.02±0.05, respectively.

The photometry of the SN, obtained by different telescopes, is given in Table 2, Table 3, and Table 4.

The photometry was transformed to the standard Johnson-Cousins system by means of instrument colour-terms, determined from observations of standard star clusters. The procedure was described in details by Elmhamdi *et al.* (2011), Tsvetkov *et al.* (2008), and Tsvetkov *et al.* (2006). The type of R- and I-filters is indicated in Table 1. We transformed the photometry in the R, I-bands to Cousins system, so R and I are equivalent to R_C, I_C. The reported errors were computed by adding in quadratures the fitting errors returned by IRAF tasks and the uncertainties of local standards calibration. The brightness of the SN near the maximum presented a significant difficulty for photometry, as no sufficiently bright comparison stars could be found close to the object. The images at the telescopes with large FoV (T50, T15) were obtained with the SN near the eastern edge, and star No 1 near the western edge. Such a position of the FoV allowed estimation of SN brightness on images with short exposures, but

Table 2. $UBVRI$ magnitudes of SN2011fe from the 50-cm reflector at Stará Lesná.

JD− 2450000	U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I
5799.38	14.08	0.07	14.36	0.03	13.98	0.04	13.91	0.05	13.94	0.04
5800.29	13.17	0.06	13.51	0.05	13.24	0.03	13.18	0.03	13.22	0.03
5801.29	12.51	0.06	12.83	0.04	12.66	0.04	12.62	0.04	12.55	0.03
5803.27	11.46	0.08	11.83	0.03	11.78	0.02	11.69	0.03	11.65	0.03
5806.29	10.27	0.27	10.79	0.03	10.90	0.02	10.77	0.03	10.76	0.02
5806.30	10.28	0.03	10.77	0.04	10.82	0.02	10.72	0.02	10.75	0.04
5807.28	10.07	0.03	10.58	0.02	10.65	0.01	10.52	0.02	10.59	0.03
5808.27	9.91	0.03	10.45	0.06	10.49	0.02	10.37	0.02	10.44	0.02
5809.31	9.79	0.03	10.31	0.05	10.37	0.02	10.29	0.03	10.35	0.02
5815.36	9.55	0.03	9.97	0.06	9.99	0.03	10.00	0.03	10.34	0.05
5817.63	9.70	0.04	10.03	0.03	10.05	0.01	10.08	0.04	10.37	0.03
5818.24	9.67	0.03	10.00	0.04	10.02	0.02	9.99	0.04	10.44	0.04
5820.24	9.82	0.03	10.14	0.02	10.08	0.02	10.09	0.03	10.57	0.03
5830.24	10.94	0.03	11.08	0.02	10.68	0.01	10.73	0.01	10.97	0.02
5833.23	11.39	0.03	11.42	0.02	10.79	0.01	10.75	0.01	10.85	0.02
5836.29	11.76	0.03	11.76	0.02	10.91	0.01	10.73	0.01	10.75	0.02
5839.65	12.22	0.07			11.13	0.02	10.85	0.02	10.67	0.03
5844.26	12.50	0.06	12.56	0.04	11.41	0.03	11.06	0.02	10.73	0.03
5856.22	13.09	0.04	13.13	0.03	12.05	0.03	11.78	0.02	11.50	0.03
5861.26	13.25	0.05	13.26	0.03	12.28	0.02	12.00	0.02	11.77	0.04
5862.68	13.16	0.06	13.23	0.06	12.25	0.05	12.01	0.04	11.82	0.04
5863.68	13.16	0.06	13.22	0.04	12.14	0.03				
5867.68	13.21	0.12	13.23	0.03	12.28	0.04	12.15	0.03	11.99	0.05
5868.64	13.30	0.06	13.32	0.02	12.38	0.02	12.19	0.01	12.06	0.02
5871.69	13.28	0.06	13.36	0.04	12.50	0.02	12.33	0.03	12.22	0.03
5872.17	13.35	0.06	13.38	0.02	12.50	0.02	12.32	0.02	12.28	0.02
5874.26	13.56	0.06	13.50	0.04	12.65	0.05	12.50	0.08	12.40	0.06
5876.26	13.29	0.08	13.58	0.02	12.70	0.03	12.51	0.04	12.50	0.05
5878.70	13.57	0.07	13.57	0.04	12.74	0.04	12.58	0.03	12.58	0.04
5883.67	13.73	0.06	13.64	0.05	12.86	0.03	12.71	0.03	12.76	0.02
5889.70	13.69	0.09	13.70	0.02	13.03	0.05	12.90	0.02	12.93	0.06
5893.71	14.08	0.30	13.72	0.06	13.09	0.03	13.06	0.05	13.28	0.09
5925.63	14.75	0.10	14.19	0.02	13.91	0.02	14.04	0.01	14.22	0.02
5933.72	15.06	0.16	14.23	0.06	14.00	0.03	14.27	0.04	14.49	0.07
5956.66	15.69	0.08	14.66	0.04	14.51	0.03	14.88	0.03	14.96	0.02
5967.45	16.24	0.15	14.79	0.03	14.74	0.03	15.12	0.02	15.15	0.04
5974.41	15.70	0.14	14.89	0.03	14.86	0.02	15.32	0.04	15.16	0.04
5981.41	16.19	0.19	15.00	0.03	14.97	0.02	15.48	0.03	15.32	0.03
5987.61	16.45	0.15	15.10	0.02	15.10	0.03	15.64	0.04	15.43	0.03
6019.60			15.54	0.03	15.61	0.02	16.26	0.06	15.80	0.05
6028.53			15.70	0.10	15.71	0.09	16.07	0.29		
6045.59	17.33	0.18	15.99	0.05	16.01	0.03	16.83	0.07	16.43	0.19

