SN 2017czd: A Rapidly Evolving Supernova from a Weak Explosion of a Type IIb Supernova Progenitor

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Abstract

We present optical and near-infrared observations of the rapidly evolving supernova (SN) 2017czd that shows hydrogen features. The optical light curves exhibit a short plateau phase (∼13 days in the R-band) followed by a rapid decline by 4.5 mag ∼20 days after the plateau. The decline rate is larger than those of any standard SNe, and close to those of rapidly evolving transients. The peak absolute magnitude is −16.8 mag in the V band, which is within the observed range for SNe IIP and rapidly evolving transients. The spectra of SN 2017czd clearly show the hydrogen features and resemble those of SNe IIP at first. The H2 line, however, does not evolve much with time, and it becomes similar to those in SNe IIb at the decline phase. We calculate the synthetic light curves using a SN IIb progenitor that has 16M⊙ at the zero-age main sequence and evolves into a binary system. The model with a low explosion energy (5 × 1050 erg) and a low 56Ni mass (0.003 M⊙) can reproduce the short plateau phase, as well as the sudden drop of the light curve, as observed in SN 2017czd. We conclude that SN 2017czd might be the first weak explosion identified from a SN IIb progenitor. We suggest that some rapidly evolving transients can be explained by such a weak progenitor explosion with a barely hydrogen-rich envelope.

Key words: supernovae: general – supernovae: individual (SN 2017czd)

1. Introduction

Supernovae (SNe) are classified using spectral features and light-curve properties, which reflect the diversity of their progenitor stars and explosion mechanisms. SNe with hydrogen absorption features in their spectra and the plateau in their optical light curves are classified as Type II plateau SNe (SNe IIP; Filippenko 1997). Through the analysis of pre-explosion data (Smartt 2009; Smartt et al. 2015), red supergiants are identified as progenitors of SNe IIP, in full accord with standard theoretical predictions (e.g., Grassberg et al. 1971; Heger et al. 2003). SNe IIb exhibit both hydrogen and helium lines in their early spectra, and their optical light curves show one or two peaks (Bersten et al. 2018). Yellow supergiant stars have been detected in pre-explosion images for some SNe IIb (e.g., Eldridge et al. 1994; Crockett et al. 2008; Van Dyk et al. 2014). SNe Ib/c do not show hydrogen features (Hunter et al. 2009; Benetti et al. 2011; Takagi et al. 2013). Although the progenitor detection is still limited for SNe Ib/c (Cao et al. 2013; Eldridge & Maund 2016; Folatelli et al. 2016; Van Dyk et al. 2018), the progenitors should be massive stars in which hydrogen-rich envelopes are stripped either by stellar wind or binary interaction.

Through the analysis of light curves and spectra, combined with that of pre-explosion images, relationships between explosion and progenitor properties have been well studied for major classes of SNe (e.g., Hamuy 2003; Pejcha & Prieto 2015; Utrobin & Chugai 2015; Lyman et al. 2016).

However, the progenitor stars are still unclear for some peculiar SNe (e.g., Arcavi et al. 2017; de Jaeger et al. 2018; Nakaoka et al. 2018). One example is so-called rapidly evolving transients such as those discovered by the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Drout et al. 2014). Their rise and decline rates are much faster than fast-evolving SNe Ib/c like SN 1994I (Richmond et al. 1996b). Recently, an increasing number of rapid transients was found with wide-field and high-cadence surveys, e.g., the Subaru Hyper Suprime-Cam Transient Survey (Tanaka et al. 2016), the Palomar Transient Factory (Whitesides et al. 2017), the Dark Energy Survey Supernova Program (Pursiainen et al. 2018), and K2/Kepler (Rest et al. 2018). Most of them were discovered in star-forming galaxies, implying massive progenitors. However, the exact nature of the progenitors and explosions remains elusive.

The absolute peak magnitudes of rapidly evolving transients have a large variety, −15 to −22 mag (Drout et al. 2014; Pursiainen et al. 2018). Spectral features are also diverse: some of them have blue featureless spectra with photospheric temperatures of 20,000–30,000 K (Drout et al. 2014; Pursiainen et al. 2018), while others have absorption features including helium lines, e.g., for SNe 2002bj (Poznanski et al. 2010), 2005ek (Drout et al. 2013) and 2010X (Kasliwal et al. 2010). However, hydrogen features have never been clearly identified in rapidly evolving transients.
Many different kinds of scenarios have been proposed for the rapidly evolving transients. For example, rapidly evolving transients may be related to peculiar core-collapse SNe, e.g., ultra-stripped SNe (e.g., Tauris et al. 2013; Moriya et al. 2017a; De et al. 2018), electron-capture SNe (e.g., Moriya & Eldridge 2016), magnetar-powered SNe (e.g., Whitesides et al. 2017), and failed core-collapse SN explosions (e.g., Moriya et al. 2010). The failed core-collapse SN explosions may also lead to the fallback, accretion-powered, rapidly evolving SNe (e.g., Dexter & Kasen 2013). Some others may be powered by the interaction between the SN ejecta and the circumstellar material (CSM; e.g., Kleiser et al. 2018b), which in fact nicely reproduces the light curves of well-observed KSN 2015K (Rest et al. 2018). Other proposed mechanisms include tidal disruption events (Drout et al. 2014) and peculiar thermonuclear explosions (Bildsten et al. 2007; Shen et al. 2010). In fact, the nature of the progenitor and explosion is not clear for many rapidly evolving transients partly due to the lack of good photometric and spectroscopic coverage. To understand the nature of rapid transients, extensive follow-up observations are necessary.

