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EARLY PHASE OBSERVATIONS OF EXTREMELY LUMINOUS TYPE IA SUPERNOVA 2009DC

M. Yamanaka[1,2], K. S. Kawabata[2], K. Kinugasa[3], M. Tanaka[4], A. Imada[5], K. Maeda[6], K. Nomoto[6], A. Arai[1], S. Chiyonobu[1], Y. Fukazawa[1], O. Hashimoto[3], S. Honda[3], Y. Ikejiri[1], R. Itoh[1], Y. Kamata[9], N. Kawai[7], T. Komatsu[1], K. Konishi[10], D. Kuroda[5], H. Miyamoto[1], S. Miyazaki[9], O. Nagae[1], H. Nakaya[9], T. Ohsugi[2], T. Omodaka[8], N. Sakai[8], M. Sasada[1], M. Suzuki[11], H. Taguchi[3], H. Takahashi[3], H. Tanaka[1], M. Uemura[2], T. Yamashita[9], K. Yanagisawa[5], and M. Yoshida[5]

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ABSTRACT

We present early phase observations in optical and near-infrared wavelengths for the extremely luminous Type Ia supernova (SN Ia) 2009dc. The decline rate of the light curve is $\Delta m_{15}(B) = 0.65 \pm 0.03$, which is one of the slowest among SNe Ia. The peak V-band absolute magnitude is estimated to be $M_V = -19.90 \pm 0.15$ mag if no host extinction is assumed. It reaches $M_V = -20.19 \pm 0.19$ mag if we assume the host extinction of $A_V = 0.29$ mag. SN 2009dc belongs to the most luminous class of SNe Ia, like SNe 2003fg and 2006gz. Our JHK_s-band photometry shows that this SN is also one of the most luminous SNe Ia in near-infrared wavelengths. We estimate the ejected ^{56}Ni mass of $1.2 \pm 0.3\ M_\odot$ for the no host extinction case (and of $1.6 \pm\ 0.4\ \mathrm{M}_\odot$ for the host extinction of $A_V = 0.29$ mag). The C II λ6580 absorption line remains visible until a week after the maximum brightness, in contrast to its early disappearance in SN 2006gz. The line velocity of Si II λ6355 is about 8000 km s^{-1} around the maximum, being considerably slower than that of SN 2006gz. The velocity of the C II line is similar to or slightly less than that of the Si II line around the maximum. The presence of the carbon line suggests that thick unburned C+O layer remains after the explosion. Spectropolarimetric observations by Tanaka et al. (2009) indicate that the explosion is nearly spherical. These observational facts suggest that SN 2009dc is a super-Chandrasekhar mass SN Ia.

Subject headings: supernovae: general — supernovae: individual (SN 2009dc) — supernovae: individual (SNe 2003fg, 2006gz)

1. INTRODUCTION

Type Ia Supernovae (SNe Ia) have been believed to occur when the mass of the progenitor white dwarf (WD) reaches the Chandrasekhar's limiting mass by mass accretion from a companion star. The homogeneity in their light curves is explained by this scenario and the calibrated luminosity of SNe Ia has been used as an important tool for the constraints on the expansion rate and the dark energy content of the universe (Perlmutter et al. 1999; Riess et al. 1998). However, their progenitors and detailed explosion mechanism have not been confirmed yet (e.g., Nomoto et al. 1997; Hillebrandt & Niemeyer 2000). The light curves of more luminous SNe Ia decline more slowly (Phillips 1993). The diversity of SNe Ia may reflect the diversities of the explosion mechanisms (e.g., Jordan et al. 2008; Kasen et al. 2009; Bildsten et al. 2007) and the progenitors. Some recent works for the latter differences include the companion's mass and metallicity in the single-degenerate scenario (e.g., Hachisu et al. 2008) and the case of collision in the double-degenerate scenario (e.g., Rosswog et al. 2009; Raskin et al. 2009).

