The Carnegie Supernova Project II

Observations of SN 2014ab possibly revealing a 2010jl-like SN IIn with pre-existing dust^{★,★★}

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ABSTRACT

We present optical and near-infrared photometry and spectroscopy of the Type IIn supernova, (SN) 2014ab, obtained by the Carnegie Supernova Project II and initiated immediately after its optical discovery. We also study public mid-infrared photometry obtained by the Wide-field Infrared Survey Explorer satellite extending from 56 days prior to the optical discovery to over 1600 days. The light curve of SN 2014ab evolves slowly, while the spectra exhibit strong emission features produced from the interaction between rapidly expanding ejecta and dense circumstellar matter. The light curve and spectral properties are very similar to those of SN 2010jl. The estimated mass-loss rate of the progenitor of SN 2014ab is of the order of $0.1 M_{\odot} \text{ yr}^{-1}$ under the assumption of spherically symmetric circumstellar matter and steady mass loss. Although the mid-infrared luminosity increases due to emission from dust, which is characterized by a blackbody temperature close to the dust evaporation temperature ($\sim 2000 \text{ K}$), there were no clear signatures of in situ dust formation observed within the cold dense shell located behind the forward shock in SN 2014ab in the early phases. Mid-infrared emission of SN 2014ab may originate from pre-existing dust located within dense circumstellar matter that is heated by the SN shock or shock-driven radiation. Finally, for the benefit of the community, we also present five near-infrared spectra of SN 2010jl obtained between 450 to 1300 days post-discovery in the appendix.

Key words. supernovae: general – supernovae: individual: SN 2014ab – supernovae: individual: SN 2010jl – circumstellar matter

1. Introduction

A Type IIn supernova (SN) exhibits conspicuous, narrow Balmer lines in emission (Schlegel 1990) formed as a result of the interaction of rapidly expanding SN ejecta with circumstellar matter (CSM, e.g., Chugai & Danziger 1994). Progenitors of SNe IIn experience significant mass loss during their pre-SN evolution, leading to a local environment that contains dense CSM (e.g., Ofek et al. 2013, 2014a; Fraser et al. 2013). The

direct detection of SNe IIn progenitors in pre-explosion imaging (Gal-Yam & Leonard 2009; Prieto et al. 2008) and environmental studies around SNe IIn (Anderson et al. 2012; Habergham et al. 2014; Taddia et al. 2015; Galbany et al. 2018) reveals that a range of masses, including both relatively low-mass progenitors such as red supergiants and high-mass progenitors such as luminous blue variables, serve as the progenitors of SNe IIn.

SNe IIn exhibit a heterogeneous light-curve (LC) evolution (e.g., Nyholm et al. 2020; Taddia et al. 2013, 2015; Stritzinger et al. 2012; Kiewe et al. 2012). Some SNe IIn have long-lasting emission and their declines are well-fit by a single power-law (cf. SN 1988Z; Stathakis & Sadler 1991; Turatto et al. 1993). Others exhibit rapid, exponentially declining LCs (cf. SN 1998S; Fassia et al. 2000). Some SN IIn have slowly evolving, Gaussian-shaped LC peaks (cf. SN 2006gy; Smith et al. 2007), while other

* This paper includes data obtained with the 6.5 m *Magellan* Telescopes located at Las Campanas Observatory, Chile, and the ESO Paranal Very Large Telescope under ESO program 092.D-0645.

** Photometry and spectra presented in this paper are available on WISEREP.

SN IIn exhibit LCs with a plateau that is akin to SNe IIP (cf. SN 1994W; Sollerman et al. 1998). Several SNe IIn exhibit multiple luminosity peaks (Stritzinger et al. 2012; Nyholm et al. 2017) and some even have documented rise times in excess of 100 days (Miller et al. 2010; Moriya et al. 2019). This LC diversity largely originates from differences in the properties of the progenitors and CSM (Moriya et al. 2013a,b; Chatzopoulos et al. 2013; Ofek et al. 2014b; Dessart et al. 2016; Tsuna et al. 2019; Takei & Shigeyama 2020), compounded by viewing angle effects (e.g., Suzuki et al. 2019).

Another important characteristic of SNe IIn is that they often exhibit a number of observational properties linked to the presence of dust. The dust in SNe IIn is revealed by the infrared (IR) luminosity evolution (e.g., Fox et al. 2011, 2013; Szalai et al. 2019), as well as by the evolution of prominent emission features (e.g., Pozzo et al. 2004; Taddia et al. 2020). The dust in SNe IIn has been well-traced in SN 2010jl. SN 2010jl is a slowly-declining 1988Z-like object that exhibits a power-law luminosity decline at early times (Stoll et al. 2011; Zhang et al. 2012; Maeda et al. 2013; Fransson et al. 2014; Ofek et al. 2014c; Jencson et al. 2016). Although SN 2010jl was observed intensively over a range of wavelengths (Chandra et al. 2012, 2015; Williams & Fox 2015; Bevan et al. 2020), the origin of the dust traced by its IR observations is still a matter of debate. The dust might have formed within a cool dense shell located within the wake of the supernova shock wave which is positioned at the interface between the rapidly expanding supernova ejecta and the dense CSM (e.g., Smith et al. 2011; Gall et al. 2014; Maeda et al. 2013). Alternatively, the IR emission could be attributed to pre-existing dust located around the progenitor (Andrews et al. 2011; Fransson et al. 2014; Sarangi et al. 2018; Chugai 2018). The possibility that most IR emission observed in SNe IIn originates from pre-existing dust has also been proposed (e.g., Fox et al. 2011). To clarify the origin of dust in SNe IIn, more detailed observations of SNe IIn covering a wide wavelength range are required.

In this paper, we report on the observations of the long-lasting (1988Z-like) Type IIn SN 2014ab, initiated by the *Carnegie Supernova Project-II* (CSP-II; Phillips et al. 2019; Hsiao et al. 2019). Although this object spectroscopically resembles the well-observed SN 2010jl, it does exhibit different LC evolution and dust signatures. SN 2014ab offers a new and important clue on the nature of slowly-declining SNe IIn, including details about the dust in their nearby environment.

2. SN 2014ab: discovery, distance, and reddening

The Catalina Real-time Transient Survey (CRTS) reported the discovery of a transient with an apparent magnitude of 16.4 in MCG +01-35-037 (Howerton et al. 2014). First designated PSN J13480599+0723164 when it was posted to the web page of the Central Bureau for Astronomical Telegrams, the transient was identified by CRTS in an image taken by the Catalina Sky Survey (CSS) on March 9.43 UT (i.e., JD-2456725.93). With coordinates RA (J2000.0) = 13h48m05s.99 and Dec (J2000.0) = +07°23'16".40, the transient (aka SNhunt237) is located 1'5 north of the host galaxy (see Fig. 1).

Within 24 h of the discovery (Mar. 10.25 UT), the CSP-II obtained a near-IR (NIR) spectrum with the Folded-port Infrared Echellette (FIRE; Simcoe et al. 2013) spectrograph attached to the *Magellan* Baade 6.5 m Telescope located at Las Campanas Observatory (LCO). This spectrum revealed an SN IIn and upon the reporting of its spectral classification, the transient obtained the International Astronomical Union (IAU) designation of

Fig. 1. Finding chart constructed using a single *r*-band image obtained on 03 March 2014 with the Swope 1.0 m telescope. The position of SN 2014ab is indicated with a dotted circle and the approximate area contained within the circle is shown in the upper right inset. Optical and NIR local sequence stars are indicated with yellow and red circles, respectively.

SN 2014ab. The CSP-II classification was promptly confirmed by PESSTO (Public ESO Spectroscopic Survey for Transient Objects; Smartt et al. 2015) based on a visual-wavelength spectrum obtained with the New Technology Telescope (+ EFOSC; Buzzoni et al. 1984), located at the ESO La Silla Paranal Observatory (Fraser et al. 2014).

According to the NASA Extragalactic Database (NED), the host-galaxy MCG +01-35-037 has a redshift $z = 0.02352$. Turning to the medium-dispersion spectra of SN 2014ab, obtained with the ESO La Silla Paranal Observatory's Very Large Telescope (VLT) equipped with the X-shooter (see below), we obtain an averaged redshift of $z = 0.02262 \pm 0.00001$ from the narrow H α emission component in the three spectra. Adopting $H_0 = 73.2 \pm 2.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Burns et al. 2018), $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$, this corresponds to a luminosity distance of $94.3 \pm 6.6 \text{ Mpc}$, or a distance modulus $\mu = 34.87 \pm 0.15 \text{ mag}$.

According to Schlafly & Finkbeiner (2011) and reported in NED¹, the Milky Way visual-band extinction in the direction of SN 2014ab is $A_V^{MW} = 0.083 \text{ mag}$. This value is inferred from infrared-based dust maps and assumes a Fitzpatrick (1999) reddening law with $R_V = 3.1$.

An inspection of the visual-wavelength spectra of SN 2014ab presented below reveals no Na I D features at the redshift of the host galaxy and there is no evidence of the 5780 Å diffuse interstellar band. We assume, therefore, in the following that SN 2014ab suffers from minimal to no host-galaxy reddening.

3. Observations

3.1. WISE mid-infrared photometry

We include ten epochs of two-channel mid-IR (MIR) imaging of SN 2014ab serendipitously obtained by the Wide-field Infrared Survey Explorer (WISE) satellite (Wright et al. 2010;

¹ <https://ned.ipac.caltech.edu/>

Table 1. Journal of spectroscopic observations of SN 2014ab.

