KSP-SN-2016kf: A Long-rising H-rich Type II Supernova with Unusually High $^{56}\text{Ni}$
Mass Discovered in the KMTNet Supernova Program

Niloufar Afsariardchi1, Dae-Sik Moon1, Maria R. Drout1,2,3, Santiago González-Gaitán4, Yuan Qi Ni1, Christopher D. Matzner1, Sang Chul Kim5,6, Youngdae Lee5,6, Hong Soo Park5, Avishay Gal-Yam7,8, Giuliano Pignata8,9, Bon-Chul Koo10, Stuart Ryder11, and Yongseok Lee5,12

1 Department of Astronomy and Astrophysics, University of Toronto, Toronto, ON M5S 3H4, Canada; afarsiardchi@astro.utoronto.ca
2 Hubble Fellow, Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA
3 Dunlap Institute, University of Toronto, Toronto, ON M5S 3H4, Canada
4 CENTRA, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal
5 Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea
6 Korea University of Science and Technology, Daejeon 34113, Republic of Korea
7 Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, 76100, Israel
8 Departamento de Ciencias Físicas—Universidad Andres Bello, Avda. Republica 252, Santiago, 8320000 Chile
9 Millennium Institute of Astrophysics (MAS), Nuncio Monsenor Sotero Sanz 100, Providencia, Santiago, Chile
10 Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Republic of Korea
11 Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia
12 School of Space Research, Kyungsung University, 1732 Deogyong-daero, Giheung-gu, Yongin-si, Gyeonggi-do, 17104, Republic of Korea

Received 2019 January 21; revised 2019 June 18; accepted 2019 June 20; published 2019 August 8

Abstract

We present the discovery and the photometric and spectroscopic study of H-rich Type II supernova (SN) KSP-SN-2016kf (SN2017it) observed in the KMTNet Supernova Program in the outskirts of a small irregular galaxy at $z \approx 0.043$ within a day of the explosion. Our high-cadence, multi-color ($BVI$) light curves of the SN show that it has a very long rise time ($t_{\text{rise}} \approx 20$ days in the $V$ band), a moderately luminous peak ($M_V \approx -17.6$ mag), a notably luminous and flat plateau ($M_V \approx -17.4$ mag and decay slope $s \approx 0.53$ mag per 100 days), and an exceptionally bright radioactive tail. Using the color-dependent bolometric correction to the light curves, we estimate the $^{56}\text{Ni}$ mass powering the observed radioactive tail to be $0.10 \pm 0.01 \, M_\odot$, making it an H-rich Type II SN with one of the largest $^{56}\text{Ni}$ masses observed to date. The results of our hydrodynamic simulations of the light curves constrain the mass and radius of the progenitor at the explosion to be $\sim 15 \, M_\odot$ (evolved from a star with an initial mass of $\sim 18.8 \, M_\odot$) and $\sim 1040 \, R_\odot$, respectively, with the SN explosion energy of $\sim 1.3 \times 10^{51}$ erg. The above-average mass of the KSP-SN-2016kf progenitor, together with its low metallicity of $Z/Z_\odot \approx 0.1$–0.4 obtained from spectroscopic analysis, is indicative of a link between the explosion of high-mass red supergiants and their low-metallicity environment. The early part of the observed light curves shows the presence of excess emission above what is predicted in model calculations, suggesting there is interaction between the ejecta and circumstellar material. We further discuss the implications of the high initial mass of the progenitor and the low-metallicity environment of KSP-SN-2016kf for our understanding of the origin of Type II SNe.

Key words: supernovae: general – supernovae: individual (KSP-SN-2016kf)

Supporting material: machine-readable table

1. Introduction

Massive stars ($M_{\text{ZAMS}} \gtrsim 8 \, M_\odot$) end their lives with the collapse of their core, leading to supernova (SN) explosions in most cases. Type II SNe are those core-collapse SNe (CCSNe) whose progenitors retain part of their H envelope until the explosion. Some H-rich Type II SNe are marked by light curves that feature a distinctive post-peak plateau of $\sim 100$ days. Following the often-undetected shock breakout (SBO) after the explosion, the envelope of the progenitor radiates shock-deposited energy (Nakar & Sari 2010; Rabinak & Waxman 2011). After a few days, as the recombination front moves inside the ejecta, the H recombination emission becomes the dominant emission powering the plateau (Popov 1993). This plateau emission is supplemented by contributions from the radioactive decay of $^{56}\text{Ni}$, depending on the $^{56}\text{Ni}$ mixing level within the envelope (Nakar et al. 2016). Later, the energy released by the radioactive decay of $^{56}\text{Ni}$ becomes the primary power source and the light curves enter the phase of the radioactive tail, followed by an optically thin nebular phase a few months later. Here, we avoid further classifying H-rich Type II SNe into traditional Type IIP and IIL subtypes because of increasing evidence that the transition between two classes is continuous (e.g., Arcavi 2017, and references therein).

Although red supergiants (RSGs) are largely considered to be the progenitors of H-rich Type II SNe, there still remains the critical uncertainty about the mass range of these progenitors. The RSGs identified in pre-explosion images of H-rich Type II SNe appear to have initial masses smaller than $\sim 17 \, M_\odot$, which is significantly lower than the upper limit of $\sim 25 \, M_\odot$ typically predicted in theories (Smartt 2015) as well as the observed RSGs in the Milky Way and Magellanic Clouds (Levesque et al. 2005, 2006). It has been argued that this discrepancy, called the “red supergiant problem” (Smartt et al. 2009), may originate from unaccounted extinction in the circumstellar dust (Walmswell & Eldridge 2012) or inaccurate bolometric correction (Davies & Beasor 2018). However, the origin of the lack of the observationally identified Type II progenitors in the mass range of $15$–$25 \, M_\odot$ remains unknown. There also...
exist theoretical uncertainties about the fate of massive stars whose initial masses are \( \gtrsim 17 \, M_\odot \), and how they explode as SNe, due largely to incomplete understanding of rotation, mixing, and mass-loss processes as well as the binary effect. It may be possible that at least some RSGs in this mass range with a significant mass-loss rate have their envelopes stripped, leading to more compact progenitors and consequently non-Type II SNe, such as Type Ib/c or IIb, although what fraction of the RSGs can have such substantial mass-loss rates is poorly understood (van Loon et al. 2005; Smith 2014). In addition, even the origins of the non-Type II—i.e., Types Ib and Ib/c—SNe are also somewhat uncertain considering the lack of observational samples of progenitors of those SNe whose initial masses are \( \gtrsim 20 \, M_\odot \) (e.g., Drout et al. 2011; Lyman et al. 2016) and the uncertainty of whether some of them originate from single stripped-envelope stars (e.g., Wolf–Rayet stars) or binary stars (Smartt 2009). Interestingly, several recent studies suggest that massive RSGs in this mass range may rather produce a failed SN and implode to a black hole (O’Connor & Ott 2013; Sukhbold et al. 2016), as potentially exemplified by the disappearance of a 25 \( M_\odot \) RSG in the nearby galaxy NGC 6946 (Adams et al. 2017), rendering the mapping between the progenitor masses and their final fates quite challenging. We note, however, that metallicity may be an important factor determining how the massive RSGs explode as SNe. This is because most of the H-rich Type II SNe observed with a smaller, i.e., \( \lesssim 17 \, M_\odot \), progenitor mass have been found in a host galaxy with a relatively high metallicity greater than 0.5 \( Z_\odot \), while Anderson et al. (2018) reported the detection of a low-metallicity, i.e., 0.1 \( Z_\odot \), H-rich Type II SN whose initial progenitor mass is thought to be in the range of 17–25 \( M_\odot \). This suggests that the RSGs whose initial masses are in the range of \( \gtrsim 17 \, M_\odot \) may prefer low-metallicity environments in which to explode as Type II SNe, and it is imperative to increase the observational sample in order to support or disapprove this tantalizing possibility.

Another important uncertainty in our understanding of Type II SNe is the mass of \( ^{56}\text{Ni} \) produced in the explosion. Statistical analyses based on the observed properties of the large number of recently discovered Type II SNe have shown that they have a significant diversity in the observational characteristics such as rise time, peak brightness, rate of decline, expansion velocity, and tail luminosity (Arcavi et al. 2012; Anderson et al. 2014; González-Gaitán et al. 2015; Sanders et al. 2015; Rubin et al. 2016; Valenti et al. 2016). The mass of \( ^{56}\text{Ni} \) produced in Type II SN explosions obtained from the analysis of their tail luminosities is considerably larger than what is predicted by neutrino-driven CCSN simulations (Ugliano et al. 2012; Pejcha & Thompson 2015; Sukhbold et al. 2016), suggesting that our understanding of how Type II SNe explode is incomplete. The identification and detailed observational studies of Type II SNe with a large \( ^{56}\text{Ni} \) mass can therefore provide valuable insights into their progenitors and explosion mechanisms.

