

## THE BROAD LINE TYPE IC SUPERNOVA SN 2007RU: ADDING TO THE DIVERSITY OF TYPE IC SUPERNOVAE

D.K. SAHU<sup>1</sup>, MASAOMI TANAKA<sup>2</sup>, G.C. ANUPAMA<sup>1</sup>, UDAY K. GURUGUBELLI<sup>1,3</sup>, AND KEN'ICHI NOMOTO<sup>4,2</sup>*Accepted for publication in The Astrophysical Journal*

## ABSTRACT

Photometric and spectral evolution of the Type Ic supernova SN 2007ru until around 210 days after maximum are presented. The spectra show broad spectral features due to very high expansion velocity, normally seen in hypernovae. The photospheric velocity is higher than other normal Type Ic supernovae. It is lower than SN 1998bw at  $\sim 8$  days after the explosion, but is comparable at later epochs. The light curve evolution of SN 2007ru indicates a fast rise time of  $8 \pm 3$  days to  $B$  band maximum and post-maximum decline more rapid than other broad-line Type Ic supernovae. With an absolute  $V$  magnitude of  $-19.06$ , SN 2007ru is comparable in brightness with SN 1998bw and lies at the brighter end of the observed Type Ic supernovae. The ejected mass of  $^{56}\text{Ni}$  is estimated to be  $\sim 0.4 M_{\odot}$ . The fast rise and decline of the light curve and the high expansion velocity suggest that SN 2007ru is an explosion with a high kinetic energy/ejecta mass ratio ( $E_K/M_{\text{ej}}$ ). This adds to the diversity of Type Ic supernovae. Although the early phase spectra are most similar to those of broad-line SN 2003jd, the [OI] line profile in the nebular spectrum of SN 2007ru shows the singly-peaked profile, in contrast to the doubly-peaked profile in SN 2003jd. The singly-peaked profile, together with the high luminosity and the high expansion velocity, may suggest that SN 2007ru could be an aspherical explosion viewed from the polar direction. Estimated oxygen abundance  $12 + \log(\text{O}/\text{H})$  of  $\sim 8.8$  indicates that SN 2007ru occurred in a region with nearly solar metallicity.

*Subject headings:* supernovae: general supernovae: individual (SN 2007ru)

## 1. INTRODUCTION

Broad-line Type Ic supernovae (SNe Ic) are a subclass of core collapse SNe Ic that have broad features in their spectra, indicating unusually high expansion velocities reaching close to  $0.1c$  at early times. Only a few candidates of this class are known. Some broad-line SNe Ic are associated with Gamma Ray Bursts (GRBs) (Galama et al. 1998; Matheson et al. 2003; Malesani et al. 2004), or X-Ray Flash (XRF) (Pian et al. 2006; Modjaz et al. 2006), while some others do not show any clear evidence of being associated with a GRB or an XRF (Kinugasa et al. 2002; Foley et al. 2003; Valenti et al. 2008).

The broad-line SNe Ic exhibit diversity in terms of the explosion energy, ejecta mass and mass of  $^{56}\text{Ni}$  produced during the explosion. The photometric and spectral features of SN 1998bw are explained with  $\sim 10 M_{\odot}$  ejected with a kinetic energy  $2 - 5 \times 10^{52}$  ergs, producing  $0.4 - 0.5 M_{\odot}$  of  $^{56}\text{Ni}$  in the explosion (Iwamoto et al. 1998; Nakamura et al. 2001; Maeda et al. 2006, Tanaka et al. 2007). On the other hand, modelling of nebular spectra of SN 2002ap indicates an ejected mass of  $\sim 2.5 M_{\odot}$  with a kinetic energy  $\sim 4 \times 10^{51}$  ergs and production of  $\sim 0.1 M_{\odot}$  of  $^{56}\text{Ni}$  (Mazzali et al. 2007), showing a large range in the physical parameters of broad-line SNe Ic. Among these, SNe with kinetic energy  $E_K > 10^{52}$

ergs are termed as "hypernovae (HNe)" (Iwamoto et al. 1998). The broad-line SNe that are not associated with GRBs are found to have smaller values of ejecta mass, explosion energy and lower luminosity as compared to the GRB-associated HNe (Nomoto et al. 2007).

SN 2007ru was discovered by Donati & Ciabattari on November 27.9 and independently by Winslow & Li with KAIT on November 30.15 in the spiral galaxy UGC 12381. There was no evidence of the supernova in the KAIT image taken on November 22.16, down to a limiting magnitude of 18.9 (Donati & Ciabattari, 2007). Based on a spectrum obtained on December 1, SN 2007ru was classified as peculiar SN Ic at premaximum phase (Chornock et al. 2007). The CaII H & K and CaII Near Infrared (NIR) triplet absorption troughs were found to be weak compared to other SNe Ic. Further, the OI line at  $7774 \text{ \AA}$  indicated an expansion velocity of  $19000 \text{ km sec}^{-1}$ , similar to the expansion velocity seen in the broad-line SN Ic SN 2006aj (Pian et al. 2006). A search through the reported discoveries of GRBs during October 15 to November 30, 2007 does not show any possible association of a GRB with this supernova.

The results of photometric and spectral monitoring of SN 2007ru until around 210 days after maximum, using the 2m Himalayan Chandra Telescope (HCT) of the Indian Astronomical Observatory (IAO), Hanle, India, are presented in this paper.

