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The light curves of type IIn supernova 2010jl

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Abstract. We present *UBVRI* photometry of the SN 2010jl in UGC 5189, obtained in the period from November 14, 2010 until November 11, 2012. We study the photometric evolution of SN 2010jl using our data and published photometry and determine the parameters of the light curves. We find a significant discrepancy between different data sets in the V band and discuss its possible origin. We compare the absolute V-band light curves of SN 2010jl and other luminous type IIn SNe and present evidence that SN 2005kd is the most similar object to SN 2010jl considering the evolution of luminosity.
Key words: supernovae: individual (SN 2010jl)

1. Introduction

Supernova (SN) 2010jl, located at $\alpha = 9^{\mathrm{h}}42^{\mathrm{m}}53^{\mathrm{s}}.33, \delta = +09^\circ 29' 41''.8$ (J2000.0), was discovered by Newton and Puckett (2010) in an irregular galaxy UGC 5189A on 2010 November 03.52 UT with an unfiltered magnitude of ~ 13.5 mag. An optical spectrum taken on November 5.08 UT showed that the object belongs to SNe of type IIn, with prominent Hα emission lines and helium lines (Benetti et al. 2010). The apparent brightness of SN 2010jl and a relative rarity of the class IIn provided motivation for a number of observational studies in the optical, infrared, radio and X-ray bands. Optical and near-IR photometry and spectroscopy were presented by Stoll et al. (2011), Andrews et al. (2011), Zhang et al. (2012), Fransson et al. (2014), Smith et al. (2012), Maeda et al. (2013), Borish et al. (2015), Gall et al. (2014), Ofek et al. (2014), and Jencson et al. (2016). Mid-IR observations were presented by Williams and Fox (2015). The X-ray data were reported by Ofek et al. (2014), and X-ray and radio emission were studied by Chandra et al. (2015).

SN 2010jl was found to be extremely luminous even among type IIn SNe, with $M_{V(max)} \sim -20$ mag. The optical light curves showed a slow decline during the first ~ 175 days. After this the light curves became almost constant, but at the phase ~ 300 days a considerably faster decline started. The NIR light curves showed a similar decline to the optical up to ~ 200 days, but later they flattened in J and H bands, and in the K-band they showed an increase in the flux. The NIR excess was attributed to the emission of dust in the CSM of the progenitor (Fransson et al., 2014).

Analysis of the spectra revealed a number of strong emission lines, with a narrow and a broad component. The narrow emission features of H and He, with the expansion velocity $\sim$100 km s^{-1} were associated with a slowly expanding circumstellar shell, ionized by the initial flash of the SN. The broad component ($\sim$ 1000 km s^{-1}) was considered as due to electron scattering in the envelope.

The X-ray luminosity of SN 2010jl was found to be one of the highest for type IIn SNe, while the radio emission was weak (Chandra et al. 2015). The high bolometric luminosity can be explained by the shock interaction of SN ejecta with a dense CSM, the shock waves accompanying the interaction heated gas to X-ray emitting temperatures and accelerate particles, giving rise to radio synchrotron emission.

2. Observations

We present CCD photometry of SN 2010jl in the *UBVRI* Johnson-Cousins passbands obtained at four telescopes, located at four different sites: the 60-cm reflector of the Crimean Observatory of the Sternberg Astronomical Institute (SAI)(Nauchnyi, Crimea) with an Apogee AP-47 CCD camera (C60); the 70-cm reflector at the Moscow Observatory of SAI (Moscow, Russia) with an Apogee AP-7 camera (M70); the 50-cm reflector, equipped with an SBIG ST-10XME camera at the Stará Lesná Observatory of the Astronomical Institute of the Slovak Academy of Sciences (T50); and at the 1-m reflector of the Simeiz Observatory of the Crimean Astrophysical Observatory with a Princeton Instruments VersArray F512 CCD camera (S100). A more detailed description of the observing facilities is presented by Tsvetkov et al. (2013).

