The BROAD-LINE TYPE Ic SUPERNOVA SN 2007ru: ADDING TO THE DIVERSITY OF TYPE Ic SUPERNOVAE

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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 (SNe Ic). It is lower than SN 1998bw at ∼8 days after the explosion, but is comparable at later epochs. The light curve (LC) evolution of SN 2007ru indicates a fast rise time of 8 ± 3 days to B-band maximum and postmaximum decline more rapid than other broad-line SNe Ic. 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 SNe Ic. The ejected mass of ^{56}Ni is estimated to be ∼0.4 $M_\odot$. The fast rise and decline of the LC and the high expansion velocity suggest that SN 2007ru is an explosion with a high kinetic energy/ejecta mass ratio (E_K/M_{ej}). This adds to the diversity of SNe Ic. Although the early phase spectra are most similar to those of broad-line SN 2003jd, the [O I] 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(O/H) of ∼8.8 indicates that SN 2007ru occurred in a region with nearly solar metallicity.

Key words: supernovae: general – supernovae: individual (SN 2007ru)

Online-only material: color figures

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}Ni produced during the explosion. The photometric and spectral features of SN 1998bw are explained with ∼10 $M_\odot$ ejected with a kinetic energy $(2–5) \times 10^{52}$ ergs, producing 0.4–0.5 $M_\odot$ of ^{56}Ni in the explosion (Iwamoto et al. 1998; Nakamura et al. 2001; Maeda et al. 2006; Tanaka et al. 2007). On the other hand, modeling of nebular spectra of SN 2002ap indicates an ejected mass of ∼2.5 $M_\odot$ with a kinetic energy ∼4 × 10^{51} erg and production of ∼0.1 $M_\odot$ of ^{56}Ni (Mazzali et al. 2007), showing a large range in the physical parameters of broad-line SNe Ic. Among these, SNe with kinetic energy $E_K > 10^{52}$ erg 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 Katzman Automatic Imaging Telescope (KAIT) on November 30.15 in the spiral galaxy UGC 12381. There was no evidence of the supernova (SN) in the KAIT image taken on November 22.16, down to a limiting magnitude of 18.9 (Donati et al. 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 Ca II H and K and Ca II near-infrared (NIR) triplet absorption troughs were found to be weak compared to other SNe Ic. Further, the O I line at 7774 Å indicated an expansion velocity of 19,000 km s^{-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 2007 October 15 to November 30 does not show any possible association of a GRB with this SN.

The results of photometric and spectral monitoring of SN 2007ru until around 210 days after maximum, using the 2 m 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 3 (JD 2454651.35). The observations were carried out with the Himalayan Faint Object Spectrograph Camera (HFOSC) mounted on the HCT. HFOSC is equipped with 2 k × 4 k pixels CCD chip. The central 2 k × 2 k region, with a plate scale of 0.296 arcsec pixel^{-1}, covering a field of 10′ × 10′, was used for imaging. Gain and readout noise of the CCD camera are 1.22 e$^-$/ADU and 4.87e$^-$, respectively. Further details on the HCT and HFOSC can be obtained from http://www.iiap.res.in/centers/iao.

Photometric standard regions (Landolt 1992) were observed on 2007 December 25 and December 26 under photometric sky

Table 1
Magnitudes for the Sequence of Secondary Standard Stars in the Field of SN 2007ru[a]

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

Note.[a]The stars are identified in Figure 1.
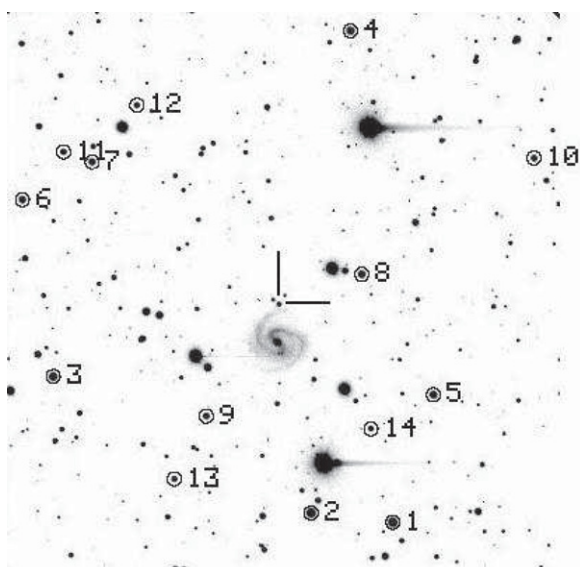
Figure 1. Identification chart for SN 2007ru. The stars used as local standards are marked as numbers 1–14.

