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Optical observations of the broad-lined type Ic supernova SN 2012ap *

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Abstract The optical observations of the type Ic supernova (SN Ic) SN 2012ap in NGC 1729 are presented. A comparison with other SNe Ic indicates that SN 2012ap is highly reddened (with $E(B-V)_{\rm host}{\sim}0.8$ mag) and may represent one of the most luminous SNe Ic ever observed, with an absolute V-band peak magnitude of $\sim -19.3\pm0.5$ mag after extinction correction. The near-maximum-light spectrum shows wide spectral features that are typical of broad-lined SNe Ic. One interesting feature in the spectrum is the appearance of some narrow absorption features that can be attributed to the diffuse interstellar bands, consistent with the large reddening inferred from the photometric method. Based on the light curves and the spectral data, we estimate that SN 2012ap produced a ^{56}Ni mass of $\sim 0.3 \pm 0.1 M_\odot$ in the explosion, with an ejecta mass of $2.4^{+0.7}_{-0.7} M_\odot$ and a kinetic energy of $E_{\rm K} = 1.1^{+0.4}_{-0.4} \times 10^{52}$ erg. The properties of its progenitor are also briefly discussed.

Key words: supernovae: general — supernovae: individual: SN 2012ap

1 INTRODUCTION

Supernovae represent the final stage of stellar evolution and are divided into two main categories by virtue of their explosion mechanisms: a core-collapse explosion of massive stars and a thermonuclear explosion of white dwarfs with masses close to the Chandrasekhar limit. Type Ic supernovae (SNe Ic) belong to the core-collapse subclass, and are identified by the absence of hydrogen and noticeable helium lines in their optical spectra (Filippenko 1997). It has been suggested that pre-supernova stars lose all of their hydrogen and most of their helium before the explosion (Filippenko & Sargent 1985; Wheeler & Levreault 1985; Uomoto & Kirshner 1985; Clocchiatti et al. 1996; Woosley et al. 2002). For massive stars, the hydrogen and helium envelopes can be lost through stellar winds or

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are stripped off by a companion star (Podsiadlowski et al. 1992). The progenitors of SNe Ic can thus be restricted to either single massive stars with main-sequence masses of 30–40 $M_{\odot}$ such as Wolf-Rayet stars (Wheeler & Levreault 1985) or relatively low-mass (but still relatively massive) stars in a binary system (Podsiadlowski et al. 1992). The fact that the explosion sites of SNe Ic are associated with the brightest regions in late-type spiral galaxies provides strong evidence for their origin as relatively massive stars (Kelly et al. 2008; Hakobyan et al. 2009).

Among SNe Ic, some luminous events show broad-lined (BL) spectral features suggestive of high ejecta velocities (e.g., $\sim$0.1c). This subclass of SNe Ic has recently gained special attention because of their relation to long-duration gamma-ray bursts (GRBs). Some representative SN-GRB pairs include SN 1998bw–GRB 980425 (Iwamoto et al. 1998), SN 2003dh–GRB 030329 (Matheson et al. 2003), SN 2003lw–GRB 031203 (Thomsen et al. 2004) and SN 2010bh–GRB 100316D (Bufano et al. 2012). However, there are also some BL SNe Ic which did not accompany GRBs, such as SN 2002ap (Foley et al. 2003), SN 2003jd (Valenti et al. 2008) and SN 2007ru (Sahu et al. 2009). The missing bursts in these BL SNe Ic could be due to ejecta motion being away from the line of sight (Mazzali et al. 2005). However, recent studies indicate that metallicity seems to play a key role in understanding this diversity. The sites of SNe Ic are found to be systematically more metal rich than core-collapse SNe of other subtypes (Modjaz et al. 2011), while BL SNe Ic with GRBs seem to occur at more metal-poor sites than those without GRBs (Modjaz 2012). This suggests that the geometric effect probably cannot explain the observed difference between the BL SNe Ic with or without GRBs (see also Soderberg et al. 2006). Nevertheless, the well-observed BL SNe Ic are still sparse and a larger sample will enable a better understanding of the origin that can explain diverse explosions of massive stars.

SN 2012ap is a BL SN Ic discovered at a relatively young phase by the Lick Observatory Supernova Search (Jewett et al. 2012). This supernova was initially classified as a young SN Ibc similar to SN 2008D according to the early spectra taken on 2012 February 11 UT (Xu et al. 2012) and was later confirmed to be a type Ic similar to the BL SN 1998bw (Milisavljevic et al. 2012). Due to the peculiarity of SN 2012ap, we performed extensive multi-band observations of it immediately after its discovery.

In this paper, we report the observations of SN 2012ap in optical bands, from about 10 days before maximum light to about one month thereafter, which provides an excellent case for comparison with other SNe Ibc. The observations and data reduction are described in Section 2. The optical light curves and the color curves are presented in Section 3. The quasi-bolometric light curve constructed by integrating the optical fluxes is given in Section 4. A spectral comparison is described in Section 5. In Section 6, we derive some explosion parameters. Discussions and the conclusion are given in Section 7.