Observationally, SNe Ia have been classified into three subclasses: normal SNe Ia (typically, $\Delta m_{15}(B) \sim 1.1$ and $M_V \sim -19.2$), overluminous SNe Ia (SN 1991T-like; $\Delta m_{15}(B) \lesssim 1.0$ and $M_V \sim -19.5$), and faint SNe Ia (SN 1991bg-like; $\Delta m_{15}(B) \gtrsim 1.5$ and $M_V \sim -18$) (Branch et al. 1993; Filippenko 1997; Li et al. 2001; Wang et al. 2006; Mazzali et al. 2007). Recently, two extremely luminous SNe Ia 2003fg and 2006gz have been discovered (Howell et al. 2006; Hicken et al. 2007). Their absolute maximum magnitudes are $M_V = -19.94 \pm 0.06$ mag for SN 2003fg and -19.74 ± 0.16 mag for SN 2006gz, and both SNe show the very slow luminosity evolution. Such an extreme brightness suggests that their progenitor's masses exceed the Chandrasekhar limit ("super-Chandrasekar mass WD"). Interestingly, these SNe showed strong carbon absorptions in their earliest spectra, although typical SNe Ia do not.

SN 2009dc was discovered on 2009 Apr 9.31 UT (-16.7 days after B-band maximum; see §3.1) at non-filter magnitude of 16.5 mag near the outer edge of an S0 galaxy UGC 10064 (Puckett et al. 2009, $\mu = 34.88 \pm 0.15$ from the *NED* database; Falco et al. 1999). A follow-

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[1] Department of Physical Science, Hiroshima University, Kagamiyama 1-3-1, Higashi-Hiroshima 739-8526, Japan; myamanaka@hiroshima-u.ac.jp
[2] Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
[3] Gunma Astronomical Observatory, Takayama, Gunma 377-0702, Japan
[4] Department of Astronomy, School of Science, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
[5] Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, Kamogata, Asakuchi-shi, Okayama 719-0232, Japan
[6] Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Japan
[7] Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
[8] Department of Physics, Faculty of Science, Kagoshima University, 1-21-35 Korimoto, Kagoshima 890-0065, Japan
[9] National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan
[10] Institute for Cosmic Ray Research, University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba, 277-8582, Japan
[11] Toyota Technical Development, Corp., 1-21 Imae, Hanamoto-cho, Toyota, Aichi 470-0334, Japan

up observation on Apr 16.22 (−9.7 days) revealed spectroscopic similarity with SN 2006gz before maximum light, including the existence of conspicuous C II features (Harutyunyan et al. 2009). The expansion velocity deduced from the Si II λ6355 line is about 8700 km s $^{-1}$ at −9.7 days (Harutyunyan et al. 2009), which is slower than that of SN 2006gz (Hicken et al. 2007), but comparable to that of SN 2003fg (Howell et al. 2006).

In this Letter, we show our photometric and spectroscopic observations of this peculiar SN from −8.1 days through +80.5 days after maximum. We derive the maximum bolometric luminosity, which is comparable to or larger than those of SNe 2003fg and 2006gz. The luminosity requires that the mass of the heating source, ^{56}Ni, is comparable to or even exceeding the Chandrasekhar mass, thus suggesting it is a super-Chandrasekhar SN Ia. We also present some peculiar properties of SN 2009dc compared with other super-Chandrasekhar SN Ia candidates.

2. OBSERVATIONS AND REDUCTION

We performed BVR_cI_c-band photometry of SN 2009dc on 30 nights from 2009 Apr 17.8 UT (−8.1 days) through Jul 14.5 (+80.5 days), using HOWPol (Hiroshima One-shot Wide-field Polarimeter; Kawabata et al. 2008) installed to the 1.5 m KANATA telescope at Higashi-Hiroshima Observatory. The images were reduced according to a standard procedure of a CCD photometry. We performed point-spread-function photometry using *DAOPHOT* package in *IRAF*. The magnitude is calibrated with photometric standard stars in Landolt fields (Landolt 1992) observed on photometric nights. Additionally, we obtained $g'R_cI_c$-band photometric data on 10 nights from −1.7 to +19.3 days, using MITSuME 0.5 m telescope (Multicolor Imaging Telescopes for Survey and Monstrous Explosions). The MITSuME R_cI_c-band magnitudes are consistent with the KANATA/HOWPol photometry within systematic differences less than 0.03 mag.