conditions to calibrate a sequence of secondary standards in the SN field. Data reduction has been done in the standard manner using various tasks available within Image Reduction and Analysis Facility (IRAF).[5] 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 color terms and the photometric zero points determined on the individual night. A sequence of secondary standards calibrated in this way is marked in Figure 1 and the *UBVRI* magnitudes of the secondary standards averaged over the two nights are listed in Table 1. The magnitudes of the SN and secondary standards were measured using point-spread function photometry, with a fitting radius equal to the full width at half-maximum (FWHM) of the stellar profile. SN magnitudes were calibrated differentially with respect to the local standards. The SN magnitudes in *U*, *B*, *V*, *R*, and *I* bands have been listed in Table 2.

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

2.2. Spectroscopy

A series of spectra were taken during 2007 December 3 to 2008 June 12, in the wavelength range (3500–7000 Å) and (5200–9200 Å), with a resolution of $\sim$7 Å. The journal of spectroscopic observations is given in Table 3. The spectrophotometric standard stars were observed on the same night to flux calibrate the SN 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 response correction was done by 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 SN spectra were corrected for the host galaxy redshift of $z = 0.01546$ (from NASA/IPAC Extragalactic Database (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 (LCs) of SN 2007ru are shown in Figure 2. The unfiltered discovery magnitudes and the prediscovery 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 $\sim\lesssim$6 days before discovery (November 25, JD 2454430 $\pm$ 3), based on the nondetection 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 ± 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 LCs 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 Figure 3. A comparison of the decline in brightness 15 days after maximum light, Δm_{15} in different bands shows that SN 2007ru has a decline similar to other broad-line SNe. In fact, the decline of SN 2007ru is faster

Table 2
Photometric Observations of SN 2007ru

Date	JD 2454000+	Phase[a] (days)	U	B	V	R	I
2 Dec 2007	437.086	−2	16.318 ± 0.021	16.562 ± 0.016	16.036 ± 0.011	15.798 ± 0.022	15.426 ± 0.020
4 Dec 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 Dec 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 Dec 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 Dec 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 Dec 2007	453.046	14		18.078 ± 0.039	16.598 ± 0.014	16.111 ± 0.035	15.501 ± 0.010
19 Dec 2007	454.056	15		18.114 ± 0.019	16.687 ± 0.012	16.184 ± 0.007	15.553 ± 0.017
22 Dec 2007	457.067	18		18.430 ± 0.024	16.954 ± 0.011	16.404 ± 0.011	15.738 ± 0.013
24 Dec 2007	459.097	20		18.540 ± 0.090	17.034 ± 0.070	16.512 ± 0.095	15.799 ± 0.095
25 Dec 2007	460.069	21		18.596 ± 0.017	17.140 ± 0.035	16.621 ± 0.016	15.929 ± 0.060
26 Dec 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 Dec 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 Dec 2007	466.029	27	19.118 ± 0.060	18.902 ± 0.036	17.517 ± 0.014	17.069 ± 0.024	16.329 ± 0.031
4 Jan 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 Jan 2008	487.041	48			18.509 ± 0.096	17.964 ± 0.037	17.181 ± 0.022
24 Jan 2008	490.063	51		19.629 ± 0.021	18.501 ± 0.019	18.130 ± 0.014	17.382 ± 0.031
3 Feb 2008	500.055	61		19.754 ± 0.044	18.665 ± 0.0924	18.282 ± 0.023	17.597 ± 0.082
29 Feb 2008	526.068	87			19.300 ± 0.026	19.075 ± 0.050	18.395 ± 0.109
3 May 2008	590.431	151			20.377 ± 0.19	20.007 ± 0.15	19.506 ± 0.164
6 Jun 2008	624.400	185			20.921 ± 0.20	20.325 ± 0.169	
17 Jun 2008	635.360	196			21.083 ± 0.088	20.466 ± 0.133	
3 Jul 2008	651.348	212			21.115 ± 0.084	20.483 ± 0.128	

Note. [a] Observed phase with respect to the epoch of maximum in B band (JD 2454438.8).