In this paper, we present our observations of the rapidly evolving SN 2017czd. SN 2017czd was discovered by Koichi Itagaki on 2017 April 12.7 (UT) (Itagaki 2017). About 1 day after the discovery, this SN was classified as a young SN II with a featureless and blue continuum through a spectroscopic observation (Hosseinzadeh et al. 2017). The host galaxy, UGC 9567, is an irregular galaxy with emission lines. The date of explosion is constrained by the last non-detection date (April 10.3) by Gaia Photometric Alerts. In this paper, the explosion date is assumed to be 2017 April 11.5 (defined as \( t = 0 \) day, where \( t \) is the time since the explosion in the rest frame), which is the middle of the last non-detection and the first detection. The observational epochs are given with respect to the explosion date.

This paper is organized as follows. We introduce our observations and the data reduction in Section 4. We show the observed light curves and compare them with other SNe and other rapidly evolving transients in Section 3. We present our spectra and discuss similarities with SNe II in Section 4. In Section 5, we discuss the nature of SN 2017czd by constructing the bolometric light curve and by comparing it with the results of radiative transfer calculations based on a binary progenitor model. Finally, we give a summary in Section 6. Throughout the paper, the distance to the host galaxy is assumed to be 32.0 ± 1.5 Mpc, adopting the distance from the recession velocity (\( z = 0.009 \); via NED\(^{11}\)).

2. Observations and Data Reduction

Optical imaging data were obtained using the Hiroshima One-shot Wide-field Polarimeter (HOWPol; Kawabata et al. 2008) and the Hiroshima Optical and Near-InfraRed Camera (HONIR; Sakimoto et al. 2012; Akitaya et al. 2014; Ui et al. 2014) installed on the 1.5 m Kanata telescope at the Higashi-Hiroshima Observatory, Hiroshima University. We obtained \( BVRI \)-band data with HOWPol for 30 nights from 2017 April 14.6 (\( t = 3.1 \) days) to 2018 April 18.5 (\( t = 327 \) days), and HONIR for 18 nights from 2017 April 13.6 (\( t = 2.1 \) days) to 2018 April 18.7 (\( t = 327 \) days). The last images obtained by HOWPol and HONIR are used for subtraction from the host galaxy. Throughout the paper, all magnitudes are given in vega magnitudes.

Contamination from the underlying emission from the host galaxy cannot be ignored in the optical data (see Figure 1). For optical photometry, we first performed image subtraction using the HOWPol and HONIR data taken at 2018 April 18 (\( t = 327 \) days). Then, we measured the brightness in the subtracted images using aperture photometry in the IRAF/DAOPHOT package (Stetson 1987). Local comparison star magnitudes were calibrated using the photometric standard stars (Landolt 1992; see Figure 1 and Table 1). The color terms were also corrected. The obtained magnitudes are summarized in Table 2. Figure 2 shows the light curves of SN 2017czd.

\(^{11}\) http://ned.ipac.caltech.edu/
We also performed the point-spread function (PSF) photometry of the SN in the discovery image obtained by Itagaki. We regard the non-filter magnitude as the $R$ band, following the literature (Zheng et al. 2014). This photometric information is also included in the $R$-band light curves presented in this paper.

For the part of the $VRi$-band images obtained using HOWPol and HONIR after $t = 25.7$ days, the SN was not detected. We derived $5\sigma$ upper-limit magnitudes by measuring dispersion of the background sky brightness using the same apertures. The light curves show these upper limits (Figure 2).

We also obtained the optical images of SN 2017czd using the Gemini Multi-Object Spectrograph (Hook et al. 2004) attached to the Gemini telescope on 2018 July 15 ($t = 456$ days). We confirmed that there was no object brighter than the underlying component of the host galaxy at the position of the SN in the $r$-band images. We also confirmed that the brightness of the underlying component of the host galaxy is consistent with pre-explosion images obtained by the Sloan Digital Sky Survey and Pan-STARRS.

The near-infrared (NIR) imaging data were obtained using HONIR for 16 nights from 2017 April 13.6 ($t = 2.1$ days) to May 27.6 ($t = 45.8$ days). We took images with dithering to accurately subtract the bright foreground sky. We did not subtract the underlying component of the host galaxy for the NIR imaging data because its contamination was less than $\sim 10\%$ ($t = 2.1$–18.8 days). After the standard data reduction, we carried out the PSF photometry. Photometric calibrations were performed using the magnitudes of reference stars given in the 2MASS catalog (Persson et al. 1998). The derived $JHK_s$-band magnitudes and the light curves are shown in Table 3 and Figure 2, respectively.