Date (UT)	JD-2 456 000 (days)	Phase ^(a) (days)	Telescope	Instrument	Range (Å)
10 Mar 2014	726.75	53.9	Baade	FIRE	8095–24 810
10 Mar 2014	726.81	54.0	NTT	EFOSC	3670–9260
18 Mar 2014	734.79	61.8	Baade	FIRE	8095–24 810
23 Mar 2014	739.73	66.6	VLT	X-shooter	3050–24 790
25 Mar 2014	741.80	68.7	Baade	FIRE	8095–24 810
23 Apr 2014	770.74	97.0	Baade	FIRE	8095–24 810
24 Apr 2014	771.66	97.9	VLT	X-shooter	3050–24 790
07 May 2014	784.72	110.6	du Pont	WFCCD	3630–9200
24 Jun 2014	832.54	157.4	VLT	X-shooter	3050–24 790
29 Jun 2014	838.48	163.2	VLT	X-shooter	3050–24 790
19 Jul 2014	858.48	182.7	VLT	X-shooter	3050–24 790

Notes. ^(a)Rest-frame days relative to the first WISE detection.

Mainzer et al. 2014), and downloaded from NASA/IPAC Infrared Science Archive². Photometry retrieved from the archive includes *W1*-band measurements at $3.4\mu\text{m}$ and *W2*-band measurements at $4.6\mu\text{m}$. This photometry was previously presented by Jiang et al. (2019). The first detection by WISE is at JD 2456671.59, which is 56 days before the optical discovery at JD 2456725.93 in the observer frame. The WISE photometry is listed in Table A.1.

3.2. Carnegie Supernova Project-II observations of SN 2014ab

The CSP-II obtained broad-band optical and NIR imaging with facilities located at LCO. In particular, twenty-two epochs of optical (*ugriBV*) imaging was taken with the Henrietta Swope 1.0 m telescope equipped with a direct optical camera containing an e2V CCD, while five epochs of NIR images were taken with the Irénée du Pont 2.5 m telescope equipped with RetroCam (Hamuy et al. 2006). The *ugriBV*-band photometry extends, relative to the first WISE detection, from +56 d to +485 d, with a significant gap between +140 d to +360 d when SN 2014ab was located behind the Sun. The NIR photometry is more limited in coverage, ranging between +56 d to +121 d. All dates presented here are in the observer frame.

The CSP-II data were reduced to photometry following standard prescriptions that are well documented in Krisciunas et al. (2017, and references therein). Prior to computing the photometry of the SN from each science image, deep optical and NIR templates of the host were obtained with the du Pont telescope equipped with a direct CCD camera and with the *Magellan Baade* telescope equipped with the NIR imager FourStar (Persson et al. 2013).

PSF photometry of SN 2014ab was computed from the template-subtracted science images and its instrumental magnitudes were calibrated relative to a local sequence of stars located in the field of the host. The optical local sequence consists of twenty-three stars and the NIR local sequence consists of six stars. The optical local sequence was calibrated relative to standard star fields observed over a minimum of three photometric nights, while the NIR sequence were calibrated relative to Persson et al. (1998) (*JH* band) and Krisciunas et al. (2017) (*Y* band) standard star fields observed over four and three pho-

tometric nights, respectively. Optical and NIR photometry of the local sequence stars in the “standard” photometric systems are listed in Table A.2 and Table A.3, respectively. Finally, the optical and NIR photometry of SN 2014ab in the natural system are listed in Table A.4.

The CSP-II obtained a single visual-wavelength spectrum of SN 2014ab with the du Pont telescope equipped with Wide Field Re-imaging CCD Camera (WFCCD) and four epochs of NIR spectra with the *Magellan Baade* telescope equipped with the FIRE spectrograph. In addition to these data, we obtained optical/NIR spectra from the VLT (+ X-shooter, Vernet et al. 2011; Program ID: 092.D-0645, PI Gall), along with a single NTT (+ EFOSC) spectrum reported by PESSTO. A journal of the spectroscopic observations is provided in Table 1. The X-shooter data were obtained in nodding (ABBA) mode and underwent basic reduction steps in “stare” mode for the UVB and VIS arms and “nodding” mode for the NIR arm using the EsoReflex workflow (Freudling et al. 2013). The UVB and VIS single-stare frames were combined using custom python scripts³ (Selsing et al. 2019) and optically extracted, slit loss corrected, and corrected for heliocentric velocity using a custom IDL programs. The telluric correction was performed by using Molecfit (Smette et al. 2015; Kausch et al. 2015). The other spectroscopic data were reduced following standard procedures as previously described by Hamuy et al. (2006) (optical) for and Hsiao et al. (2019) (NIR). Finally, the flux scale of each of the one-dimensional, visual-wavelength spectra were adjusted such that their synthetic colors match the more accurate broad-band colors computed from photometry (see, e.g., Boldt et al. 2014).

In addition to the spectra of SN 2014ab, we also present CSP-II spectra of SN 2010jl in Appendix B. As demonstrated below, SN 2014ab shares some common features with SN 2010jl. These spectra were reduced following the same manner as applied to the data of SN 2014ab.

4. Results

4.1. Photometry and *B–V* color-curve evolution

Plotted in Fig. 2 are the two-channel MIR LCs computed from WISE observations covering over 1600 days of evolution. The object reached a maximum between 200 and 400 days post-detection, followed by a slow decline ($\sim 0.0015\text{ mag day}^{-1}$) over

² <https://irsa.ipac.caltech.edu/>

³ <https://github.com/jselsing/xsh-postproc>

Fig. 2. Mid-infrared light curves of SN 2014ab obtained with the WISE satellite. The open symbols show the raw data and the filled symbols show co-added magnitudes of the nearby epochs. We also present the photometry of KISS15s, which is another SN IIn with serendipitous WISE observations (Kokubo et al. 2019). The KISS15s photometry is plotted with the right and top axes. The time origin in KISS15s is its optical discovery.

the next 1200 days. The object appears to have reached a *W1*-band peak brightness of ≤ -22.5 mag and the *W2*-band reached a peak of ≤ -23 mag.

The CSP-II optical and NIR LCs of SN 2014ab are plotted in Fig. 3. The optical photometry extends from +56 d to +485 d relative to the first WISE detection in the observer frame, while the NIR photometry extends between +56 d to +121 d. The photometry shown in the figure has been corrected for Galactic reddening, and placed on the absolute magnitude scaling adopting the distance computed in Sect. 2. The optical LCs at the time of discovery range from -17.5 mag to -19 mag, while the NIR absolute magnitudes reach around -20 mag. In the initial phases of our follow-up, the optical/NIR LCs slowly evolve until +123 d when follow-up ceased for ~ 200 days. For example, the *g*-band LC declines 0.36 mag per 100 days. Follow-up then continued at around +350 d and extended until around +480 d. During this time the *g*-band LC decline rate was 1.4 mag per 100 days.

Figure 4 presents the *B* – *V* color evolution of SN 2014ab and other representative SNe IIn. SN 2014ab has little color evolution during our observations lasting for about 100 days. A lack of significant color evolution appears to be a hallmark of other slowly declining SNe IIn such as SN 1988Z and SN 2010jl. In particular, the color-curve evolution of SN 2010jl is very much like that of SN 2014ab. As discussed later, the spectra of SN 2014ab are also very similar to those of SN 2010jl.

4.2. Spectral energy distributions and the UVOIR light curve

Here, we use the broad-band optical through MIR photometry of SN 2014ab to construct spectral energy distributions (SEDs) for each observed epoch. These are then fit with black-body (BB) functions in order to estimate the BB temperature (T_{BB}), BB radius (R_{BB}), and BB luminosity (L_{BB}) profiles associated with the underlying emission region(s).

Plotted in Fig. 5, we present the SEDs of SN 2014ab, extending from +56 d to +485 d relative to the first WISE detection.

To build these SEDs, first the photometry at each epoch was corrected for reddening and then each optical and NIR point was placed on the AB system using the AB offsets given in Krisciunas et al. (2017); see their Table 16. Then each photometric point was converted to flux following Eq. (F5) of Krisciunas et al. (2017). If there were gaps in the optical or NIR coverage at any particular epoch, they were estimated from neighboring photometry through the use of linear interpolation. The WISE photometry, which is given in the Vega system, was converted to flux using the flux zero points given in Wright et al. (2010).

Next, each SED was fit with a BB function. When we compute the best-fit BB functions to the SEDs, the *u*- and *r*-band flux points were excluded because they are affected by significant line blanketing and the strong *H α* emission line, respectively (Sect. 4.3). We find that the obtained BB fit matches well to the continuum of the spectra when available. The BB temperature at the early epochs is around 8000 K. An inspection of Fig. 5 reveals that from the +360 d SED and onwards, an excess of MIR flux is present relative to expectations of a single BB function fit (blue dashed line). We therefore fit the SEDs extending from +360 d to +484 d with an additional BB-function component, which is plotted as red dashed line, while the combined BB functions are overplotted in magenta. We refer to the first hot BB component as BB_{hot} and the second warm BB component as BB_{warm} . BB_{hot} remains around 8000 K, although the uncertainty is large at the late epochs. We cannot tell if BB_{warm} is affected by the presence of emission lines in the MIR bands because we lack MIR spectra. We therefore turn to the MIR spectra of the intermediate-luminosity-red-transient NGC 300-2008-OT, which were obtained around 400 days and 600 days (Ohsawa et al. 2010). This gap transient is thought to have been powered by circumstellar interaction (Bond et al. 2009; Berger et al. 2009). These spectra reveal no prevalent emission features. The BB_{warm} component fit to the MIR flux points of SN 2014ab suggests $T_{\text{BB}}^{\text{warm}} \sim 2000$ K, which is similar to the value inferred for SN 2010jl (1500–2000 K, Fransson et al. 2014). We note that $T_{\text{BB}}^{\text{warm}}$ is mostly constrained by the two MIR photometric bands. We also tried BB fits by forcing $T_{\text{BB}}^{\text{warm}} = 1000$ K and found that the BB fit significantly overestimates the *W2* photometry. Therefore, $T_{\text{BB}}^{\text{warm}}$ would not be far from 2000 K (≈ 1500 –2000 K) and is close to the dust evaporation temperature.