## 2. OBSERVATIONS AND DATA REDUCTION

## 2.1. Photometry

SN 2007ru was observed in  $UBVRI$  bands during 2007 December 2 (JD 2454437.09) to 2008 July 03 (JD 2454651.35). The observations were carried out with the Himalayan Faint Object Spectrograph Camera (HFOSC) mounted on the HCT. HFOSC is equipped with  $2K \times 4K$

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<sup>1</sup> Indian Institute of Astrophysics, II Block Koramangala, Bangalore 560034, India: dks@iiap.res.in, gca@iiap.res.in, uday@iiap.res.in

<sup>2</sup> Department of Astronomy, Graduate School of Science, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan: mtanaka@astron.s.u-tokyo.ac.jp

<sup>3</sup> Joint Astronomy Programme, Indian Institute of Science, Bangalore 560012, India

<sup>4</sup> Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Chiba 277-8582, Japan: nomoto@astron.s.u-tokyo.ac.jp

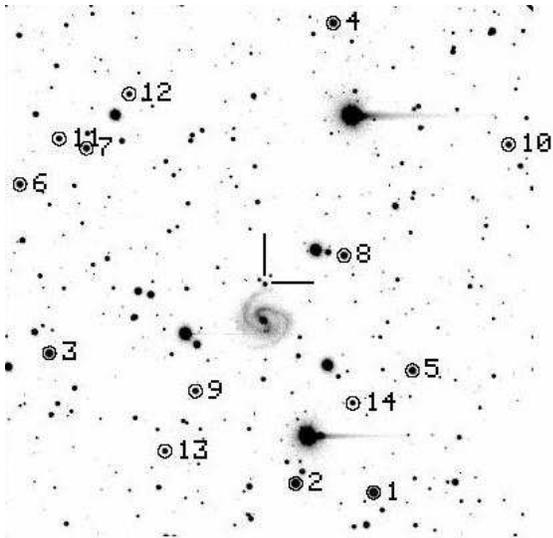


FIG. 1.— Identification chart for SN 2007ru. The stars used as local standards are marked as numbers 1-14.

pixels CCD chip. The central  $2K \times 2K$  region, with a plate scale of  $0.296 \text{ arcsec pixel}^{-1}$ , covering a field of  $10' \times 10'$ , was used for imaging. Gain and readout noise of the CCD camera are  $1.22 \text{ e}^{-1}/\text{ADU}$  and  $4.87 \text{ e}^{-1}$ , respectively. Further details on the HCT and HFOSC can be obtained from “<http://www.iap.res.in/centers/iao>”.

Photometric standard regions (Landolt 1992) were observed on 2007 December 25 and December 26 under photometric sky conditions to calibrate a sequence of secondary standards in the supernova field. Data reduction has been done in the standard manner using various tasks available within Image Reduction and Analysis Facility (IRAF). Aperture photometry was performed on the photometric standard stars and secondary standards, at an aperture radius determined using the aperture growth curve. The secondary standard stars were then calibrated using the average colour terms and the photometric zero points determined on the individual night. A sequence of secondary standards calibrated in this way is marked in Fig. 1 and the *UBVRI* magnitudes of the secondary standards averaged over the two nights are listed in Table 1. The magnitudes of the supernova and secondary standards were measured using point spread function photometry, with a fitting radius equal to the FWHM of the stellar profile. Supernova magnitudes were calibrated differentially with respect to the local standards. The supernova magnitudes in *U*, *B*, *V*, *R* and *I* bands have been listed in Table 2.

### 2.2. Spectroscopy

A series of spectra were taken during 2007 December 3 to 2008 June 12, in the wavelength range ( $3500\text{\AA} - 7000\text{\AA}$ ) and ( $5200\text{\AA} - 9200\text{\AA}$ ), with a resolution of  $\sim 7 \text{ \AA}$ . The journal of spectroscopic observations is given in Table 3. The spectrophotometric standard stars were observed on the same night to flux calibrate the supernova spectra. Spectroscopic data reduction was carried out using tasks available within IRAF. The spectra were bias subtracted, flat-fielded and the one dimensional spectra were extracted using the optimal extraction method. The arc lamp spectra of FeAr and FeNe were used for wavelength calibration. The instrumental

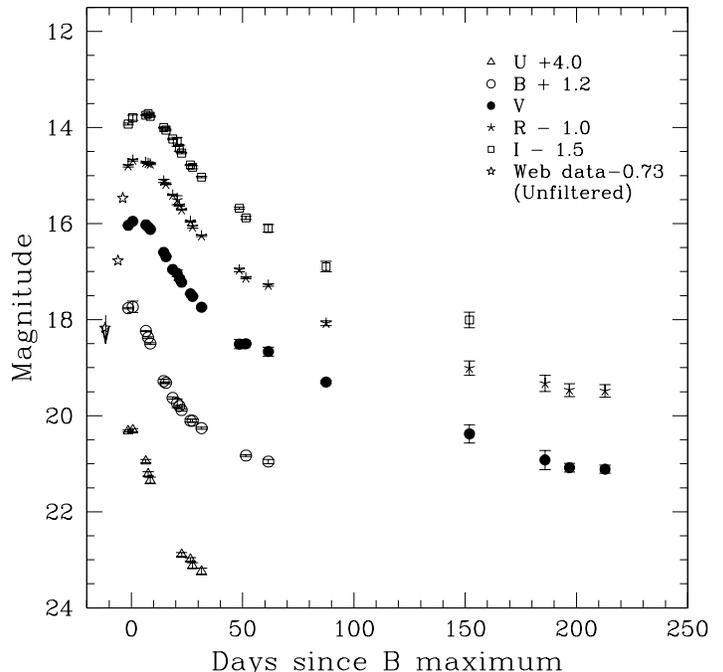


FIG. 2.— The *UBVRI* LCs of SN 2007ru. The LCs have been shifted by the amount indicated in the legend. The unfiltered magnitudes reported by amateurs and the pre-discovery limiting magnitudes have been included with *R* band magnitudes in the figure.

response correction was effected using the spectroscopic standard spectrum. The spectra in the two different regions were combined, scaled to a weighted mean, to give the final spectrum on a relative flux scale, which were then brought to an absolute flux scale using the *UBVRI* magnitudes. The supernova spectra were corrected for the host galaxy redshift of  $z = 0.01546$  (from NED) and dereddened by the total reddening  $E(B - V) = 0.27$  as estimated in Section 5.

### 3. OPTICAL LIGHT CURVES

The *UBVRI* light curves (LC) of SN 2007ru are shown in Fig. 2. The unfiltered discovery magnitudes and the pre-discovery limiting magnitude are also included in the figure. The LCs indicate that the maximum occurred earlier in the blue, similar to other broad-line SNe Ic. The date of explosion can be constrained to  $\lesssim 6$  days before discovery (November 25, JD  $2454430 \pm 3$ ), based on the non-detection on November 22 by KAIT and the subsequent discovery on November 27.9. The rise time to *B* maximum, which occurred on December 3, is 5-11 ( $8 \pm 3$ ) days, indicating SN 2007ru is a fast rising SN Ic with a rise time similar to broad-line SNe 2002ap (Foley et al. 2003), and 2006aj (Modjaz et al. 2006), marginally faster than SN 2003jd (Valenti et al. 2008) but considerably faster than the GRB-associated SNe 1998bw and 2003dh (Galama et al. 1998, Matheson et al. 2003).