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 LCs of SN 2007ru decline with decline rates of 0.021 mag day^{-1} in V, 0.028 mag day^{-1} in R, and 0.030 mag day^{-1} in I bands during days 45–80. These decline rates are comparable to the LC 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 LCs of SN 2007ru decline with decline rates of 0.0152 and 0.0116 mag day^{-1}, respectively, slower than both SN 2003jd and SN 1998bw during the corresponding epochs (Figure 3). The decline rate of SN 2007ru during the late phases, is faster than the rate expected due to the radio active decay of ^{56}Co into ^{56}Fe. This indicates inefficient trapping of γ-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 Section 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 ± 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 GRB 980425/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 (MV = -18.02 ± 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,

Table 3
Log of Spectroscopic Observations of SN 2007ru

Date	JD 2454000+	Phase[a] (days)	Range (Å)
3 Dec 2007	438.21	+8	5200–9100
10 Dec 2007	445.06	+15	3500–7000; 5200–9100
11 Dec 2007	446.07	+16	3500–7000; 5200–9100
15 Dec 2007	450.14	+20	3500–7000; 5200–9100
19 Dec 2007	454.13	+24	3500–7000; 5200–9100
22 Dec 2007	457.09	+27	3500–7000
4 Jan 2008	470.09	+40	3500–7000; 5200–9100
3 Feb 2008	500.08	+70	3500–7000
12 Jun 2008	630.38	+200	5200–9100

Note. [a] Relative to the epoch of date of explosion JD = 2454430.

where t is days after explosion (the rise time is assumed to be 8 days, see Section 3) shows broad absorption features at ~ 6000 Å due to Si II (and a possible contamination as discussed by Valenti et al. 2008), at ~ 7200 Å due to O I, and at ~ 8200 Å due to weak Ca II NIR triplet. The spectrum at $t \sim 20$ days shows well-developed broad absorptions due to Mg II $\lambda 4481$, blends of Fe II at ~ 4700 Å, Si II $\lambda 6355$, O I $\lambda 7774$, and Ca II NIR triplet. The continuum gets redder by $t \sim 20$ days. No significant evolution is seen in the spectrum taken at $t \sim 40$ days. The last spectrum presented here, obtained ~ 200 days after explosion indicates the SN 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 (Figures 5 and 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 $t \sim 40$ days.

4.1. Photospheric Velocity

The high velocity of the SN ejecta usually results in blending of the spectral lines, making direct measurement of the

Table 4
Comparison of Parameters of SNe Ic

SN	M_V	Δm_{15} (V)	γ_V	γ_R	γ_I	$E_K/10^{51}$ ergs	$M_{ej}/M_\odot$	$M_{Ni}/M_\odot{}^{a}$	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 ± 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

Notes.
[a] M_{Ni} given in parenthesis are the values estimated using the Arnett's rule (including NIR contribution in the bolometric light curves, see the text), γ represents the magnitude decline rates (mag day^{-1}) between 45 and 80 days.

References. (1) Richmond et al. (1996); (2) Nomoto et al. (1994); (3) Sauer et al. (2006); (4) Taubenberger et al. (2006); (5) Valenti et al. (2008); (6) Mazzali et al. (2007); (7) Foley et al. (2003); (8) Tomita et al. (2006); (9) Galama et al. (1998); (10) Iwamoto et al. (1998); (11) Nakamura et al. (2001); (12) Modjaz et al. (2006); (13) Mazzali et al. (2006).
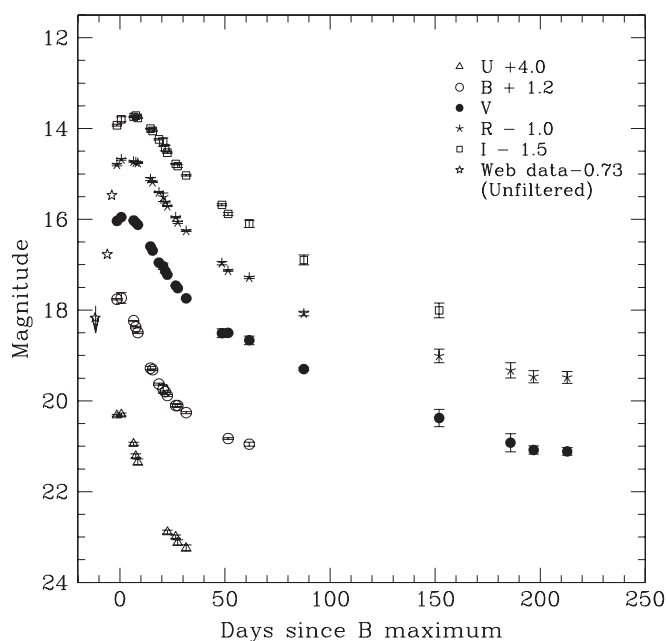
Figure 2. *UBVRI* LCs of SN 2007ru. The LCs have been shifted by the amount indicated in the legend. The unfiltered magnitudes reported by amateurs and the prediscovery limiting magnitudes have been included with *R*-band magnitudes in the figure.