Next, by integrating the BB function fits we obtain the UVOIR LC of SN 2014ab as plotted in the top panel of Fig. 6. Specifically, we plot $L_{\text{BB}}^{\text{hot}}$ (blue), $L_{\text{BB}}^{\text{warm}}$ (red) and the summation of the two (black). We find that on +56 d, SN 2014ab reached $L_{\text{BB}}^{\text{tot}} \approx 1.0 \times 10^{43} \text{ erg s}^{-1}$, and by +360 d this dropped by an order of magnitude. Furthermore, we find that at +360 d that the $L_{\text{BB}}^{\text{warm}}$ dominates over the emission of $L_{\text{BB}}^{\text{hot}}$ by a factor of ~ 3 and this increases to a factor of ~ 5 by +485 d. Comparison of the $T_{\text{BB}}^{\text{warm}}$ and $T_{\text{BB}}^{\text{hot}}$ values reveals that the former characterized by $T_{\text{BB}}^{\text{warm}} \sim 2000$ K is around a factor of ~ 4 lower than the latter over the duration covered by our late phase data. Over the same time, $R_{\text{BB}}^{\text{warm}}$ is found to be around a factor of ~ 6 higher than $R_{\text{BB}}^{\text{hot}}$. These attributes suggest that the emission of the BB_{warm} component is related to dust reprocessing of shorter wavelength photons to longer wavelength photons.

The radiated energy from +56 d to +140 d in Fig. 6 is $6.5 \times 10^{49} \text{ erg}$ and that from +360 d to +455 d is $6.2 \times 10^{48} \text{ erg}$. The total radiated energy during our observation is therefore $7 \times 10^{49} \text{ erg}$. Because of the limited LC coverage of our observation, the actual radiated energy should be much larger than $7 \times 10^{49} \text{ erg}$.

Fig. 3. Multi-color, optical (*ugriBV*) and NIR (*YJH*) light curves of SN 2014ab obtained by the CSP-II. The data have been corrected for Galactic extinction. Vertical lines indicate epochs that optical (green), NIR (red), or optical+NIR (blue) spectroscopic observations were obtained.

Fig. 4. Observed $B - V$ color curve of SN 2014ab compared with those of three different SNe IIn subtypes. The reddening is corrected based on the values reported in the literature. The explosion date, i.e., day zero, for SN 2014ab is arbitrarily set to be 100 days before the optical discovery, or 46 days before the WISE first detection in the rest frame. The comparison sample including objects of the slowly-declining 1988Z-like subtype (solid lines) including SN 2010jl (Fransson et al. 2014), SN 2006tf (Smith et al. 2008), and SN 1988Z (Turatto et al. 1993), as well as the 1994W-like plateau subtype (dashed lines) including SN 1994W (Sollerman et al. 1998), SN 2009kn (Kankare et al. 2012), and SN 2011ht (Mauerhan et al. 2013), and finally, the prototypical rapidly-declining SN 1998S (dot-dashed line, Fassia et al. 2000).

The bolometric luminosity we presented is obtained by fitting BB functions to the SEDs from photometry. When we have both spectra and photometry, we compare the results of the BB fits from spectra and photometry. We found that the uncertainty from our use of the photometry to fit the BB function is up to 10%. The systematic uncertainty caused by the use of the two BB functions to fit the SEDs is, however, uncertain.

4.3. Spectroscopy

Plotted in Fig. 7, we present our visual-wavelength and NIR spectra of SN 2014ab extending from +54 d to +183 d, relative to the first WISE detection in the rest frame. The spectra are dominated by narrow emission lines, justifying a SN IIn classification.

Figure 8 shows the temporal evolution of prevalent hydrogen emission-line profiles. The hydrogen emission-line profiles exhibit little evolution over the first 120 days of spectroscopic observations. The broad component matches the Lorentzian function with a full-width half maximum (FWHM) velocity of 3500 km s^{-1} . This Lorentzian line profile is formed by the multiple electron scattering in the optically thick CSM (e.g., Chugai 2001, but see also Huang & Chevalier 2018). In superposing the broad component, we find a narrow emission component as shown in the top panel of Fig. 8. The peak of the narrow $H\alpha$ component in the X-shooter spectra match well and are used to determine the redshift of SN 2014ab ($z = 0.02262 \pm 0.00001$). The difference between the host galaxy redshift ($z = 0.02352$) and the SN redshift ($z = 0.02262$) corresponds to the line-of-sight velocity difference of 270 km s^{-1} . The difference may originate from the host galaxy's rotation and is within the normal distribution of radial velocity of SN host galaxies (Galbany et al. 2018). We can also see a tentative absorption component in the narrow $H\alpha$ lines with a minimum at -80 km s^{-1} . This feature could be produced from an unshocked wind with a characteristic velocity of 80 km s^{-1} . Such an absorption with the minimum velocity of around 100 km s^{-1} is often observed in SNe IIn (e.g., Taddia et al. 2013). The peak of the broad component is shifted by -500 km s^{-1} .

The broad emission lines show little evolution during our spectroscopic observations (Fig. 8). The emission-line luminosities of the representative Balmer lines are $\approx 7 \times 10^{41} \text{ erg s}^{-1}$ ($H\alpha$) and $\approx 2 \times 10^{41} \text{ erg s}^{-1}$ ($H\beta$). The flux ratio of $H\alpha$ to $H\beta$ is ≈ 4 , and is similar to that of SN 2010jl at around 100 days after the estimated explosion date (Fransson et al. 2014). Similarly, the emission line luminosities of the representative Paschen lines are $\approx 2 \times 10^{41} \text{ erg s}^{-1}$ ($Pa\alpha$) and $\approx 9 \times 10^{40} \text{ erg s}^{-1}$ ($Pa\beta$). The

Fig. 5. Spectral energy distributions (SEDs) of SN 2014ab. The first 16 quadrants from the top contain SEDs constructed from flux points covering optical, NIR, and MIR wavelengths and extend from +56 d to +140 d relative to the time of first WISE detection. Each of these SEDs are fit with a single black body (BB) function, where the optical flux is dominating. We excluded *u* and *r* band from the fit due to line blanketing and the strong $H\alpha$ emission line, respectively. The SEDs plotted in the other quadrants are constructed from optical and MIR flux points and extend from +360 d to +485 d relative to first WISE detection. The late-phase SEDs clearly exhibit an excess of flux relative to a single BB fit to the optical flux points. We therefore fit the late SEDs with a two-component BB function. In the last quadrant the optical BB fit is not reliable as only *g* and *i* are available.

luminosity of $\text{Pa}\alpha$ is difficult to measure because of the strong telluric absorption and we therefore measure it by using the +97 d spectrum which has a better telluric correction.

5. Discussion

5.1. Comparison of SN 2014ab to other SNe IIn

We now compare SN 2014ab with other SNe IIn. The explosion date of SN 2014ab is not well-constrained. Here, we arbitrarily assume that the explosion date is 100 days before the optical discovery in the rest frame which is 46 days before the first WISE detection. With this assumption on the explosion date, the LC of SN 2014ab matches that of SN 2010jl well, which is shown to be very similar to SN 2014ab later. Figure 9 presents the LC comparison. In the first 200 days, the LC of SN 2014ab declines slowly and it resembles slowly declining SNe IIn such as SN 1988Z and SN 2010jl. SN 2014ab is significantly brighter than SN 1988Z and it is slightly fainter than SN 2010jl. The optical LC of SN 2014ab is found to be similar to that of KISS15s in the early phases (Kokubo et al. 2019). However, their MIR LCs have different properties (Fig. 2). Specifically, the MIR luminosity of KISS15s rises gradually for 700 days, while in the case of SN 2014ab, the MIR luminosity increases suddenly at around +300 d and subsequently gradually declines.

One important characteristic that makes SN 2014ab distinct from other slowly declining SNe IIn is the optical luminosity drop that occurred between +200 d and +400 d (Fig. 9). The optical LCs of slowly evolving SNe IIn sometimes start to decline rapidly from several hundred days after the explosion. The optical LC drop displayed by SN 2014ab is the most abrupt among

slowly declining SNe IIn. The change in the optical LC decline rate in slowly-declining SNe IIn is often accompanied by an IR luminosity increase. Indeed, the sudden optical luminosity decline in SN 2014ab follows after an increase in luminosity at MIR wavelengths.

Figure 10 shows the spectral comparison of SN 2014ab with different SNe IIn subtypes. This includes the slowly declining 1988Z-like Type IIn SN 2010jl, the rapidly declining Type IIn SN 1998S and, finally, the 1994W-like Type IIn SN 2009kn with its LC akin to normal SNe IIP. The spectrum of SN 2010jl closely resembles that of SN 2014ab, with both SNe having a very similar shape of their continua and the same spectral features. Furthermore, the hydrogen-line flux ratios measured from the spectra of both objects are nearly identical. Comparison of the spectra of these two objects with that of SN 2009kn reveals that the latter has much narrower emission-line features. Finally, the spectrum of SN 1998S is quite distinct from that of SN 2014ab. The spectral comparison also confirms that SN 2014ab is a member of the slowly declining, 1988Z-like subclass of SNe IIn.

Inspection of the emission-lines associated with $H\alpha$ and the other hydrogen lines in SN 2014ab have the centroid of the broad emission line blue-shifted by 500 km s^{-1} as shown in Fig. 8. A similar blue-shift of the order of 100 km s^{-1} in the emission peak is also found in SN 2010jl, although the shift velocity is time-dependent (Gall et al. 2014; Fransson et al. 2014). In the case of SN 2014ab, we do not find the time dependent shift of the peak of the broad component as in SN 2010jl. In addition, we do not find the bluer emission peaks in bluer emission lines as observed in SN 2010jl. Indeed, the shape of the hydrogen emission lines in the spectra of SN 2014ab do not strongly depend on either emission wavelengths or time (Fig. 11).