It is worthwhile to note that the observational studies of SNe, including H-rich Type II, often rely on insufficiently sampled light curves without early coverage or color information. However, light curves with an early rise time contain vital information on key progenitor parameters, especially progenitor radius (e.g., Rubin et al. 2016; Rubin & Gal-Yam 2017). Furthermore, the small number of SNe observed with early light curves make it difficult to investigate important processes involved in the explosions, including potential interactions with a binary companion (Kasen 2010), aspherical behaviors (Afariardchi & Matzner 2018) as well as the mass-loss history of progenitors prior to the explosion (e.g., Yaron et al. 2017, and references therein).

Indeed, the growing number of early SN detections have shown strong indications for the presence of the circumstellar material (CSM) in the vicinity of their progenitors, including excess emission in the early light curve compared to the predictions of the model of SBO cooling emission (Forster et al. 2018; Morozova et al. 2018) as well as “flash-ionized” narrow H or He emission lines in the early spectra that disappear within hours or days following the explosion (Gal-Yam et al. 2014; Khazov et al. 2016; Yaron et al. 2017; Bullivant et al. 2018; Hosseinzadeh et al. 2018). These facts suggest that the progenitors of these SNe may have undergone a short period of enhanced pre-SN mass loss or outbursts in their final years, leading to core collapse. The nature of this dense CSM is still unclear, but one promising mechanism that can lead to its formation is pre-SN wave heating outbursts (Quataert & Shiode 2012; Fuller 2017; Ro & Matzner 2017; Fuller & Ro 2018). High-cadence early observations of SNe are crucial for constraining the structure of such CSM and shining light on the types of SNe experiencing enhanced pre-SN mass loss.

In this paper, we present the discovery and observational studies, supplemented by numerical simulation work, of an H-rich Type II SN KSP-SN-2016kf that we detected at a very early epoch, likely within \( \sim 1 \) day of the explosion, using the high-cadence, multi-color data obtained in the Korea Microlensing Telescope Network (KMTNet) SN Program (Moon et al. 2016). Our multi-color (BVI) coverage from the early epoch allows us to model the early light curves and precisely measure the explosion epoch and the rise time of the light curves, leading to important insights into the progenitor of the SN, especially the progenitor radius and potential CSM characteristics.

This paper is organized as follows. In Section 2 we describe the discovery and photometric and spectroscopic observations of KSP-SN-2016kf, which is followed by analysis of the light curve and the estimation of \( ^{56}\text{Ni} \) mass in Section 3. Sections 4 and 5 provide the spectroscopic analyses of the SN and its host, respectively, whereas Section 6 presents the hydrodynamic simulations for the progenitor and potential interaction with the CSM. We discuss the implications of our results for understanding Type II SNe in Section 7, and conclude in Section 8.

2. Observations and Discovery

2.1. Photometry and Discovery

KSP-SN-2016kf (SN2017it\textsuperscript{13}) was first detected on 2016 December 24 as part of the KMTNet Supernova Program (KSP; Moon et al. 2016). The KMTNet is a network of three 1.6 m telescopes located in Chile, South Africa, and Australia, providing 24 hr continuous sky coverage. Each telescope of the KMTNet is equipped with a wide-field CCD camera covering a \( 2^\circ \times 2^\circ \) field at 0′′4 pixel sampling (Kim et al. 2016). The KSP

\textsuperscript{13} https://wis-tns.weizmann.ac.il/object/2017it. Note that although the first detection of KSP-SN-2016kf was made in 2016 by the KMTNet as we report in this paper, the official registration of the source in the Transient Name Server as an astronomical transient was made by the Gaia Alerts team based on its detection of the source on 2017 January 5.
conducts high-cadence $BVI$ monitoring of a sample of fields, and focuses on studying early SNe and rapidly evolving transients (e.g., He et al. 2016; Antoniadis et al. 2017; Park et al. 2017; Brown et al. 2018; Lee et al. 2018). Between 2016 October and 2017 May, we obtained about 600 images per $BVI$ band, with a mean cadence of roughly 9 hr per band, for a field around the nearby galaxy NGC 2188. All the images were obtained with 60 s exposure time, reaching limiting magnitudes of $\sim 20.5$–$22.5$ depending on the filter and observational conditions.

Figure 1 shows $B$-band images of a field containing KSP-SN-2016kf, including (a) a deep stack image of a $\sim 4' \times 4'$ field around the source, (b) the last image before the detection of KSP-SN-2016kf at MJD = 57745.488, (c) the first detection image of KSP-SN-2016kf at MJD = 57746.867, and (d) an image around peak brightness at MJD = 57759.146. As in Figure 1(b), KSP-SN-2016kf was first captured in the $B$ band with a magnitude of $\sim 20.4$ at (R.A., decl.) (J2000) = (06h10m37.156, $-34^\circ 08'28''3$) in the outskirts of an elongated faint irregular galaxy $\sim 4''$ (or $\sim 3.6$ kpc at the angular diameter distance of 181.5 Mpc, see Section 2.3 below for the measurement of distance to the galaxy) away in the western direction. See Section 5 for the identification of the galaxy as the host galaxy of KSP-SN-2016kf based on spectroscopic information.

The KSP real-time data processing pipeline first performs the bias subtraction, cross-talk removal, and flat-fielding of the science images. Next, the astrometric solution is obtained by SCAMP (Bertin 2006) using $\sim 10,000$ unsaturated stars that have a counterpart in the second Hubble guide star catalog (Lasker et al. 2008), resulting in a precision of $\sim 0''$.12.

For KSP-SN-2016kf, we subtracted from the science images reference images made from pre-SN images of the field using the HOTPANTS program (Becker 2015). Since the SN is close to its host galaxy, image subtraction is crucial for reducing the effect of the host galaxy on the SN photometry. By adjusting HOTPANTS parameters, we ensured that the subtraction is done efficiently and does not introduce bias in the subtracted science images. The photometry was then carried out on subtracted science images using our custom-developed software that performs point-spread function fitting and obtains the photometric solution based on $\sim 35$ nearby standard stars from the AAVSO All-Sky Survey. The photometry of KSP-SN-2016kf before applying any corrections is provided in Table 1.

2.2. Spectroscopy

We obtained a spectrum of KSP-SN-2016kf on 2017 March 27, which is 93 days after the first detection, using the WFCCD spectrograph mounted on the 2.5 m du Pont telescope at Las Campanas Observatory. The spectrum was acquired with the low-resolution “blue” grism and a 1''65 slit aligned with the parallactic angle, providing a wavelength coverage of $\sim 5500$–$9000$ Å.

Bias and flat-field correction, sky subtraction, spectral extraction, and wavelength calibration were performed using standard tasks in IRAF (Tody 1993). In addition to the spectrum of KSP-SN-2016kf we also extracted a spectrum of the host galaxy from the same data. Flux calibration and telluric correction of both spectra were performed using a set of custom IDL scripts (see, e.g., Matheson et al. 2008; Blondin et al. 2012). The observation of standard stars for flux calibration was made after the SN observation on the same night. The

14 All magnitudes are reported in the Vega system.
15 http://www.astromatic.net/software/scamp

Figure 1. $B$-band images of the KSP-SN-2016kf field. (a) A deep stacked image of the field made from 114 high-quality images from 2016 October until 2016 December, before the SN explosion. The host galaxy of KSP-SN-2016kf is indicated by letter “G” and the SN position is identified by a red cross. The numbered stars are a few of the standard stars used for photometric calibration. On the right panel, the evolution of KSP-SN-2016kf is shown in the $B$ band at different epochs including (b) the last non-detection at MJD = 57745.488, (c) the first detection at MJD = 57746.867, and (d) around maximum brightness at MJD = 57759.146.

16 http://www.astro.washington.edu/users/becker/v2.0/hotpants.html
17 https://www.aavso.org/apass
18 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.
observed spectra and the results of our spectroscopic analysis are presented in Section 4.