The light curves of SN 2007ru are compared with those of broad-line SNe SN 2002ap, SN 2003jd, GRB 980425/SN 1998bw, normal SNe Ic SN 1994I and SN 2004aw in Fig. 3. A comparison of the decline in brightness 15 days after maximum light,  $\Delta_{m15}$  in different bands shows that SN 2007ru has a decline similar to other broad-line supernovae. In fact, the decline of SN 2007ru

is faster than SN 1998bw but slower than SNe 2003jd and 2006aj (refer Table 4). The decline rates are estimated to be  $\Delta m_{15}(B)=1.57$ ,  $\Delta m_{15}(V)=0.92$ ,  $\Delta m_{15}(R)=0.69$  and  $\Delta m_{15}(I)=0.50$ . The light curves of SN 2007ru decline with decline rates of  $0.021 \text{ mag day}^{-1}$  in  $V$ ,  $0.028 \text{ mag day}^{-1}$  in  $R$  and  $0.030 \text{ mag day}^{-1}$  in  $I$  bands during days 45 – 80. These decline rates are comparable to the light curve decline rates of the broad-line SN 2003jd and marginally faster than SN 1998bw. The decline rate in  $B$  cannot be estimated due to a sparse coverage during this period. During the late phases ( $> 80$  days after explosion), the  $V$  and  $R$  band light curves of SN 2007ru decline with decline rates of  $0.0152$  and  $0.0116 \text{ mag day}^{-1}$ , respectively, slower than both SN 2003jd and SN 1998bw during the corresponding epochs (Fig. 3). The decline rate of SN 2007ru during the late phases, is faster than the rate expected due to the radioactive decay of  $^{56}\text{Co}$  into  $^{56}\text{Fe}$ . This indicates inefficient trapping of  $\gamma$ -rays by the ejecta, which suggests a low column density.

The peak absolute magnitudes were estimated using the apparent magnitude at maximum in different bands (see §5 for reddening and distance estimate). From a comparison of the absolute magnitude, SN 2007ru appears to lie at the brighter end of the observed SNe Ic. With an absolute  $V$  magnitude of  $-19.06 \pm 0.2$ , SN 2007ru is fainter than GRB 031203/SN 2003lw [ $M_V = -19.75 \pm 0.5$ ; Malesani et al. 2004], comparable in brightness with SN 1998bw [ $M_V = -19.12 \pm 0.05$ , Galama et al. 1998], and brighter than XRF 060218/SN 2006aj [ $M_V = -18.67 \pm 0.08$ ; Modjaz et al. 2006], broad-line SNe 2002ap [ $M_V = -17.37 \pm 0.05$ ; Foley et al. 2003, Tomita et al. 2006], 2003jd [ $M_V = -18.9 \pm 0.3$ ; Valenti et al. 2008] and normal SNe Ic 1994I [ $M_V = -17.62 \pm 0.3$ ; Richmond et al. 1996, Sauer et al. 2006], and 2004aw [ $M_V = -18.02 \pm 0.3$ ; Taubenberger et al. 2006].

#### 4. SPECTRAL EVOLUTION

The spectral evolution of SN 2007ru is presented in Figure 4. The first spectrum, obtained on 2007 December 3, at  $t \sim 8$  days, where  $t$  is days after explosion, (the rise time is assumed to be 8 days, see §3) shows broad absorption features at  $\sim 6000\text{\AA}$  due to SiII (and a possible contamination as discussed by Valenti et al. 2008), at  $\sim 7200\text{\AA}$  due to OI and at  $\sim 8200\text{\AA}$  due to weak CaII NIR triplet. The spectrum at  $t \sim 20$  days shows well developed broad absorptions due to MgII  $\lambda 4481$ , blends of FeII at  $\sim 4700\text{\AA}$ , SiII  $\lambda 6355$ , OI  $\lambda 7774$  and CaII NIR triplet. The continuum gets redder by  $t \sim 20$  days. No significant evolution is seen in the spectrum taken at  $t \sim 41$  days. The last spectrum presented here, obtained  $\sim 200$  days after explosion indicates the supernova to be in the nebular phase.

Comparing the spectrum and its evolution with that of the broad-line SN 2003jd and the 'normal spectrum' Ic supernova SN 2004aw (Fig.5 and Fig.6), it is seen that SN 2007ru is very similar to the broad-line SN Ic, indicating high expansion velocities. The spectral features continue to remain broad and similar to those of SN 2003jd even at  $t \sim 41$  days.

##### 4.1. Photospheric velocity

The high velocity of the supernova ejecta usually results in blending of the spectral lines, making direct measurement of the photospheric velocity difficult. The pho-

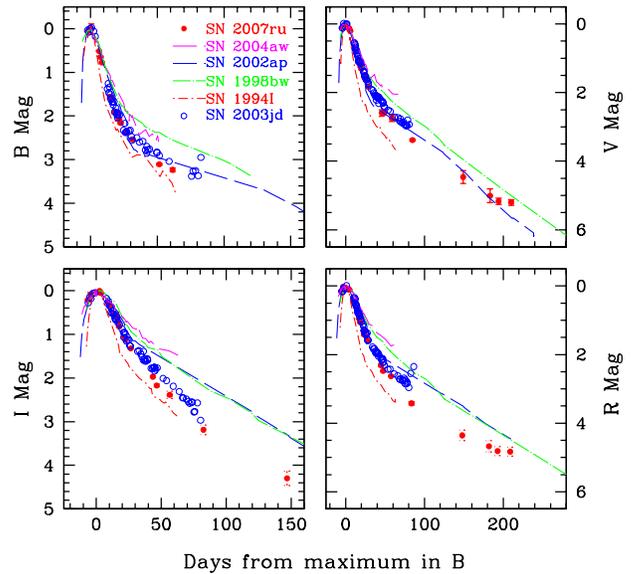


FIG. 3.— Comparison of LCs of SN 2007ru with other Type Ib/c SNe. The LCs of the supernovae in comparison have been shifted arbitrarily to match the date of maximum and magnitude at maximum.