2 OBSERVATION AND DATA REDUCTION

SN 2012ap was discovered on 2012 February 10.23 UT by Jewett et al. (2012). Its coordinates are $\alpha = 5^{\rm h}00^{\rm m}13.72^{\rm s},\ \delta = -3^{\circ}20'51.2''$ (J2000). It exploded at a position $29.2''$ west and $16.9''$ north of the nucleus of NGC 1729. Its host is a nearby spiral (Sc) galaxy at a distance of about 40 Mpc (Springob et al. 2009). Follow-up observations of SN 2012ap started immediately after the discovery. Photometric observations of SN 2012ap were obtained with the 0.8 m THU-NAOC Telescope (TNT) at Xinglong Station administered by NAOC (Wang et al. 2008; Huang et al. 2012), spanning the time from about 10 days before the maximum light to about one month after it.

All of the TNT images were reduced with standard procedures in the Image Reduction and Analysis Facility (IRAF[1]), including corrections for bias, flat-field division, and removal of cosmic rays. To minimize light contamination from the host galaxy, we subtracted light from the host galaxy

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation (NSF).

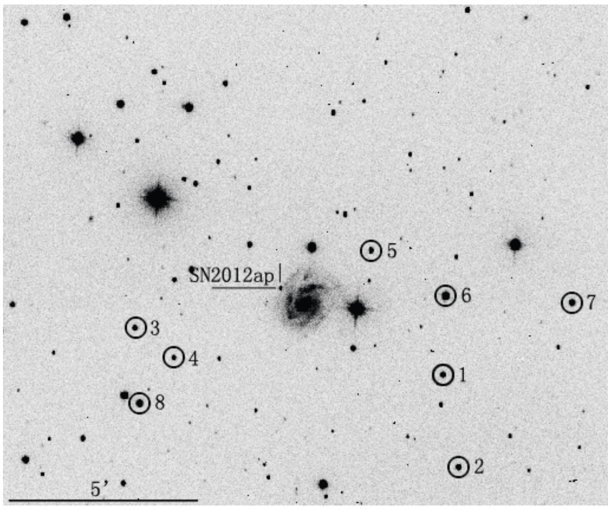

Fig. 1 SN 2012ap in NGC 1729. This is a V-band image taken with the 0.8 m TNT on 2012 February 11. The supernova and eight local reference stars are marked. North is up and west is to the left.

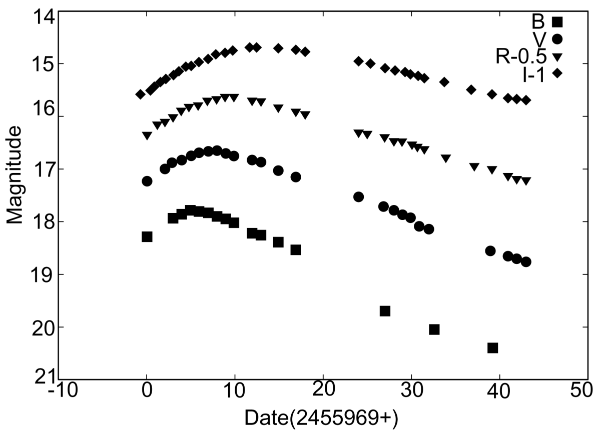

Fig. 2 The *BVRI* light curves of SN 2012ap. The light curves have been shifted by the amount indicated in the legend.

before performing the photometry. A method of fitting the point-spread function was applied to obtain the instrumental magnitudes of SN 2012ap and eight local standard stars, as shown in Figure 1.

The instrumental magnitudes were then converted into the standard Johnson UBV (Johnson 1966) and Kron-Cousins RI (Cousins 1981) systems, with the color terms and zeropoints determined by observing a series of Landolt standard stars covering a certain range of airmass and color (Landolt 1992) on photometric nights. The *BVRI* magnitudes and uncertainties in the local standard stars are listed in Table 1. The final flux-calibrated *BVRI* magnitudes are presented in Table 2 and the corresponding light curves are shown in Figure 2.

Table 1 Photometric Standards in the SN 2012ap Field

ID	B	V	R	I
1	14.214±0.010	14.741±0.019	13.753±0.001	13.133±0.061
2	15.757±0.006	14.878±0.015	14.340±0.014	13.832±0.062
3	15.126±0.004	15.774±0.024	14.634±0.006	14.783±0.034
4	16.040±0.005	15.289±0.011	14.849±0.014	14.425±0.022
5	16.215±0.006	15.336±0.023	15.957±0.002	14.782±0.017
6	18.271±0.010	16.915±0.014	16.071±0.001	15.323±0.016
7	17.136±0.001	16.332±0.017	15.635±0.007	14.692±0.014
8	16.729±0.004	15.939±0.022	15.455±0.009	14.997±0.023

Notes: see Fig. 1 for a chart of SN 2012ap and the comparison stars. 1σ uncertainties are given.