Table 3. Photometry of SN2011fe from the 60-cm reflector at Crimea.

JD− 2450000	U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I
5799.35			14.33	0.03	14.03	0.02	13.91	0.02	13.72	0.03
5800.31	13.54	0.10	13.50	0.04	13.23	0.02	13.16	0.01	12.97	0.03
5801.30			12.83	0.02	12.68	0.01	12.57	0.01	12.42	0.03
5802.31			12.32	0.02	12.16	0.02	12.11	0.01	11.95	0.03
5803.31			11.81	0.01	11.75	0.01	11.64	0.01	11.54	0.02
5804.32			11.45	0.04	11.42	0.03	11.27	0.01	11.20	0.03
5807.27			10.64	0.08	10.69	0.02	10.56	0.03	10.57	0.06
5807.33	10.14	0.08	10.65	0.02	10.66	0.02	10.55	0.01	10.57	0.02
5808.36			10.49	0.01	10.51	0.02	10.39	0.02	10.42	0.02
5811.31	9.48	0.05	10.07	0.03	10.13	0.01	10.11	0.01	10.21	0.02
5879.16	13.86	0.09	13.58	0.02	12.72	0.04	12.60	0.03	12.41	0.05
5916.59					13.65	0.03	13.70	0.02	13.69	0.03
6153.30			17.92	0.08	17.76	0.04	18.30	0.04		
6155.26			17.69	0.05	17.79	0.03	18.28	0.04		
6156.30					17.87	0.06	18.34	0.10		
6160.31					17.85	0.03	18.36	0.03		
6166.28					17.96	0.03	18.42	0.04		
6172.25			18.04	0.12	18.00	0.03	18.52	0.05		
6173.25					18.05	0.03	18.47	0.04		
6174.27					18.09	0.02	18.59	0.04		
6176.26					18.18	0.03	18.65	0.07		
6177.28					18.10	0.03	18.67	0.05		
6249.62					19.32	0.04	19.73	0.07		
6250.61			19.38	0.06	19.38	0.06	19.62	0.07		
6252.65					19.40	0.10				

could result in field errors, which were difficult to account for. While observing at telescopes with smaller FoV, we sometimes used the star No 2 as the main standard, or fainter but nearer stars No 3, 4, 5. At late stages only these fainter stars were used. The background of the host galaxy was negligible for most of the monitoring period, this is evident from our images and from the analysis presented by RS12. However, for the images obtained later than 570 days after the B-maximum, we applied image subtraction using SDSS[2] images of the field around the SN position.

The spectroscopic observations were carried out at the 6-m BTA telescope of SAO RAS (N600) on UT 2011 December 24.13. The focal reducer SCORPIO with the grism VPHG1200G provided the wavelength range of 4044–5858 Å

[2]http://www.sdss.org

Table 4. Photometry of SN2011fe at 6 telescopes.