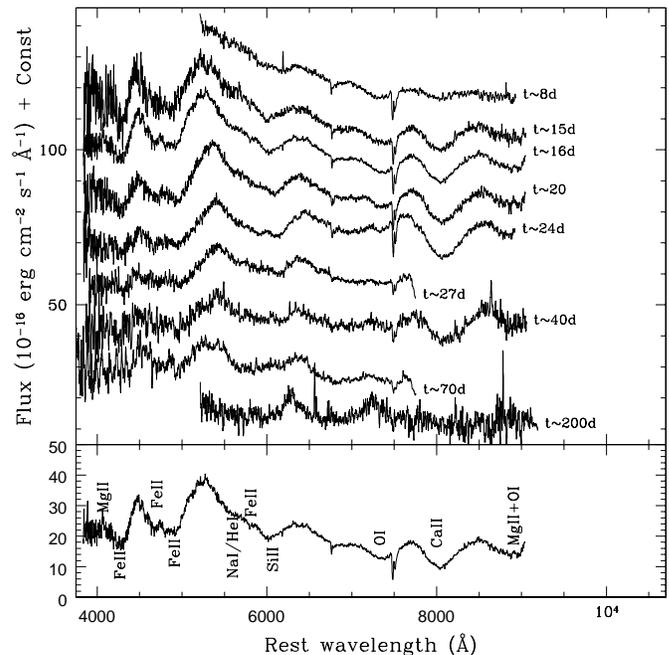


FIG. 4.— Optical spectral evolution of SN 2007ru (top panel). The spectra are corrected for the host galaxy redshift. Time in days since the day of explosion (2008 November 25- see text) is indicated for each spectrum. For clarity, the spectra have been displaced vertically. Main spectral features are identified and marked in the spectrum taken  $\sim 16$  days after explosion (bottom panel).

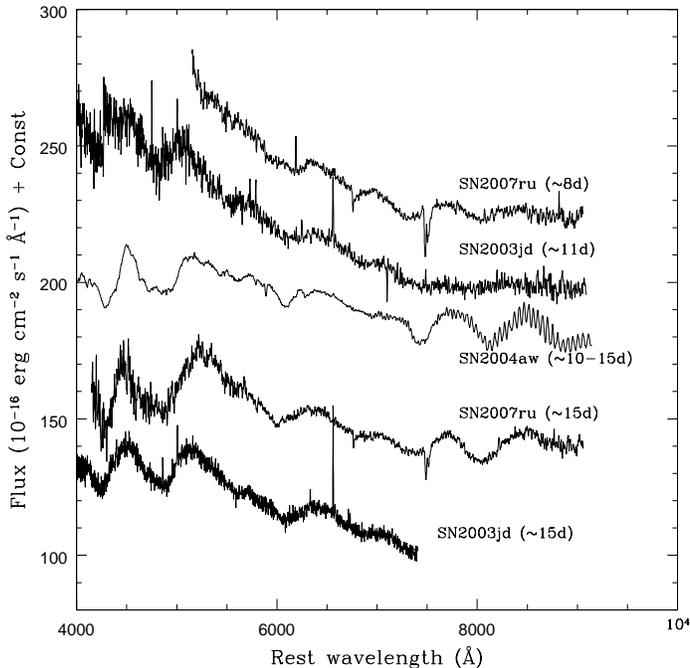


FIG. 5.— Comparison of spectra of SN 2007ru with broad-line type Ic SN 2003jd and normal spectrum type Ic SN 2004aw at different epochs.

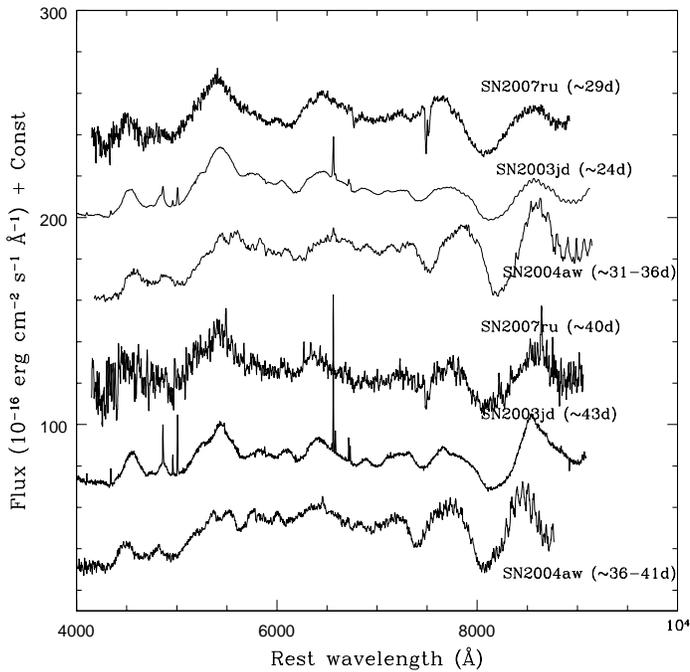


FIG. 6.— Same as figure 5 but at different epochs.

photospheric velocity of SN 2007ru is estimated by fitting a Gaussian profile to the minimum of the absorption trough of Si II 6355Å line, in the redshift corrected spectra. In the first spectrum,  $\sim 8$  days after the explosion, the absorption feature at 6200Å consists of two components, similar to that seen in the premaximum spectra of the broad-line SN 2003jd (Valenti et al. 2008). Assuming