Table 2 Optical Photometry of SN 2012ap

UT Date	JD	B	V	R	I
2012/02/11	2455969.05	18.286±0.045	17.231±0.052	16.846±0.031	16.509±0.023
2012/02/13	2455971.08	...	16.999±0.031	16.599±0.047	16.426±0.052
2012/02/14	2455971.99	17.935±0.047	16.893±0.032	16.500±0.024	16.323±0.095
2012/02/15	2455972.98	17.859±0.036	16.812±0.086	16.430±0.015	16.246±0.032
2012/02/16	2455973.95	17.814±0.081	16.757±0.086	16.360±0.013	16.172±0.056
2012/02/17	2455974.93	17.786±0.095	16.692±0.036	16.319±0.024	16.119±0.074
2012/02/18	2455975.99	17.779±0.048	16.675±0.058	16.245±0.061	16.063±0.045
2012/02/19	2455976.98	17.859±0.056	16.661±0.032	16.207±0.015	16.020±0.047
2012/02/20	2455977.97	17.917±0.068	16.645±0.078	16.164±0.024	15.959±0.059
2012/02/21	2455978.89	17.980±0.028	16.654±0.075	16.135±0.047	15.861±0.047
2012/02/23	2455980.95	18.170±0.023	16.799±0.047	16.107±0.023	15.793±0.015
2012/02/24	2455981.96	18.255±0.058	16.860±0.027	16.170±0.042	15.735±0.068
2012/02/26	2455983.92	18.389±0.051	17.030±0.075	16.327±0.023	15.709±0.048
2012/02/28	2455985.90	18.534±0.062	17.153±0.068	16.405±0.058	15.738±0.058
2012/02/29	2455986.96	...	...	16.455±0.069	15.775±0.050
2012/03/05	2455993.01	...	17.529±0.042	16.801±0.048	15.954±0.026
2012/03/06	2455993.99	...	...	16.826±0.077	16.036±0.038
2012/03/08	2455995.96	...	17.604±0.069	16.890±0.021	16.087±0.042
2012/03/09	2455997.01	19.655±0.069	17.784±0.033	16.965±0.025	16.145±0.091
2012/03/10	2455997.99	...	17.868±0.023	17.029±0.048	16.201±0.068
2012/03/11	2455998.90	...	17.925±0.092	17.192±0.026	16.251±0.058
2012/03/12	2455999.88	...	18.088±0.065	17.253±0.075	16.304±0.014
2012/03/12	2456000.98	19.822±0.092	18.141±0.048	17.311±0.038	16.361±0.065
2012/03/14	2456002.94	...	...	17.415±0.069	16.455±0.044
2012/03/17	2456005.93	...	...	17.515±0.069	16.555±0.039
2012/03/19	2456007.95	20.111±0.096	18.555±0.075	17.597±0.078	16.616±0.014
2012/03/21	2456009.94	...	18.655±0.059	17.625±0.069	16.655±0.042
2012/03/22	2456010.92	...	18.704±0.075	17.685±0.062	16.673±0.021
2012/03/23	2456011.98	...	18.762±0.053	17.706±0.073	16.694±0.025

A low-resolution optical spectrum of SN 2012ap was obtained on 2012 February 23.45 UT with the BFOSC system on the 2.16-m telescope at Xinglong Station administered by NAOC. The spectrum was reduced with standard IRAF routines, and was flux-calibrated using a standard star observed during the same night at an airmass similar to that of the SN. The spectrum was further corrected for the host-galaxy redshift of $z = 0.012$ (Springob et al. 2005), and is displayed in Figure 3.

3 LIGHT CURVE AND COLOR EVOLUTION

Our photometric observations of SN 2012ap began ~ 10 d before maximum light in the R-band and lasted till about one month after that; the final *BVRI* light curves are shown in Figure 2. From

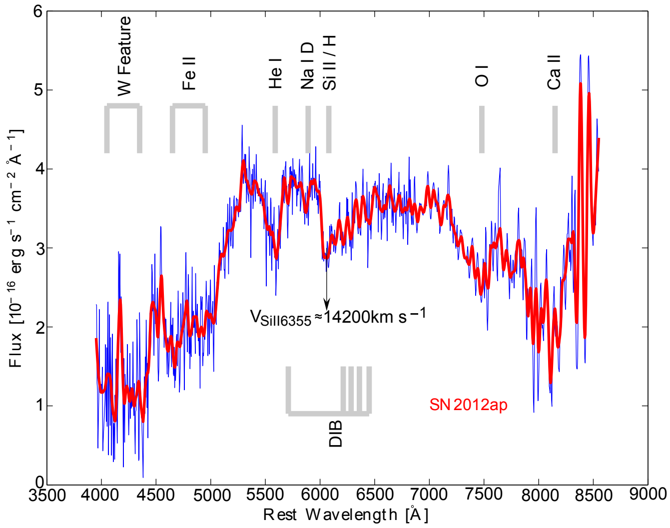

Fig. 3 Spectrum of SN 2012ap obtained at $t = +7$ d after the B-band maximum. The positions marked with lines could be diffuse interstellar bands at 5710 Å, 5780 Å, 6213 Å, 6284 Å, 6360 Å and 6450 Å.