3. Light Curves

3.1. Light-curve Properties

The light curves of SN 2017czd can be divided into four stages based on the slopes of the $R$-band light curve: (i) the rising phase (up to $t \sim 3$ days), (ii) the plateau phase (between $t \sim 3$ and 16 days), (iii) the declining phase (between $t \sim 16$ and 30 days), and (iv) the tail phase (after $t \sim 30$ days). Below, we discuss the light-curve properties in each stage.

A rapid rise is found in the early phases. The rising rate is $\sim 0.3$ mag day$^{-1}$ in the $R$ band between $t = 1.4$ and 3.1 days. Using the $i$-band magnitude of 17.8 mag obtained by Pan-STARRS at $t = 1.1$ days,\footnote{https://wis-tns.weizmann.ac.il/object/2017czd} we obtain the rising rate of $\sim 1.6$ mag day$^{-1}$ in the $i$ band between $t = 1.1$ and 2.1 days. Combined with the fact that the pre-discovery upper-limit magnitude of 21.5 mag at $t = -1.2$ days, it is evident that this SN experiences a rapid rise just after the explosion.

Between $t \sim 3$ and 16 days, the light curves show a short plateau except for the $B$ band. The flat shapes of the light curves are most evident in the $R$ and $I$ bands. We define $t_p$ as the duration for which magnitude is constant within 0.2 mag. We find $t_p \sim 13$ days in the $R$ and $I$ bands. In the $V$ band, the plateau is also seen, but the duration is shorter than that in the $R$ and $I$ bands, i.e., the $V$-band light curve starts to decline around $t \sim 13$ days. In the $B$ band, the light curve reaches the peak at $t \sim 5$ days and then starts to decline. These characteristics of the plateau are similar to the normal SNe IIP except for the plateau length (see also Figure 6). Given the sparse NIR data, the plateau shapes in the $J$ and $H$ band light curves are not as clear as those in the $R$ and $I$ bands, but they also show relatively flat light curves between $t \sim 3$ and 16 days.

After the plateau, the optical light curves show the rapid declines. In particular, the $R$ and $I$ band light curves suddenly drop after their plateau phases. The light curves at shorter wavelengths exhibit more rapid evolution: the decline rates between $t = 15.9$ days and 21.9 days are estimated to be 0.5, 0.3, and 0.2 mag day$^{-1}$ in the $V$, $R$, and $I$ bands, respectively. We see a slowdown in the decline rate of the $R$-band light curve after $t \sim 35$ days (0.1 mag day$^{-1}$), although the photometric error at $t = 47.7$ days is rather large.

3.2. Comparison with Other Transients

Compared with normal SNe, the light curves of SN 2017czd show more rapid evolution, but its absolute magnitudes are within the range of normal SNe. Figure 4 compares the $R$-band magnitude of SN 2017czd with those of normal SNe; SNe Ib 2008D (Modjaz et al. 2009), IIL 1986L (Anderson et al. 2014), IIP 19993J (Richmond et al. 1996a), IIP 1999em (Leonard et al. 2002), Ibf 2008ax (Pastorello et al. 2008), and IIn 2009ip (Fraser et al. 2013). In order to compare their rise times quantitatively, we define the time it takes from the half maximum luminosity to reach the maximum luminosity as $t_{1/2,\text{rise}}$. For SN 2017czd, it is estimated to be 2.6 days, which is much shorter than those of SNe 1993J (7.64 days) and 2008ax (9.05 days).

The $R$-band magnitude around the peak is $-16.5$ mag for SN 2017czd, which is comparable to those of SNe 1999em and 2008D. After the light-curve drop, the absolute magnitude of SN 2017czd becomes much fainter than those of SNe 1986L, 1993J, 1999em, 2008D, 2008ax, and 2009ip. The luminosity at

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**Table 1**

| ID | $B$ (mag) | $V$ (mag) | $R$ (mag) | $I$ (mag) |
|----|-----------|-----------|-----------|-----------|
| C1 | 17.75(0.03)| 17.15(0.02)| 16.67(0.01)| 16.20(0.06)|
| C2 | 17.06(0.03)| 16.56(0.02)| 16.11(0.02)| 15.71(0.04)|
| C3 | 16.62(0.04)| 16.28(0.06)| 15.94(0.02)| 15.57(0.03)|
| C4 | 15.99(0.04)| 15.48(0.01)| 14.83(0.05)| 14.36(0.04)|