Fig. 6. Bolometric LC (*top*) and the BB-temperature (*middle*) and BB-radius (*bottom*) profiles of SN 2014ab, computed from fitting single and double BB functions to the SEDs of SN 2014ab.

An interesting difference found between the spectra of SN 2014ab and SN 2010jl is in the blended emission line of the O I $\lambda 8446$ and Ca II NIR triplet $\lambda\lambda 8498, 8542, 8662$ features. These lines appear to be brighter in SN 2014ab than in SN 2010jl. The Ca II NIR triplet is likely produced within the cold dense shell where the hydrogen emission lines also originate (e.g., Dessart et al. 2016). Since the strength of the hydrogen emission lines are similar in SN 2014ab and SN 2010jl, the difference in the emission strength found here is presumably due to the O I line rather than the Ca II NIR triplet. Indeed, the emission peak is bluer in SN 2014ab. Since the emission from the inner SN ejecta is hidden by the electron scattering and no other O I lines are observed, the O I $\lambda 8446$ emission is likely to be excited by Ly β fluorescence (Bowen 1947; Bhatia & Kastner 1995; Kastner & Bhatia 1995).

5.2. Luminosity evolution

As we have discussed so far, SN 2014ab is similar to SN 2010jl in many respects. Figure 12 shows a comparison between the bolometric LCs of SN 2014ab and SN 2010jl. The bolometric LC of SN 2014ab is obtained by integrating the two blackbody components shown in Sect. 4.2 and the bolometric LC of SN 2010jl is obtained by integrating the photometry in optical (3400–9000 Å) and NIR (9000–24 000 Å) as given in Fransson et al. (2014). We assumed that the explosion date of SN 2014ab is 100 days before the optical discovery, which provides a good match to the bolometric LC of SN 2010jl. The explosion date, however, is uncertain. Under this assumption, the bolometric LC can be fit with the same power-law function as in SN 2010jl with a different scaling factor (Fransson et al. 2014):

$$L = 1.2 \times 10^{44} \left(\frac{t}{1 \text{ day}} \right)^{-0.54} \text{ erg s}^{-1}, \quad (1)$$

which is plotted in Fig. 12.

Assuming that the mass loss from the progenitor is steady, the CSM density structure can be expressed as

$$\rho_{\text{CSM}}(r) = \frac{\dot{M}}{4\pi V_{\text{wind}}} r^{-2}, \quad (2)$$

where $\dot{M}$ is the mass-loss rate and V_{wind} is the wind velocity. The bolometric luminosity from the shock interaction with the shock velocity of V_{shock} can be expressed as

$$L = \frac{\epsilon}{2} \frac{\dot{M}}{V_{\text{wind}}} V_{\text{shock}}^3, \quad (3)$$

where ϵ is the conversion efficiency from kinetic energy to radiation energy (e.g., Moriya et al. 2013a). The mass-loss rate, therefore, can be estimated as

$$\dot{M} = 0.3 \left(\frac{\epsilon}{0.3} \right)^{-1} \left(\frac{L}{10^{43} \text{ erg s}^{-1}} \right) \left(\frac{V_{\text{shock}}}{3000 \text{ km s}^{-1}} \right)^{-3} \frac{V_{\text{wind}}}{80 \text{ km s}^{-1}} M_{\odot} \text{ yr}^{-1}. \quad (4)$$

The bolometric luminosity of SN 2014ab is around $10^{43} \text{ erg s}^{-1}$ at around 100–200 days (Fig. 12). Although V_{shock} is not constrained in SN 2014ab, well-observed SNe IIn including SN 2010jl (Fransson et al. 2014) and SN 2013L (Taddia et al. 2020) typically show $V_{\text{shock}} \approx 3000 \text{ km s}^{-1}$. The conversion efficiency, ϵ , is another uncertain parameter. Numerical simulations often indicate that this parameter is on the order of 0.1 (van Marle et al. 2010; Moriya et al. 2013b). It has also been suggested to be time dependent (Tsunai et al. 2019; Takei & Shigeyama 2020). For simplicity, we assume that ϵ is constant and adopt the value $\epsilon \approx 0.3$, which is on the order of 0.1. These assumptions are reasonable enough for our order-of-magnitude estimate. Assuming the wind velocity estimated obtained from the narrow H α P Cygni profile ($\approx 80 \text{ km s}^{-1}$, Sect. 4.3), Eq. (4) then implies a mass-loss rate of SN 2014ab's progenitor of $0.3 M_{\odot} \text{ yr}^{-1}$. This estimated mass-loss rate is similar to that found by Fransson et al. (2014) for SN 2010jl ($\sim 0.1 M_{\odot} \text{ yr}^{-1}$). We note that the mass-loss rate estimated here should be regarded as a very rough estimate, given the uncertain shock velocity information and ϵ . It is an order-of-magnitude estimate.

A significant difference between SN 2014ab and SN 2010jl appears at the late phases beginning around 400 days after explosion. The bolometric luminosity (hot + warm in Fig. 12) of SN 2014ab decreases by a factor of ≈ 7 during the gap in observations between 200 and 400 days, while over the same period, the bolometric luminosity (optical + NIR in Fig. 12) of SN 2010jl decreases by a factor of ≈ 1.5 . One possible reason for this discrepancy could be due to differences in the structure of their CSM. Because the interaction luminosity is proportional to $\dot{M}$ (Eq. (4)), the luminosity decrease by a factor of 0.15 corresponds to the $\dot{M}$ decrease by a factor of 0.15. Thus, the mass-loss rate of the progenitor of SN 2014ab may have been around $10^{-2} M_{\odot} \text{ yr}^{-1}$ and increased to the order of $0.1 M_{\odot} \text{ yr}^{-1}$ shortly before the explosion, while the progenitor of SN 2010jl maintained the large mass-loss rate for a longer time. The difference in the mass-loss timescale may originate from the difference in the progenitor mass. The duration of extensive mass loss induced by pulsational pair-instability SNe, for example, strongly depends on the progenitor mass (e.g., Woosley 2017).

Fig. 7. Optical through NIR wavelength spectroscopy of SN 2014ab, extending from +54 d to 183 d (restframe days) past the first WISE detection. The numbers in the parentheses indicate the flux offset adopted for the spectra in the unit of $10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$. The shaded wavelength regions indicate areas of strong telluric absorption. The last three spectra are not calibrated by photometry because of the lack in the photometric information.

We note that the late-phase bolometric luminosity decline is consistent with the nuclear decay rate of ^{56}Co (Fig. 12). However, the required initial ^{56}Ni mass to account for the late-phase luminosity is $3 M_{\odot}$. If the ejecta have such a large amount of ^{56}Ni , it is likely to have an impact on the LC in the early phase because the total luminosity from the nuclear decay is larger than the observed luminosity over the entire early phase (Fig. 12). We also note that we cannot rule out the possibility that the majority of the radioactive energy in the ejecta is thermalized and diffused with a long diffusion time to avoid the early effect on the luminosity. In such a case, however, the diffusion time in the ejecta needs to be more than 200 days following “Arnett’s rule” (Arnett 1982), which would require an extremely large ejecta mass. It may be argued that the NIR luminosity originates from light echoes and only the optical (hot) component should be regarded as the true bolometric luminosity. If this is the case, the initial ^{56}Ni mass required to account for the luminosity becomes $0.8 M_{\odot}$ (Fig. 12) and it does not affect the early luminosity much. However, this amount of ^{56}Ni is still much larger than would normally be synthesized in SNe (Anderson 2019; Meza & Anderson 2020).

Finally, we assumed that the dense CSM is spherically symmetric and comes from steady wind when analyzing the bolometric LC and deriving the mass-loss rate in this section. While we do not have clues on the CSM geometry in SN 2014ab, the dense CSM around SN 2010jl is likely to be aspherical (e.g., Patat et al. 2011). We do not know whether or not if the mass loss is eruptive (cf. Moriya et al. 2014). Despite of the possible asphericity and non-steady mass loss, Fransson et al. (2014) estimate the mass-loss rate for SN 2010jl by assuming the spherical symmetry and steady mass loss for simplicity as we have done in this section. Thus, the estimated mass-loss rate of $\sim 0.3 M_{\odot} \text{ yr}^{-1}$ should be, again, regarded as a rough estimate.

5.3. Origin of dust

Although SN 2014ab and SN 2010jl share many common characteristics, one big difference is in the signatures of dust. The IR excess indicates the existence of warm dust in both cases. However, while the peak of the broad emission lines observed in

SN 2010jl shifts towards shorter wavelengths over time (Smith et al. 2011; Gall et al. 2014; Fransson et al. 2014), this is not the case in SN 2014ab (Fig. 8). A shift of the broad emission peak to shorter (bluer) wavelengths is a signature of ongoing dust formation (cf. Kozasa et al. 2009). The peak of the broad hydrogen emission lines in SN 2010jl also shows the wavelength dependence expected from the dust absorption, that is, the peak of the emission lines with shorter wavelengths shifts more to the blue (Maeda et al. 2013; Gall et al. 2014). As demonstrated in Fig. 11, this phenomenon is not observed in SN 2014ab. The overall blue-shift of the broad emission lines can be explained by the acceleration of the unshocked CSM by precursor photons as suggested by Fransson et al. (2014) for SN 2010jl (see also Moriya et al. 2011; Chevalier & Irwin 2011). It has also been suggested that blue-shift is affected by the radiation transfer effect in addition to the pre-shock acceleration (Dessart et al. 2015). SN 2014ab can be a good object to investigate the blue-shift caused by the hydrodynamic and radiation transfer effects because it may be less affected by dust as we discuss below.