the parabolic fit to the observed light curves, we found that SN 2012ap reached a peak magnitude in B-band of 17.78±0.06 mag on JD 2455975.6. Likewise, the V-band light curve reached a peak magnitude of 16.63 ± 0.03 on JD 2455978.5, about 3.0 d after the B-band maximum. Following the definition of the initial magnitude decline rate as used for SNe Ia (dubbed Δm_{15}; Phillips 1993), we also estimated the decline rates within 15 d after the peak for SN 2012ap. The corresponding values in the *BVRI* bands are $\Delta m_{15}(B) = 1.36$ mag, $\Delta m_{15}(V) = 0.89$ mag, $\Delta m_{15}(R) = 0.71$ mag and $\Delta m_{15}(I) = 0.44$ mag, respectively. The best-fit parameters are listed in Table 3.

Table 3 Light curve Parameters of SN 2012ap

Filter	JD at max. 2455900+	$m_{\rm peak}$ (mag)	$M_{\rm peak}$ (mag)	Δm_{15} (mag)
B	75.6±0.5	17.78±0.06	–19.06±0.34	1.36
V	78.5±0.4	16.63±0.04	–19.28±0.48	0.89
R	80.7±0.3	16.10±0.07	–19.41±0.41	0.71
I	82.2±0.4	15.70±0.05	–19.55±0.39	0.44

Notes: $m_{\rm peak}$ represents the peak apparent magnitude; $M_{\rm peak}$ represents peak absolute magnitude.

In Figure 4, we compare the light curves of SN 2012ap with those of a well-studied sample including SN 1994I (Filippenko et al. 1995), SN 1998bw (McKenzie & Schaefer 1999), SN 2002ap (Foley et al. 2003), SN 2003jd (Valenti et al. 2008), SN 2004aw (Taubenberger et al. 2006), SN 2007gr (Hunter et al. 2009), SN 2007ru (Sahu et al. 2009) and SN 2009bb (Pignata et al. 2011). The light curves of these SNe have been normalized to peak magnitudes and phases in different bands. In this sample, SNe 1994I, 2004aw and 2007gr are classified as normal SNe Ic but the rest can be put into the BL subclass according to their spectral features. It can be seen that SN 2012ap lies between SN 1994I and SN 2004aw, with close resemblances to those of the BL Ic SN 2002ap and SN 2003jd in terms of the shapes of the light curve. Among our sample, we noticed that the

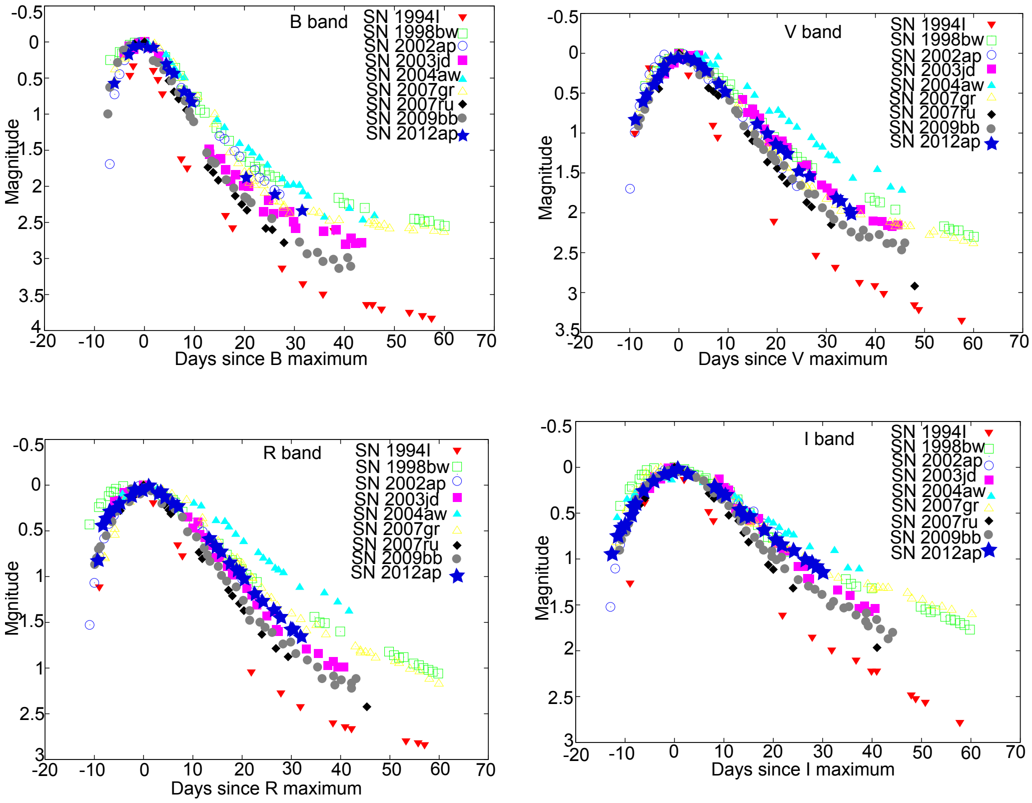

Fig. 4 Comparison of the *BVRI* light curves of SN 2012ap with those of SN 1994I, SN 1998bw, SN 2002ap, SN 2003jd, SN 2004aw, 2007gr, SN 2007ru and SN 2009bb. The light curves have been normalized as described in the text.