JD− 2450000	U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I	Tel.
5808.30					10.50	0.01	10.38	0.02	10.42	0.02	T15
5817.25	9.80	0.04	10.05	0.01	10.04	0.01	10.04	0.01			S100
5818.24	9.92	0.04	10.09	0.01	10.05	0.01					S100
5819.24	9.92	0.04	10.15	0.01	10.07	0.01	10.06	0.01			S100
5820.24	10.10	0.04	10.20	0.01	10.10	0.01					S100
5821.23	10.15	0.04	10.24	0.01	10.12	0.01					S100
5822.20	10.31	0.04	10.32	0.01	10.18	0.01	10.23	0.01			S100
5823.25	10.33	0.04	10.40	0.01	10.20	0.01	10.30	0.01			S100
5825.22	10.56	0.04	10.55	0.01	10.32	0.01	10.43	0.01			S100
5825.22	10.42	0.05	10.65	0.01	10.30	0.03	10.44	0.03	10.89	0.01	N100
5830.22	11.27	0.04	11.11	0.01	10.63	0.01	10.73	0.01			S100
5831.22	11.39	0.08	11.22	0.01	10.72	0.01	10.75	0.01			S100
5832.21	11.70	0.05	11.36	0.01	10.76	0.02	10.75	0.02			S100
5835.22			11.61	0.03	10.86	0.02	10.75	0.04	10.77	0.03	T15
5852.25					11.91	0.02	11.59	0.02	11.27	0.02	T15
5852.26	13.20	0.08	13.07	0.01	11.90	0.02	11.63	0.02	11.18	0.03	T60
5853.22			13.06	0.05							T60
5853.22					11.94	0.02	11.66	0.02	11.33	0.02	T15
5856.23					12.06	0.02	11.79	0.03	11.51	0.03	T15
5856.23			13.16	0.02							T60
5919.61					13.64	0.04					N600
5953.49			14.61	0.03	14.48	0.02	14.65	0.02	14.54	0.03	M70
5954.69			14.63	0.05	14.59	0.03	14.81	0.02	14.63	0.04	T60
5955.60	15.71	0.08	14.58	0.02	14.58	0.02	14.80	0.02	14.56	0.03	T60
5987.61			15.17	0.04	15.19	0.02	15.61	0.03	15.59	0.04	T15
6014.35			15.50	0.03	15.46	0.03	15.97	0.04	15.60	0.05	M70
6022.45	17.17	0.11	15.65	0.02	15.77	0.03	16.21	0.02	15.73	0.03	S100
6025.40			15.69	0.03	15.84	0.06	16.31	0.06			S100
6194.23			18.16	0.05	18.39	0.04	18.86	0.05			S100
6196.20					18.45	0.06	18.81	0.09			S100
6199.20			18.30	0.08	18.46	0.07	18.88	0.08			S100
6387.48			21.20	0.14							S100
6441.31					21.23	0.07	22.00	0.12			S100
6442.34							22.07	0.11			S100
6446.28					21.15	0.17					S100
6450.36					21.36	0.08					S100

with a dispersion of 0.88 Åpixel^{-1}. The spectra were bias and flat-field corrected, extracted and wavelength calibrated in ESO/MIDAS. The spectrophotometric standard AGK+81°266 was used for flux calibrated spectra, but the night was not photometric and the absolute flux values may have significant errors.