2.3. Redshifts, Reddening Correction, and K-Corrections

We measure the redshift of the host galaxy of KSP-SN-2016kf to be 0.043 ± 0.002 using the He λ line in the spectrum of the host galaxy. The value is consistent with the redshift measured with the SN spectrum, confirming that the irregular galaxy G (Figure 1) is the host galaxy of KSP-SN-2016kf (see Sections 4 and 5 for the details of the spectroscopic analysis and the redshift measurements). In this paper we adopt the standard ΛCDM cosmology with Hubble constant $H_0 = 67.4$ km s$^{-1}$ Mpc$^{-1}$, matter density parameter $\Omega_M = 0.315$, and vacuum density parameter $\Omega_\Lambda = 0.685$ (Planck Collaboration et al. 2018). The luminosity distance and the distance modulus of the host galaxy based on these parameters are 197.4 Mpc and 36.48 mag, respectively. Table 2 contains a list of the key parameters of KSP-SN-2016kf obtained in our analysis.

Since KSP-SN-2016kf is located in the outskirts of the host galaxy, it is highly unlikely that there exists any substantial host galaxy extinction. We therefore only consider the extinction from the Milky Way in our reddening correction. This is supported by the absence of the Na I D $\lambda\lambda5890, 5896$ doublet absorption feature, which is known to be indicative of host galaxy extinction (e.g., Poznanski et al. 2012), from our SN spectrum (see Section 4). Our extinction measurement using the observed Balmer decrement also shows that the host galaxy extinction is negligible (see Section 5 for the details). We obtain the Galactic extinction $E(B - V) \approx 0.029$ mag toward the location of KSP-SN-2016kf using the extinction model of Schlafly & Finkbeiner (2011) and conduct a reddening correction of the extinction assuming $A_V/E(B - V) = 3.1$.

In addition to the reddening correction, we also carry out $K$-corrections to obtain the final photometric solution using the default $(1 + z)$ $K$-correction factor (Oke & Sandage 1968). Note that we ignore the effect of the shape of the spectral energy distribution (SED) on the $K$-corrections because our photometric solution based on the SN spectrum indicates that the effect is negligible at the redshift of KSP-SN-2016kf. We also ignore the time dilation effect given its low redshift.

3. Light-curve Analysis

3.1. Light-curve Evolution

As explained above, KSP-SN-2016kf was first detected on 2016 December 24, MJD = 57746.867, in the $B$ band at 20.56 ± 0.14 mag followed by detections in the $V$ and $I$ bands, 2 and 4 minutes later, respectively, at 20.41 ± 0.15 mag ($V$) and 20.36 ± 0.23 mag ($I$). The last $BV$-non-detection images were obtained ∼33 hr before the first detections, with limiting magnitudes of ∼21.01 ($B$), ∼21.04 ($V$), ∼20.62 ($I$) mag at the 3σ confidence level.

Figure 2 provides the entire light curves that we obtained for KSP-SN-2016kf with KMTNet, spanning over 140 days. As can be seen in Figure 2, the $V$-band light curve of KSP-SN-2016kf rises for ∼20 days (see below for the precise measurement of rise time) before entering a plateau phase of ∼105 days, during which the light curve slowly declines. Over the interval of ∼90–110 days from the SBO, the light curves dim for ∼1.5 mag and transition into a slowly decaying tail. The described light-curve evolution, and particularly the prominent plateau phase of KSP-SN-2016kf, together with the timescales of its distinctive phases of evolution, identify this transient as an H-rich Type II SN (Type IIP SN, Arcavi et al. 2012). Note that the SN nature is also confirmed by the spectroscopic information presented in Section 4.

In order to obtain the epoch of first light of KSP-SN-2016kf, which is the SBO epoch for CCSNe (Matzner & McKee 1999), we fit the early part of the light curves with the following equation:

$$N_\lambda = \begin{cases} C_i(t - t_0)^n & t > t_0 \\ 0 & t \leq t_0 \end{cases},$$

where $N_\lambda$ is the flux normalized by its peak value in each band, $t$ is the time measured from the epoch of the first detection, $t_0$ the epoch of SBO relative to the epoch of the first detection, $n$ a power index, and $C_\lambda$ a fitting coefficient. We only consider the epochs within five days of the first detection as well as upper limits for the epochs of non-detections in the fitting procedure. We fit the $BV$ light curves of KSP-SN-2016kf simultaneously and find the following best-fit parameters: $t_0 = -0.12 \pm 0.07$ days, $(C_B, C_V, C_I) = (0.69 \pm 0.04, 0.63 \pm 0.03, 0.39 \pm 0.02)$, and $n = 0.32 \pm 0.04$. Figure 3 compares the best-fit power laws with the observed $BVI$ early light curves, where the SBO
Figure 2. Light curves of KSP-SN-2016kf in BVI bands, vertically shifted for readability. The x-axis represents time since our estimated $t_{SBO} = 57746.74$. The filled circle, diamond, and square markers indicate the observations made by South African, Chilean, and Australian telescopes, respectively. The open inverted triangles mark non-detection upper limits. The yellow line represents the spectroscopy epoch and the dashed line is our estimated circle, diamond, and square markers indicate the observations made by South African, Chilean, and Australian telescopes, respectively. The open inverted triangles in Schlauf & Finkbeiner2011.

We use two methods to measure the rise time of KSP-SN-2016kf: (1) $t_{rise}$ is the time from $t_{SBO}$ to the maximum light $t_{peak}$ found by fitting a low-order polynomial to the observed light curves; (2) $t_{max}$ is defined as the time from $t_{SBO}$ to the maximum of the exponential functional form of Bazin et al. (2009) fitted to the observed light curves. Table 3 summarizes the best-fit $t_{rise}$ and $t_{max}$. We found that $t_{max}$ is smaller than $t_{rise}$ for KSP-SN-2016kf. The difference between the two times is notable for the $I$ band, for which the early light curve exhibits two distinct slopes over 50 days: an initial steep rise during the first $\sim 20$ days and a slow rise to the peak during which the magnitude changes only $\sim 0.3$ mag over $\sim 30$ days. Note that $t_{max}$ tends to represent the timescale of the former slope (González-Gaitán et al. 2015) and therefore it is particularly shorter than $t_{rise}$ in the $I$ band. In Table 3, the high uncertainty in the $B$-band $t_{rise}$ is due to the lack of data between $\sim 4$ and $\sim 10$ days post-discovery.

After the rise, the light curves reach the peak magnitude $M_{peak} \approx -17.40$ mag ($B$), $-17.62$ mag ($V$), and $-17.92$ mag ($I$), followed by the plateau phase. During the plateau phase, the light curves decay slowly, especially in the $V$ and $I$ bands. We measure the plateau length of $\sim 105$ days by fitting a Fermi–Dirac function to the transition part of the light curves (Valenti et al. 2016). Table 3 contains the $BVI$ decay rates of the light curves during the plateau phase. Between the epochs of $\sim 90$ and $\sim 118$ days, the light curves decline rapidly by more than 2 mag in the $V$ and $I$ bands, after which they settle into a radioactive tail, lasting for an extended period of time with a slow, gradual dimming.

3.2. Light-curve Comparison

Figure 4 compares the light curves of KSP-SN-2016kf with those of eight other Type II SNe in $BVI$ bands—all of them are of H-rich Type II, except for SN1987A, which is classified as Type II-Peculiar. The epochs are relative to $B$-band peak brightness for each SN, except for SN1987A, where they are relative to the first $B$-band detection due to the double-peaked shape of its light curve. We can identify in Figure 4 that there exists a significant diversity among Type II SNe in their luminosities and decay rates. KSP-SN-2016kf has a higher luminosity than the other SNe shown: in particular, both its plateau and tail luminosities are higher. Furthermore, the decay rate of KSP-SN-2016kf is among the smallest, which makes the plateau look nearly flat in the $I$ band. In terms of the shape of the light curves, KSP-SN-2016kf resembles SN2014cx, SN1999em, and LSQ13dpa but is notably more luminous. The $I$-band light curve of KSP-SN-2016kf has a peculiar bell shape, which has also been observed for SN2014cx.

Comparing the rise time of KSP-SN-2016kf to the rise-time distribution of González-Gaitán et al. (2015), we find that the
V- and I-band rise times of KSP-SN-2016kf are, respectively, more than 1σ and 2σ above the median of \( t_{\text{rise}} \) —i.e., 11.5 days (\( V \)) and 19.3 days (\( I \)). Likewise, \( t_{\text{haz}} \) of KSP-SN-2016kf in the \( I \) band is more than 3σ above the median of Type II SNe, while in \( B \) and \( V \) bands \( t_{\text{haz}} \) is within 1σ of the median. Based on this high value of \( t_{\text{rise}} \) KSP-SN-2016kf can be considered a "long riser" Type II SN in the definition of Taddia et al. (2016b).