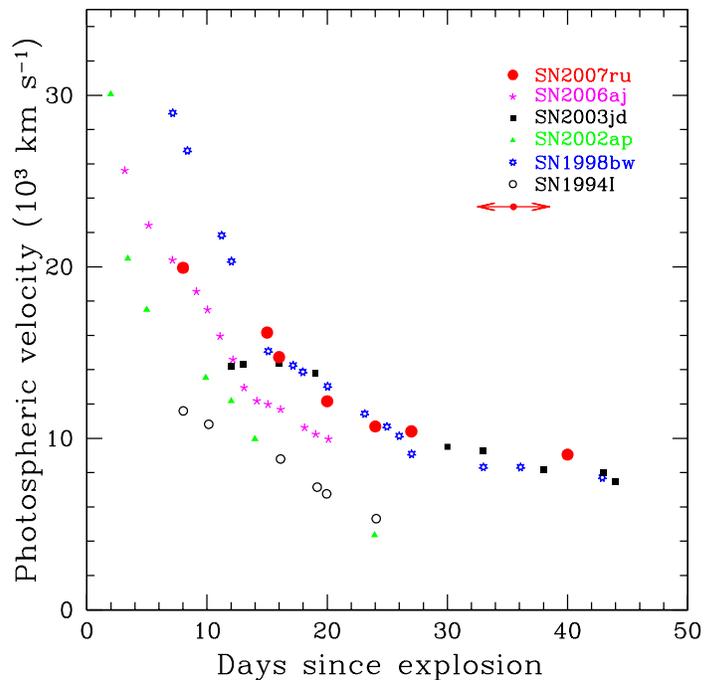


FIG. 7.— Evolution of the photospheric velocity of SN 2007ru and other SNe Ic inferred from Si II  $\lambda$  6355 line. Uncertainty in estimating days since explosion for SN 2007ru due to error in the date of explosion (JD 2454430 $\pm$ 3) is indicated by the horizontal arrow.

the blue component is due to Si II and the red wing is due to possible contamination by other species, the photospheric velocity is estimated to be 20,000 km sec $^{-1}$ . This is consistent with the velocity estimate by Chornock et al. (2007) using OI line in the spectrum.

The photospheric velocity of SN 2007ru, measured using Si II lines, and its evolution is compared with other SNe Ic in Fig 4.1. The photospheric velocity of SN 2007ru at  $\sim 8$  days after explosion is lower than GRB 980425/SN 1998bw (Patat et al. 2001), but comparable to XRF 060218/SN 2006aj (Pian et al. 2006) and broad-line SN 2002ap (Foley et al. 2003). However, at the later epochs, the photospheric velocity of SN 2007ru is comparable to those of SN 1998bw and SN 2003jd and higher than other SNe Ic in comparison. Except for the early phase ( $< 15$  days after explosion) the photospheric velocity evolution of SN 2007ru is very similar to that of the broad-line SN 2003jd.

#### 4.2. Nebular spectrum

The spectrum of SN 2007ru taken  $\sim 200$  days after explosion (refer Fig 8) is dominated by the forbidden emission lines of [OI]  $\lambda\lambda$ 6300, 6364 and [CaII]  $\lambda\lambda$ 7291, 7323, possibly blended with [OII]  $\lambda\lambda$ 7320, 7330 (Taubenberger et al. 2006). These lines show a broad profile. Due to poor signal-to-noise ratio of our spectrum it is difficult to identify other spectral lines in the spectrum. However, narrow lines due to H $\alpha$ , [NII]  $\lambda$ 6583, [SII]  $\lambda\lambda$ 6713, 6731, originating from the underlying HII region at the supernova location and superimposed on the spectrum of the supernova, are clearly seen in the spectrum, and are identified in Fig 8.

A comparison of the nebular spectrum of SN 2007ru is made with those of other SNe Ic in Fig 8. The line pro-

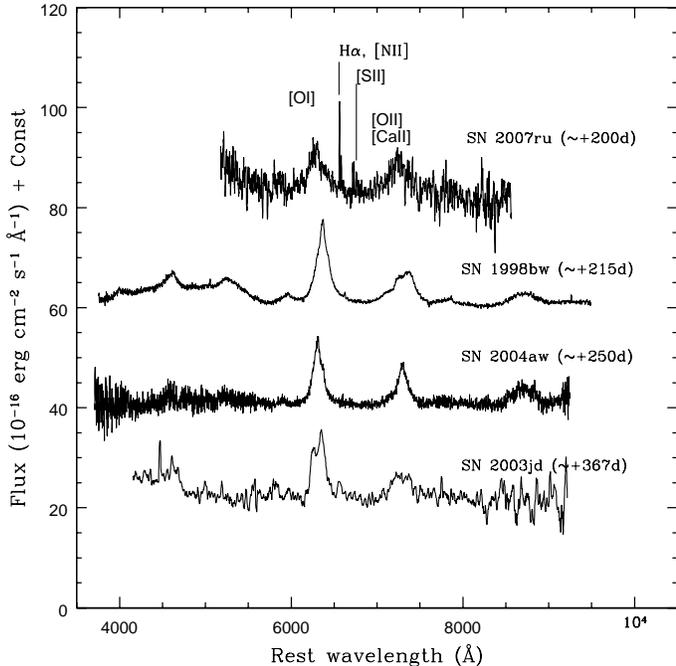


FIG. 8.— Comparison of the nebular spectrum of SN 2007ru with other Type Ic supernovae.

file of the [OI]  $\lambda\lambda 6300, 6364$  lines shows a sharp peak, very similar to that seen in SN 1998bw, SN 2004aw and SN 2007ru. Interestingly, despite the spectral similarity between SN 2007ru and SN 2003jd at early phase, the [OI] line profile in the nebular spectra is different: SN 2003jd shows a double peaked structure (see §7 for implications). The profile of [CaII]  $\lambda\lambda 7291, 7323$ /[OII]  $\lambda\lambda 7320, 7330$  line is similar to the [OI] line profile, as seen in SN 2004aw (Taubenberger et al. 2006), but different from the profiles seen in SNe 1998bw and 2003jd, which show a flat topped profile.

The [OI]  $\lambda\lambda 6300, 6364$  and [CaII]  $\lambda\lambda 7291, 7323$  lines show a blueshift of  $2300 \pm 300$  km sec $^{-1}$  and  $1200 \pm 200$  km sec $^{-1}$ , respectively. This could be due to a kinematic offset (Maeda et al. 2007), optical depth effect (Filipenko et al. 1994), or extinction by the dust formed in the SN ejecta (although there is no strong indication of the dust formation in the light curve (§3))

The velocities derived from full width at half maximum of [OI] and [CaII] lines are found to be  $14000 \pm 2200$  km sec $^{-1}$  and  $13500 \pm 1300$  km sec $^{-1}$ , respectively. These values are comparable to those seen in SN 1998bw and SN 2003jd. The reddening corrected [OI]/[CaII] flux ratio is found to be  $\sim 1.6$ , which is again comparable to the ratios in SN 1998bw and SN 2003jd. Thus, though the profile of the [OI] and [CaII] lines in the the nebular spectrum of SN 2007ru and SN 2003jd differ, other properties like line width and [OI]/[CaII] flux ratio are similar.