Figure 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.
(A color version of this figure is available in the online journal.)

photospheric velocity difficult. The photospheric velocity of SN 2007ru is estimated by fitting a Gaussian profile to the minimum of the absorption trough of Si II 6355 Å line, in the redshift-corrected spectra. In the first spectrum, ∼8 days after the explosion, the absorption feature at 6200 Å consists of two components, similar to that seen in the premaximum spectra of the broad-line SN 2003jd (Valenti et al. 2008). Assuming 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 s^{-1}. This is consistent with the velocity estimated by Chornock et al. (2007) using O I 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 Figure 7. The photospheric velocity of SN 2007ru at ∼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 ∼200 days after explosion (refer Figure 8) is dominated by the forbidden emission lines of [O I] λλ6300, 6364 and [Ca II] λλ7291, 7323, possibly blended with [O II] λλ7320, 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 Hα, [N II] λ6583, and [S II] λλ6717, 6731, originating from the underlying H II region at the SN location and superimposed on the spectrum of the SN, are clearly seen in the spectrum, and are identified in Figure 8.

A comparison of the nebular spectrum of SN 2007ru is made with those of other SNe Ic in Figure 8. The line profile of
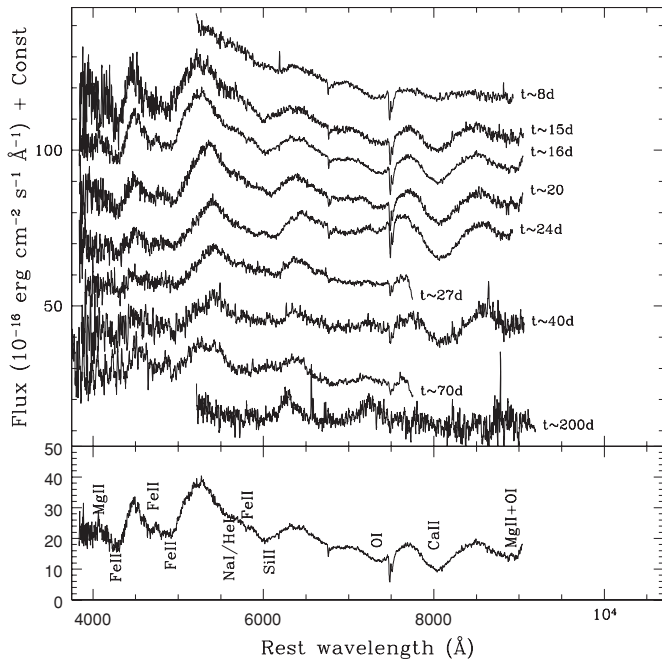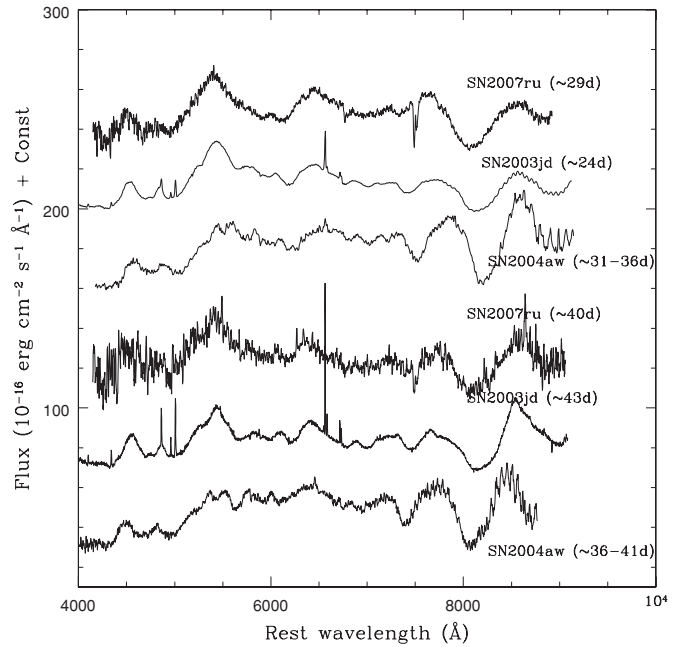
Figure 4. Optical spectral evolution of SN 2007ru (top panel). The spectra are corrected for the host galaxy redshift. Time in days since the day of explosion (2008 November 25; see the text) is indicated for each spectrum. For clarity, the spectra have been displaced vertically. Main spectral features are identified and marked in the spectrum taken ~16 days after explosion (bottom panel).
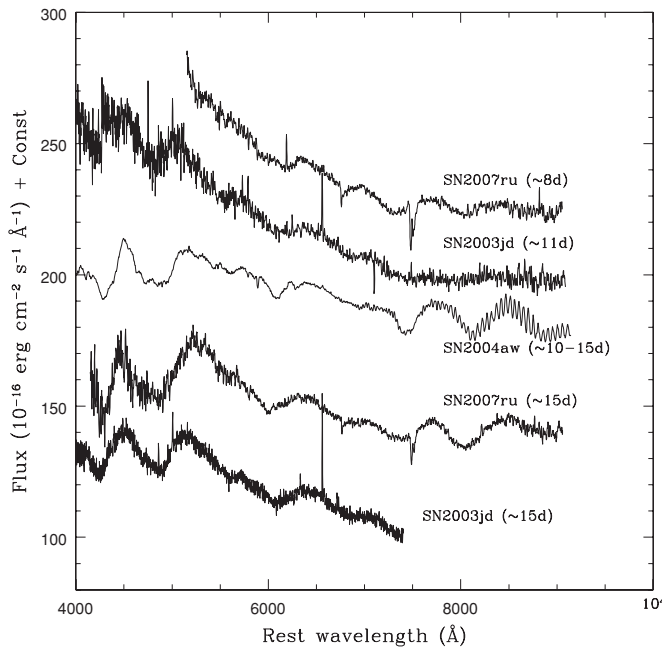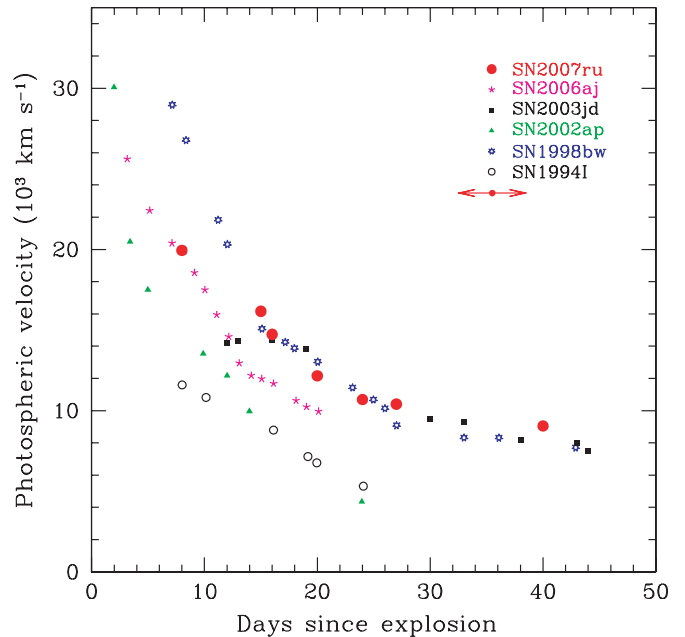