Additionally, the plateau of KSP-SN-2016kf at 50 days is among the most luminous ones observed, with absolute magnitude \( M_V \approx -17.47 \) mag, while its peak magnitude is only moderately bright at \( M_V \approx -17.62 \) mag. This highlights that the decay rate of KSP-SN-2016kf is relatively small. The decay rates of Type II SNe are often characterized by two slopes: an initial steep slope that immediately follows the peak of the light curve and a smaller decay rate that precedes the end of the plateau (Anderson et al. 2014). However, as Valenti et al. (2016) highlights, not all H-rich Type II SNe exhibit distinct slopes during the plateau phase. Indeed, KSP-SN-2016kf— similar to SN2014cx and prototypical SN1999em—shows nearly constant decay at the rate \( s \approx 0.53 \) mag per 100 days in the \( V \) band in the interval 30–70 days.

The decay rate and peak magnitude of Type II SNe are strongly correlated (Sanders et al. 2015). We test whether KSP-SN-2016kf also follows this correlation by setting \( s = 0.53 \) mag per 100 days in the relation between peak magnitude and decay rate of Anderson et al. (2014). This gives the expected V-band peak magnitude of \( \sim -16.58 \) mag, which is \( \sim 1 \) mag fainter than the observed V-band \( M_{\text{peak}} \approx -17.62 \) mag presented in Table 3, indicating that KSP-SN-2016kf is not compatible with this correlation.

### 3.3. Color Analysis

Figure 5 (top panel) compares the \( B-V \) and \( V-I \) color evolution of KSP-SN-2016kf with those of a sample of other H-rich Type II SNe for the entire 130 days evolution, while Figure 5 (bottom panel) presents the same for the first five days of the evolution. Overall, the color evolution of KSP-SN-2016kf is similar to that of other shown SNe, confirming its H-rich Type II nature. As in the figure, the colors of these SNe redden during the first \( \sim 50 \) days in an almost linear manner, after which the rates of change of color become small before the SNe enter the phase of the radioactive tail. While the color evolution of KSP-SN-2016kf is broadly similar to that of other prototypical H-rich Type II SNe, KSP-SN-2016kf is redder than the other SNe, especially in \( B-V \) and during the first five days. The redder color of KSP-SN-2016kf does not appear to follow the correlations between the peak absolute magnitude and color in de Jaeger et al. (2018a). Based on this correlation, it is expected that fainter Type II SNe (in terms of peak absolute magnitude) will be redder in color, although it is worth noting that the dispersion on this correlation is quite large, and as pointed by de Jaeger et al. (2018a) the intrinsic differences in the SN progenitors, including progenitor radius and the CSM characteristics, are the factors contributing to the dispersion of the color. Note that the color of KSP-SN-2016kf's radioactive tail is only shown in the \( V-I \) plot because of a lack of data at \( t \gtrsim 100 \) days in the \( B \) band. During the tail, \( V-I \) rapidly reddens by \( \sim 0.3 \) mag over \( \sim 10 \) days. A similar behavior has been previously observed for other Type IIP SNe (e.g., SN2005cs; Pastorello et al. 2009).

### 3.4. Bolometric Light Curve and \( ^{56}\text{Ni} \) mass

Figure 6 shows the evolution of the bolometric luminosity (filled black circles) of KSP-SN-2016kf in comparison with that of SN1987A (red solid curve) as well as the relative decay rates of \( ^{56}\text{Co} \to ^{56}\text{Fe} \) (dashed blue curve) and \( ^{56}\text{Ni} \to ^{56}\text{Co} \) (dashed-dotted green curve). In order to obtain bolometric luminosities of KSP-SN-2016kf, the absolute V-band magnitudes of KSP-SN-2016kf, shown in Figure 4, are converted to bolometric magnitudes using BC = \( M_{\text{bol}} - M_V \), where BC is the bolometric correction of Lyman et al. (2014). In this formalism, BC is a color-dependent (here, we use \( V-I \) index) polynomial with coefficients listed in their Tables 3 and 4. Finally, bolometric magnitudes are converted to luminosities assuming \( M_{\text{bol,\odot}} = 4.74 \) mag and \( L_{\text{bol,\odot}} = 3.83 \times 10^{33} \text{ erg s}^{-1} \). Since the bolometric luminosity depends on the evolution of \( V-I \) color, our bolometric light curve is cut off at \( \sim 130 \) days when KSP-SN-2016kf goes below the detection limit in the \( V \) band.

The \( ^{56}\text{Ni} \) mass \( (M_{\text{Ni}}) \) synthesized in Type II SNe is often estimated by using the bolometric luminosity of the tail, because the tail is dominantly powered by the \( ^{56}\text{Ni} \to ^{56}\text{Co} \to ^{56}\text{Fe} \) radioactive decay chain. Figure 6 indicates that for \( t \gtrsim 115 \) days the bolometric light curve of KSP-SN-2016kf transitions to a linearly declining radioactive tail, which is \( \sim 25\% \) more luminous than that of SN1987A, implying a higher synthesized \( M_{\text{Ni}} \) based on the direct comparison of luminosities (see Equation (3) of Valenti et al. 2016). Following Appendix A of Valenti et al. (2008), we estimate \( M_{\text{Ni}} = 0.10 \pm 0.01 \) M\(_{\odot}\), as presented in Table 2, using the known decay times of \( ^{56}\text{Ni} \) and \( ^{56}\text{Co} \) as well as their associated energy generation rates assuming the complete trapping of \( \gamma \) rays and positrons (supported by the similar slopes of the radioactive tail and \( ^{56}\text{Co} \to ^{56}\text{Fe} \) decay rate, as shown in Figure 6).
Figure 4. The light curve of KSP-SN-2016kf is compared against other well-observed or similar Type II SNe: SN1999em (Elmhamdi et al. 2003), LSQ13dpa (Valenti et al. 2016), ASASSN-14dq (Valenti et al. 2016), SN1987A (Hamuy et al. 1988), SN2014cx (Huang et al. 2016), SN2009ib (Takáts et al. 2015), SN2013fs, SN2005cs (Pastorello et al. 2009). Here, the light curves of KSP-SN-2016kf are binned into 1 day intervals to reduce the variance of the data points. The x-axis is time since B-band peak magnitude for each SN (except for SN1987A, which is presented relative to the first B-band detection). The shape of the light curves of KSP-SN-2016kf resembles those of SN2014cx, SN1999em, and LSQ13dpa, but it is notably more luminous; in particular, KSP-SN-2016kf has a more luminous plateau (measured at 50 days) and greater tail luminosity than other Type II SNe shown here.

4. Spectroscopy of KSP-SN-2016kf

Figure 7 (top panel) compares the spectrum of KSP-SN-2016kf taken at an epoch of 93 days, which is near the transition from the plateau phase to the radioactive tail phase, with those of the other three well-observed H-rich Type II SNe at a similar phase. The spectrum of KSP-SN-2016kf exhibits prominent P-Cygni Balmer lines, classifying it as a Type II SN. The spectrum is de-redshifted to the rest frame using the redshift of \( z = 0.043 \pm 0.002 \) obtained from the host galaxy (see Section 5).

In order to obtain the expansion velocities of KSP-SN-2016kf, we fit a Gaussian profile to the absorption feature of the P-Cygni profile of four Balmer lines—H\( \alpha \), H\( \beta \), H\( \gamma \), and H\( \delta \)—as well as prominent iron lines—Fe\( \text{II} \ \lambda 4924 \), Fe\( \text{II} \ \lambda 5018 \), and Fe\( \text{II} \ \lambda 5169 \)—and measure the expansion velocity of each line at the minimum absorption of the fitted Gaussian profile. The measured expansion velocities, listed in Table 4, have a wide range of values; H\( \alpha \) has the highest velocity at about \( 7960 \text{ km s}^{-1} \), while Fe\( \text{II} \ \lambda 4924 \) has the lowest velocity among the selected lines at about \( 2798 \text{ km s}^{-1} \). We can see that all Balmer lines have a higher expansion velocity than any of the three Fe\( \text{II} \) lines. This is because H lines are formed at much lower optical depths than Fe\( \text{II} \) lines, and hence exhibit higher velocities. The velocities of Fe\( \text{II} \ \lambda 5018 \) and Fe\( \text{II} \ \lambda 5169 \) are often associated with the photospheric expansion velocity, because they are formed closer to the photosphere (Takáts & Vinkó 2012).