3. Light and colour curves

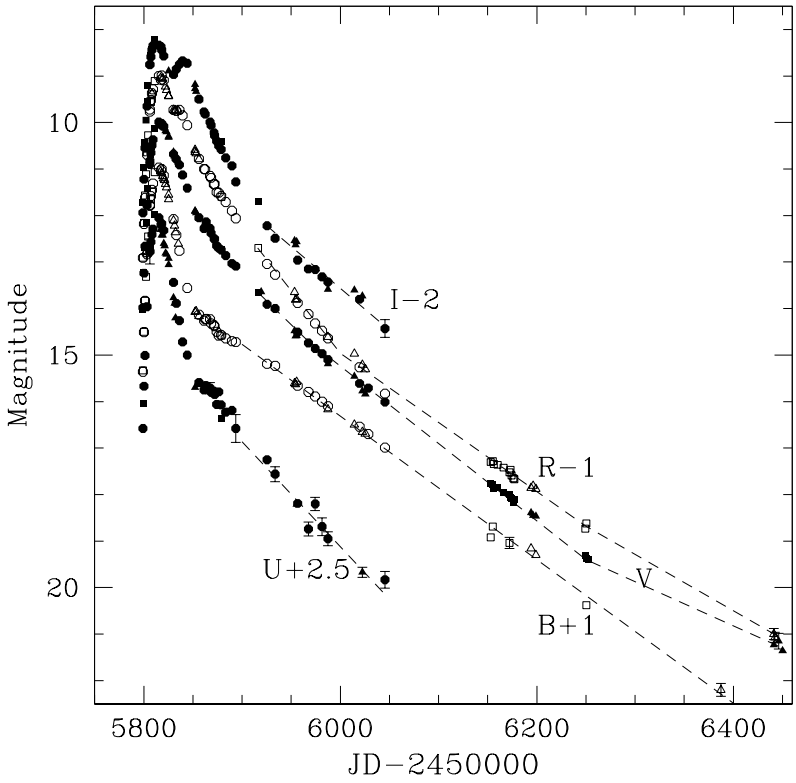

Figure 2. The light curves of SN 2011fe in the *UBVRI* bands. Circles show the data from T50, squares – from C60, triangles – from other telescopes. For clarity of presentation, the data in *BR* bands are plotted with open symbols and the curves are shifted in magnitude. The shifts for every band are reported. The error bars are plotted only when they exceed the size of a symbol. Dashed lines present the linear fits to the late phases.

The light curves of SN 2011fe are presented in Fig. 2. The results for all the telescopes are in a fairly good agreement, the largest differences are found in the U-band. The shape of the light curves is typical for SNe Ia.

We fitted the light curves with cubic splines and determined the dates and magnitudes of maximum light in different bands and the decline rate parameters Δm_{15}. These are reported in Table 5. The errors of magnitudes at maximum and Δm_{15} are about 0.02–0.05 mag, the errors of their times are 0.1–0.2 days. The results are consistent with the data reported by other authors (V12, RS12, M13). At late phases we used linear fits for the light curves. The resulting parameters are listed in Table 6. The rates of decline in the interval JD 2456000–6250 (which corresponds to phases 180–430 days after the B-maximum) in the BVR- bands are significantly greater than the mean values for SNe Ia (Lair *et al.*, 2006). The comparison with the data for SN 2003du, which has similar Δm_{15} (Stanishev *et al.*, 2007), reveals that the rate of decline for SN 2011fe is larger in the B- and V-band and lower in the R-band. After JD 2456250 (phase 430 days) the decline in the VR- bands slows down. Similar behaviour of the V-band light curve can be noticed for SN 2000E (Lair *et al.*, 2006) and SN 1992A (Cappellaro *et al.*, 1997).

Table 5. Dates and magnitudes of maximum light and the decline rate parameters in different passbands.

Band	JD−2455000	mag	Δm_{15}
Primary	maximum		
U	813.3	9.53	1.36
B	815.1	10.01	1.10
V	815.9	10.02	0.67
R	815.4	9.97	0.75
I	812.8	10.21	0.76
Secondary	maximum		
I	839.9	10.68	

Fig. 3 presents the comparison of photometry by different authors near the maximum brightness. The superposed light curves are in a good agreement. We may only note some outlying points by RS12 in the R-band and for our data in the I-band. We computed mean differences between our data and other four main sets (RS12, M13, V12, P13) in different bands. We found the best consistency with the RS12 and M13 data, where the mean difference does not exceed 0.04 mag. The agreement with the V12 and P13 data is worse. The maximum mean difference is 0.13 mag.

As seen from colour curves, presented in Fig. 4, the data from different telescopes are in a fairly good agreement. Some inconsistencies and large errors are evident for the $U-B$ colour and for the late-time $R-I$ data. The colour

Table 6. Rates of brightness decline (in mag/100^d) at different late stages of SN 2011fe evolution.

Band	JD 2455900-6000	JD 2456000-6250	JD 2456250-6450
U	2.26 ± 0.12		
B	1.51 ± 0.02	1.64 ± 0.07	
V	2.05 ± 0.03	1.60 ± 0.01	0.99 ± 0.03
R	2.62 ± 0.03	1.54 ± 0.01	1.23 ± 0.05
I	1.85 ± 0.03		