Figure 5. Comparison of spectra of SN 2007ru with broad-line type Ic SN 2003jd and normal spectrum type Ic SN 2004aw at different epochs.

Figure 6. Same as Figure 5 but at different epochs.

Figure 7. Evolution of the photospheric velocity of SN 2007ru and other SNe Ic inferred from Si II λ 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.

(A color version of this figure is available in the online journal.)

the [O I] $\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 [O I] line profile in the nebular spectra is different: SN 2003jd shows a double-peaked structure (see Section 7 for implications). The profile of [Ca II] $\lambda\lambda$7291, 7323/[O II] $\lambda\lambda$7320, 7330 line is similar to the [O I] 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 [O I] $\lambda\lambda$6300, 6364 and [Ca II] $\lambda\lambda$7291, 7323 lines show a blueshift of 2300 $\pm$ 300 km s^{-1} and 1200 $\pm$ 200 km s^{-1}, respectively. This could be due to a kinematic offset (Maeda et al. 2007), optical depth effect (Filippenko 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 LC (Section 3)).

The velocities derived from FWHM of [O I] and [Ca II] lines are found to be 14000 $\pm$ 2200 km s^{-1} and 13500 $\pm$ 1300 km s^{-1}, respectively. These values are comparable to those seen in SN 1998bw and SN 2003jd. The reddening-corrected [O I]/[Ca II] flux ratio is found to be ~1.6, which is again