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[2] https://wis-tns.weizmann.ac.il/object/2017czd
Table 2
Log of the Optical Photometry of SN 2017czd

| MJD     | Epoch (days) | B (mag)       | V (mag)       | R (mag)       | I (mag)       | Instrument |
|---------|--------------|---------------|---------------|---------------|---------------|------------|
| 57856.6 | 2.1          | ...           | 16.5(0.07)    | ...           | 16.19(0.05)  | HONIR      |
| 57857.6 | 3.1          | 16.38(0.03)   | 16.36(0.02)   | 16.11(0.02)   | 16.08(0.02)  | HONIR      |
| 57859.6 | 5.0          | 16.28(0.02)   | 16.39(0.03)   | 16.12(0.04)   | 16.02(0.03)  | HOWPol     |
| 57861.6 | 7.0          | ...           | 16.47(0.06)   | ...           | 16.11(0.05)  | HONIR      |
| 57862.6 | 8.0          | 16.5(0.05)    | 16.46(0.02)   | 16.14(0.05)   | 16.04(0.02)  | HOWPol     |
| 57864.5 | 9.9          | ...           | ...           | ...           | ...           | HOWPol     |
| 57865.7 | 11.1         | 16.79(0.02)   | 16.51(0.02)   | 16.18(0.06)   | 16.14(0.02)  | HOWPol     |
| 57866.6 | 12.0         | ...           | 16.6(0.04)    | 16.19(0.04)   | 16.11(0.04)  | HONIR      |
| 57867.6 | 13.0         | ...           | 16.77(0.05)   | ...           | 16.16(0.04)  | HOWPol     |
| 57870.6 | 15.9         | ...           | ...           | 16.32(0.05)   | 16.25(0.05)  | HOWPol     |
| 57871.6 | 16.9         | ...           | 17.22(0.07)   | 16.71(0.05)   | 16.52(0.04)  | HONIR      |
| 57873.5 | 18.8         | ...           | 18.13(0.07)   | 17.27(0.05)   | 16.96(0.05)  | HONIR      |
| 57876.6 | 21.9         | ...           | 18.38(0.06)   | ...           | ...           | HOWPol     |
| 57880.5 | 25.7         | ...           | ...           | >18.59        | 19.38(0.19)  | HONIR      |
| 57884.5 | 29.7         | ...           | ...           | >18.79        | ...           | HONIR      |
| 57890.8 | 36.0         | ...           | 20.44(0.17)   | ...           | ...           | HOWPol     |
| 57919.6 | 36.7         | ...           | 20.34(0.15)   | ...           | ...           | HOWPol     |
| 57902.7 | 37.8         | ...           | 20.55(0.15)   | >20.29        | ...           | HOWPol     |
| 57909.7 | 45.8         | ...           | >20.8         | >20.96        | ...           | HOWPol     |
| 57902.6 | 47.7         | ...           | >20.76        | 21.26(0.28)   | >20.32       | HOWPol     |
| 57913.6 | 58.6         | ...           | >19.92        | >20.38        | >19.87       | HOWPol     |
| 57917.6 | 62.5         | ...           | >20.46        | >20.6         | >20.2        | HOWPol     |
| 57947.6 | 92.2         | ...           | >18.87        | >19.33        | >19.14       | HOWPol     |
| 57950.6 | 95.2         | ...           | >20.75        | >20.75        | >19.95       | HOWPol     |

Table 3
Log of the NIR Photometry of SN 2017czd

| MJD     | Epoch (days) | J (mag)       | H (mag)       |
|---------|--------------|---------------|---------------|
| 57856.6 | 2.1          | 15.8(0.03)    | 15.75(0.03)   |
| 57857.6 | 3.1          | 15.64(0.03)   | 15.59(0.03)   |
| 57861.6 | 7.0          | 15.54(0.03)   | 15.53(0.03)   |
| 57865.7 | 11.1         | 15.56(0.02)   | 15.51(0.03)   |
| 57866.6 | 12.0         | 15.64(0.03)   | 15.58(0.04)   |
| 57871.6 | 16.9         | 15.77(0.03)   | ...           |
| 57873.5 | 18.8         | 16.33(0.09)   | 16.06(0.05)   |

Table 4
Log of the Spectroscopic Observations of SN 2017czd

| MJD     | Epoch (days) | Exposure (s) |
|---------|--------------|--------------|
| 57856.6 | 2.1          | 2400         |
| 57857.6 | 3.1          | 2700         |
| 57859.6 | 5.0          | 2700         |
| 57861.8 | 7.2          | 2700         |
| 57865.6 | 11.0         | 2700         |
| 57866.6 | 12.0         | 2700         |
| 57867.7 | 13.1         | 3600         |
| 57870.7 | 16.0         | 2700         |
| 57873.7 | 19.0         | 2700         |