Our near-infrared (NIR) photometric data were obtained from −2.8 through +44.0 days using the 1 m telescope in Kagoshima University and the 1.88 m telescope at Okayama Astrophysical Observatory of NAOJ equipped with ISLE (near-infrared imager and spectrograph; Yanagisawa et al. 2006). This is the first NIR photometry of super-Chandrasekhar SNe Ia ever published. Their magnitude calibrations were performed with nearby stars in 2MASS catalogue.

The optical spectra were obtained using GLOWS (Gunma LOW dispersion Spectrograph) installed to the 1.5 m telescope at Gunma Astronomical Observatory on six nights from −3.3 through +53.7 days. The wavelength coverage was 4200–8000 Å and the spectral resolution was $R = \lambda/\Delta\lambda = 330$ at 6000 Å. The flux was calibrated using several spectrophotometric standard stars taken in the same night. We have removed the strong telluric absorption features from the object spectra using the standard star spectra.

3. RESULTS AND DISCUSSION

3.1. *Light Curves*

We show optical and NIR light curves of SN 2009dc in Figure 1 (a). The data have been corrected for the Galactic extinction of $E(B-V) = 0.071$ mag and $R_V = 3.1$

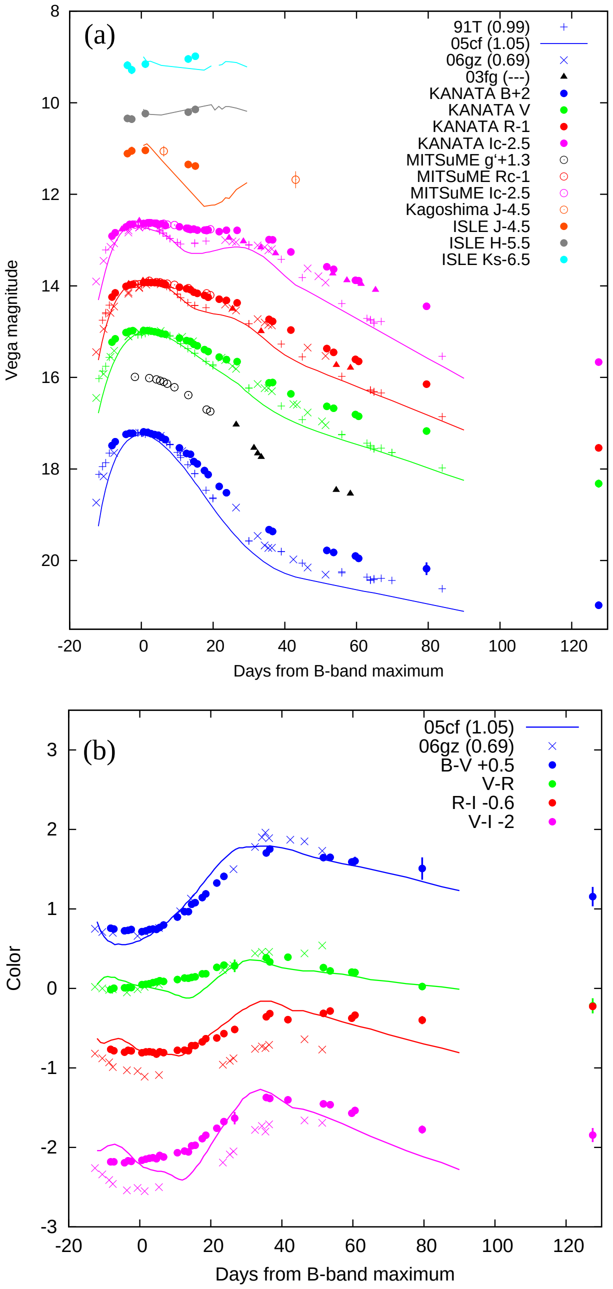

FIG. 1.— (a) Light curves of SN 2009dc, compared with a super-Chandrasekhar SNe Ia 2006gz (Hicken et al. 2007) and 2003fg (Howell et al. 2006) an overluminous SN Ia 1991T (Lira et al. 1998) and a normal SN 2005cf (Wang et al. 2009). The Galactic extinction has been corrected for in SN 2009dc. For other SNe the light curves are corrected for Our and host galactic reddening ($E(B-V) = 0.3$ mag for SN 1991T, 0.12 for SN 2005cf, 0.12 for SN 2006gz). They are shifted to match the maximum magnitude. (b) $B-V$, $V-Rc$, $Rc-Ic$, $V-Ic$ color evolutions, compared with those of SNe 1991T, 2005cf and 2006gz. In SN 2009dc, only Galactic extinction ($E(B-V) = 0.071$ mag and $R_V = 3.1$) is corrected for. In other SNe Ia, the extinctions in both our and host galaxies are corrected for ($E(B-V) = 0.3$ mag for SN 1991T, 0.12 for SN 2005cf, 0.12 for SN 2006gz). The color evolution of SN 2009dc is unique compared with those of the other SNe Ia.