comparable to the ratios in SN 1998bw and SN 2003jd. Thus, though the profile of the [O I] and [Ca II] lines in the nebular spectrum of SN 2007ru and SN 2003jd differ, other properties like line width and [O I]/[Ca II] flux ratio are similar.
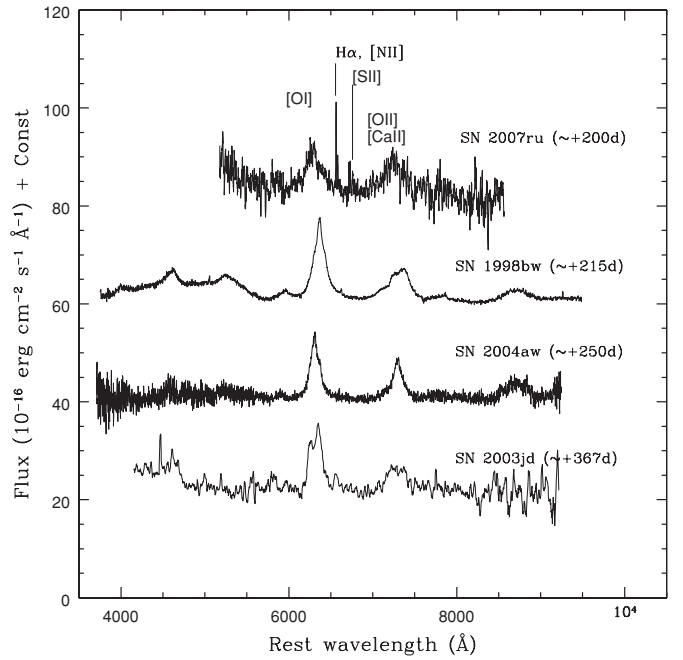
5. BOLOMETRIC LIGHT CURVE

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 s^{-1} (LEDA). For $H_0 = 72$ km s^{-1} Mpc^{-1}, the distance modulus to UGC 12381 is 34.15 ± 0.10, where the error is estimated taking into account the errors in H I 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 ± 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 ± 0.19 and 0.27 ± 0.06. The Galactic interstellar reddening in the direction of UGC 12381 is estimated to be 0.26 (Schlegel et al. 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.
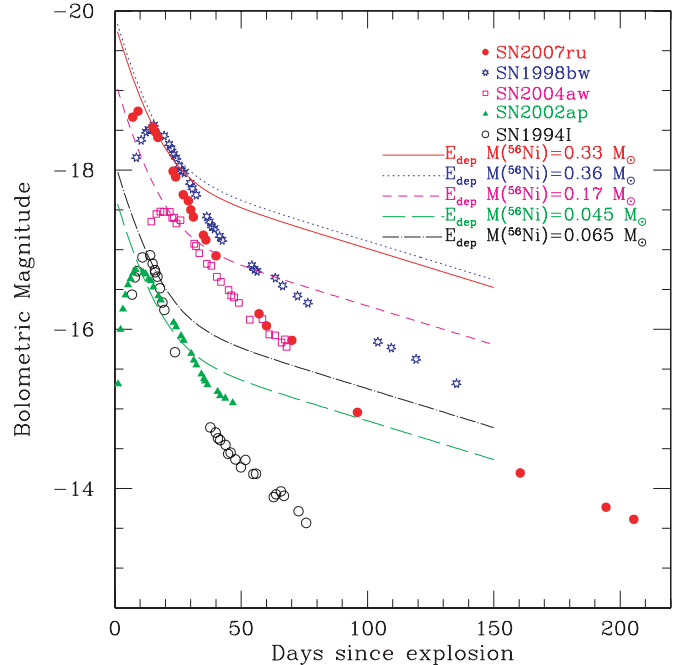
The quasi-bolometric LC of SN 2007ru is estimated using the *UBVRI* magnitudes corrected for reddening with $E(B - V) = 0.27$ and the Cardelli et al. (1989) extinction law. The magnitudes were converted to the monochromatic flux, using zero points from Bessell et al. (1998). The fluxes were then spline interpolated and integrated from 3100 Å to 1.06 μm. 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 ∼35 days is estimated to be ≲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 Figure 9. Adding a conservative uncertainty of ± 0.2, the bolometric magnitude at maximum is estimated as -18.78 ± 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 Figure 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}Ni required to power the quasi-bolometric LC of SN 2007ru is estimated to be 0.33 $M_\odot$, whereas it is 0.36 $M_\odot$ for SN 1998bw (Figure 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 ∼30% (Tomita et al. 2006; Valenti et al. 2008), whereas for SN 1994I it is only ∼10%, while for SN 2004aw the NIR contribution increases from ∼31% to ∼45% between +10 and +30 days (Taubenberger et al. 2006). Assuming an NIR contribution to the bolometric flux similar to SNe 2002ap and 1998bw (∼30%), the mass of ^{56}Ni for SN 2007ru is estimated to be ∼0.4 $M_\odot$. The

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

Figure 9. Quasi-bolometric light curves of SN 2007ru, SN 1998bw, SN2002ap, SN1994I, and SN 2004aw, estimated as explained in the text. The lines represent the rate of energy production via ^{56}Ni–^{56}Co chain for different values of $M(^{56}$Ni).