## 5. BOLOMETRIC LIGHT CURVE

Direct distance estimates to the host galaxy of SN 2007ru are not available in the literature. The radial velocity of UGC 12381, corrected for Local Group infall onto the Virgo Cluster is  $4832$  km sec $^{-1}$  (LEDA). For  $H_0 = 72$  km sec $^{-1}$  Mpc $^{-1}$ , the distance modulus to UGC

12381 is  $34.15 \pm 0.10$ , where the error is estimated taking into account the errors in HI velocity measurement of the galaxy (Paturel et al. 2003) and the uncertainty in  $H_0$ .

The NaID absorption line is clearly seen in the spectrum with an average equivalent width of  $1.67 \pm 0.37$  Å. Based on the equivalent widths of NaID absorption seen in several SNe, Turatto et al. (2003) find two distinct relations between NaID equivalent width and the reddening  $E(B - V)$ . Using these relations, the observed NaID equivalent width indicates  $E(B - V)$  values of  $0.85 \pm 0.19$  and  $0.27 \pm 0.06$ . The Galactic interstellar reddening in the direction of UGC 12381 is estimated to be 0.26 (Schlegel, Finkbeiner & Davis 1998). The NaID absorption seen in the spectra of SN 2007ru is clearly from the Milky Way galaxy and no component due to the host galaxy is detected. Hence, an  $E(B - V)$  value of 0.27 is used for extinction correction.

The quasi bolometric LC of SN 2007ru is estimated using the  $UBVRI$  magnitudes corrected for reddening with  $E(B - V) = 0.27$  and the Cardelli et al. (1989) extinction law. The magnitudes were converted to the monochromatic flux, using zero points from Bessell et al. (1998). The fluxes were then spline interpolated and integrated from  $3100\text{Å}$  to  $1.06\mu\text{m}$ . Since  $U$  band observations are not available beyond 35 days since  $B$  maximum, the bolometric LC is estimated by integrating the  $BVRI$  fluxes only. The contribution of  $U$  band to the bolometric flux at phases  $\sim 35$  days is estimated to be  $\lesssim 10\%$ . In the later phases when only  $V, R, I$  or  $V, R$  magnitudes are available, the bolometric magnitudes are derived by applying a bolometric correction to the available magnitudes. The bolometric corrections were estimated based on the last four points for which  $B, V, R$  and  $I$  measurements are available.

The quasi bolometric LC is shown in Fig 9. Adding a conservative uncertainty of  $\pm 0.2$ , the bolometric magnitude at maximum is estimated as  $-18.78 \pm 0.2$ . The quasi bolometric LCs, estimated in a similar manner, for SN 1998bw, SN 2002ap, SN 2004aw and SN 1994I, are also plotted in Fig. 9. The quasi bolometric LC of SN 2007ru is brighter than the other well studied non-GRB broad-line SN 2002ap and normal SNe Ic, and comparable to SN 1998bw. The decline in the bolometric LC of SN 2007ru is considerably faster than SN 1998bw and comparable to SN 2002ap.

Using Arnett's rule (Arnett 1982), the mass of  $^{56}\text{Ni}$  required to power the quasi bolometric LC of SN 2007ru is estimated to be  $0.33M_{\odot}$ , whereas it is  $0.36M_{\odot}$  for SN 1998bw (Fig. 9). It is to be noted here that the contribution due to NIR bands is not included in the bolometric LC. The NIR contribution to bolometric flux for broad-line SNe 2002ap and 1998bw is  $\sim 30\%$  (Tomita et al. 2006, Valenti et al. 2008), whereas for SN 1994I it is only  $\sim 10\%$ , while for SN 2004aw the NIR contribution increases from  $\sim 31\%$  to  $\sim 45\%$  between +10 and +30 days (Taubenberger et al. 2006). Assuming an NIR contribution to the bolometric flux similar to SNe 2002ap and 1998bw ( $\sim 30\%$ ), the mass of  $^{56}\text{Ni}$  for SN 2007ru is estimated to be  $\sim 0.4M_{\odot}$ . The total rate of energy production via  $^{56}\text{Ni} - ^{56}\text{Co}$  chain estimated using the analytical formula by Nadyozhin (1994), for different values of mass of  $^{56}\text{Ni}$  synthesized during the explosion and are plotted with the quasi bolometric LC (thin lines) in



The maximum luminosity of SN 2007ru is comparable to SN 1998bw. The light curve reaches a peak in only  $\sim 8 \pm 3$  days, which is remarkably faster than in SN 1998bw ( $\sim 20$  days). The mass of  $^{56}\text{Ni}$  ejected in SN 2007ru is estimated as  $\sim 0.4M_{\odot}$ , which is similar to that estimated for SNe 1998bw and 2003jd, slightly larger than that for SN 2004aw, and much larger than that for the broad-line SNe 2002ap and 2006aj and the normal SN Ic 1994I (Table 4).

From the rise time of the light curve ( $\tau$ ) and the expansion velocity ( $v$ ), we estimate mass of SN ejecta ( $M_{\text{ej}}$ ) and the kinetic energy of the ejecta ( $E_{\text{K}}$ ). If the optical opacity is assumed to be constant, the timescale of the light curve is expressed as  $\tau \propto M_{\text{ej}}^{3/4} E_{\text{K}}^{-1/4}$  (Arnett 1982).