Although the spectrum of KSP-SN-2016kf in Figure 7 (top panel) is broadly similar to those of the other H-rich Type II SNe that we compare with, there are a few notable differences: (1) the H\( \alpha \) line resembles that of SN2012aw, but is broader (in both emission and absorption) with a shallower absorption feature, (2) the H\( \beta \) line appears much stronger than that of other SNe, producing a deep and broad absorption trough redward of a prominent emission peak, which could be due to blending with other nearby lines, and (3) the Ba\( \text{II} \) line has a very small emission peak with no notable trough and is weaker than that of other H-rich Type II SNe.

For constraining the metallicity of the SN progenitor, we measure the pseudo-equivalent width (pEW) of the absorption feature of the Fe\( \text{II} \ \lambda 5018 \) line. Recently, it has been shown that the pEW of this line during the plateau phase can probe the progenitor metallicity of H-rich Type II SNe (Dessart et al. 2014; Taddia et al. 2016a; Gutiérrez et al. 2018). According to Figure 1 of Taddia et al. (2016a), pEW of Fe\( \text{II} \ \lambda 5018 \) is correlated with the SN phase and metallicity. Our measured pEW of about \( 18 \text{ Å} \) at the epoch of 93 days corresponds to a metallicity of \( 0.1–0.4 Z_{\odot} \). This metallicity measurement complements the metallicity estimated based on several line diagnostics of the host galaxy spectrum (see Section 5).

5. Host Galaxy of KSP-SN-2016kf

Figure 7 (bottom panel) shows the spectrum of the galaxy identified by “G” in Figure 1. The spectrum exhibits prominent Balmer H emission lines including H\( \alpha \) and H\( \beta \) as well as several other lines such as [O\( \text{III} \) \( \lambda \lambda 3727, 4959, 5007 \), [N\( \text{II} \) \( \lambda 6584 \), and [S\( \text{II} \) \( \lambda 6717 \). The redshift of the galaxy, measured from the H\( \alpha \) line, is \( z \approx 0.043 \), which is equivalent to the luminosity distance of \( 197.4 \text{ Mpc} \) (see Section 2.3). This redshift is consistent with that of KSP-SN-2016kf as shown in Section 4, confirming that the galaxy is the host galaxy of the SN.
The distance of 181.5 Mpc and its direction. It has a small effective radius of similar Type II SNe: SN2014cx

Color index of KSP-SN-2016kf along with other well-observed or well-studied Type II SNe: SN2011ub, SN2013fs, SN2005cs, and SN2016esw (de Jaeger et al. 2018b), SN2016esw (Pastorello et al. 2019), and SN2005cs (Pastorello et al. 2009). Top: the B − V and V − i/1 of SNe are shown for less than 120 days since SBO. Bottom: the same as above but zoomed-in on the first week of evolution.

The host galaxy is 4″ (or ~3.4 kpc at the angular diameter distance of 181.5 Mpc) away from the SN in the eastern direction. It has a small effective radius of ~2.2 kpc (or ~2′′5). The galaxy is relatively bright for its size with absolute magnitude of −17.57 ± 0.06 mag (B), −18.17 ± 0.08 mag (V), and −19.05 ± 0.06 mag (I). Using the FAST stellar population synthesis code (Kriek et al. 2009) we find a best-fit stellar mass for the host galaxy of log(M/M☉) = 8.73±0.5. These model calculations are based on the stellar library of Maraston (2005) and the assumption of an exponential star formation history and Salpeter initial mass function.

The observed line intensity ratio between Hα and Hβ lines integrated over the host galaxy is 3.11 ± 0.26 (Figure 7). Within the temperature range of 5000–20,000 K, the intrinsic line intensity ratio of the two lines changes between 3.04 and 2.75 (Dopita & Sutherland 2003) for an electron number density of 100 cm−3. By comparing the observed and intrinsic ratios, we obtain the extinction E(B − V) in the range of 0.02–0.10 mag Groves et al. 2012, or A_V = 0.07–0.33 mag for R_V = 3.1 using the extinction correction model by Fitzpatrick (1999). Considering that KSP-SN-2016kf is located substantially away from the host galaxy (Figure 1), this small estimated extinction toward the center of the host galaxy is consistent with a negligible host-galaxy extinction toward the SN (see Section 2.3).

We find the metallicity of the host galaxy of KSP-SN-2016kf to be subsolar, i.e., Z/Z☉ ≃ 0.4, based on the analysis of the observed line ratios sensitive to O abundance and metallicity. For this estimate, we use O3N2 and N2 line ratio indicators (Marino et al. 2013) obtained with the observed fluxes of H, O, and N lines in the host galaxy spectrum (Figure 7). The O3N2 and N2 indicators provide an O abundance of 8.23 ± 0.03 and 8.24 ± 0.06, respectively, for the host galaxy, corresponding to Z/Z☉ = 0.4 ± 0.1 assuming 12 + log(O/H)☉ = 8.69 (Asplund et al. 2009). All abundances are calculated in PyMCZ code with the observed line fluxes (Bianco et al. 2016). The abundances from O3N2 and N2 line indicators are ~0.22 and ~0.21 dex, respectively, smaller than the median value of the O abundance found in other Type II SNe (Anderson et al. 2016). The host galaxy metallicity of Z/Z☉ ≃ 0.4 coincides with the upper bound of the SN metallicity, i.e., Z/Z☉ ≃ 0.1–0.4 (Section 4). We note that this is consistent with the location of KSP-SN-2016kf in the outskirts of the host galaxy since the galaxy metallicity tends to drop from the center to the outskirts (Taddia et al. 2015).

6. Progenitor and Explosion Parameters

6.1. Hydrodynamic Modeling

To constrain the physical parameters of KSP-SN-2016kf, we conduct the radiation transfer hydrodynamical simulations that give the best-fit parameters for the light curves. The simulations are carried out in open-source code SNEC (Morozova et al. 2015), a 1D flux-limited radiation transfer code that treats ionization levels and recombination under the assumption of local thermodynamic equilibrium (LTE). Similar to Morozova et al. (2018), we construct a grid of simulations with non-rotating RSG progenitor models in the zero-age main sequence...
The Astrophysical Journal, 881:22 (14pp), 2019 August 10

Afsariardchi et al.

(ZAMS) mass range of 11–28 $M_{\odot}$ with 0.6 $M_{\odot}$ resolution created by the KEPLER stellar evolution code (Woosley & Heger 2007). The explosion is launched by the thermal bomb mechanism and is evolved for 120 days, i.e., before the onset of the optically thin phase. We excise 1–2 $M_{\odot}$ at the center of the explosion to account for the mass of the proto-neutron SN remnant (Morozova et al. 2018). We adopt the equation of state of Paczynski (1983) implemented in SNEC for the RSG model and set the numerical grid size to 1000 cells in all of our simulations. In addition to varying the ZAMS mass of the KEPLER progenitor models, we also vary the explosion energy in the range of 0.25–1.96 foe (where 1 foe = $10^{51}$ erg) with 0.06 foe resolution. For $^{56}$Ni mixing, we adopt three schemes for which the $^{56}$Ni is roughly mixed in the progenitor up until 3 $M_{\odot}$, 5 $M_{\odot}$, and 7 $M_{\odot}$ in the mass coordinate within the progenitor. As described in Section 3.4, we fixed $M_{\text{Ni}} = 0.10 M_{\odot}$ in the simulations.

The $BVI$ light curves from SNEC simulations are then compared to the observed light curves by calculating $\chi^2$ as below:

$$\chi^2 = \sum_{\lambda \in \{V,J\}} \sum_{t_o, t_e, \text{105 day}} \frac{(M_{\text{obs,}\lambda}(t_o) - M_{\lambda}(t_e))^2}{(\sigma_{\text{obs,}\lambda}(t_e))^2},$$

where $\lambda$ denotes the corresponding band, $t_o$ the time of observation, $M_{\text{obs,}\lambda}$ the observed absolute magnitudes, $M_{\lambda}$ the simulated absolute magnitudes, and $\sigma_{\text{obs,}\lambda}$ the uncertainty of the observed magnitudes. We exclude the $B$-band light-curve data due to the non-negligible effect of iron-group line blanketing on the observed brightness (Dessart & Hillier 2010). We also exclude data from $t_e > 105$ days because the LTE assumption may not hold for those epochs.