(A color version of this figure is available in the online journal.)

total rate of energy production via ^{56}Ni–^{56}Co chain estimated using the analytical formula by Nadyozhin (1994), for different values of mass of ^{56}Ni synthesized during the explosion and is plotted with the quasi-bolometric LC (thin lines) in Figure 9. The plots indicate a good match of the energy production rate for 0.33 $M_\odot$ of ^{56}Ni with the initial decline of the quasi-bolometric LC of SN 2007ru, in agreement with the estimate based on Arnett's rule.

6. PROPERTIES OF THE HOST GALAXY OF SN 2007RU

6.1. *The Supernova Region*

An attempt is made to estimate the metallicity of the region where the SN exploded, based on the observed [N II]/Hα flux ratio, from the underlying H II region, superimposed in the nebular spectrum of the SN. Following Pettini & Pagel (2004), the N2 index (log[N II]/Hα) is estimated to be −0.36. Using this, an oxygen abundance of $12 + \log(O/H) = 8.78$ is derived. Another way of deriving oxygen abundance is using the (log[N II]/Hα) diagnostic diagram (Kewley & Dopita 2002), which requires an estimate of the ionization parameter q or U ($U = q/c$; c is the speed of light) also. The ionization parameter U can be estimated from the [S II]/[S III] ratio following Diaz et al. (1991). The observed flux of [S II] lines λλ6717, 6731 and [S III] line λ9069, seen in the nebular spectrum can be used to estimate the ionization parameter, however, our spectrum does not cover the [S III] λ9532 region. In the extragalactic H II regions ratio ([S III]λ9532/[S III]λ9069) is found to vary in the range 1.58–3.77 with an observed mean of 2.66 ± 0.46, against the theoretical value of 2.44 (Diaz et al. 1985; Vilchez & Pagel 1988; Kennicutt & Garnett 1996). This indicates that the ionization parameter q can vary in the range $\sim 10^6$ to 3×10^6. Using the log([N II]/Hα) diagnostic diagram for the above-estimated range of the ionization parameter, the oxygen abundance $12 + \log(O/H)$ is found to lie close to 8.8, which is in good agreement with the independent estimate of $12 + \log(O/H) = 8.78$. This indicates the oxygen abundance in region where the supernova SN 2007ru occurred is close to solar.

In a recent study, Modjaz et al. (2008b) have concluded that the broad-line SNe associated with GRBs are generally found in metal-poor environments as compared to the broad-line SNe without GRBs. They have shown that, in their sample, the oxygen abundance $12 + \log(O/H)_{KD2} = 8.5$ can be treated as the boundary between galaxies that have GRBs associated SNe and those without GRBs. The estimated oxygen abundance of ~ 8.8 at the location of SN 2007ru fits well in the range expected for a broad-line SN without GRB.

6.2. *The Nuclear Region*

The nuclear spectrum of the host galaxy of SN 2007ru (obtained on 2008 October 29) is shown in Figure 10. The nuclear spectrum shows strong hydrogen lines of the Balmer series, permitted as well as forbidden lines of oxygen, lines due to helium and the calcium NIR triplet (refer Figure 10). The FWHM velocities of the lines indicate velocities of the order of 500–700 km s^{-1}. The hydrogen Balmer lines show broad wings, with a noticeable asymmetry in the blue wing. Such broad wings are not seen in the forbidden lines. Another interesting feature of the nuclear spectrum of the host galaxy is the presence of numerous Fe II lines seen at wavelengths 4400–4600 Å, 4924 Å, 5018 Å, and 5100–5400 Å, similar to the spectra of active galactic nuclei (AGNs; Veron-Cetty et al. 2004, 2006).

Using the diagnostic diagram (Ho et al. 1997) based on the line ratio log([O III]λ5007/Hβ) versus log([O I]λ6300/Hα) and log([O III]λ5007/Hβ) versus log([S II]λλ6717, 6731/Hα) the nucleus of UGC 12381 can be classified as belonging to the H II region class, with very weak [S II] and [N II] lines.
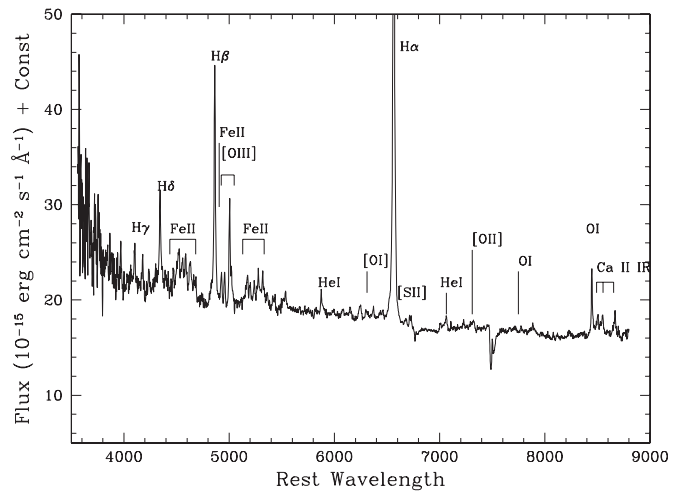