The standard image reductions and photometry were made using the IRAF[1]. The magnitudes of the SN were derived by a PSF-fitting relatively to three local standard stars. The CCD image of SN 2010jl and local standard stars is shown in Fig. 1. Stars 2 and 3 were calibrated by Zhang et al. (2012) and Andrews et al. (2011). We accepted their magnitudes and measured star 1 relative to stars 2 and 3 on our frames. The resulting magnitudes for star 1 are: $U = 12.99; B = 13.00; V = 12.54; R = 12.28$; and $I = 11.95$, with errors of 0.03 mag for the U-, I-bands and 0.02 mag for other bands.

We applied subtraction of the galaxy background for all frames. The template images were constructed from frames obtained at C60 in 2013 and 2014, when the SN was significantly fainter than the limiting magnitude. They were transformed to match the images obtained at other telescopes using appropriate IRAF tasks.

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

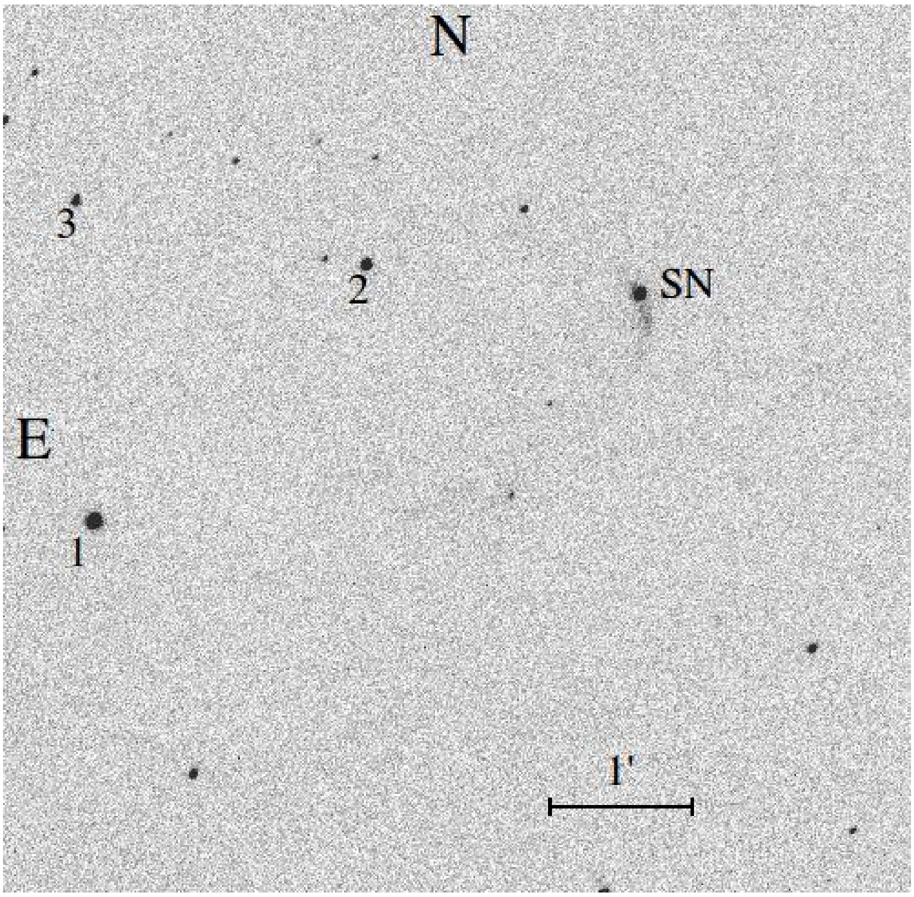

Figure 1. The image of SN 2010jl and local standard stars, obtained at the C60 telescope in the V-band on November 11, 2010.

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 detail by Elmhamdi *et al.* (2011).

Our photometry of the SN is presented in Table 1.

3. Light curves

The light curves of SN 2010jl are presented in Fig. 2.

We plotted our data and the photometry from Zhang et al. (2012), Stoll et al. (2011), Andrews et al. (2011), and Jencson et al. (2016), B, V magnitudes from Fransson et al. (2014), and R magnitudes by Ofek et al. (2014). The data

Table 1. $UBVRI$ magnitudes of SN2010jl.