(see §3.3). We derive the B-band maximum magnitude of 15.19 ± 0.16 mag and its date of 54946.9 ± 0.2 MJD (Apr 25.9±0.2 UT) by fitting of the third-order polynomial to the light curve. We also derived the B-band maximum of 54948.3 ± 0.3 MJD by fitting the SALT2 model (Guy et al. 2007), which is 1.43 days later than that of the polynomial fitting. Since the light curves of SN 2009dc is atypical, we should be careful for the result of the SALT2 model. The density of our data points is likely sufficient for polynomial fitting. In this paper, we adopt the B-band maximum day of 54946.9 ± 1.4 MJD (Apr 25.9 ± 1.4).

In Figure 1, we compare SN 2009dc with the super-Chandrasekhar SN Ia 2006gz (Hicken et al. 2007; $\Delta m_{15}(B) = 0.69$), an over-luminous SN Ia 1991T (Lira et al. 1998; $\Delta m_{15}(B) = 0.99$) and a normal SN Ia 2005cf (Wang et al. 2009; $\Delta m_{15} = 1.05$). We notice that the brightness evolution of SN 2009dc across the maximum is slower than those of SNe 1991T and 2005cf in all bands. We derive the decline rate of $\Delta m_{15}(B) = 0.65 \pm 0.03$ for SN 2009dc, which is similar to $\Delta m_{15}(B) = 0.69 \pm 0.04$ of SN 2006gz (Hicken et al. 2007). The decline rate of SN 2009dc is one of the slowest ones among SNe Ia which have ever been published. It indicates that SN 2009dc is extremely bright at the peak. In fact, even if the extinction within the host galaxy is negligible, the absolute maximum magnitude is $M_V = -19.90 \pm 0.15$ mag, indicating that SN 2009dc is one of the most luminous SNe Ia ever discovered (see §3.3).

The J-band light curve shows a significant dip between the first and second maximum compared with the I-band light curve. The H and K-band magnitudes suggest the existence of more luminous secondary peak than the first one. These characteristics are likely typical for SNe Ia (Krisciunas et al. 2004; Wang et al. 2009)

3.2. *Color Evolution*

We show the evolution of color indices of SN 2009dc in Figure 1 (b), together with those of SNe 1991T, 2005cf and 2006gz for comparison. The data of SN 2009dc have been corrected for only the Galactic extinction ($E(B-V) = 0.071$ mag and $R_V = 3.1$), while those of other comparison SNe Ia have been corrected for both our Galaxy and host galaxies. The evolution of $B-V$ of SN 2009dc is similar to those of SNe 1991T, 2005cf and 2006gz; this suggests that the Lira-Phillips relation (homogeneous $B-V$ evolution at 30–90 days, Phillips et al. 1999) also holds for SN 2009dc, which will be discussed in §3.3. On the other hand, the evolutions of $V-R$, $R-I$ and $V-I$ colors in SN 2009dc are somewhat different from those of SNe 1991T and 2005cf; the color indices of SN 2009dc become redder monotonically, while the other SNe Ia (except for SN 2006gz) have small troughs at 10–15 days after the B-band maximum. SN 2006gz shows the color evolution similar to SN 2009dc, while it keeps bluer at −8 through +60 days and shows broad troughs in the $R-I$ and $V-I$ curves.

3.3. *Host Galaxy Extinction and Absolute Magnitude*

To derive the accurate luminosity of SN 2009dc, it is important to determine the total extinction toward this SN.