Figure 8 shows the value of $\chi^2$ normalized by minimum $\chi^2_{\text{min}}$ from our SNEC simulations as a function of explosion energy ($E$) and $M_{\text{ZAMS}}$ for the case of 5 $M_{\odot}$ $^{56}$Ni mixing. We found that the 5 $M_{\odot}$ $^{56}$Ni mixing scheme fits the observed light curves much better than the other two mixing schemes. The hatched squares represent the best 2-percentile of best-fit models. The $E$ and $M_{\text{ZAMS}}$ of these models are, respectively, in the ranges of 1.24–1.4 foe and 15.8–19.4 $M_{\odot}$, among which a model with 1.3 foe and 18.8 $M_{\odot}$ ZAMS mass best fits the observed light curves and is marked with a filled black square. The evolved RSG progenitor of this model has mass $M \simeq 15 M_{\odot}$ and radius $R \simeq 1040 R_{\odot}$. Figure 9 compares the light curves of the best-fit model with the observed light curves of KSP-SN-2016kf. The model closely fits the observed values during the late time evolution (i.e., $t > 20$ days) in $V$ and $I$ bands, but during the early epochs the fits underestimate the luminosity of the

![Figure 7](image_url)

**Figure 7.** Top: comparison of KSP-SN-2016kf (red curve) and other H-rich Type II SNe (black curves) at similar epochs. Note that the flux density for each SN is scaled by its distance squared for the fair comparison of features. The gray vertical lines indicate the wavelengths of typical spectral lines visible at this epoch. Bottom: the spectrum of KSP-SN-2016kf’s host galaxy. The emission lines are marked with dashed lines.

**Table 4** Line Velocities at Epoch of 93 days

| Line & Wavelength | Velocity ($\text{km s}^{-1}$) |
|-------------------|-----------------------------|
| H$\alpha$ 6563    | 7960 ± 60                   |
| Fe $\Pi$ $\lambda$ 5169 | 3192 ± 63                   |
| Fe $\Pi$ $\lambda$ 5018 | 3134 ± 84                   |
| Fe $\Pi$ $\lambda$ 4924 | 2798 ± 55                   |
| H$\beta$ 4861     | 5860 ± 45                   |
| H$\gamma$ 4340    | 5452 ± 167                  |
| H$\delta$ 4101    | 4818 ± 141                  |

Note. The uncertainties are associated with the profile and continuum fitting method used for finding the minimum of the absorption features.
observed and simulated light curves of KSP-SN-2016kf. Bottom: same as top panel but zoomed-in to show the early rise epochs.

Figure 8. Scaled goodness of fit, \( \log(\chi^2/\chi^2_{\text{min}}) \), where \( \chi^2_{\text{min}} = 5100 \) represents the goodness of fit for the best-fit model, for a grid of SNEC simulations with a 5 \( M_\odot \) Ni mixing scheme and different ZAMS masses and explosion energies. The hatched squares represent the best 2-percentile of fitted models. The best-fit model is marked with a filled black square and has ~18.8 \( M_\odot \) ZAMS mass, \( \sim 1.3 \) foe explosion energy, and 5 \( M_\odot \) Ni. The evolved RSG progenitor of this model has \( M \approx 15 \ M_\odot \) and \( R \approx 1040 \ R_\odot \).

Figure 9. Comparison of the light curves for (1) the best-fit model without a CSM component (solid curves), (2) the best-fit model with a dense CSM component (dashed curves), and (3) observed values (open circles). Top: the observed and simulated light curves of KSP-SN-2016kf. Bottom: same as top panel but zoomed-in to show the early rise epochs.

Figure 10. Blackbody temperature, bolometric luminosity, and photospheric velocity for the best-fit model without CSM component (solid blue curve) and with dense CSM component (dashed green curve) as well as the corresponding observationally estimated values. Top: photospheric temperature over time. Red open circles represent the blackbody temperature for the observed \( BVJ \) magnitudes. Middle: bolometric light curve. The observed luminosities are shown with red open circles. Bottom: photospheric velocity. Several line velocities are also plotted.

The evolved RSG progenitor of this model has \( M \approx 15 \ M_\odot \) and \( R \approx 1040 \ R_\odot \). We assume that the composition and temperature of the CSM are equal to those of the outer part of an RSG with H fraction of 0.61, He fraction of 0.37, and temperature of 2400 K. The adoption of this type of dense, optically thick CSM is motivated by the increasing evidence of RSGs undergoing strong mass loss shortly prior to the collapse of the core (see, e.g., Khazov et al. 2016; Yaron et al. 2017; Bullivant et al. 2018; Forster et al. 2018; Hosseinzadeh et al. 2018).

We select the best-fit model with CSM component using Equation (2) in a similar manner to that in Section 6.1 and find that a model with \( R_{\text{CSM}} \approx 1640 \ R_\odot \) and \( K \approx 4 \times 10^{17} \ \text{g cm}^{-1} \) best matches observations. With these values of \( K \) and \( R_{CSM} \), the total CSM mass between the progenitor and the CSM is 0.11 \( M_\odot \), and this CSM mass along with the above \( K \) is equivalent to the mass loss rate of \( \sim 0.08 \ M_\odot \ \text{yr}^{-1} \) assuming a typical wind velocity of 10 km s\(^{-1}\). The SNEC simulations also provide information for the SBO, which occurs inside the CSM near its outer edge at radius \( \sim 1.5 \ R_\odot \) or optical depth \( \tau \approx 95 \). Figure 9 also shows the light curves of the best-fit model with the CSM component along with the best-fit model without the CSM component. As in the figure, the model that includes the CSM component fits the observed early light curves significantly better than the best-fit model without it.

Figure 10 compares observationally estimated blackbody temperatures (top panel) and bolometric luminosities (middle panel) with those of the best-fit models, both with and without the CSM component. The temperatures represent best-fit

6.2. Potential Interaction with Dense CSM

As shown in Figure 9, the comparison between the best-fit light curve and the observed light curves indicate the existence of additional emission in the early epochs. In order to understand the nature of this emission, we conducted additional SNEC simulations including a CSM component. We adopt a dense, optically thick, constant-velocity CSM with the density profile \( \rho(r) = K/r^2 \) for \( r < R_{\text{CSM}} \) (e.g., Morozova et al. 2018).
blackbody temperatures from the observed $BVI$ magnitudes, while the observed bolometric luminosity is calculated after applying proper BCs (Section 3.4). The modeled bolometric luminosity is measured at the photosphere. Figure 10 (bottom panel) also compares velocities of several spectral lines at the epoch of 93 days (presented in Table 4) and the simulated photospheric velocities.

As seen in Figure 10, the temperature and luminosity derived from observations match well with those from the best-fit model during the later epoch. There are, however, slight discrepancies in temperature and luminosity during the early ($t \lesssim 5$ days) epoch: (1) in temperature: the models (both with and without CSM) predict higher (by 2500 K) temperature than the observations; (2) in luminosity: while the observations match the predictions from the model without the CSM component, the model with CSM overpredicts the observed luminosity. The discrepancy (1) can be due to inaccurate temperatures estimated from $BVI$ light curves because the temperature is high and the observed bands do not cover the peak SED intensity or potential deviation from a blackbody spectrum in the presence of CSM (Chevalier & Irwin 2011), while the apparent discrepancy in (2) may arise from inaccurate BC for the early envelope cooling phase for SNe with CSM. These overall agreements in temperature and luminosity, together with the similarity in the photospheric velocities of the model and Fe II line velocities—which is associated with the photospheric velocity as discussed in Section 4—indicate that the observed light curves of KSP-SN-2016kf are reasonably well reproduced in our simulations.

It is worth noting that our estimates of $K$ and $R_{\text{CSM}}$ of the potential dense CSM component should be regarded as lower limits due to the LTE assumption in SNEC. It is likely that this assumption breaks down when the shock moves into the CSM, in which case the temperature of the photons would significantly exceed that calculated in the simulations under the LTE assumption. This leads to a longer rise time because it takes longer for the color temperature (i.e., spectrum peak) to drop into the observed band (Nakar & Sari 2010).

7. Discussion

KSP-SN-2016kf is an H-rich Type II SN with a long rise time ($t_{\text{rise}} \simeq 19.9$ days in the V band), a relatively luminous peak ($M_V \simeq -17.62$ mag), a highly luminous plateau ($M_V \simeq -17.47$ mag at the epoch of 50 days), and a low decay rate ($s \simeq 0.53$ mag per 100 days). Its tail part ($t \gtrsim 105$ days) is exceptionally bright, requiring a large $^{56}\text{Ni}$ mass of $\sim 0.1 M_\odot$ to power the tail luminosity. The SN likely resulted from an explosion with $\sim 1.3$ foe energy in an RSG, evolved from an $\sim 18.8 M_\odot$ ZAMS mass, whose mass and radius are $\sim 15 M_\odot$ and $\sim 1040 R_\odot$, respectively, at the time of explosion. The early light curves of KSP-SN-2016kf indicate the presence of CSM.