The fact that we do not see clear observational signatures of ongoing dust formation in SN 2014ab may indicate that the dust found to be associated with it is not formed within the cool, dense shell where the emission lines are formed during our early-phase observations. The BB_{warm} component does not exist at early phases. At late phases with T_{warm}^{BB} estimated to be $\sim 2000 \text{ K}$, we find that this temperature is too high to originate from the inner SN ejecta located below the cold dense shell (e.g., Wooden et al. 1993; Nozawa et al. 2003). Indeed, $T_{\text{warm}}^{BB} \sim 2000 \text{ K}$ is close to the dust evaporation temperature. Therefore, the pre-existing dust in the dense CSM may be heated by the SN shock or radiation, which drives an increase in the MIR luminosity (Fox et al. 2010). Interestingly, the MIR luminosity keeps decreasing after the sudden MIR luminosity increase that occurs between 200 days and 300 days (Fig. 2). In the case of KISS15s, shown in the same figure, the MIR luminosity keeps increasing with the increasing mass of the presumably newly formed dust. Although we cannot rule out the possibility that dust is newly formed in the late phases, the MIR luminosity decline in SN 2014ab is probably indicative of little to no ongoing dust formation. The decline in the MIR luminosity could be explained by the destruction of

Fig. 8. Time-evolution of the narrow- (*top panel*) and broad-component (*middle panel*) H α profiles, and the broad-component (*bottom panel*) of the Pa- β profile, plotted in velocity space. Over-plotted as dashed cyan lines are Lorentzian functions with the FWHM velocity of 3500 km s^{-1} and the peak shifted by -500 km s^{-1} . The redshift is determined by the average of the narrow emission peak. Both broad components are overall symmetric and do not exhibit significant evolution over the duration of our followup observations.

the pre-existing dust by the SN shock wave as the ejecta expands over time.

In summary, dust formation in SN 2014ab appears to be inefficient and the observed emission seems to be associated with pre-existing dust formed in the dense CSM prior to the final demise of the progenitor star. SN 2014ab indicates that the ori-

Fig. 9. Absolute V-band LC of SN 2014ab compared with well-observed examples of the three subtypes of SN IIn discussed by Taddia et al. (2013). This includes the long-lasting 1988Z-like objects (circles) SN 1988Z (Turatto et al. 1993), SN 2006tf (Smith et al. 2008), SN 2010jl (Stoll et al. 2011; Zhang et al. 2012; Maeda et al. 2013; Fransson et al. 2014), and KISS15s (Kokubo et al. 2019), the 1994W-like objects (squares) including SN 1994W (Chugai et al. 2004), SN 2009kn (Kankare et al. 2012), and SN 2011ht (Mauerhan et al. 2013), which show a LC plateau, and finally, the prototypical, rapidly-declining SN 1998S (triangles, Fassia et al. 2000).

gin of dust emission observed in SNe IIn may not always be due to newly formed dust but rather sometimes could be due to pre-existing dust. The exact reason why dust formation in SN 2014ab is inefficient is not clear and warrants further investigation. Finally, we note that we cannot exclude the possibility that newly-formed dust may contribute to the late-phase MIR radiation. Indeed, both newly formed and pre-existing dust can appear at the same time, as has been suggested for SN 2006jd (Stritzinger et al. 2012) and other SNe IIn (e.g., Gerardy et al. 2002; Fox et al. 2009).

6. Conclusions

We have reported the optical and NIR observations of Type IIn SN 2014ab by CSP-II, as well as the serendipitous MIR observations by WISE. Although the CSP-II observations started immediately after the optical discovery, the MIR observation showed that SN 2014ab had already been bright at 56 days before the optical discovery and the explosion date of SN 2014ab is uncertain. Nonetheless, we find that SN 2014ab shows similarities with SN 2010jl, one of the best-observed slowly declining SNe IIn. SN 2014ab is fainter than SN 2010jl by a factor of ~ 2 , but its LC evolution is similar to that of SN 2010jl. The spectroscopic properties are almost identical to those of SN 2010jl. Based on the bolometric LC and assuming a spherically symmetric dense CSM and steady mass loss, the mass-loss rate of the progenitor immediately before the explosion is estimated to be on the order of $0.1 M_{\odot} \text{ yr}^{-1}$.

The MIR observation of SN 2014ab revealed that dust emission with the blackbody temperature of around 2000 K (close to the dust evaporation temperature) exists from around 350 days after the WISE first detection. The MIR luminosity increases up to 350 days and then declines afterwards. Although we observe the warm dust emission at late phases, no clear observational

Fig. 10. Comparison of our +67 d visual-wavelength (*top*) and NIR-wavelength (*bottom*) spectrum of SN 2014ab with other SN IIn subtypes. Comparison objects are the slowly declining SN 2010jl (Borish et al. 2015), the 1994W-like SN 2009kn (Kankare et al. 2012), and the rapid-declining SN 1998S (Fassia et al. 2001). Prominent ions are indicated and labeled. Regions suffering from strong telluric lines are shaded. Note that the NIR spectrum of SN 1998S is composed of data taken on two different but close in time epochs as indicated. Note that the previously unpublished visual-wavelength spectrum of SN 2010jl was obtained by the CSP-II (see Appendix B for details).

signatures of dust formation within the cool dense shell such as the blue-shift of the broad line emission peaks with time and the wavelength-dependent shift of the emission peak are observed at early phases. These features were observed in SN 2010jl. In addition, KISS15s, which is another SN 2010jl-like SN IIn with serendipitous MIR observations by WISE, showed a gradual increase in the MIR luminosity, rather than the continuous decline found in SN 2014ab. Based on these differences, we presume that the dust emission observed in SN 2014ab originates from pre-existing dust located within the dense circumstellar matter heated by the SN shock or radiation, and the dust formation at the cool dense shell is much less efficient in SN 2014ab as compared with SN 2010jl; however, the possibility of some contribution from newly-formed dust in the late-phase radiation is not excluded. The continuous MIR luminosity decline of SN 2014ab may also indicate that the heated dust is continuously destroyed by the shock. Our study of SN 2014ab reveals a diversity of plausible origins for dust emission and dust formation in SNe IIn.

Fig. 11. Peak of the hydrogen emission lines. We use the optical spectrum at +67 d and the NIR spectrum at +69 d. The peak of the broad component does not show a wavelength-dependent shift expected if dust is formed at the emission line forming region, i.e., the emission lines at the shorter wavelengths to have more blue-shifted peaks. The flux is normalized to match the emission peak.

Fig. 12. Bolometric LC of SN 2014ab compared to that of SN 2010jl. Here, the explosion epoch of SN 2014ab is assumed to occur one hundred days prior to the optical discovery. The “hot + warm” luminosity is obtained by adding the two blackbody components and the “hot” luminosity is obtained only with the optical blackbody component in SN 2014ab. The LCs of SN 2010jl are from Fransson et al. (2014). The “optical + NIR” luminosity is the luminosity in the wavelength range from 3600 Å to 24 000 Å. The “optical” luminosity wavelength range is from 3600 Å to 9000 Å. We show the power-law bolometric LC fit that is analytically expected for interacting SNe and the total nuclear deposition energy from the decay of ⁵⁶Ni and ⁵⁶Co.