The expansion velocity is given by  $v \propto M_{\text{ej}}^{-1/2} E_{\text{K}}^{1/2}$ . The rise time of SN 2007ru ( $8 \pm 3$  days) is comparable to that of the well studied SN 1994I, while the expansion velocity ( $v = 20,000 \text{ km sec}^{-1}$  at maximum) is about twice. Assuming  $M_{\text{ej}} = 1.0M_{\odot}$  and  $E_{\text{K}} = 1.0 \times 10^{51}$  ergs for SN 1994I (see Table 4), and the observed expansion velocity of SN 2007ru, we estimate  $M_{\text{ej}} = 1.3_{-0.8}^{+1.1}M_{\odot}$  and  $E_{\text{K}} = 5_{-3.0}^{+4.7} \times 10^{51}$  ergs for SN 2007ru. A similar analysis for SN 1998bw, assuming the rise time and the velocity of SN 1998bw to be twice that of SN 1994I, leads to  $M_{\text{ej}} \approx 8M_{\odot}$  and  $E_{\text{K}} \approx 30 \times 10^{51}$  ergs, qualitatively consistent with the results of detailed modelling (Iwamoto et al. 1998; Nakamura et al. 2001)<sup>5</sup>. If we take SN 2003jd as a reference (Valenti et al. 2008),  $M_{\text{ej}} = 1.7_{-1.0}^{+1.5}M_{\odot}$  and  $E_{\text{K}} = 8.6_{-5.2}^{+7.2} \times 10^{51}$  ergs are derived for SN 2007ru. It should however be noted, that a detailed modelling is required to derive accurate values of  $M_{\text{ej}}$  and  $E_{\text{K}}$ <sup>6</sup>.

SN 2007ru has a large kinetic energy while the ejecta mass is close to that of normal SNe Ic. Studies of SNe Ic (e.g., Nomoto et al. 2007) have shown a trend, although weak, wherein SNe having massive ejecta tend to have a larger kinetic energy and eject more  $^{56}\text{Ni}$ , connecting normal SNe to GRB-associated SNe. In contrast to this trend, SN 2007ru which resides at the higher energy end has a lower mass ejecta, leading to a higher  $E/M$ . SN 2007ru thus adds to the diversity of SNe Ic.

The spectroscopic properties of SN 2007ru at early phases are most similar to SN 2003jd. Also if we take the higher end of  $M_{\text{ej}}$ , the ejecta properties of SN 2007ru are also close to those of SN 2003jd (although the estimated  $E/M$  is higher for SN 2007ru). However, the [OI] line profiles in the nebular spectra are dissimilar. SN 2007ru shows a single peaked profile while SN 2003jd shows a

double-peaked profile. In aspherical explosions, we would expect a single-peaked [OI] profile for the polar-viewed case, and a double-peaked profile for the side-viewed case (Mazzali et al. 2005; Maeda et al. 2008; Modjaz et al. 2008a). Also, the polar-viewed aspherical explosion tends to show a brighter peak (Maeda et al. 2006) and faster velocity (Tanaka et al. 2007). This matches with the properties of SN 2007ru. Thus, we suggest that SN 2007ru could be an aspherical explosion viewed from the polar direction. Detailed multidimensional modelling is required to answer if the high  $E/M$  derived for SN 2007ru results from the effect of asphericity.

The nebular spectrum of SN 2007ru shows narrow emission lines due to H $\alpha$ , [NII], [SII] and [SIII], arising from the underlying/neighbouring host galaxy HII region. The flux ratios indicate an oxygen abundance of  $\sim 8.8$  in the region of the supernova. The nearly solar oxygen abundance at the location of the supernova matches well with earlier abundance studies for supernova host galaxies.

The nuclear spectrum of the host galaxy of SN 2007ru shows broad hydrogen Balmer lines, with an asymmetric blue wing. Emission lines due to FeII are also fairly prominent. Low ionization emission lines are also present. It appears that the galaxy hosts a mild AGN with nuclear HII region.

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<sup>5</sup> Given the very high  $M_{\text{Ni}}/M_{\text{ej}}$  ratio ( $\sim 0.3$ ), the higher end of the ejecta mass may be preferred ( $M_{\text{ej}} \sim 2.4M_{\odot}$ , and  $E_{\text{K}} \sim 9.7 \times 10^{51}$  erg). Since the explosion with a larger kinetic energy can produce a larger amount of  $^{56}\text{Ni}$ , the large  $^{56}\text{Ni}$  mass in SN 2007ru may also support this.

<sup>6</sup> An attempt was made to estimate the mass of the ejecta  $M_{\text{ej}}$  and kinetic energy  $E_{\text{K}}$  using the width of the light curve. The width is defined as the time from peak of the bolometric light curve

to the time when the luminosity is equal to the  $1/e$  times the peak luminosity, which is equivalent to a decline of 1.1 mag from peak. The derived width is  $\sim 18$  days for SN 2007ru. With this value, we have estimated  $M_{\text{ej}}$  and  $E_{\text{K}}$  in the same manner and derived larger values of  $M_{\text{ej}}$  and  $E_{\text{K}}$  ( $M_{\text{ej}} \sim 4.5M_{\odot}$  and  $E_{\text{K}} \sim 20 \times 10^{51}$  erg). Our conclusion of large  $E/M$  is thus not affected.

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TABLE 1  
MAGNITUDES FOR THE SEQUENCE OF SECONDARY STANDARD STARS IN THE FIELD OF SN  
2007RU.\*

ID	U	B	V	R	I
1	14.433 ± 0.015	14.396 ± 0.006	13.877 ± 0.005	13.531 ± 0.005	13.116 ± 0.006
2	14.918 ± 0.017	14.790 ± 0.013	14.073 ± 0.018	13.618 ± 0.016	13.111 ± 0.023
3	15.111 ± 0.020	15.020 ± 0.016	14.343 ± 0.020	13.953 ± 0.017	13.488 ± 0.024
4	15.870 ± 0.030	15.554 ± 0.010	14.714 ± 0.021	14.232 ± 0.012	13.689 ± 0.019
5	16.105 ± 0.030	15.670 ± 0.021	14.796 ± 0.024	14.317 ± 0.002	13.783 ± 0.004
6	15.390 ± 0.025	15.339 ± 0.014	14.780 ± 0.022	14.406 ± 0.021	13.995 ± 0.021
7	15.773 ± 0.032	15.616 ± 0.019	14.869 ± 0.024	14.444 ± 0.024	13.933 ± 0.030
8	16.138 ± 0.030	15.900 ± 0.012	15.046 ± 0.021	14.550 ± 0.023	13.985 ± 0.030
9	16.792 ± 0.036	16.136 ± 0.018	15.139 ± 0.022	14.553 ± 0.014	13.951 ± 0.025
10	17.312 ± 0.045	16.619 ± 0.017	15.631 ± 0.017	15.066 ± 0.014	14.471 ± 0.014
11	17.321 ± 0.040	16.730 ± 0.014	15.739 ± 0.025	15.153 ± 0.014	14.555 ± 0.021
12	17.970 ± 0.052	16.954 ± 0.019	15.766 ± 0.025	15.083 ± 0.024	14.362 ± 0.031
13	16.552 ± 0.045	16.505 ± 0.020	15.796 ± 0.030	15.368 ± 0.026	14.864 ± 0.030
14	17.518 ± 0.050	16.997 ± 0.005	16.045 ± 0.018	15.513 ± 0.018	14.937 ± 0.027