BL Ic SN 2007ru has the second fastest decline in its light curve, although it has broader spectral features (Sahu et al. 2009). This indicates that BL SNe Ic do not necessarily have broader peaks in their light curve.

The color evolution of SN 2012ap is shown in Figure 5. Also overplotted are the color curves of SNe 1994I, 1998bw, 2002ap, 2004aw, 2007gr and 2007ru. The color curves of the comparison SNe have been further corrected for the host-galaxy reddening, which is 0.30 mag for SN 1994I, 0.06 mag for SN 1998bw, 0.08 mag for SN 2002ap, 0.11 mag for SN 2004aw, 0.09 mag for SN 2007gr, 0.27 mag for SN 2007ru, and 0.58 mag for SN 2009bb. One can see that SN 2012ap shows a color evolution that is similar overall to the comparison SNe Ic (especially SN 2002ap and SN 2007gr), becoming progressively redder after the maximum light and reaching a peak at $t \sim 20 - 30$ d, but it appears much redder than the reddening-corrected SNe Ic used for comparison. The observed red color suggests that SN 2012ap suffers a significant reddening due to the host galaxy, as the Galactic component is $E_{BV} = 0.054$ mag (Schlegel et al. 1998). As for type Ia supernovae, we can also estimate reddening for the host galaxy based on a photometric method proposed by Drout et al. (2011), who found that the $V - R$ color of extinction-corrected SNe Ibc is tightly clustered around 0.26 ± 0.06 mag at $t \approx 10$ d after the V-band maximum. Applying this empirical relation to the

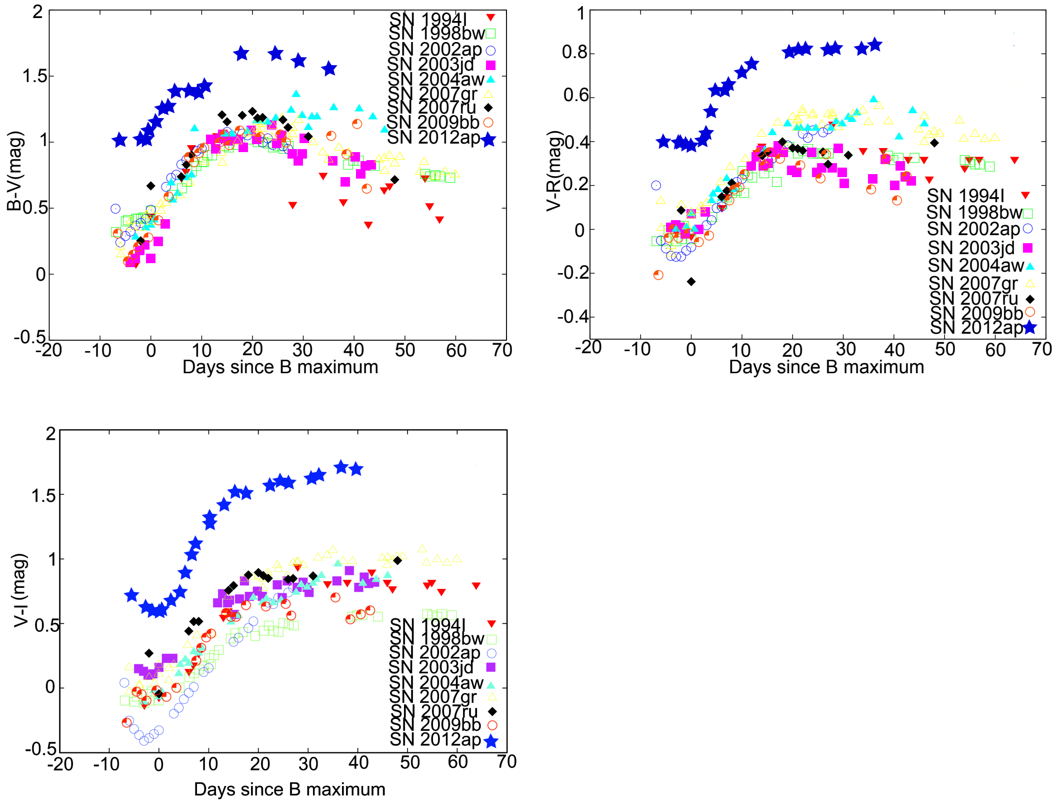

Fig. 5 $B-V$, $V-R$ and $V-I$ color curves of SN 2012ap compared with those of SN 1994I, SN 1998bw, SN 2002ap, SN 2003jd, SN 2004aw, 2007gr, SN 2007ru and SN 2009bb. All of the color curves have been dereddened with the values described in the text.

observed $V-R$ color (which is estimated to be 0.74 ± 0.10) yields a host-galaxy reddening of $E_{BV} = 0.83 \pm 0.12$ mag for SN 2012ap.