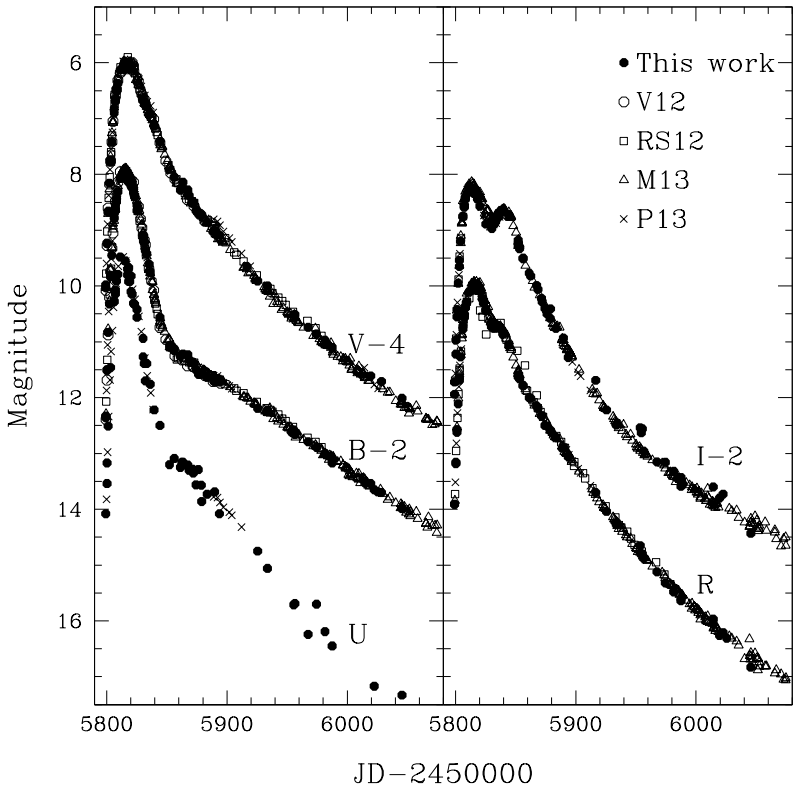

Figure 3. The photometric data for SN 2011fe from different authors.

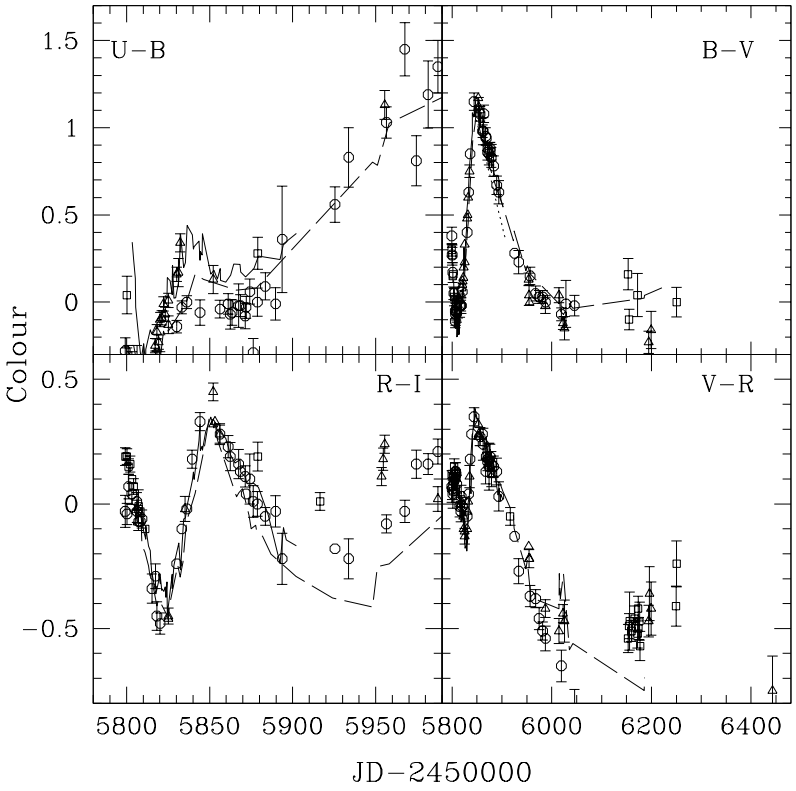

Figure 4. The colour curves of SN 2011fe. The meaning of the symbols is the same as in Fig. 2. The colour curves of SN 2003du (dashed line) and SN 2005cf (solid line) are plotted for comparison. The curves for SN 2005cf were corrected for $E(B-V) = 0.097$. The dotted line on the $B - V$ diagram is the Lira-Phillips relation.

evolution is typical for SN Ia, this is confirmed by comparison with the colour curves for "normal", unreddened SNe Ia with nearly the same value of Δm_{15}: SN 2003du (Stanishev *et al.*, 2007) and SN 2005cf (Pastorello *et al.*, 2007). The $B - V$ colour curve is also compared with the "Lira-Phillips relation" (Phillips *et al.*, 1999), showing the time dependence of $B - V$ in the phase interval 30-90 days for most of SNe Ia that suffered no extinction. It is obvions, that the interstellar extinction towards SN 2011fe is very low.