The Galactic color excess is estimated to be $E(B-V) = 0.071$ mag (Schlegel et al. 1998), corresponding to an extinction of $A_V = 0.22$ mag within our Galaxy (a typical selective extinction $R_V = 3.1$ is assumed). On the other hand, the extinction within the host galaxy is somewhat uncertain. If the Lira-Phillips relation holds for SN 2009dc, it predicts a reddening of $E(B-V) = 0.37 \pm 0.08$ mag. However, this is likely an overestimation because the equivalent width (EW) of the Na I D absorption line in the host galaxy (1.0 Å) is only twice the EW of Na I D in our Galaxy (0.5 Å; Tanaka et al. 2009). If we assume that the extinction is simply proportional to the EW, $E(B-V) = 0.14$ mag is plausible for the host extinction. Additionally, the empirical relation between the color excess and the EW of Na I D (Turatto et al. 2003; we adopt their lower extinction case) predicts $E(B-V) = 0.15$ mag. These two values are consistent. This also suggests that the relation is consistent with the combination of our Galaxy's values $E(B-V) = 0.071$ mag and the EW of Na I D line of = 0.5 Å. There is an another uncertainty due to the diversity of R_V (Wang et al. 2006; Krisciunas et al. 2006; Elias-Rosa et al. 2006). We adopt $R_V = 2.1$ and 3.1 following Hicken et al. (2006). In Table 1 we summarize our absolute magnitude estimation for various cases of extinction parameters.

Krisciunas et al. (2004) pointed out that the absolute maximum magnitude in NIR bands does not depend on the decline rate (except for faint SNe Ia) and derived the mean values of $M_J = -18.6$ mag, $M_H = -18.2$ mag and $M_{Ks} = -18.4$ mag at maximum. Our observation for SN 2009dc show $M_J = -19.20 \pm 0.16$ mag, $M_H = -19.00 \pm 0.17$ mag, $M_{Ks} = -19.19 \pm 0.17$ mag for zero host extinction case, which suggests that SN 2009dc is exceptionally luminous even in NIR wavelengths.

It is interesting to examine whether the M_V-$\Delta m_{15}(B)$ relation (e.g. Altavilla et al. 2004) holds for this brightest SN Ia. If the SN suffers from no host extinction, the absolute V magnitude derived from our observations is roughly consistent with the relation, i.e., the defference is less than $\sim 1\sigma - 2\sigma$. On the other hand, it becomes much brighter (by $3\sigma - 4\sigma$) than the prediction of this relation if the host extinction is $A_V = 0.29$ mag.

3.4. *Bolometric Light Curve and ^{56}Ni Mass*

We obtain the bolometric luminosity of SN 2009dc using our BVR_cI_c-band data, assuming that the optical luminosity occupies about 60% of the bolometric one around maximum brightness (Wang et al. 2009). Because of the uncertainty involved in this assumption, we consider that this bolometric luminosity may have a somewhat large systematic error (∼ 20%) in this Latter. To confirm the reliability, we also calculate the bolometric luminosity from $BVRI$+$JHKs$ data at −3 days and check the consistency. We assume that the integrated $BVRIJHKs$ luminosity is 80% of the total (Wang et al. 2009). They agree within an error of ∼ 12%.

The obtained bolometric light curves are shown in Figure 2. Even if we assume that the host extinction is zero, the maximum bolometric luminosity is $L_{\rm max} = (2.1 \pm 0.5) \times 10^{43}$erg s^{-1}, which is comparable to that of SN 2006gz, $(2.18 \pm 0.39) \times 10^{43}$ erg s^{-1} for $E(B-V) = 0.18$ mag (Hicken et al. 2007). When we adopt the host extinction of $E(B-V) = 0.14$ mag and $R_V = 3.1$, $L_{\rm max}$ reaches $(3.3 \pm 0.9) \times 10^{43}$erg s^{-1}, likely to exceed even that of SN 2003fg ($\sim (2.5 - 2.8) \times 10^{43}$ erg s^{-1}; Howell