Figure 11 compares the $^{56}\text{Ni}$ mass and the plateau magnitude of KSP-SN-2016kf at the epoch of 50 days to those of most other Type II SNe at the same epoch presented in Valenti et al. (2016), showing a positive correlation between the two parameters. This correlation has also been reported in several previous studies (Hamuy 2003; Spiro et al. 2014; Pejcha & Prieto 2015; Valenti et al. 2016). KSP-SN-2016kf appears to have the most luminous plateau among the sample of Type II SNe shown as well as one of the highest inferred $^{56}\text{Ni}$ masses, while it still follows the known correlation. The $^{56}\text{Ni}$ mass of Type II SNe has also been known to be correlated with the explosion energy (Hamuy 2003; Pejcha & Thompson 2015; Müller et al. 2017), and the $^{56}\text{Ni}$ mass of $\sim 0.1 M_\odot$ and 1.3 foe explosion energy of KSP-SN-2016kf appear to follow the correlations in those studies.

Figure 12 shows the V-band light curves of a sample of Type II SNe presented in Anderson et al. (2014) in comparison with that of KSP-SN-2016kf. We can easily identify that the plateau of KSP-SN-2016kf is flatter than those of other SNe with comparable luminosity. The known correlation between the high peak luminosity and the plateau decay rate (Anderson et al. 2014) predicts a much higher decay rate than what we observed for KSP-SN-2016kf. Since we estimated a large amount of $^{56}\text{Ni}$, its flatter plateau may indicate the presence of an early contribution of the radioactive decay of $^{56}\text{Ni}$ to the plateau luminosity (Nakar et al. 2016).

As seen in Figure 11, KSP-SN-2016kf has one of the largest $M_{\text{Ni}}$ among the sample of Valenti et al. (2016). This is also consistent with the sample of 19 H-rich Type IIP SNe in Müller et al. (2017), whose median $M_{\text{Ni}}$ is 0.031 $M_\odot$. High $^{56}\text{Ni}$ masses in the range of 0.1–1.6 $M_\odot$ have been previously reported for several Type II SNe including SN1992H (Hamuy 2003), SN1992af (Valenti et al. 2016), SN1992am (Hamuy 2003), SN...
alternative power sources at later epochs, unknown dust extinction, and limited photometric data over the tail of the light curve.

It appears that the observationally estimated $^{56}$Ni mass of a group of SNe, including those mentioned above, is higher than the typical $M_{\text{Ni}}$ upper limit of $\sim 0.12 M_{\odot}$ predicted by neutrino-driven CCSN simulations (e.g., Ugliano et al. 2012; Pejcha & Thompson 2015; Sukhbold et al. 2016). Therefore, it is important to increase the sample size of SNe with large $^{56}$Ni mass to draw firm conclusions on the compatibility of neutrino-driven CCSN simulations and the observations in terms of $^{56}$Ni mass production. For KSP-SN-2016kf, our estimated $M_{\text{Ni}} \sim 0.1 M_{\odot}$ is within the predicted $M_{\text{Ni}}$ range of 0.003–0.12 $M_{\odot}$ for the successful SN explosions in the neutrino-driven CCSN simulations of Sukhbold et al. (2016), and our obtained explosion energy of 1.3 foe is compatible with the production of 0.1 $M_{\odot}$ of $^{56}$Ni based on the positive correlation between the two parameters (Sukhbold et al. 2016, see their Figure 17).

The large ZAMS mass, $\sim 18.8 M_{\odot}$ (Section 6), of the progenitor of KSP-SN-2016kf provides an important insight into how H-rich Type II SNe explode. According to Smartt et al. (2009), large RSGs, whose masses during their ZAMS phase were greater than $\sim 17 M_{\odot}$, have been very rare as progenitors of Type II SNe. This lack of RSG progenitors with a large ZAMS mass, known as the “RSG problem,” appears to be consistent with what is predicted by numerical simulations of neutrino-driven CCSNe, which substantially favor ZAMS stars of smaller mass, $\lesssim 17 M_{\odot}$, as the progenitor of Type II SNe (Ugliano et al. 2012; O’Connor & Ott 2013; Sukhbold et al. 2016). In this scenario, ZAMS stars of mass $\gtrsim 17 M_{\odot}$ tend to directly implode to a black hole or produce failed SNe without SN-like activity. The recent discovery of a massive RSG progenitor with metallicity of $\sim 0.1$ (Anderson et al. 2016) shows that metallicity may play an important role, although it is difficult to reach a firm conclusion due to the lack of other observational examples supporting the idea. KSP-SN-2016kf appears to support the interpretation that a link between low-metallicity progenitors and SNe in massive RSGs may exist.

The light curves of KSP-SN-2016kf indicate the presence of a CSM component similar to the one assumed in Morozova et al. (2018). However, recent numerical simulations including wind acceleration predict a CSM component that is more extended and less massive than what is required in KSP-SN-2016kf. This emphasizes the need to obtain early spectra that can constrain the properties of CSM more rigorously.

Finally, we note that our results for the progenitor parameters of KSP-SN-2016kf are based on model calculations relying on three key assumptions: (1) the SN explosion is spherical; hence, a 1D model is sufficient; (2) the LTE assumption holds for the first 105 days since the explosion; and (3) non-rotating pre-SN models are adequate for the progenitor. Although these assumptions have been commonly adopted in similar studies of Type II SNe in practice, the results based on these assumptions should be taken with caution in principle since we cannot rule out the possibility that the real situations are in fact much different from the assumptions. The first assumption on the sphericity of the SN progenitor and explosion is motivated by the fact that developing significant asymmetries and non-radial flows is much more difficult in RSGs than in compact stripped-envelope progenitors and requires extremely aspherical explosions or oblate progenitors (e.g., Matzner et al. 2013). Similarly, the LTE assumption is relevant for RSG progenitors because the post-SN RSG shock propagates slowly enough for the shocked material to generate sufficient photons for maintaining the equilibrium (Nakar & Sari 2010), although departure from LTE may happen considering CSM interaction as discussed in Section 6.2. For the third assumption on non-rotating RSG models, it is important to note that fast rotation may cause the H envelope of the stars in the initial mass range of 15–20 $M_{\odot}$ to be removed due to changes in core structure and enhanced mass loss, leading to Type Ib or Ib/c SNe rather than Type II SNe (Hirschi et al. 2004). It is therefore more difficult for a rapidly rotating and massive RSG to explode as a Type II SN.

8. Summary and Conclusion

In this paper, we present the photometric and spectroscopic analyses of KSP-SN-2016kf and its host galaxy discovered by KMTNet. Our multi-color high-cadence observations of KSP-SN-2016kf give a tight constraint on the SBO epoch as well as reliable estimates of its rise time. Based on a comprehensive modeling of the observed properties and also comparison with other Type II SNe, we summarize the properties and peculiarities of KSP-SN-2016kf as follows.

(1) KSP-SN-2016kf has an exceptionally long rise time for an H-rich Type II SN, particularly among high-luminosity ones, with $t_{\text{rise}} \approx 20$ and $\approx 50$ days in V and I bands, respectively.

(2) The light curves of KSP-SN-2016kf have a moderately bright peak with $M_V \approx -17.6$ mag, but a highly luminous plateau with $M_V \approx -17.4$ mag at 50 days. The plateau is one of the most luminous ones ever observed for H-rich Type II SNe.

(3) KSP-SN-2016kf also has an exceptionally luminous radioactive tail, which requires $0.10 \pm 0.01 M_{\odot}$ of $^{56}$Ni mass to power it.

(4) The plateau phase of the light curves shows a decay rate of $\sim 0.53$ mag per 100 days in the V band, which is smaller that what is expected from the known correlation between decay rate and peak luminosity (Anderson et al. 2014). This may indicate the early contribution of $^{56}$Ni radioactive decay to the luminosity as discussed by Nakar et al. (2016).

(5) From modeling of the light curves, the best-fit progenitor is an $\sim 18.8 M_{\odot}$ ZAMS star that evolved into a mass of $\sim 15 M_{\odot}$ and radius of $\sim 1040 R_{\odot}$ before an explosion of $\sim 1.3$ foe.

(6) KSP-SN-2016kf appears to have subsolar metallicity with $Z/Z_{\odot} \approx 0.1–0.4$.