Figure 2. Optical and NIR light curves of SN 2017czd. The circles show the HOWPol and HONIR data. The diamond shapes at the early epochs show the non-filter magnitude in K. Hagaki’s image is in red and the Pan-STARRS i-band magnitude is in magenta. The Galactic extinction (Schlafly & Finkbeiner 2011) has been corrected. The upper limits are denoted by the triangles.
∼20 days after the maximum are available only for PS1-10ah, and SN 2017czd shows a faster decline than PS1-10ah. The bottom panel of Figure 5 compares the light curves relative to the peak. Compared with the other rapidly evolving transients in the figure, only SN 2017czd exhibits the plateau in the light curve. Because the data are sparse for the rapidly evolving transients, we define the decline time ($t_{1/2,\text{decline}}$) as the time it takes from the light-curve maximum to the half maximum for the comparison. The timescale of SN 2017czd ($t_{1/2,\text{decline}} = 14.5$ days in the R-band) is similar to those of SN 2002bj (8.3 days in the R band; Poznanski et al. 2010) and the Pan-STARRS rapidly evolving transients ($t_{1/2,\text{decline}} = 3–17$ days in the $r$ band; Drout et al. 2014).

Motivated by the presence of the short plateau in the light curves, we also compare the light curves of SN 2017czd with SNe II. Figure 6 shows the $R$-band light curve of SN 2017czd compared with SNe 1993J, 1999em, and SN impostor 1997bs (Van Dyk et al. 2000). As in other Type IIP SNe, SN 1999em shows a plateau for ∼100 days in the $R$ band. We stretch the $R$ band light curve of SN IIP 1999em to match that of SN 2017czd by assuming a stretch factor of 0.17 in time (green in Figure 6). The stretched light curve is in fact quite similar to that of SN 2017czd until $t \sim 20$ days. The sharp drop after the

Figure 3. Spectral evolution of SN 2017czd. The epoch for each spectrum is given in days since the explosion.

Figure 4. (Top) $R$-band absolute magnitudes of SN 2017czd compared with those of well-observed SNe. The extinction of each SNe has been corrected. The light curves are shifted on the time axis to match their maximum dates. (Bottom) Same as the top panel but the magnitudes are relative to the peaks. Both figures are compared in the rest frames.

Figure 5. (Top) $R$-band absolute magnitudes of SN 2017czd compared with those of rapidly evolving transients by Drout et al. (2014) in the $r$ band. The extinction of each SNe has been corrected. The days of these SNe are shifted to match their maximum dates. (Bottom) Same as the top panel but the magnitudes are relative to the peaks. Both figures are compared in the rest frames.

Figure 6. The $R$-band light curve of SN 2017czd compared with SNe II. The extinction of each SNe has been corrected. The days of these SNe are shifted to match their maximum dates.
plateau is also similar, although the light curve of SN 2017czd keeps declining rapidly.

Some SNe II are known to show fast-evolving light curves (so-called SNe II; e.g., Bose et al. 2013, 2016; Faran et al. 2014). Figure 7 shows the V-band light curve of SN 2017czd and those of SNe II presented in Anderson et al. (2014). The V-band light curve of SN 2017czd until 15 days has a similar evolution to that of SN 2006Y, which shows the fastest decline among their samples, while SN 2017czd declines more rapidly after 15 days. As shown in Figure 7, the duration of the plateau of SN 2017czd is among the shortest in the samples of SNe II collected by Anderson et al. (2014).

Note that SN (or SN impostor) 1997bs also shows a short plateau in the R-band light curve (Figure 6), whose timescale is comparable to that in SN 2017czd. However, several characteristics are different from those of SN 2017czd: the plateau luminosity of SN 1997bs is lower than that of SN 2017czd, and the light curve after the short plateau becomes flat again. Furthermore, spectra of SN 1997bs show narrow emission lines, which are not seen in SN 2017czd (see Section 4).

Figure 8 is compared with the V − R color evolution of SN 2017czd and some Type II SNe; SNe IIn 1993J (Richmond et al. 1996a), IIP 1999em (Leonard et al. 2002), and Iib 2008ax (Pastorello et al. 2008). Until \( t \sim 10 \) days, the \( V − R \) color of SN 2017czd is similar to or slightly redder than those of SNe 1993J and 1999em. However, after \( t \sim 15 \) days, the color in SN 2017czd rapidly becomes redder. Such a rapid change is not seen in other SNe IIn and IIP, confirming that SN 2017czd is a rapidly evolving object also in color.

4. Spectra

Figure 3 shows the time evolution of the optical spectra from the rising phase (\( t = 2.1 \) days) to the declining phase (\( t = 19.0 \) days). Note that narrow emission lines of H\( \alpha \), H\( \beta \), [O III] \( \lambda \lambda 4959, 5007 \), [N II] \( \lambda \lambda 6583 \), and [S II] \( \lambda \lambda 6716, 6731 \) come from the HII region in the host galaxy. Initially, the spectra are dominated by the blue continuum in SNe IIP in their early phases (e.g., Huang et al. 2018). The broad absorption component of H\( \alpha \) around 6000 Å is present from \( t = 3.1 \) days. This broad H\( \alpha \) feature led us to classify SN 2017czd as an SN II, as discussed below. In addition to H\( \alpha \), the broad feature of Ca II IR triplets are seen in the spectra at \( t = 16.0 \) and 19.0 days.