TABLE 1
ESTIMATED MAXIMUM ABSOLUTE MAGNITUDE, LUMINOSITY AND THE ^{56}NI MASS IN SOME EXTINCTION CASES

E($B-V$) Galactic	(mag) host	host A_V (mag)	R_V	$M_{V,\mathrm{max}}$ (mag)	L_{max} (erg s^{-1})	^{56}Ni mass ($M_\odot$)
0.07	0	–	3.1	-19.90 ± 0.15	$(2.1 \pm 0.5) \times 10^{43}$	1.2 ± 0.3
0.07	0.14	0.29	2.1	-20.19 ± 0.19	$(2.9 \pm 0.8) \times 10^{43}$	1.6 ± 0.4
0.07	0.14	0.43	3.1	-20.32 ± 0.19	$(3.3 \pm 0.9) \times 10^{43}$	1.8 ± 0.5

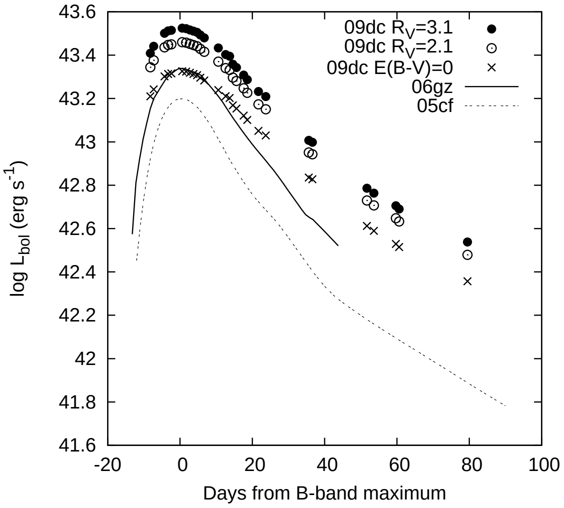

FIG. 2.— Bolometric light curve of SN 2009dc. Filled and open circles show the cases of the host extinction $E(B-V) = 0.14$ mag with $R_V = 3.1$ and 2.1, respectively The asterisk shows the case with no host extinction. The bolometric light curves of the normal SN Ia 2005cf (dashed line; Wang et al. 2009) and the super-Chandrasekhar SN 2006gz (thick line; Hicken et al. 2007) are shown for comparison.

et al. 2006).

The luminosity of a SN Ia is originated from γ-rays and positrons from the decay chain $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$. Thus, the mass of ejected ^{56}Ni can be approximately estimated from the peak luminosity (e.g., Arnett 1982). Stritzinger & Leibudgut (2005) suggested that the ^{56}Ni mass depends approximately on the peak bolometric luminosity and its rising time (t_r days), as

$$L_{\mathrm{max}} = \left(6.45\, e^{\frac{-t_r}{8.8\mathrm{d}}} + 1.45\, e^{\frac{-t_r}{111.3\mathrm{d}}}\right) \left(\frac{M_{\mathrm{Ni}}}{M_\odot}\right) \times 10^{43} \text{ erg s}^{-1}. \tag{1}$$

The slow evolution of brightness in SN 2009dc around the maximum suggests that the rising time of the bolometric luminosity is comparable to or slightly longer than those of SN 2006gz (~ 18.5 days; Hicken et al. 2007) or typical SNe Ia (~ 19 days; e.g., Conley et al. 2006). Assuming $t_r = 20$ days for SN 2009dc, we derive the ^{56}Ni mass of $1.2 \pm 0.3\ M_\odot$ for no host extinction case. It reaches $1.8 \pm 0.5\ M_\odot$ if we assume the host extinction of $E(B-V) = 0.14$ mag and $R_V = 3.1$ (Table 1). Although the derived L_{max} and the ^{56}Ni mass still include somewhat large uncertainties, the observational results suggest that the mass of the progenitor might exceed the Chandrasekhar-limit one.

3.5. *Spectral Evolution*

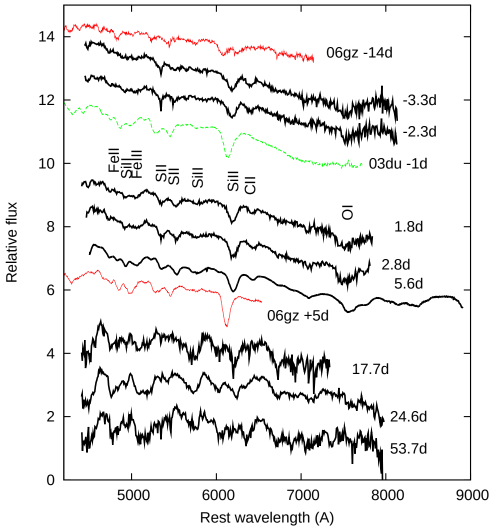

FIG. 3.— Spectra of SN 2009dc compared with those of other SNe Ia; a typical SN Ia 2003du and the super-Chandrasekhar SN Ia 2006gz. The spectrum of SN 2009dc at +5.5 days is from Tanaka et al. (2009). The telluric absorption feature have been removed.