(7) Comparison between the observed light curves and modeled light curves of KSP-SN-2016kf indicates that a CSM component may have been present around its progenitor.

(8) The production of $0.10 \pm 0.01 M_{\odot}$ of $^{56}$Ni mass in an explosion of $\sim 1.3$ foe is consistent with the predictions of the neutrino-driven CCSN simulations of Sukhbold et al. (2016).

(9) The estimated ZAMS mass of $\sim 18.8 M_{\odot}$ for the KSP-SN-2016kf progenitor is higher than the range of $M_{\text{ZAMS}} \lesssim 17 M_{\odot}$ obtained for the RSG progenitor of
This research has made use of the KMTNet facility operated by the Korea Astronomy and Space Science Institute and the data were obtained at three host sites of CTIO in Chile, SAAO in South Africa, and SSO in Australia. We acknowledge with thanks the variable-star observations from the AAVSO International Database contributed by observers worldwide and used in this research. Our simulations were carried out on Compute Canada resources. PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA. N.A. was supported by QUII-GSST and OGS Fellowships. D.S.M. was supported in part by a Leading Edge Fund from the Canadian Foundation for Innovation (Project No. 30951) and a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada. Support for this work was provided to M.R.D. by NASA through Hubble Fellowship grant NSG-HF2-51373 awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555. M.R.D. acknowledges support from the Dunlap Institute at the University of Toronto. S.G.G. acknowledges the support from the Portuguese Foundation for Science and Technology. B.M. is sponsored by the Dunlap Institute at the University of Toronto. Collaboration was provided to M.R.D. by NASA through Hubble Fellowship grant NSG-HF2-51373 awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555. M.R.D. acknowledges support from the Dunlap Institute at the University of Toronto. S.G.G. acknowledges the support from the Portuguese Foundation for Science and Technology. B.M. is sponsored by the Dunlap Institute at the University of Toronto.

Facilities: KMTNet, DuPont, SciNet, AAVSO.

References

Adams, S. M., Kochanek, C. S., Gerke, J. R., Stanek, K. Z., & Dai, X. 2017, MNRAS, 468, 4968
Adams, N., & Matzner, D. C. 2018, ApJ, 856, 146
Anderson, J. P., Dessart, L., Gutiérrez, C. P., et al. 2018, NatAs, 2, 574
Anderson, J. P., González-Gaitán, S., Hamuy, M., et al. 2014, ApJ, 786, 67
Anderson, J. P., Gutiérrez, C. P., Dessart, L., et al. 2016, A&A, 589, A110
Antoniadis, J., Moon, D.-S., Ni, Y. Q., et al. 2017, ApJ, 844, 160
Arcavi, I. 2017, in Handbook of Supernovae, ed. A. W. Alsubi & P. Mordin (New York: Springer), 239
Arcavi, I., Gal-Yam, A., Cenko, S. B., et al. 2012, ApJL, 756, L30
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, AJ, 156, 123
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Bazin, G., Palanque-Delabrouille, N., Rich, J., et al. 2009, A&A, 499, 653
Becker, A. 2015, HOTPANTS: High Order Transform of PSF Anid Template Subtraction. Astrophysics Source Code Library, ascl:1504.004
Bertin, E. 2006, in ASP Conf. Ser. 351, Astronomical Data Analysis Software and Systems XV, ed. C. G. Caroli et al. (San Francisco, CA: ASP), 112
Bertin, E., Mellier, Y., Radovich, M., et al. 2002, in ASP Conf. Ser. 281, Astronomical Data Analysis Software and Systems XI, ed. D. A. Bohleender, D. Durand, & T. H. Handley (San Francisco, CA: ASP), 228
Bianco, F. B., Modjaz, M., Oh, S. M., et al. 2016, A&Cl, 16, 54
Blondin, S., Matheson, T., Kirshner, R. P., et al. 2012, AJ, 143, 126
Bose, S., Dong, S., Kochanek, C. S., et al. 2018, ApJ, 862, 107
Brown, S., Moon, D.-S., Ni, Y. Q., et al. 2018, ApJ, 860, 21
Bullivant, C., Smith, N., William, A., et al. 2018, MNRAS, 476, 1497
Chevalier, R. A., & Irwin, C. M. 2011, ApJL, 729, L6
Davies, B., & Beason, E. R. 2018, MNRAS, 474, 2116
de Jaeger, T., Anderson, J. P., Galbany, L., et al. 2018a, MNRAS, 476, 4592
de Jaeger, T., Galbany, L., Gutiérrez, C. P., et al. 2018b, MNRAS, 478, 3776
Dessart, L., Gutiérrez, C. P., Hamuy, M., et al. 2014, MNRAS, 440, 1856
Dessart, L., & Hillier, D. J. 2010, MNRAS, 405, 2141
Dopita, M. A., & Sutherland, R. S. 2003, Astrophysics of the Diffuse Universe (Berlin: Springer)
Drout, M. R., Soderberg, A. M., Gal-Yam, A., et al. 2011, ApJ, 741, 97
Elmhaimd, A., Danziger, I. J., Chugai, N., et al. 2003, MNRAS, 338, 939
Fitzpatrick, E. L. 1999, PASP, 111, 63
Freedman, W. L., et al. 2019, AJ, 157, 12
Forster, F., Moriya, T. J., Maureira, J. C., et al. 2018, NatAs, 2, 808
Fuller, J. 2017, MNRAS, 470, 1642
Fuller, J., & Ro, S. 2018, MNRAS, 476, 1853
Gal-Yam, A., Arcavi, I., Ofek, E. O., et al. 2014, Nat, 509, 471
González-Gaitán, S., Tomimaga, N., Molina, J., et al. 2015, MNRAS, 451, 2212
Groves, B., Brüchmann, J., & Walcher, C. J. 2012, MNRAS, 419, 1402
Gutiérrez, C. P., Anderson, J. P., Sullivan, M., et al. 2018, MNRAS, 479, 3232
Hamuy, M. 2003, ApJ, 582, 905
Hamuy, M., Suntzeff, N. B., Gonzalez, R., & Martin, G. 1988, AJ, 95, 93
He, M. Y., Moon, D.-S., Neilson, H., et al. 2016, JKAS, 49, 209
Hirschi, R., Meynet, G., & Maeder, A. 2004, A&A, 425, 649
Hosseinzadeh, G., Vallen, S., McCully, C., et al. 2018, ApJ, 861, 63
Huang, F., Wang, X., Zampieri, L., et al. 2016, ApJ, 832, 139
Hunter, J. D. 2007, CSE, 9, 90
Joyce, W. A., & Mandel, E. 2003, in ASP Conf. Ser. 295, Astronomical Data Analysis Software and Systems XII, ed. E. H. Payne, R. I. Jedrzejewski, & R. N. Hook (San Francisco, CA: ASP), 489
Kasen, D. 2010, ApJ, 708, 1025
Khazov, D., Yaron, O., Gal-Yam, A., et al. 2016, ApJ, 818, 3
Kim, S.-L., Lee, C.-U., Park, B.-G., et al. 2016, JKAS, 49, 37
Kriek, M., van Dokkum, P. G., Labbé, I., et al. 2009, ApJ, 700, 221
Lasker, B. M., Lattanzi, M. G., McLean, B. J., et al. 2008, AJ, 136, 735
Lasker, Y., Park, H. S., Kim, S. C., et al. 2018, ApJ, 859, 5
Levesque, E. M., Massey, P., Olsen, K. A. A., et al. 2005, ApJ, 628, 973
Levesque, E. M., Massey, P., Olsen, K. A. A., et al. 2005, ApJ, 645, 1102
Lyman, J. D., Bersier, D., & James, P. A. 2014, MNRAS, 437, 3848
Lyman, J. D., Bersier, D., James, P. A., et al. 2016, MNRAS, 457, 328
Maraston, C. 2005, MNRAS, 362, 799
Marino, A. R., Rosales-Ortega, F. F., Sánchez, S. F., et al. 2013, A&A, 559, A114
Matzner, C. D., Levin, Y., & Ro, S. 2013, ApJ, 779, 60
Matzner, C. D., & McKee, C. F. 1999, ApJ, 510, 379
Moon, D.-S., Kim, S. C., Lee, J.-J., et al. 2016, Proc. SPIE, 9906, 99064I
Morozova, V., Piro, A. L., & Valenti, S. 2018, ApJ, 858, 15
Nakar, E., & Sari, R. 2010, ApJ, 725, 221
Oke, J. B., & Sandage, A. 1968, ApJ, 154, 21