The spectra of SN 2017czd are similar to those of SNe IIP in early phases. Figure 9 shows the spectral comparison with various types of SNe; SN 2017czd at \( t = 7 \) days, SN IIP 2006bp at \( t = 6 \) days (Quimby et al. 2007), SN II 2006Y at \( t = 11 \) days (Gutiérrez et al. 2017), SN Iib 1993J at \( t = 5 \) days (Barbon et al. 1995), SN IIn 1998S at \( t = 2 \) days (Fassia et al. 2001), luminous SN Ia 1991T at \( t = 10 \) days (Mazzali et al. 1995), and broad-lined SN Ic 2006aj at \( t = 14 \) days (Pian et al. 2006). The blue continuum and the broad H\( \alpha \) line in the spectrum of SN 2017czd match those of SN 2006bp at \( t = 6 \) days. This supports our classification of SN 2017czd as an SN II. SNe 1993J and 2006aj show more prominent absorption lines than SN 2017czd. SNe 1998S, 2006Y, and 1991T also show a blue continuum. However, SN 1998S shows the characteristic strong narrow emission lines observed in SNe IIn, SN 2006Y has no features except for the H\( \alpha \) emission from the host galaxy, and SN 1991T shows a strong absorption feature of Fe III around 5000 Å. Thus, they are clearly different from SN 2017czd.

In Figure 10, we compare SN 2017czd with type II SNe, SNe IIP 1999em (Leonard et al. 2002) and 2012aw (Bose et al. 2013), and SNe Iib 1993J (Barbon et al. 1995) and 2008ax (Pastorello et al. 2008), at around \( t = 5 \) days. The H\( \alpha \) absorption line of SN 2017czd is shallow and blueshifted.
compared with those of SNe IIP. Figure 11 shows a comparison with the same SNe but at later epochs. The spectrum of SN\,2017czd shows weak absorption lines of H$\alpha$, Ca\,II IR triplet, and He\,I \(\lambda\) 5876 at \(t = 20\) days. The spectral features of SN\,2017czd are broadly similar to SNe IIP at the early phase (\(\sim 5\) days) and similar to SNe IIb SN\,1993J at the decline phase (\(\sim 20\) days).

Figure 12 shows the evolution of the H$\alpha$ line velocity in SN\,2017czd. We fit the Gaussian function to the H$\alpha$ absorption line profile. We consider the difference between the rest wavelength and the wavelength at the minimum of the fitted Gaussian as the line velocity. The wavelength resolution corresponds to the velocity resolution of 750 km s$^{-1}$.

Figure 12 shows the evolution of the H$\alpha$ line velocity in SN\,2017czd. We fit the Gaussian function to the H$\alpha$ absorption line profile. We consider the difference between the rest wavelength and the wavelength at the minimum of the fitted Gaussian as the line velocity. The wavelength resolution corresponds to the velocity resolution of 750 km s$^{-1}$.

Figure 12 shows the evolution of the H$\alpha$ line velocity in SN\,2017czd. We fit the Gaussian function to the H$\alpha$ absorption line profile. We consider the difference between the rest wavelength and the wavelength at the minimum of the fitted Gaussian as the line velocity. The wavelength resolution corresponds to the velocity resolution of 750 km s$^{-1}$.

5. Discussion

We have shown that SN\,2017czd has different light-curve characteristics than other currently known rapidly evolving transients, and it has a plateau phase like an SNe IIP although it is very short (Section 3). We have also shown that SN\,2017czd clearly has a broad hydrogen feature in the spectra (Section 4).
Based on these facts, we discuss the nature of SN 2017czd in this section.

5.1. Power Source

First, to clarify the power source of SN 2017czd, we construct the bolometric light curve based on our optical and infrared photometry. We find that the SED in the BVRJHI band can be well explained by a single blackbody function until the end of the plateau phase when the multi-band photometry is available. Therefore, we estimate the bolometric luminosity of SN 2017czd from the rising phase to the declining phase by integrating the single blackbody function matching the photometry.

Because we only have the R-band photometry during the tail phase after the plateau, we estimate the bolometric luminosity in the tail phase based only on the R-band photometry. Lyman et al. (2014) investigated the bolometric correction of SNe IIP and SNe Ib and found that the R-band should cover 20%–25% of the total fluxes in the tail phases. Assuming this fraction (20%), we obtain the quasi-bolometric luminosity of SN 2017czd at the tail phase. The bolometric light curve of SN 2017czd is presented in Figure 13.

One possible power source of SN 2017czd is the radioactive decay of $^{56}$Ni, which is a standard power source of SNe. The radioactive luminosity from the decay of $^{56}$Ni is (Nadyozhin 1994)

$$L_{\text{rad}} = 6.5 \exp \left( \frac{-t}{8.8 \text{ days}} \right) + 1.45 \exp \left( \frac{-t}{111.3 \text{ days}} \right) \times M_{\text{Ni}}^{56} 10^{43} \text{ erg s}^{-1},$$

where $M_{\text{Ni}}^{56}$ is the initial mass of radioactive $^{56}$Ni.