4 ABSOLUTE MAGNITUDE AND BOLOMETRIC LIGHT CURVE

A distance modulus of 33.17 ± 0.48 mag for the host galaxy NGC 1729 (Springob et al. 2005) is used in calculating the absolute magnitudes and bolometric light curve. The total extinctions are obtained with an extinction law $R_V = 3.1$ mag (Cardelli et al. 1989). The absolute peak magnitudes of SN 2012ap are listed in Table 3. The errors in the absolute magnitudes are estimated using uncertainties in the peak magnitude and the distance modulus of the host galaxy. SN 2012ap appears to lie at the brighter end of the comparison SNe Ic, with an absolute V-band magnitude of -19.28 ± 0.48. It has a luminosity comparable to SN 2007ru and SN 2003jd but is much brighter than SN 2002ap.

To better understand the amount of energy released and other relevant parameters describing the explosion, we construct the quasi-bolometric light curve of SN 2012ap using the *BVRI* light curves presented in this paper. For this calculation, we used the normalized passband transmission curves given by Bessell (1990). The reddening-corrected magnitudes were converted to integrated fluxes in each filter by using the mean flux multiplied by the effective width of the passband. The missing data at some epochs were interpolated by using the neighboring measurements. According to the study of SN 2003jd by Valenti et al. (2008), the contribution of the U-band emission to the optical flux is about $\sim 15\%$ during the first week after the explosion and it decreases later to only 5%–10% .

In Figure 6, we compare the *BVRI* bolometric light curve of SN 2012ap with those of SN 1994I, SN 1998bw, SN 2002ap, SN 2003jd, SN 2004aw, SN 2007gr and SN 2007ru. The bolometric light curves of these SNe Ic were constructed in a manner similar to SN 2012ap. Of the SN Ic sample selected for comparison, SN 1998bw is the most luminous and exhibits the slowest post-maximum decline and SN 2012ap shows the second highest luminosity among our sample. Despite similar light curve shapes for our sample, they show a wide spread in peak luminosity. This perhaps indicates that SNe Ibc may not follow a width-luminosity relation as seen in SNe Ia (Phillips 1993). A similar conclusion was reached by Drout et al. (2011) based on the analysis of a larger SN Ibc sample.

5 FEATURES IN THE SPECTRUM OF SN 2012AP

Figure 3 shows the spectrum obtained on 2012 February 23.45 UT, which corresponds to a phase of about 7 d after the maximum light in B-band. In Figure 7, we compare the spectrum of SN 2012ap with those of SN 2002ap, SN 2004aw, SN 2007gr, SN 2007ru and SN 2009bb. As can be seen, the $t = +7$ d spectrum of 2012ap shows a close resemblance to that of the SN 2002ap and SN 2007ru at similar phases (see Fig. 7), with the main spectral features of Fe II, Si II, O I and Ca II lines being much broader than those of a normal SN Ic such as SN 2007gr. The expansion velocity of SN 2012ap is estimated to be 14 200 km s^{-1} and 11 800 km s^{-1}, respectively, by fitting a Gaussian profile to the blueshifted absorption minima of Si II 6355Å and O I 7774 Å. This large discrepancy is likely due to the low S/N ratio in our spectrum. Thus, we take an average of the measurements of these two line features in the calculation of kinetic energy analysis, which is 13 000±1200 km s^{-1}. This velocity is similar to that of BL SNe Ic but much larger than the normal SNe Ic (also see fig. 7 in Sahu et al. 2009). This confirms the classification of SN 2012ap as a member of the BL population.

We notice that there is an abnormal feature at 6500–7000 Å in the $t = +7$ d spectrum of SN 2012ap compared with other BL SNe Ic, with stronger flux emitted in this range of wavelengths where the comparisons are characteristic of a broad and shallow absorption trough, as shown in Figure 7. As we only have one spectrum for SN 2012ap, it is not clear whether this unusual feature is intrinsic to this supernova or just due to an error in data reduction. Another interesting feature in SN 2012ap is the absorption trough near 5873 Å, which seems to be a result of blending of the Na I D absorption from the Milky Way with that from the host galaxy. Closer inspection of the spectrum of SN 2012ap reveals that the minor absorptions at 5710 Å, 5780 Å, 6213 Å, 6284 Å, 6360 Å and 6450 Å might all be due to the corresponding diffuse interstellar bands (DIBs)[1] (Jenniskens & Desert 1994). These absorption features have been also identified by Milisavljevic et al. (2014). The detection of noticeable DIBs in the spectra of SN 2012ap implies that there is a significant amount of interstellar medium (gas and dust) along the line of sight, consistent with the large reddening inferred from the photometric data.