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References

- Anderson, J. P. 2019, *A&A*, **628**, A7
- Anderson, J. P., Haberman, S. M., James, P. A., & Hamuy, M. 2012, *MNRAS*, **424**, 1372
- Andrews, J. E., Clayton, G. C., Wesson, R., et al. 2011, *AJ*, **142**, 45
- Arnett, W. D. 1982, *ApJ*, **253**, 785
- Berger, E., Soderberg, A. M., Chevalier, R. A., et al. 2009, *ApJ*, **699**, 1850
- Bevan, A. M., Kraft, K., Wesson, R., et al. 2020, *ApJ*, **894**, 111
- Bhatia, A. K., & Kastner, S. O. 1995, *ApJS*, **96**, 325
- Boldt, L. N., Stritzinger, M. D., Burns, C., et al. 2014, *PASP*, **126**, 324
- Bond, H. E., Bedin, L. R., Bonanos, A. Z., et al. 2009, *ApJ*, **695**, L154
- Borish, H. J., Huang, C., Chevalier, R. A., et al. 2015, *ApJ*, **801**, 7
- Bowen, I. S. 1947, *PASP*, **59**, 196
- Burns, C. R., Parent, E., Phillips, M. M., et al. 2018, *ApJ*, **869**, 56
- Buzzoni, B., Delabre, B., Dekker, H., et al. 1984, *The Messenger*, **38**, 9
- Chandra, P., Chevalier, R. A., Irwin, C. M., et al. 2012, *ApJ*, **750**, L2
- Chandra, P., Chevalier, R. A., Chugai, N., Fransson, C., & Soderberg, A. M. 2015, *ApJ*, **810**, 32
- Chatzopoulos, E., Wheeler, J. C., Vinko, J., Horvath, Z. L., & Nagy, A. 2013, *ApJ*, **773**, 76
- Chevalier, R. A., & Irwin, C. M. 2011, *ApJ*, **729**, L6
- Chugai, N. N. 2001, *MNRAS*, **326**, 1448
- Chugai, N. N. 2018, *MNRAS*, **481**, 3643
- Chugai, N. N., & Danziger, I. J. 1994, *MNRAS*, **268**, 173
- Chugai, N. N., Blinnikov, S. I., Cumming, R. J., et al. 2004, *MNRAS*, **352**, 1213
- Dessart, L., Audit, E., & Hillier, D. J. 2015, *MNRAS*, **449**, 4304
- Dessart, L., Hillier, D. J., Audit, E., Livne, E., & Waldman, R. 2016, *MNRAS*, **458**, 2094
- Fassia, A., Meikle, W. P. S., Vacca, W. D., et al. 2000, *MNRAS*, **318**, 1093
- Fassia, A., Meikle, W. P. S., Chugai, N., et al. 2001, *MNRAS*, **325**, 907
- Fitzpatrick, E. L. 1999, *PASP*, **111**, 63
- Fox, O., Skrutskie, M. F., Chevalier, R. A., et al. 2009, *ApJ*, **691**, 650
- Fox, O. D., Chevalier, R. A., Dwek, E., et al. 2010, *ApJ*, **725**, 1768
- Fox, O. D., Chevalier, R. A., Skrutskie, M. F., et al. 2011, *ApJ*, **741**, 7
- Fox, O. D., Filippenko, A. V., Skrutskie, M. F., et al. 2013, *AJ*, **146**, 2
- Fransson, C., Ergon, M., Challis, P. J., et al. 2014, *ApJ*, **797**, 118
- Fraser, M., Magee, M., Kotak, R., et al. 2013, *ApJ*, **779**, L8
- Fraser, M., Blagorodnova, N., Walton, N., et al. 2014, *ATel*, **5968**, 1
- Freudling, W., Romaniello, M., Bramich, D. M., et al. 2013, *A&A*, **559**, A96
- Gal-Yam, A., & Leonard, D. C. 2009, *Nature*, **458**, 865
- Galbany, L., Anderson, J. P., Sánchez, S. F., et al. 2018, *ApJ*, **855**, 107
- Gall, C., Hjorth, J., Watson, D., et al. 2014, *Nature*, **511**, 326
- Gerardy, C. L., Fesen, R. A., Nomoto, K., et al. 2002, *ApJ*, **575**, 1007
- Guillochon, J., Parent, J., Kelley, L. Z., & Margutti, R. 2017, *ApJ*, **835**, 64
- Haberman, S. M., Anderson, J. P., James, P. A., & Lyman, J. D. 2014, *MNRAS*, **441**, 2230
- Hamuy, M., Folatelli, G., Morrell, N. I., et al. 2006, *PASP*, **118**, 2
- Howerton, S., Drake, A. J., Djorgovski, S. G., et al. 2014, *Cent. Bureau Electron. Tel.*, **3826**, 1
- Hsiao, E. Y., Phillips, M. M., Marion, G. H., et al. 2019, *PASP*, **131**, 014002
- Huang, C., & Chevalier, R. A. 2018, *MNRAS*, **475**, 1261
- Jencson, J. E., Prieto, J. L., Kochanek, C. S., et al. 2016, *MNRAS*, **456**, 2622
- Jiang, N., Wang, T., Mou, G., et al. 2019, *ApJ*, **871**, 15
- Kankare, E., Ergon, M., Bufano, F., et al. 2012, *MNRAS*, **424**, 855
- Kastner, S. O., & Bhatia, A. K. 1995, *ApJ*, **439**, 346
- Kausch, W., Noll, S., Smette, A., et al. 2015, *A&A*, **576**, A78
- Kiewe, M., Gal-Yam, A., Arcavi, I., et al. 2012, *ApJ*, **744**, 10
- Kokubo, M., Mitsuda, K., Morokuma, T., et al. 2019, *ApJ*, **872**, 135
- Kozasa, T., Nozawa, T., Tominaga, N., et al. 2009, in *Dust in Supernovae: Formation and Evolution*, eds. T. Henning, E. Grün, J. Steinacker, et al., *ASP Conf. Ser.*, **414**, 43
- Kriszunas, K., Contreras, C., Burns, C. R., et al. 2017, *AJ*, **154**, 211
- Maeda, K., Nozawa, T., Sahu, D. K., et al. 2013, *ApJ*, **776**, 5
- Mainzer, A., Bauer, J., Cutri, R. M., et al. 2014, *ApJ*, **792**, 30
- Mauerhan, J. C., Smith, N., Silverman, J. M., et al. 2013, *MNRAS*, **431**, 2599
- Meza, N., & Anderson, J. P. 2020, *A&A*, in press, <https://doi.org/10.1051/0004-6361/201937113>
- Miller, A. A., Silverman, J. M., Butler, N. R., et al. 2010, *MNRAS*, **404**, 305
- Moriya, T., Tominaga, N., Blinnikov, S. I., Baklanov, P. V., & Sorokina, E. I. 2011, *MNRAS*, **415**, 199
- Moriya, T. J., Maeda, K., Taddia, F., et al. 2013a, *MNRAS*, **435**, 1520
- Moriya, T. J., Blinnikov, S. I., Tominaga, N., et al. 2013b, *MNRAS*, **428**, 1020
- Moriya, T. J., Maeda, K., Taddia, F., et al. 2014, *MNRAS*, **439**, 2917
- Moriya, T. J., Tanaka, M., Morokuma, T., et al. 2019, *ApJ*, **882**, 70
- Nozawa, T., Kozasa, T., Umeda, H., Maeda, K., & Nomoto, K. 2003, *ApJ*, **598**, 785
- Nyholm, A., Sollerman, J., Taddia, F., et al. 2017, *A&A*, **605**, A6
- Nyholm, A., Sollerman, J., Tartaglia, L., et al. 2020, *A&A*, **637**, A73
- Ofek, E. O., Sullivan, M., Cenko, S. B., et al. 2013, *Nature*, **494**, 65
- Ofek, E. O., Sullivan, M., Shaviv, N. J., et al. 2014a, *ApJ*, **789**, 104
- Ofek, E. O., Arcavi, I., Tal, D., et al. 2014b, *ApJ*, **788**, 154
- Ofek, E. O., Zoglauer, A., Boggs, S. E., et al. 2014c, *ApJ*, **781**, 42
- Ohsawa, R., Sakon, I., Onaka, T., et al. 2010, *ApJ*, **718**, 1456
- Patat, F., Taubenberger, S., Benetti, S., Pastorello, A., & Harutyunyan, A. 2011, *A&A*, **527**, L6
- Persson, S. E., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J. 1998, *AJ*, **116**, 2475
- Persson, S. E., Murphy, D. C., Smeed, S., et al. 2013, *PASP*, **125**, 654
- Phillips, M. M., Contreras, C., Hsiao, E. Y., et al. 2019, *PASP*, **131**, 014001
- Pozzo, M., Meikle, W. P. S., Fassia, A., et al. 2004, *MNRAS*, **352**, 457
- Prieto, J. L., Kistler, M. D., Thompson, T. A., et al. 2008, *ApJ*, **681**, L9
- Sarangi, A., Dwek, E., & Arendt, R. G. 2018, *ApJ*, **859**, 66
- Schlaflly, E. F., & Finkbeiner, D. P. 2011, *ApJ*, **737**, 103
- Schlegel, E. M. 1990, *MNRAS*, **244**, 269
- Selsing, J., Malesani, D., Goldoni, P., et al. 2019, *A&A*, **623**, A92
- Simcoe, R. A., Burgasser, A. J., Schechter, P. L., et al. 2013, *PASP*, **125**, 270
- Smartt, S. J., Valenti, S., Fraser, M., et al. 2015, *A&A*, **579**, A40
- Smette, A., Sana, H., Noll, S., et al. 2015, *A&A*, **576**, A77
- Smith, N., Li, W., Foley, R. J., et al. 2007, *ApJ*, **666**, 1116
- Smith, N., Chornock, R., Li, W., et al. 2008, *ApJ*, **686**, 467
- Smith, N., Li, W., Miller, A. A., et al. 2011, *ApJ*, **732**, 63
- Sollerman, J., Cumming, R. J., & Lundqvist, P. 1998, *ApJ*, **493**, 933
- Stathakis, R. A., & Sadler, E. M. 1991, *MNRAS*, **250**, 786
- Stoll, R., Prieto, J. L., Stanek, K. Z., et al. 2011, *ApJ*, **730**, 34
- Stritzinger, M., Taddia, F., Fransson, C., et al. 2012, *ApJ*, **756**, 173
- Suzuki, A., Moriya, T. J., & Takiwaki, T. 2019, *ApJ*, **887**, 249
- Szalai, T., Zsíros, S., Fox, O. D., Pejchar, O., & Müller, T. 2019, *ApJS*, **241**, 38
- Taddia, F., Stritzinger, M. D., Sollerman, J., et al. 2013, *A&A*, **555**, A10
- Taddia, F., Sollerman, J., Fremling, C., et al. 2015, *A&A*, **580**, A131
- Taddia, F., Stritzinger, M. D., Fransson, C., et al. 2020, *A&A*, **638**, A92
- Takei, Y., & Shigezawa, T. 2020, *PASJ*, **72**, 67
- Tsuna, D., Kashiyama, K., & Shigezawa, T. 2019, *ApJ*, **884**, 87
- Turatto, M., Cappellaro, E., Danziger, I. J., et al. 1993, *MNRAS*, **262**, 128
- van Marle, A. J., Smith, N., Owocki, S. P., & van Veen, B. 2010, *MNRAS*, **407**, 2305
- Vernet, J., Dekker, H., D'Odorico, S., et al. 2011, *A&A*, **536**, A105
- Williams, B. J., & Fox, O. D. 2015, *ApJ*, **808**, L22
- Wooden, D. H., Rank, D. M., Bregman, J. D., et al. 1993, *ApJS*, **88**, 477
- Woosley, S. E. 2017, *ApJ*, **836**, 244
- Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, *AJ*, **140**, 1868
- Yaron, O., & Gal-Yam, A. 2012, *PASP*, **124**, 668
- Zhang, T., Wang, X., Wu, C., et al. 2012, *AJ*, **144**, 131

Appendix A: Photometric data

Table A.1. continued.

Photometric data of SN 2014ab used in our analysis are provided in this appendix. This includes two-channel WISE photometry of SN 2014ab listed in Table A.1, optical and NIR local sequences of SN 2014ab in Tables A.2 and A.3, respectively, and optical/NIR photometry of SN 2014ab in Table A.4.