Assuming that the major power source at the tail phase is the $^{56}$Ni decay, we compare the estimated bolometric light curve with the total available decay energy (Equation (1)) in Figure 13. The total luminosity is consistent with the total decay energy from 0.005 $M_\odot$ of $^{56}$Ni. However, the peak luminosity of SN 2017czd is much brighter than the expected luminosity from this $^{56}$Ni mass, assuming the full trapping of gamma-rays from the $^{56}$Ni decay. Therefore, radioactive decay of $^{56}$Ni is unlikely as a power source for SN 2017czd.

Another possibility is that the light curve is powered by the interaction between SN ejecta and CSM. In fact, some SNe IIn are known to show a plateau phase in the light curves (e.g., Chugai et al. 2004; Kankare et al. 2012; Mauerhan et al. 2013). But their plateau phase lasts more than 100 days, they are more luminous than SN 2017czd, and they have strong hydrogen emission. In addition, SNe interacting with the CSM are usually observed as SNe IIn with strong hydrogen emission lines, which are not observed in SN 2017czd. Therefore, although the possible contribution from the interaction between SN ejecta and CSM to the plateau part is not clear, we believe that the interaction is unlikely to be a main power source.

5.2. SN 2017czd as a Weak SN Ib progenitor Explosion

In this section, we argue that the luminosity source of the early phase of SN 2017czd is the thermal energy provided by the SN shock, as in the case of SNe IIP during the plateau phase.

Assuming that SN 2017czd is powered by thermal energy from the SN shock, as in SNe IIP, we first estimate the SN properties to account for the observed properties of SN 2017czd by using the scaling relation formulated by Popov (1993). We adopt $-16.8$ mag as the absolute $V$-band magnitude during the plateau and the plateau length $t_p = 13$ days. Fe II line velocity is typically used to estimate the photospheric velocity in SNe IIP but Fe II absorption lines are not found in the spectra of SN 2017czd. We only obtain the Hα line velocity ($\sim 20,000$ km s$^{-1}$) at $t = 16.0$ days. Fe II line velocities for SNe IIP are roughly half of the Hα (e.g., Bose et al. 2013). Assuming this relation, we set the photospheric velocity of $v_{\text{ph}} = 10,000$ km s$^{-1}$. With these parameters, the explosion energy is estimated to be $3 \times 10^{50}$ erg. The hydrogen-rich envelope mass and radius of the progenitor of SN 2017czd are estimated to be 0.04 $M_\odot$ and $860 R_\odot$, respectively.

Such an extended progenitor with a small amount of the hydrogen-rich envelope is similar to the progenitors of SNe Ib that result from the evolution of the massive binary stars (e.g., Bersten et al. 2012; Ouchi & Maeda 2017; Yoon et al. 2017). To confirm if such a progenitor can explain the observational properties of SN 2017czd, we perform numerical light-curve calculations using a progenitor model obtained from stellar evolution modeling.

We take a progenitor model with a small hydrogen-rich envelope calculated by Ouchi & Maeda (2017) using MESA ( Paxton et al. 2011, 2013, 2015, 2016, 2018). The progenitor we adopt has 16 $M_\odot$ and solar metallicity at the zero-age main sequence (ZAMS). It is in a binary system in which the initial secondary star is 15.2 $M_\odot$ (the mass ratio of 0.95) and the initial period is 1000 days. The mass transfer in the binary system is treated in a non-conservative way, with a mass accretion efficiency of 0.5. We refer to Ouchi & Maeda (2017) for further details on the progenitor evolution. The progenitor evolution is followed until the end of the central carbon burning. The envelope structure is not much affected by the rest of the evolution and we take this model for the light-curve modeling. The final progenitor mass is $5.4 M_\odot$, with a hydrogen-rich envelope mass of 0.4 $M_\odot$ and helium core mass of 5.0 $M_\odot$. The hydrogen fraction in the envelope is 0.46. The progenitor radius is 767 $R_\odot$. The progenitor properties match those of extended SN Ib progenitors (e.g., Chevalier & Soderberg 2010).
The synthetic light curves are calculated using STELLA, which is a one-dimensional multi-group radiation hydrodynamics code developed by Blinnikov et al. (1998, 2000, 2006). We set the mass cut of the progenitor at 1.4 $M_\odot$ and put the thermal energy just above the mass cut to initiate the SN explosions. We also put the radioactive $^{56}$Ni just above the mass cut.