6 PARAMETERS DESCRIBING THE EXPLOSION

With the derived quasi-bolometric luminosity, we can estimate the synthesized ^{56}Ni mass which is one of the primary physical parameters determining the peak luminosity and the light curve width of SNe Ic. Assuming the Arnett law (Arnett 1982), with spherical homologous expansion, no nickel mixing and a constant optical opacity, the relationship between the mass of ^{56}Ni and the maximum luminosity can be written as (Nadyozhin 1994)

$$M_{\rm Ni} = L_{\rm max}/\left[1.45e^{-t_r/(111.3{\rm d})} + 6.45e^{-t_r/(8.8{\rm d})}\right], \tag{1}$$

[1] DIBs are absorption features thought to be associated with carbon-rich polyatomic molecules in interstellar gas and are usually observed in optical and near-infrared spectra of stars (Herbig 1995).

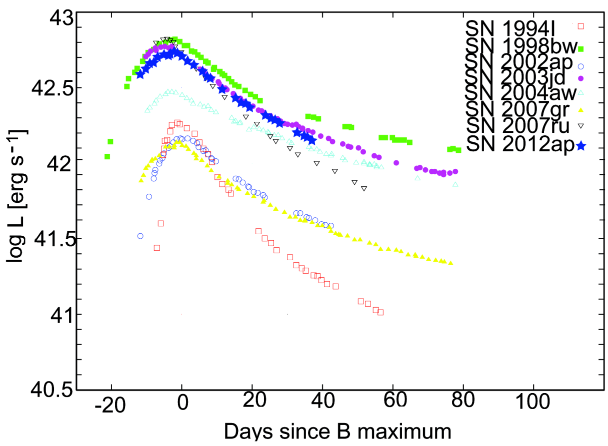

Fig. 6 Quasi-bolometric light curves of SN 2012ap compared with SN 1994I, SN 1998bw, SN 2002ap, SN 2003jd, SN 2004aw, SN 2007gr and SN 2007ru.

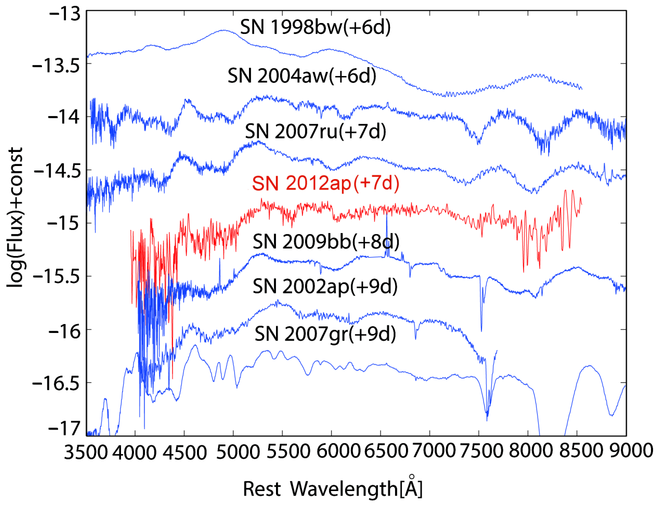

Fig. 7 Comparison of the $t = +7$ d spectrum of SN 2012ap with those of SN 1998bw, SN 2002ap, SN 2004aw, SN 2007ru, SN 2007gr and SN 2009bb at similar phases (see text for the references).

where t_r is the rise time of the bolometric light curve and $M_{\rm Ni}$ is the ^{56}Ni mass (in units of solar masses, $M_\odot$). SN 2012ap was not detected in a KAIT image taken on 2012 February 05.21 (~ 5 d before the discovery date) at a limit of ~ 18.7 mag (Jewett et al. 2012). Assuming an explosion date in the middle of this interval, we found a rise time to the maximum of 14.0 ± 2.5 d in the R band. With this value and the maximum bolometric luminosity, we derived a ^{56}Ni mass of $0.23 \pm 0.06 M_\odot$ for SN 2012ap. It should be noted that the contribution of the near-infrared (IR) emission is not included in calculating the bolometric light curve. The contribution from near-IR radiation to the bolometric flux is $\sim 30\%$ for SN 2002ap and SN 1998bw (Tomita et al. 2006;Valenti et al. 2008), but this contribution increases from $\sim 30\%$ to $\sim 45\%$ between +10 d and +30 d for SN 2004aw (Taubenberger et al. 2006). Assuming a near-IR contribution that is approximately the same as SN 2002ap and SN 1998bw, the mass of ^{56}Ni produced in SN 2012ap is estimated to be $0.30 \pm 0.08 M_{\odot}$.