JD− 2450000	U	σ_U	B	σ_B	V	σ_V	R	σ_R	I	σ_I	Tel.
5514.64	13.74	0.04	14.23	0.05	13.86	0.02	13.41	0.03	13.19	0.04	C60
5515.63	13.77	0.05	14.19	0.03	13.89	0.02	13.46	0.02	13.19	0.03	C60
5516.60	13.79	0.06	14.28	0.03	13.90	0.02	13.46	0.03	13.19	0.05	C60
5517.55	13.76	0.04	14.25	0.03	13.88	0.02	13.45	0.02	13.18	0.03	C60
5518.51	13.79	0.04	14.25	0.03	13.92	0.01	13.50	0.02	13.21	0.03	C60
5520.45	13.77	0.05	14.29	0.04	13.92	0.03	13.47	0.03	13.16	0.04	C60
5529.49	14.00	0.05	14.35	0.03	13.89	0.06	13.49	0.03	13.27	0.04	C60
5567.60	14.29	0.05	14.85	0.03	14.34	0.02	13.84	0.02	13.72	0.03	T50
5578.49	14.36	0.06	14.85	0.03	14.39	0.02	13.87	0.01	13.74	0.03	T50
5591.57	14.55	0.04	14.90	0.05	14.39	0.05	13.89	0.05	13.85	0.04	T50
5622.49	14.70	0.05	14.97	0.03	14.66	0.03	14.02	0.02	13.81	0.04	M70
5625.27	14.75	0.04	15.11	0.02	14.82	0.01	14.10	0.01			S100
5628.21	14.80	0.05	15.14	0.02	14.84	0.01	14.09	0.01			S100
5630.37	14.71	0.07	15.01	0.03	14.72	0.02	14.03	0.01	13.88	0.03	M70
5633.49	14.70	0.04	15.19	0.02	14.83	0.01	14.10	0.01			S100
5650.27	14.79	0.06	15.09	0.04	14.79	0.03	14.08	0.02	13.94	0.03	M70
5655.34	14.74	0.06	14.98	0.03	14.72	0.02	14.02	0.01	13.87	0.03	M70
5678.30	14.64	0.12	15.11	0.03	14.90	0.03	14.09	0.02	13.98	0.03	M70
5692.29			15.02	0.03	14.81	0.02	14.03	0.01	13.94	0.04	M70
5885.55	16.10	0.10	16.66	0.05	16.35	0.03	15.18	0.03	14.78	0.04	C60
5953.42			17.34	0.08			15.77	0.05	15.44	0.05	M70
6014.29							16.12	0.05	15.68	0.06	M70
6237.51							16.90	0.05			C60
6240.47					19.34	0.12	17.16	0.04			C60
6244.43					19.25	0.11	17.09	0.02			C60
6250.59					19.12	0.08	17.22	0.04			C60

from various sources are in a fairly good agreement up to JD 2455560, but later significant differences in the V-band are evident. The magnitudes by Fransson et al. (2014) are approximately 0.3 mag fainter than those by Zhang et al. (2012), while our data is somewhere between them, closer to the data by Fransson et al. (2014), and in good agreement with the V-magnitudes from Andrews et al. (2011). We suppose that the reason for this large difference is the strong Hβ emission line near the edge of the response curve for the V-band. In this case small differences in the instrumental response for various observing facilities may result in large differences of magnitudes. This effect is known for the observations of Novae and SNe (see e.g. Chochol et al. 2005).