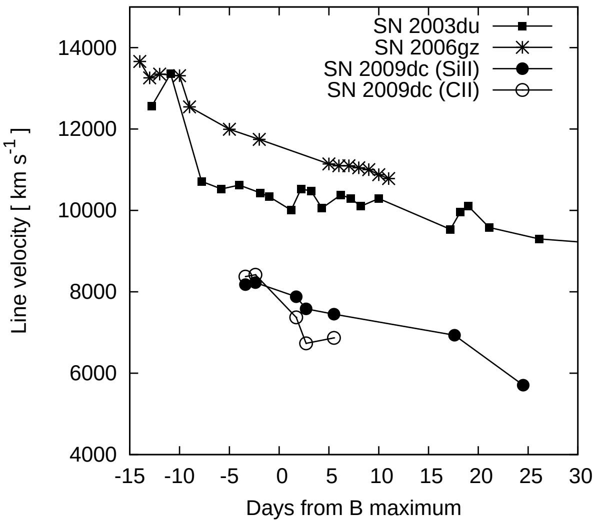

FIG. 4.— Si II λ6355 line velocity evolution of SN 2009dc and comparative SNe Ia, 2006gz (Hicken et al. 2007), 2003du (Stanishev et al.2007). We also show the C II λ6580 line velocity of SN 2009dc with black open circles. The low expansion velocity of SN 2009dc is remarkable.

In Figure 3, we compare the spectra of SN 2009dc with those of the super-Chandrasekhar SN 2006gz at −14 days and +5 days (Hicken et al. 2007) and the typical SN 2003du (Stanishev et al.2007) around maximum. The spectra of SN 2009dc near the maximum show Si II λ6355 absorption, a W-shape S II absorption feature and Fe-group multiple absorptions. Additionally, the absorption line of C II λ6580 is seen, even a few days after the maximum. This feature is seen only in a small fraction of SNe Ia at their earliest epochs (Tanaka et al. 2008). In the super-Chandrasekhar SN 2006gz, the carbon feature also exists; however, the feature is significant only in the earliest stages ($\lesssim -10$ days; Hicken et al. 2007). In another, more distant super-Chandrasekhar SN 2003fg, the C II λ6580 feature is not significant at +2 days, while there is a possible carbon feature around 4150 Å at the same epoch. The persistence of the strong carbon feature in SN 2009dc indicates that a massive C+O layer exists in the atmosphere. The Fe multiplet features seen around 5000 Å are slightly different between SN 2009dc and SN 2006gz. The spectral evolution is slow between +25 and +54 days, being consistent with the slow decline of the light curve.

In Figure 4, we show the line velocity of Si II λ6355 together with those in other SNe Ia. The Si II line velocity of SN 2009dc is $\sim$ 8000 km s^{-1} at −4 days and then decreases to $\sim$ 6000 km s^{-1} by +24 days. This indicates that SN 2009dc is one of the most slowly expanding SNe Ia (except for faint SNe Ia). The line velocity is much lower than that of SN 2006gz, but comparable with that of SN 2003fg (8000 ± 500 km s^{-1} at +2 days; Howell et al. 2006). The velocity of the C II λ6580 line in SN 2009dc is a similar to or slightly less than of the Si II line (Fig. 4). This implies that the Si layer and the C+O layer partly co-exist.