The "quasi-bolometric" light curve for SN 2011fe, constructed by integrating the flux from U- to I-bands, assuming distance modulus $\mu = 29.04$ (Shappee and Stanek, 2011) and extinction $E(B - V) = 0.009$ (Schlegel *et al.*, 1998) is shown in Fig. 5. On the dates when observations in some bands were miss-

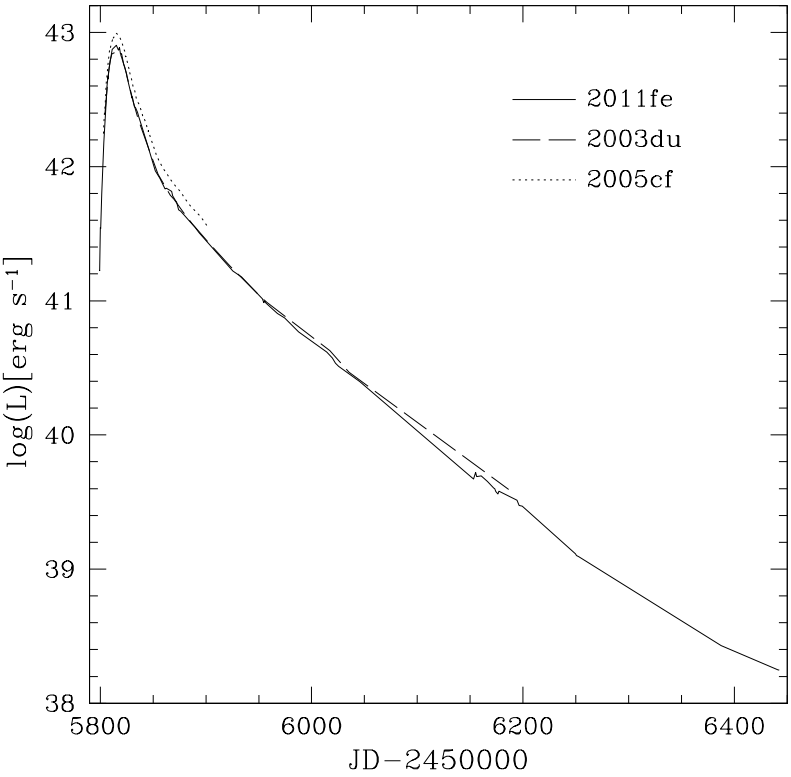

Figure 5. The "quasi-bolometric" light curve of SN 2011fe, compared to the light curves of SNe 2003du and 2005c.

ing, we interpolated or extrapolated the colour curves to estimate the colour of SN and then calculated the missing magnitudes. We compare SN 2011fe to SNe 2003du and 2005cf, for which the "quasi-bolometric" light curves were constructed analogously. The adopted distance modulus and extinction for these objects are: $\mu = 32.50$, $E(B-V) = 0.01$ for SN 2003du (Tsvetkov *et al.*, 2011) and $\mu = 32.51$, $E(B-V) = 0.097$ for SN 2005cf (Pastorello *et al.*, 2007). The "quasi-bolometric" light curves for SN 2011fe and 2003du are nearly identical, while SN 2005cf is slightly brighter. The rate of decline for bolometric luminosity is 1.72±0.03 mag/100^d in the interval JD 2455900-2456100, 1.55±0.04 in the interval JD 2456150-2456250, and 1.33±0.04 in the interval JD 2456250-2456450. The gradual reduction of the rate of brightness decline is evident from this data. Intergating the "quasi-bolometric" light curve of SN 2011fe over time we find that the total optical energetic output of the SN equals 2.05×10^{49} ergs.