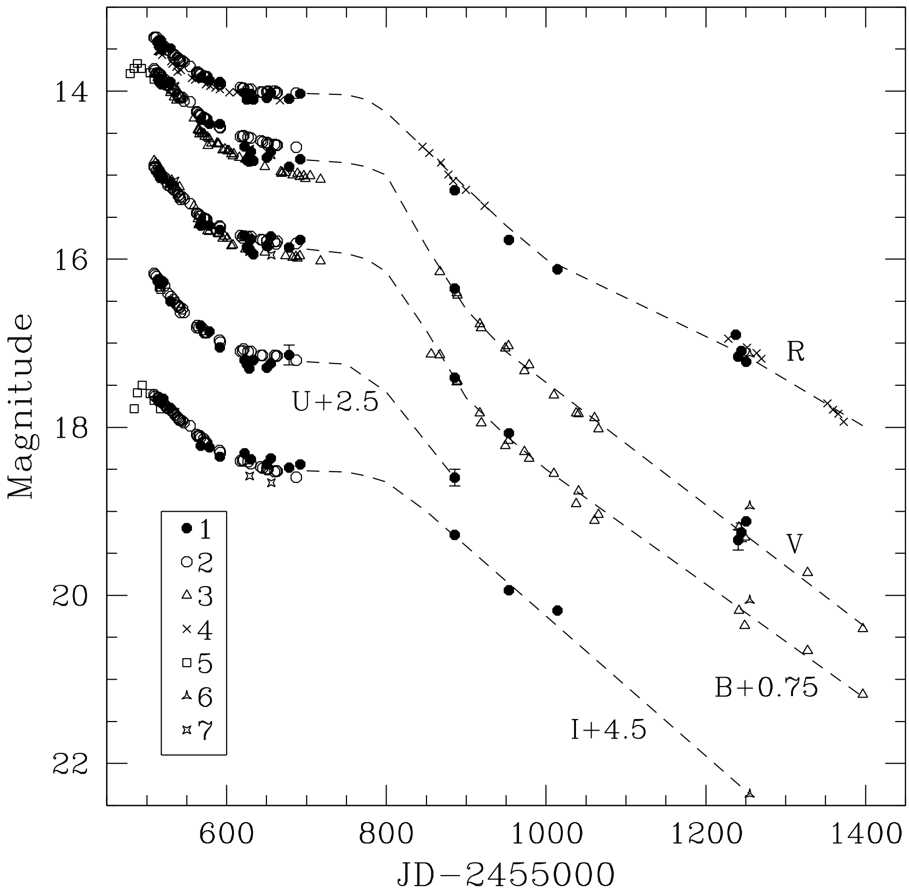

Figure 2. The light curves of SN 2010jl in the *UBVRI* bands. The sets of data are denoted by symbols: 1 – our data; 2 – Zhang et al. (2012); 3 – Fransson et al.(2014); 4 – Ofek et al. (2014); 5 – Stoll et al. (2011); 6 – Jencson et al. (2016); 7 – Andrews et al. (2011). The error bars are plotted for our data only when they exceed the size of a symbol. The bands and shifts of the curves are shown in the figure, the lines are plotted for clearer presentation.

The I magnitudes from Andrews et al. (2011) are about 0.2 mag fainter than the other data in that period.

The date of maximum light in the V-band is JD 2455488 (October 19), and in the I-band approximately 6 days later, from the prediscovery observations by Stoll et al. (2011). The maximum magnitudes are $V_{max} = 13.7$, $I_{max} = 13.0$. After the maximum light until JD 2455550 the brightness in all bands declined linearly with slightly different rates: 1.29; 1.15; 1.01; 0.82; 0.94 mag/100 days,