Figure 10. Nuclear spectrum of the host galaxy UGC 12381 of SN 2007ru.

It thus appears that the host galaxy of SN 2007ru probably hosts a mild AGN with a nuclear H II region, which needs further detailed study.

7. DISCUSSION AND CONCLUSIONS

The optical spectra of SN 2007ru presented here show broad spectral features similar to that seen in GRB-associated SN 1998bw, XRF-associated SN 2006aj, and the broad-line SN 2003jd. The expansion velocity of the ejecta of SN 2007ru is higher than that of the normal SN Ic SN 1994I and SN 2006aj, but comparable to that of SN 1998bw and SN 2003jd.

The maximum luminosity of SN 2007ru is comparable to SN 1998bw. The LC reaches a peak in only $\sim 8 \pm 3$ days, which is remarkably faster than in SN 1998bw (~ 20 days). The mass of ^{56}Ni ejected in SN 2007ru is estimated as $\sim 0.4 \ M_\odot$, 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 LC (τ) and the expansion velocity (v), we estimate mass of SN ejecta (M_{ej}) and the kinetic energy of the ejecta (E_K). If the optical opacity is assumed to be constant, the timescale of the LC is expressed as $\tau \propto M_{ej}^{3/4} E_K^{-1/4}$ (Arnett 1982). The expansion velocity is given by $v \propto M_{ej}^{-1/2} E_K^{1/2}$. The rise time of SN 2007ru (8 ± 3 days) is comparable to that of the well-studied SN 1994I, while the expansion velocity ($v = 20,000$ km s^{-1} at maximum) is about twice. Assuming $M_{ej} = 1.0 \ M_\odot$ and $E_K = 1.0 \times 10^{51}$ ergs for SN 1994I (see Table 4), and the observed expansion velocity of SN 2007ru, we estimate $M_{ej} = 1.3^{+1.1}_{-0.8} \ M_\odot$ and $E_K = 5^{+4.7}_{-3.0} \times 10^{51}$ 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 $M_{ej} \approx 8 \ M_\odot$ and $E_K \approx 30 \times 10^{51}$ ergs, qualitatively consistent with the results of detailed modeling (Iwamoto et al. 1998; Nakamura et al. 2001)[6]. If we take

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[6] Given the very high M_{Ni}/M_{ej} ratio (~ 0.3), the higher end of the ejecta mass may be preferred ($M_{ej} \sim 2.4 \ M_\odot$, and $E_K \sim 9.7 \times 10^{51}$ ergs). Since the explosion with a larger kinetic energy can produce a larger amount of ^{56}Ni, the large ^{56}Ni mass in SN 2007ru may also support this.

SN 2003jd as a reference (Valenti et al. 2008), $M_{ej} = 1.7^{+1.5}_{-1.0}\ M_\odot$ and $E_K = 8.6^{+7.2}_{-5.2} \times 10^{51}$ ergs are derived for SN 2007ru. It should, however, be noted that a detailed modeling is required to derive accurate values of M_{ej} and E_K.[7]

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}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_{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 [O I] 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 [O I] 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 modeling 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 Hα, [N II], [S II], and [S III], arising from the underlying/neighboring host galaxy H II region. The flux ratios indicate an oxygen abundance of $\sim$8.8 in the region of the SN. The nearly solar oxygen abundance at the location of the SN matches well with earlier abundance studies for SN 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 Fe II are also fairly prominent. Low-ionization emission lines are also present. It appears that the galaxy hosts a mild AGN with nuclear H II region.

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[7] An attempt was made to estimate the mass of the ejecta M_{ej} and kinetic energy E_K using the width of the LC. The width is defined as the time from peak of the bolometric LC 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$18 days for SN 2007ru. With this value, we have estimated M_{ej} and E_K in the same manner and derived larger values of M_{ej} and E_K ($M_{ej} \sim 4.5\ M_\odot$ and $E_K \sim 20 \times 10^{51}$ ergs). Our conclusion of large E/M is thus not affected.