4. CONCLUSIONS

We summarize the observational characteristics of the peculiar SN Ia 2009dc as follows: (1) one of the slowest evolving light curve ($\Delta m_{15}(B) = 0.65 \pm 0.03$), (2) one of the most luminous SNe Ia ($M_V = -19.90 \pm 0.15$ or brighter), (3) a strong carbon feature in the early spectra, and (4) the lowest expansion velocity among extremely luminous SNe Ia. The first three features are similar to another super-Chandrasekhar SN 2006gz, while the last item is clearly different. Although the detailed data for the distant super-Chandrasekhar candidate SN 2003fg are lacking, the expansion velocity of SN 2003fg is comparable to that of SN 2009dc. If the ejecta is strongly aspherical, the amount of ^{56}Ni could be reduced (e.g., Sim et al. 2007). However, the polarization measurement indicates that the photosphere is almost symmetric along the line of sight (Tanaka et al. 2009). Thus, SN 2009dc is much likely a SN Ia explosion with a super-Chandrasekhar mass WD.

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REFERENCES

Arnett, W. D. 1982, ApJ, 253, 785
Altavilla, G., et al. 2004, MNRAS, 349, 1344
Bildsten, L., Shen, K., Weinberg, N. N., & Nelemans, G. 2007, ApJ, 662, L95
Branch, D., Fisher, A., & Nugent, P. 1993, AJ, 106, 2383
Conley, A., et al. 2006, AJ, 132, 1707
Elias-Rosa, N., et al. 2006, MNRAS, 369, 1880
Falco, E. E., et al. 1999, PASP, 111, 438
Filippenko, A. V. 1997, ARA&A, 35, 309
Hachisu, I., Kato, M., & Nomoto, K. 2008, ApJ 679, 1390
Harutyunyan, A., Elias-Rosa, N. & Benetti, S. 2009, CBET, 1768, 1
Hicken, M., Garnavich, P. M., Prieto, J. L., Blondin, S., Depoy, D. L., Kirshner, R. P., & Parrent, J. 2007, ApJ, 669, L17
Hillebrandt, W., & Niemeyer, J. C. 2000, ARA&A, 38, 191
Howell, D. A., et al. 2006, Nature, 443, 308
Jordan IV, G. C., et al. 2008, ApJ 681, 1448
Kasen, D., Röpke, F. K., & Woosley, S. E. 2009, Nature, 460, 869
Kawabata, K. S., et al. 2008, Proc, SPIE, 7014, 10144
Krisciunas, K., Phillips, M. M. & Suntzeff, N. B. 2004, ApJ, 602, L81
Krisciunas, K., Prieto, J. L., Garnavich, P. M., Riley, J.-L. G., Rest, A., Stubbs, C., & McMillan, R. 2006, AJ, 131, 1639
Landolt, A. U. 1992, AJ, 104, 340
Li, W., Filippenko, A. V., Treffers, R. R., Riess, A. G., Hu, J., & Qiu, Y. 2001, ApJ, 546, 734
Lira, P., et al. 1998, AJ, 115, 453
Mazzali, P. A., Röpke, F. K., Benetti, S., & Hillebrandt, W. 2007, 315, 825
Nomoto, K., Iwamoto, K., & Kishimoto, N. 1997, Science, 276, 1378
Perlmutter, S., et al. 1999, ApJ, 517, 565
Phillips, M. M. 1993, ApJ, 413, L105
Phillips, M. M. 1999, ApJ, 118, 1776
Riess, A. G., et al. 1998, AJ, 116, 100
Puckett, T., Moore, R., Newton, J., & Orff, T. 2009, CBET, 1762
Raskin, C., Timmes, F. X., Scannapieco, E., Diehl, S., & Fryer, C. 2009, MNRAS 399, L156
Rosswog, S., Kasen, D., Guillochon, J., & Ramirez-Ruiz, E. 2009, ApJL, in press
Shlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Stanishev, V., et al. 2007, A&A, 469, 645
Stritzinger, M. & Leibudgut, B. 2005, A&A, 431, 423
Tanaka, M., et al. 2008, ApJ, 677, 448
Tanaka, M., et al. 2009, ApJ submitted (arXiv:0908.2057)
Turatto, M., Benetti, S. & Cappellaro, E. 2003, in From Trilight to Highlight: The Physics of Supernovae, ed. W. Hillebrandt & B. Leibundgut(Berlin: Springer), 200
Wang, X. F., et al. 2006, ApJ, 645, 488
Wang, X. F., et al. 2009, ApJ, 697, 380
Yanagisawa, K., et al. 2006, SPIE, 6269, 118