Table A.1. WISE photometry of SN 2014ab in the Vega system.

Filter	JD	Magnitude	Error
W1	2456671.59	13.223	0.034
	2456671.72	13.163	0.031
	2456671.85	13.173	0.033
	2456671.98	13.094	0.038
	2456672.05	13.146	0.031
	2456672.11	13.194	0.031
	2456672.18	13.207	0.034
	2456672.18	13.187	0.046
	2456672.25	13.191	0.033
	2456672.31	13.099	0.044
	2456672.44	13.229	0.040
	2456672.57	13.216	0.035
	2456851.08	13.130	0.033
	2456851.21	13.108	0.039
	2456851.34	13.144	0.039
	2456851.47	13.126	0.039
	2456851.54	13.086	0.035
	2456851.60	13.124	0.031
	2456851.67	13.070	0.041
	2456851.74	13.134	0.031
	2456851.80	13.006	0.036
	2456851.93	13.124	0.032
	2456852.06	13.142	0.033
	2457035.48	12.526	0.024
	2457038.31	12.511	0.023
	2457038.44	12.478	0.022
	2457038.57	12.533	0.024
	2457038.63	12.397	0.024
	2457038.70	12.537	0.026
	2457038.77	12.472	0.023
	2457039.16	12.453	0.028
	2457039.16	12.503	0.028
	2457209.95	12.805	0.029
	2457210.09	12.807	0.029
	2457210.22	12.805	0.030
	2457210.28	12.809	0.030
	2457210.35	12.789	0.026
	2457210.41	12.811	0.028
	2457210.48	12.789	0.026
	2457210.54	12.837	0.030
	2457210.68	12.764	0.028
	2457210.81	12.739	0.026
	2457210.94	12.742	0.026
	2457400.64	13.174	0.032
	2457400.77	13.217	0.031
	2457400.91	13.219	0.039
	2457400.91	13.248	0.035
	2457401.10	13.129	0.032
	2457401.17	13.142	0.043

Filter	JD	Magnitude	Error
	2457401.23	13.185	0.034
	2457401.30	13.167	0.034
	2457401.36	13.221	0.036
	2457401.36	13.201	0.036
	2457401.50	13.323	0.040
	2457568.71	13.532	0.046
	2457568.84	13.529	0.046
	2457568.98	13.581	0.049
	2457569.11	13.656	0.046
	2457569.17	13.522	0.040
	2457569.24	13.440	0.038
	2457569.30	13.560	0.045
	2457569.37	13.470	0.039
	2457569.43	13.471	0.040
	2457569.70	13.616	0.040
	2457569.83	13.450	0.039
	2457764.80	13.738	0.047
	2457764.93	13.717	0.045
	2457765.06	13.896	0.072
	2457765.06	13.842	0.047
	2457765.19	13.848	0.071
	2457765.26	13.842	0.060
	2457765.39	14.008	0.069
	2457765.46	13.793	0.050
	2457765.52	13.760	0.050
	2457765.65	13.856	0.047
	2457765.78	13.937	0.054
	2457929.20	13.876	0.059
	2457929.33	14.027	0.053
	2457929.46	13.841	0.050
	2457929.53	14.095	0.052
	2457929.59	13.925	0.049
	2457929.66	13.933	0.070
	2457929.72	13.985	0.075
	2457929.92	13.919	0.047
	2457930.05	13.925	0.054
	2457930.18	14.048	0.056
	2457930.18	14.020	0.060
	2457936.99	13.957	0.057
	2458132.49	13.949	0.049
	2458132.56	14.049	0.053
	2458132.63	14.040	0.053
	2458132.69	13.920	0.064
	2458289.73	14.184	0.075
	2458289.99	14.193	0.056
	2458290.19	14.206	0.058
	2458290.58	14.152	0.067
	2458292.61	14.018	0.073
	2458293.07	14.033	0.055
	2458293.20	14.228	0.074
W2	2456671.59	12.716	0.055
	2456671.72	12.801	0.073
	2456671.85	12.685	0.055
	2456671.98	12.654	0.069
	2456672.05	12.689	0.057
	2456672.11	12.731	0.055
	2456672.18	12.800	0.057

Table A.1. continued.

Filter	JD	Magnitude	Error
	2456672.18	12.478	0.074
	2456672.25	12.771	0.059
	2456672.31	12.606	0.065
	2456672.44	12.655	0.058
	2456672.57	12.775	0.072
	2456851.08	12.689	0.053
	2456851.21	12.732	0.061
	2456851.34	12.622	0.056
	2456851.47	12.704	0.074
	2456851.54	12.712	0.054
	2456851.60	12.529	0.053
	2456851.67	12.672	0.065
	2456851.74	12.710	0.054
	2456851.80	12.761	0.082
	2456851.93	12.683	0.058
	2456852.06	12.690	0.056
	2457035.48	12.054	0.051
	2457038.31	12.009	0.034
	2457038.44	12.054	0.040
	2457038.57	12.016	0.036
	2457038.63	12.011	0.036
	2457038.70	12.019	0.037
	2457038.77	11.995	0.044
	2457039.16	12.032	0.037
	2457039.16	12.011	0.037
	2457209.95	12.200	0.039
	2457210.09	12.176	0.052
	2457210.22	12.172	0.041
	2457210.28	12.218	0.039
	2457210.35	12.151	0.043
	2457210.41	12.131	0.041
	2457210.48	12.154	0.039
	2457210.54	12.299	0.050
	2457210.68	12.240	0.043
	2457210.81	12.161	0.039
	2457210.94	12.212	0.039
	2457400.64	12.476	0.046
	2457400.77	12.445	0.044
	2457400.91	12.449	0.042
	2457400.91	12.468	0.046
	2457401.10	12.500	0.047
	2457401.17	12.486	0.051
	2457401.23	12.457	0.051
	2457401.30	12.489	0.061
	2457401.36	12.569	0.047
	2457401.36	12.484	0.046
	2457401.50	12.430	0.054

Table A.1. continued.

Filter	JD	Magnitude	Error
	2457568.71	12.818	0.062
	2457568.84	12.727	0.054
	2457568.98	12.757	0.053
	2457569.11	12.810	0.055
	2457569.17	12.690	0.066
	2457569.24	12.675	0.053
	2457569.30	12.723	0.062
	2457569.37	12.758	0.055
	2457569.43	12.679	0.053
	2457569.70	12.729	0.055
	2457569.83	12.764	0.056
	2457764.80	13.053	0.070
	2457764.93	13.050	0.077
	2457765.06	13.018	0.067
	2457765.06	13.088	0.083
	2457765.19	13.169	0.134
	2457765.26	12.990	0.067
	2457765.39	13.053	0.107
	2457765.46	12.942	0.077
	2457765.52	13.114	0.092
	2457765.65	13.032	0.074
	2457765.78	13.175	0.087
	2457929.20	13.260	0.101
	2457929.33	13.260	0.100
	2457929.46	13.350	0.108
	2457929.53	13.277	0.087
	2457929.59	13.132	0.105
	2457929.66	13.315	0.090
	2457929.72	13.111	0.114
	2457929.92	13.277	0.081
	2457930.05	13.314	0.114
	2457930.18	13.301	0.078
	2457930.18	13.485	0.094
	2457936.99	13.187	0.132
	2458132.49	13.337	0.136
	2458132.56	13.640	0.115
	2458132.63	13.546	0.114
	2458132.69	13.711	0.205
	2458289.73	13.480	0.117
	2458289.99	13.372	0.197
	2458290.19	13.551	0.229
	2458290.58	13.764	0.161
	2458292.61	13.612	0.226
	2458293.07	13.890	0.213
	2458293.20	13.265	0.140

Table A.2. Optical photometry of the local sequence for SN 2014ab in the “standard” system.

ID	α (2000)	δ (2000)	B	V	u'	g'	r'	i'
1	207.103256	7.430505	14.464(011)	13.444(023)	16.446(044)	13.917(012)	13.080(018)	12.797(009)
2	207.016541	7.351987	14.614(015)	13.689(015)	16.259(038)	14.130(016)	13.290(016)	12.963(009)
3	207.015869	7.294901	14.590(016)	13.720(012)	16.146(012)	14.119(011)	13.414(008)	13.161(006)
4	207.114792	7.291261	15.526(023)	14.808(022)	16.747(049)	15.147(028)	14.583(017)	14.361(015)
5	207.009033	7.314421	16.291(023)	15.588(018)	17.388(055)	15.904(019)	15.344(016)	15.145(014)
6	207.011932	7.279015	16.564(024)	15.738(011)	17.678(082)	16.132(023)	15.420(007)	15.151(006)
7	207.056549	7.408627	17.366(107)	16.557(053)	18.886(080)	16.966(029)	16.254(035)	15.985(021)
8	207.066711	7.456894	17.197(040)	16.651(063)	17.893(045)	16.893(050)	16.533(038)	16.401(037)
9	206.970734	7.467194	17.873(095)	16.667(049)	20.172(175)	17.312(076)	16.086(020)	15.526(021)
10	206.985626	7.469990	17.387(093)	16.748(044)	18.374(047)	17.066(053)	16.548(034)	16.378(036)
11	207.005112	7.462066	17.547(076)	16.980(068)	18.446(177)	17.231(050)	16.807(047)	16.680(051)
12	207.083344	7.439429	17.800(123)	17.094(045)	18.862(072)	17.432(045)	16.804(053)	16.574(035)
13	207.017670	7.366422	17.598(063)	17.004(032)	18.429(073)	17.302(041)	16.820(037)	16.564(043)
14	207.042816	7.346911	17.631(082)	17.268(079)	18.254(360)	17.414(081)	17.191(062)	17.105(065)
15	207.089340	7.359910	17.796(093)	17.428(077)	17.735(102)	17.632(061)	17.415(070)	17.500(060)
16	206.964035	7.465946	17.983(056)	17.435(057)	18.840(110)	17.674(050)	17.280(060)	17.103(082)
17	207.051956	7.360322	18.002(088)	17.609(058)	18.643(084)	17.769(036)	17.461(051)	17.394(094)
18	207.099777	7.315611	18.480(085)	17.496(060)	...	18.019(075)	17.077(052)	16.648(038)
19	207.090088	7.375126	18.332(037)	17.644(083)	19.249(020)	17.987(091)	17.401(066)	17.143(065)
20	206.999039	7.336068	18.927(048)	17.627(049)	...	18.281(056)	17.015(036)	16.112(028)
21	207.094254	7.321296	19.040(093)	17.863(081)	...	18.449(077)	17.279(072)	16.671(040)
22	207.026749	7.289460	19.266(047)	17.956(091)	...	18.602(057)	17.344(086)	16.760(047)
23	207.071671	7.423058	18.691(154)	18.198(109)	19.223(054)	18.381(053)	17.966(113)	17.762(075)

Notes. Values in parenthesis are $1-\sigma$ uncertainties that correspond to the rms of the instrumental errors of the photometry obtained over a minimum of three nights observed relative to standard star fields.