4. Spectrum

The spectrum of SN 2011fe obtained by N600 telescope on December 24.13 UT (JD 2455919.63, 105 days after the B-band maximum) is shown in Fig. 6. The spectrum of SN 2003du obtained 109 days after its maximum by Stanishev *et al.* (2007) is displayed for comparison. The observed wavelengths are plotted for the spectrum of SN 2011fe, while the spectrum of SN 2003du was deredshifted using $z = 0.006384$.

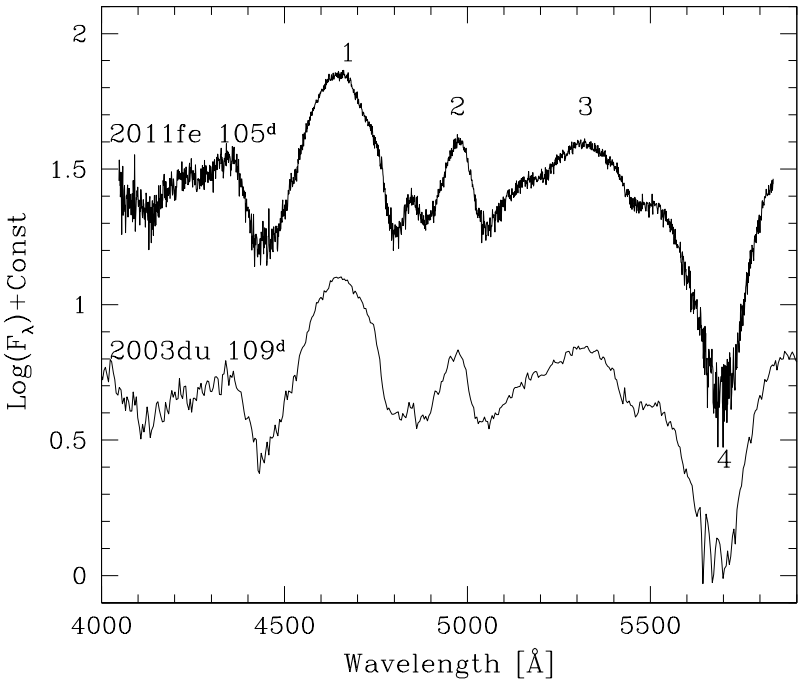

Figure 6. Spectra of SN 2011fe and 2003du.

The two spectra are nearly identical, confirming the physical resemblance of both SNe. This phase in the evolution of type Ia SNe is considered as transitional between photospheric and nebular stages. The identification of prominent emission peaks was proposed by Bowers *et al.* (1997): features labeled 1,2 and 3 are blends of forbidden lines of [Fe III] and [Fe II]. We measured the wavelength centroid of the peaks in our spectrum: 1 – 4646Å, 2 – 4971Å, 3 – 5309Å. The absorption feature 4 is attributed to Na I by Branch *et al.* (2008). The wavelength of this line in our spectrum is 5697Å which corresponds to the expansion velocity of about 10100 km s^{-1}.

5. Conclusions

We present the light and colour curves of SN 2011fe during 652 days after its discovery, as well as one spectrum taken 105 days after its B-band maximum. The photometry was carried out at five sites, with 8 telescopes, equipped with different CCD cameras and filter sets. We used linear colour-terms to transform photometry to the standard Johnson-Cousins system. It is well known that these colour corrections do not work well for SNe, because the SN spectral energy distribution is different from that of normal stars, and the so-called "S-correction" method is preferrable (see, e.g., Stanishev *et al.*, 2007). Another sources of errors were the use of different comparison stars at different telescopes and possible field errors. Nevertheless, the results were found to be generally consistent when comparing data from different telescopes from our set and comparing our data with that of other authors.

The light and colour curves for SN 2011fe show that it belongs to the "normal" subset of type Ia SNe and is almost unreddened. The decline rate parameter $\Delta m_{15}(B) = 1.10$ is close to the mean value for SNe Ia (see, e.g., Wang *et al.*, 2008). The comparison of light, colour curves and spectrum show that SN 2011fe is nearly identical in all observed parameters to the well-studied "normal" SNIa 2003du during the first ∼200 days of evolution.

We found out that the rate of brightness decline in the BVR bands is higher than average for SNe Ia in the interval of phases 180–430 days. Afterwards, the decline for V, R and "quasi-bolometric" light curves slows down. This may be caused by the emergence of the light echo, but some models of late-time luminosity evolution also predict slowing–down of the decline at that phase (see, e.g., Milne *et al.*, 2001).

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