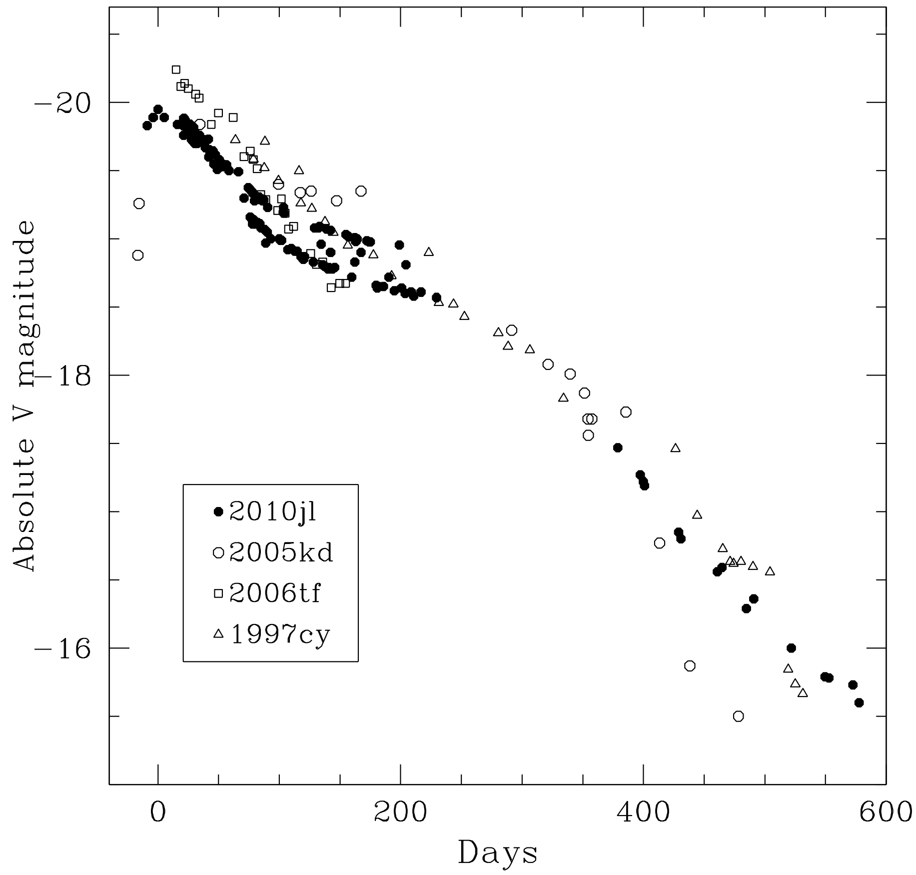

Figure 3. The V-band absolute magnitude light curves for SNe 2010jl, 2005kd, 2006tf and 1997cy. For SN 2010jl we plotted our data and the results from Stoll et al. (2011), Fransson et al. (2014) and Zhang et al. (2012).

respectively, in the U, B, V, R, I bands. After JD 2455590 the light curves start flattening and become almost constant up to JD 2455700, when observations were interrupted due to a conjunction with the Sun. Photometric coverage resumed on JD 2455820, when the phase of constant brightness already finished. The most likely data for the end of the "plateau" stage is JD 2455760-790. The rate of a late decline in the interval JD 2455900-2456400 can be determined more reliably in the B- and V- bands, and for both bands it has the same value of 0.73 mag/100 days. There is indication that the decline was slightly faster before JD 2455900, but the data are too scarse for a definite conclusion. A possible change of the decline rate can be noticed for the R-band light curve, with a break near JD 2456000.

The V-band absolute magnitude light curve for SN 2010jl is shown in Fig.2. We accepted the distance modulus $\mu = 33.45$ mag and total absorption $A_V = 0.17$ mag, as in Fransson et al. (2014). We compare SN 2010jl with the most luminous type IIn SNe: 1997cy (Turatto et al. 2000), 2005kd (Tsvetkov 2008), and 2006tf (Smith et al. 2008).

The maximum luminosity is very close for all four objects, $M_V \approx -20$ mag, with SN 2006tf about 0.3 mag brighter. The shapes of the light curves are different: for SNe 1997cy and 2006tf a linear decline is observed, while for SNe 2005kd and 2010jl there is a period of nearly constant flux. SN 2005kd was recently found to be among the most luminous SNe at X-ray wavelengths (Dwarkadas et al. 2016). The X-ray luminosities of SNe 2005kd and 2010jl were close at the phase ~ 1000 days past the explosion. So we may suppose that the similarity of light curves and X-ray emission for the two SNe is the consequence of similar parameters of the explosion, mass and structure of the CSM.

4. Conclusions

We present our photometric observations of the luminous type IIn SN 2010jl and investigate the photometric evolution using all available data in the literature. We determine the rates of the flux decline at different stages of SN evolution. We find large differences between the V-magnitudes from various sources in the period 100 – 200 days past the maximum light and suggest that the main reason may be the strong Hβ emission near the edge of the V-band response curve. We compare the absolute magnitude light curve of SN 2010jl with those for most luminous SNe IIn and conclude that SN 2005kd is similar to SN 2010jl considering the photometric evolution. SNe 2010jl and 2005kd are also the brightest X-ray sources among SNe IIn, and we may suppose that their physical parameters, mass and structure of the CSM are similar.

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