Figure 14 presents the synthetic multi-color light curves. The explosion energy and $^{56}$Ni mass of the model are $5 \times 10^{50}$ erg and 0.003 $M_\odot$, respectively. The synthetic light curves after $\sim$35 days follow the decline rate of the light curve expected from the $^{56}$Co decay. Both the multi-color and bolometric light curves are well reproduced by this model. Given the constraint from the Gaia upper limit, SN 2017czd is found to rise more quickly than our model, but the early rise may be caused by the confined dense CSM around the progenitor (e.g., Moriya et al. 2017b, 2018; Förster et al. 2018; Morozova et al. 2018). The early discrepancy in the bolometric light curves is due to the fact that the bolometric luminosity constructed from the observations does not include contributions from the ultraviolet wavelengths that are included in the model. While the model shows some discrepancy in the tail phase in the bolometric light curve, we note that the bolometric luminosities in the tail have large uncertainty, because the tail is constructed solely by the $R$ band. The photospheric velocity of the model presented in Figure 14 is consistent with that estimated from the observation ($v_{\phi h} = 10,000$ km s$^{-1}$), although our model shows a slightly different time evolution. This difference might be due to our use of the Rosseland-mean opacity in estimating the photospheric velocity. The estimated explosion energy and hydrogen-rich envelope mass by our numerical modeling are about a factor of 10 more than those estimated by the Popov formula. We presume that this is partly because of the large helium fraction in our envelope (Kasen & Woosley 2009), as well as the limitation of the simple semi-analytic formula.

Figure 15 shows the synthetic light curves with the same progenitor models and explosion energy but with different $^{56}$Ni masses. The synthetic light curve with a large amount of $^{56}$Ni (0.1 $M_\odot$) shows the secondary peak due to the $^{56}$Ni heating, as in ordinary SNe Ib.

Overall, the observations of SN 2017czd are explained by an explosion of the SN Ib progenitor. The $^{56}$Ni mass of SN 2017czd ($\sim$0.001 $M_\odot$) is much smaller than those of SNe Ib ($\sim$0.1 $M_\odot$; e.g., Lyman et al. 2016). Thus, we suggest that SN 2017czd is a weak explosion from the SN Ib progenitor. This explosion would not eject much $^{56}$Ni and the secondary luminosity peak due to the nuclear energy input would not be observed (see also Milisavljevic et al. 2013). It is worth noting that such a weak explosion with a small amount of $^{56}$Ni may be consistent with the explosions obtained by the current state-of-the-art neutrino-driven core-collapse SN simulations. It is well known that the current core-collapse SN simulations fail to reproduce standard SN explosions an the explosion energy of $\sim10^{51}$ erg (e.g., Takiwaki et al. 2016). In addition, Suwa et al. (2019) pointed out that the amount of $^{56}$Ni produced in the explosions obtained by the current numerical simulations would be very small because they take too much time for the shock recovery. Although the current simulations do not yet reproduce ordinary core-collapse SN explosions, their results match the explosion properties of SN 2017czd. Alternatively, the low $^{56}$Ni mass may also be a result of fallback (Tominaga et al. 2007; Moriya et al. 2010). A weak explosion can result in the unsuccessful explosion of the inner layers of the progenitor where $^{56}$Ni exists. Then, little $^{56}$Ni remains in ejecta with low explosion energy.
Our result indicates that some rapidly evolving transients may be related to the weak explosions of SNe Ib progenitors with little $^{56}$Ni ejection. $^{56}$Ni-free core-collapse SN explosions that produce rapidly evolving transients have been previously suggested to be hydrogen-free extended progenitors (e.g., Kleiser & Kasen 2014; Kleiser et al. 2018a). However, we propose that there is too little hydrogen left in the progenitor in the case of SN 2017czd. This causes an extremely short plateau in the light curve, and the hydrogen features are also expected to be observed in this case.

6. Summary

We present our optical and NIR observations of rapidly evolving SN 2017czd with hydrogen features. The light curves of SN 2017czd show a short plateau ($\sim$13 days in $R$ band) followed by a rapid decline. The decline rate of SN 2017czd (0.3 mag day$^{-1}$ in $R$ band) is faster than those of the standard SNe IIP and Ib (Figure 4), yet it is similar to those of the rapidly evolving transients (e.g., Drout et al. 2014, Figure 5). The peak absolute magnitude ($\sim$16.5 mag in the $R$ band) is consistent with those of SNe IIP and Ib. The peak luminosity is also consistent with those of rapidly evolving transients. The spectra exhibit the hydrogen features, and overall spectra are similar to those of SNe IIP in the early phases and SNe Ib in the late phases. However, the hydrogen features are broader than those of SNe Ib and IIP, and the line velocities are larger.

We calculate synthetic light curves based on a binary progenitor model ($16 M_{\odot}$ at ZAMS and $5.4 M_{\odot}$ at the explosion) with a small hydrogen-rich envelope ($0.4 M_{\odot}$) at the pre-explosion stage. The observed properties of SN 2017czd, including the short plateau duration and rapid decline, are explained by a model with relatively low explosion energy ($5 \times 10^{50}$ erg) and low $^{56}$Ni mass ($0.003 M_{\odot}$). We conclude that SN 2017czd is a weak SN Ib progenitor explosion that does not eject much $^{56}$Ni. Our results suggest that some rapidly evolving transients are also caused by such weak SN Ib progenitor explosions.

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