We further estimated the mass ($M_{\rm ej}$) and the kinetic energy of the ejecta ($E_{\rm K}$) using the relationship established through the rise time of the light curve t_r and the ejecta velocity $v_{\rm ej}$ (Soderberg et al. 2008): $t_r = 0.36(\kappa^2 M_{\rm ej}^3/c^2 E_{\rm K})^{1/4}$ and $v_{\rm ej} = (10E_{\rm K}/3M_{\rm ej})^{1/2}(1 - 9.3E_{\rm K}\ t^2/\kappa M_{\rm ej}^2)$, where κ is the optical opacity and is usually assumed to be ∼0.05 (e.g., Soderberg et al. 2008). $v_{\rm ej}$ represents the expansion velocity at t days after the explosion, which is measured at $t \approx 16$ d (as we estimated the rise time in the R band as 14 days, 5 days later than in the B band, and this spectrum is obtained at 7 days after the B-band maximum), as about 13000±1200 km s^{-1} by averaging the results of Si II 6355 and O I 7774 absorption lines. Inputting these parameters, we derive $M_{\rm ej} = 2.4^{+0.7}_{-0.7} M_{\odot}$ and $E_{\rm K} = 1.1^{+0.4}_{-0.4} \times 10^{52}$ erg for SN 2012ap. The values of these two parameters are slightly larger than those of other BL SNe Ic (Drout et al. 2011), but closer to SN 2009bb (Pignata et al. 2011).

7 DISCUSSION AND CONCLUSIONS

In this paper, we present optical observations of BL type Ic SN 2012ap. This object bears close resemblance to BL SNe Ic, such as SN 2002ap and SN 2003jd with regard to the shape of the light curve, except that SN 2012ap is much redder in comparison. After corrections are made for the dust extinctions inferred from the $V - R$ color, SN 2012ap appears to be one of the most luminous SNe Ic ever observed, with an absolute V-band peak magnitude of -19.3±0.5.

The spectrum of SN 2012ap is similar overall to those of other BL SNe Ic at comparable phases, but it shows relatively narrower absorption features at 5710 Å, 5780 Å, 6213 Å, 6284 Å, 6360 Å and 6450 Å. These absorptions can be identified as DIBs, which are also reported by Milisavljevic et al. (2014) based on their multi-epoch spectra. Moreover, some of the absorptions showed variations in intensity over short timescales in a manner that suggests the interactions of an SN explosion with local carriers of DIBs. Therefore, the presence of noticeable DIBs in the vicinity of SN 2012ap suggests that its progenitor system likely underwent a significant mass loss before the explosion, favoring an origin from a massive star such as a Wolf-Rayet star or luminous blue variable (Le Bertre & Lequeux 1993). Moreover, strong DIBs are also signatures of large reddening along the line of sight (e.g., Phillips et al. 2013), which is consistent with the significant reddening inferred from the photometric method.

Based on the quasi-bolometric light curve constructed with our light curves, we further derived parameters describing the explosion of SN 2012ap, with nickel mass $M_{\rm Ni} = 0.30 \pm 0.08\ M_{\odot}$, ejected mass $M_{\rm ej} = 2.4^{+0.7}_{-0.7} M_{\odot}$ and kinetic energy $E_{\rm K} = 1.1^{+0.4}_{-0.4} \times 10^{52}$ erg. The kinetic energy obtained for SN 2012ap is an order of magnitude higher than that of normal SNe Ic, suggestive of an energetic explosion of a more massive star. The parameters of the explosion derived for SN 2012ap are very similar to those of SN 2009bb (Pignata et al. 2011) except that the latter have a slightly lower mass of ^{56}Ni (e.g., 0.22±0.06 $M_{\odot}$). Moreover, these two objects show remarkable DIB absorptions and have relativistic ejecta (Pignata et al. 2011; Milisavljevic et al. 2014) compared with other BL SNe Ic. Note that the metallicity is also found to be similar at the sites of these two SNe, e.g. oxygen abundance $\log{\rm (O/H)} + 12 = 8.8$ for SN 2012ap and 9.0±1.0 for SN 2009bb.

Although BL SNe Ic having relativistic ejecta show remarkable similarities to GRB events, the faint X-ray emission suggests that their explosions are still not strong enough to penetrate the stellar envelope to produce a jet breakout (Margutti et al. 2014). This is also consistent with the ejecta energy of BL SNe Ic like SN 2012ap still being lower than that of GRB-associated events. The difference between these two subclasses of SNe Ic could be due to the different properties of their progenitors. For example, BL SNe Ic with relativistic ejecta tend to have higher metallicity at the explosion site compared to those with GRBs (Modjaz 2012). At higher metallicity, massive stars lose more mass and produce stronger outflows than their lower-metallicity counterparts. Thus, detection of strong DIBs in the vicinity of the SN 2012ap-like SNe Ic is not unexpected, as they may have metal-rich progenitors. As suggested by Chakraborti et al. (2014), SN 2012ap may therefore represent a transition object linking normal BL SNe Ic to GRB-associated SNe Ic. This object further adds to the diversity of known SNe Ic, providing new clues to understand the supernova-GRB connection (see also Kelly et al. 2014).

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