\*The stars are identified in Figure. 1

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TABLE 2  
PHOTOMETRIC OBSERVATIONS OF SN 2007RU

Date	J.D. 2454000+	Phase* (days)	U	B	V	R	I
02/12/2007	437.086	-2	16.318 ± 0.021	16.562 ± 0.016	16.036 ± 0.011	15.798 ± 0.022	15.426 ± 0.020
04/12/2007	439.155	0	16.299 ± 0.029	16.533 ± 0.120	15.951 ± 0.015	15.678 ± 0.019	15.296 ± 0.056
10/12/2007	445.029	6	16.943 ± 0.034	17.036 ± 0.008	16.025 ± 0.012	15.726 ± 0.012	15.244 ± 0.014
11/12/2007	446.047	7	17.211 ± 0.045	17.172 ± 0.019	16.070 ± 0.011	15.746 ± 0.008	15.215 ± 0.011
12/12/2007	447.027	8	17.346 ± 0.067	17.296 ± 0.019	16.121 ± 0.011	15.759 ± 0.014	15.265 ± 0.016
18/12/2007	453.046	14		18.078 ± 0.039	16.598 ± 0.014	16.111 ± 0.035	15.501 ± 0.010
19/12/2007	454.056	15		18.114 ± 0.019	16.687 ± 0.012	16.184 ± 0.007	15.553 ± 0.017
22/12/2007	457.067	18		18.430 ± 0.024	16.954 ± 0.011	16.404 ± 0.011	15.738 ± 0.013
24/12/2007	459.097	20		18.540 ± 0.090	17.034 ± 0.070	16.512 ± 0.095	15.799 ± 0.095
25/12/2007	460.069	21		18.596 ± 0.017	17.140 ± 0.035	16.621 ± 0.016	15.929 ± 0.060
26/12/2007	461.079	22	18.889 ± 0.040	18.681 ± 0.021	17.221 ± 0.024	16.711 ± 0.010	16.031 ± 0.016
30/12/2007	465.061	26	18.990 ± 0.038	18.902 ± 0.032	17.460 ± 0.008	16.956 ± 0.013	16.278 ± 0.008
31/12/2007	466.029	27	19.118 ± 0.060	18.902 ± 0.036	17.517 ± 0.014	17.069 ± 0.024	16.329 ± 0.031
04/01/2008	470.045	31	19.241 ± 0.069	19.057 ± 0.021	17.741 ± 0.024	17.252 ± 0.015	16.532 ± 0.016
21/01/2008	487.041	48			18.509 ± 0.096	17.964 ± 0.037	17.181 ± 0.022
24/01/2008	490.063	51		19.629 ± 0.021	18.501 ± 0.019	18.130 ± 0.014	17.382 ± 0.031
03/02/2008	500.055	61		19.754 ± 0.044	18.665 ± 0.0924	18.282 ± 0.023	17.597 ± 0.082
29/02/2008	526.068	87			19.300 ± 0.026	19.075 ± 0.050	18.395 ± 0.109
03/05/2008	590.431	151			20.377 ± 0.19	20.007 ± 0.15	19.506 ± 0.164
06/06/2008	624.400	185			20.921 ± 0.20	20.325 ± 0.169	
17/06/2008	635.360	196			21.083 ± 0.088	20.466 ± 0.133	
03/07/2008	651.348	212			21.115 ± 0.084	20.483 ± 0.128	

\* Observed phase with respect to the epoch of maximum in *B* band (JD 2454438.8).

TABLE 3  
LOG OF SPECTROSCOPIC OBSERVATIONS OF SN 2007RU

Date	J.D. 2454000+	Phase* (days)	Range Å
03/12/07	438.21	+8	5200-9100
10/12/07	445.06	+15	3500-7000; 5200-9100
11/12/07	446.07	+16	3500-7000; 5200-9100
15/12/07	450.14	+20	3500-7000; 5200-9100
19/12/07	454.13	+24	3500-7000; 5200-9100
22/12/07	457.09	+27	3500-7000
04/01/08	470.09	+40	3500-7000; 5200-9100
03/02/08	500.08	+70	3500-7000
12/06/08	630.38	+200	5200-9100

\* Relative to the epoch of date of explosion JD = 2454430

TABLE 4  
COMPARISON OF PARAMETERS OF SNE IC

	$M_V$	$\Delta m_{15}(V)$	$\gamma_V$	$\gamma_R$	$\gamma_I$	$E_K/10^{51}$ ergs	$M_{ej}/M_\odot$	$M_N/M_\odot$	$E_K/M_{ej}$	References
SN 1994I	-17.62	1.65	0.029	0.028	0.026	1	0.9-1	0.07(0.07)	~ 1	1, 2, 3
SN 2004aw	-18.02	0.62	0.014	0.017	0.015	3.5-9.0	3.5-8.0	0.25-0.35(0.2)	~ 1	4
SN 2003jd	-18.9	1.44	0.022	0.022	0.029	$7^{+3}_{-2.0}$	$3.0 \pm 1.0$	0.36	~ 2.3	5
SN 2002ap	-17.35	0.87				4	2.5	0.1(0.06)	~ 1.6	6, 7, 8
SN 2007ru	-19.06	0.92	0.021	0.028	0.030	$5^{+4.7}_{-3.0}$	$1.3^{+1.1}_{-0.8}$	0.4	~ 3.8	This work
SN 1998bw	-19.13	0.75	0.020	0.022	0.022	30	10	0.40(0.5)	~ 3	9, 10, 11
SN 2006aj	-18.7	1.14				2	2	0.21	~ 1	12, 13

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\*  $M_N$  given in parenthesis are the values estimated using the Arnett's rule (including NIR contribution in the bolometric light curves, see text),  $\gamma$  represents the magnitude decline rates (mag/day) between 45 - 80 days