Table A.3. NIR photometry of the local sequences for SN 2014ab in the “standard” system.

ID	α (2000)	δ (2000)	Y	J	H
101	13.803147	7.379118	14.173 ± 0.011	13.742 ± 0.011	13.132 ± 0.004
102	13.803267	7.379149	14.385 ± 0.023	14.036 ± 0.006	13.500 ± 0.010
103	13.802220	7.406726	15.159 ± 0.007	14.724 ± 0.023	14.238 ± 0.005
104	13.800127	7.382974	16.225 ± 0.008	15.775 ± 0.029	15.136 ± 0.027
105	13.802920	7.378393	16.685 ± 0.067	16.402 ± 0.049	15.866 ± 0.058
106	13.800973	7.380912	17.274 ± 0.109	16.859 ± 0.085	16.192 ± 0.082

Notes. Values in parenthesis are $1-\sigma$ uncertainties and correspond to an rms of the instrumental errors of the photometry obtained over a minimum of three photometric nights.

Table A.4. Photometry of SN 2014ab in the “natural” system.

Filter	JD	Magnitude	Error
<i>u</i>	2456727.77	17.142	0.021
	2456729.78	17.193	0.021
	2456731.86	17.151	0.017
	2456733.82	17.166	0.020
	2456741.83	17.182	0.017
	2456743.75	17.203	0.026
	2456745.73	17.179	0.019
	2456750.88	17.237	0.016
	2456756.68	17.238	0.018
	2456760.70	17.267	0.021
	2456767.75	17.284	0.018
	2456774.66	17.353	0.017
	2456785.67	17.393	0.019
	2456792.65	17.471	0.024
	2456804.53	17.554	0.019
	2456811.58	17.608	0.019
	2457033.85	20.132	0.136
<i>g</i>	2456727.76	16.439	0.017
	2456729.78	16.437	0.016
	2456731.86	16.447	0.012
	2456733.81	16.469	0.016
	2456741.82	16.494	0.010
	2456743.74	16.496	0.013
	2456745.72	16.486	0.012
	2456750.87	16.538	0.011
	2456756.67	16.528	0.015
	2456760.69	16.553	0.016
	2456767.75	16.589	0.017
	2456774.66	16.619	0.011
	2456785.67	16.684	0.017
	2456792.65	16.732	0.013
	2456804.52	16.802	0.012
	2456811.58	16.844	0.016
	2457031.84	20.180	0.162
	2457033.84	20.136	0.056
	2457065.87	20.715	0.089
	2457095.82	20.824	0.092
	2457126.69	21.331	0.091
	2457156.73	21.963	0.198

Table A.4. continued.

Filter	JD	Magnitude	Error
<i>r</i>	2456727.77	15.870	0.015
	2456729.78	15.877	0.017
	2456731.85	15.867	0.010
	2456733.81	15.859	0.017
	2456741.83	15.881	0.012
	2456743.74	15.886	0.014
	2456745.72	15.889	0.015
	2456750.87	15.892	0.011
	2456756.67	15.938	0.017
	2456760.69	15.925	0.017
	2456767.75	15.941	0.017
	2456774.66	15.977	0.011
	2456785.67	16.052	0.017
	2456792.65	16.044	0.015
	2456804.52	16.087	0.016
	2456811.58	16.148	0.015
	2457031.84	19.006	0.053
<i>i</i>	2457033.83	19.162	0.034
	2457065.88	19.344	0.040
	2457095.81	19.989	0.053
	2457126.69	20.267	0.049
	2457156.72	20.737	0.105
	2456727.77	16.114	0.021
	2456729.78	16.135	0.024
	2456731.85	16.142	0.011
	2456733.82	16.134	0.020
	2456741.83	16.167	0.014
	2456743.74	16.221	0.026
	2456745.72	16.181	0.015
	2456750.87	16.223	0.010
	2456756.67	16.262	0.022
	2456760.69	16.294	0.023
	2456767.75	16.317	0.021
	2456774.66	16.357	0.013
	2456785.67	16.431	0.020
	2456792.65	16.538	0.021
	2456804.52	16.551	0.019
	2456811.58	16.614	0.018
	2457033.84	19.691	0.065
	2457065.88	19.790	0.081
	2457156.73	20.805	0.180

Notes. Uncertainties correspond to the 1- σ instrumental magnitude uncertainty added in quadrature with the nightly zero-point uncertainty.

Table A.4. continued.

Filter	JD	Magnitude	Error
<i>B</i>	2456727.77	16.683	0.019
	2456729.77	16.703	0.017
	2456731.87	16.732	0.017
	2456733.81	16.716	0.021
	2456741.82	16.760	0.013
	2456743.74	16.741	0.020
	2456745.72	16.735	0.015
	2456750.88	16.791	0.014
	2456756.67	16.784	0.019
	2456760.69	16.785	0.020
	2456767.76	16.823	0.017
	2456774.65	16.855	0.015
	2456785.67	16.941	0.020
	2456792.64	16.948	0.020
	2456804.53	17.069	0.014
	2456811.57	17.115	0.013
	2457033.86	20.492	0.092
	2457065.87	20.996	0.104
	2457095.83	21.261	0.123
	2457126.68	21.572	0.126
<i>V</i>	2456727.77	16.319	0.021
	2456729.77	16.319	0.016
	2456731.87	16.328	0.013
	2456733.81	16.315	0.017
	2456741.82	16.341	0.012
	2456743.74	16.340	0.015
	2456745.72	16.369	0.014
	2456750.88	16.390	0.013
	2456756.67	16.387	0.016
	2456760.69	16.420	0.018
	2456767.76	16.454	0.016
	2456774.65	16.475	0.012
	2456785.67	16.553	0.019
	2456792.64	16.619	0.017
	2456804.53	16.673	0.015
	2456811.57	16.723	0.014
	2457031.84	20.000	0.153

Table A.4. continued.

Filter	JD	Magnitude	Error
<i>Y</i>	2457033.85	20.148	0.081
	2457065.87	20.643	0.107
	2457095.82	20.763	0.104
	2457126.69	21.059	0.122
	2456727.81	15.290	0.008
	2456731.82	15.302	0.007
	2456762.74	15.395	0.007
	2456786.67	15.566	0.011
<i>J</i>	2456796.65	15.586	0.007
	2456727.83	15.177	0.009
	2456731.86	15.217	0.008
	2456762.76	15.267	0.008
	2456786.69	15.393	0.009
<i>H</i>	2456796.67	15.424	0.008
	2456727.83	15.002	0.008
	2456731.85	15.055	0.007
	2456762.75	15.126	0.008
	2456786.69	15.226	0.009
	2456796.66	15.273	0.009

Appendix B: CSP-II spectra of SN 2010jl

In Fig. B.1, we present unpublished NIR spectra of SN 2010jl, which is shown in this paper to have common features with SN 2014ab. A journal summarizing the spectra obtained by the CSP-II of SN 2010jl is provided in Table B.1. The spectroscopic data was reduced following standard techniques. The visual-wavelength spectrum of SN 2010jl is shown in Fig. 10, while five NIR spectra obtained with the Baade (+ FIRE) telescope are plotted in Fig. B.1, and the rest-frame axes assumes the host-galaxy redshift of 0.0107. Optical spectra of SN 2010jl at similar epochs have already been presented and analysed in the literature, but the NIR spectra cover late epochs than those published in the literature to our knowledge. These data are presented here for the benefit of the community.

Table B.1. Journal of spectroscopic observations of SN 2010jl.

Date (UT)	JD-2,455,000 (days)	Phase ^(a) (days)	Telescope	Instrument	Range (Å)
04 Jan 2011	565.76	85.8	du Pont	WFCCD	3630–9200
07 Jan 2012	933.75	449.9	Baade	FIRE	8095–24 810
19 Apr 2012	1036.54	551.6	Baade	FIRE	8095–24 810
19 Nov 2012	1250.83	763.7	Baade	FIRE	8095–24 810
25 Nov 2012	1256.82	769.6	Baade	FIRE	8095–24 810
03 Jan 2013	1295.82	808.2	Baade	FIRE	8095–24 810

Notes. ^(a)Rest-frame days relative to date of first detection, i.e., JD–2,455,479.0 (Fransson et al. 2014).

Fig. B.1. NIR spectra of SN 2010jl obtained by the CSP-II. The epochs are in the rest frame relative to the first detection which occurred on JD = 2455479.0. The number in the parenthesis next to the epochs indicate the constant value added to each spectrum for presentation purposes and are in the unit of $10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$.