A long-duration luminous Type IIn supernova KISS15s: Strong recombination lines from the inhomogeneous ejecta–CSM interaction region and hot dust emission from newly formed dust

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Abstract
We report the discovery of an SN 1988Z–like type IIn supernova KISS15s found in a low-mass star-forming galaxy at redshift z = 0.038 during the course of the Kiso Supernova Survey (KISS). KISS15s shows long-duration optical continuum and emission line light curves, indicating that KISS15s is powered by a continuous interaction between the expanding ejecta and dense circumstellar medium (CSM). The Hα emission line profile can be decomposed into four Gaussians of narrow, intermediate, blueshifted intermediate, and broad velocity width components, with a full width at half maximum of ≲100, ~2000, and ~14,000 km s⁻¹ for the narrow, intermediate, and broad components, respectively. The presence of the blueshifted intermediate component, of which the line-of-sight velocity relative to the systemic velocity is about ~5000 km s⁻¹, suggests that the ejecta-CSM interaction region has an inhomogeneous morphology and anisotropic expansion velocity. We found that KISS15s shows increasing infrared continuum emission, which can be interpreted as hot dust thermal emission of T ~ 1200 K from newly formed dust in a cool, dense shell in the ejecta-CSM interaction region. The progenitor mass-loss rate, inferred from bolometric luminosity, is M ~ 0.4 M☉ yr⁻¹ (vw/40 km s⁻¹), where vw is the progenitor’s stellar wind velocity. This implies that the progenitor of KISS15s was a red supergiant star or a luminous blue variable that had experienced a large mass loss in the centuries before the explosion.

Key words: circumstellar matter — stars: mass-loss — supernovae: general — supernovae: individual (KISS15s, 1988Z)

1. Introduction
Type IIn supernovae (SNe IIn) are a rare class of core collapse SNe (CC SNe; ~7% of all CC SNe; Li et al. 2011b; Smith et al. 2011a; Shivvers et al. 2017) that show strong interactions between SN ejecta and dense circumstellar medium (CSM) produced by progenitor mass-loss episodes prior to the SN explosion (Chevalier 1981; Schlegel 1990). SNe IIn are generally characterized by strong, narrow hydrogen and helium emission lines on top of broad- and intermediate-width emission lines, accompanied by slowly fading, highly luminous blue continua (e.g., Schlegel 1990; Richardson et al. 2002).

Emission line profiles in SNe IIn provide rich information on the SN ejecta and the CSM. The strong narrow lines associated with SNe IIn (v ~ 10–100 km s⁻¹) are thought to originate from the unshocked CSM outside of the forward shock, which is photoionized by radiation from a cool dense shell (CDS) between forward and reverse shocks (Chevalier & Fransson 1994; Smith et al. 2008, 2009; Taddia et al. 2013; de Jaeger et al. 2015; Chugai 2018, and references therein). The intermediate emission lines (v ~ 1000 km s⁻¹) may originate from the CDS (e.g., Smith et al. 2008; Smith 2017) or radiative shock regions of dense clumpy wind (Chugai & Danziger 1994; Chugai 2018), although they can also be produced by the broadening of intrinsically narrow lines by multiple thermal electron scattering in the opaque CSM (Chugai 2001; Dessart et al. 2009). The broad emission lines (v ~ 10,000 km s⁻¹) may be attributed to shocked and/or unshocked photoionized ejecta (Chugai & Danziger 1994; Smith et al. 2008; Smith 2017); however, multiple electron scattering events in the opaque ejecta/CSM can contribute to the production of very broad emission lines (Chugai 2001; Dessart et al. 2009).

The absence of a P Cygni absorption feature in many of the SNe IIn indicates that the CSM formed around the progenitors of SNe IIn is optically thick enough to obscure the underlying SN photosphere expansion (e.g., Chatzopoulos et al. 2012). It has been suggested that the optical continuum emission of long-duration SNe IIn can be produced from the CDS region; however, there may be a second photosphere in the SN ejecta that can be seen if the CDS develops clumps and/or becomes optically thin (Smith et al. 2008).

Another interesting observational property of SNe IIn is late-time mid-infrared (MIR) excess emission at ~3–4 μm observed in several SNe IIn (Fox et al. 2011, 2013; Szalai et al. 2018).
The MIR emission can readily be identified as hot dust thermal emission at dust temperatures of $T_d \sim 1000$ K, which can be produced from either IR echoes from radiatively heated preexisting dust grains in the unshocked CSM or newly formed dust in the CDS (Fox et al. 2013; Gall et al. 2014; Chugai 2018; Sarangi et al. 2018). Therefore, the dust IR emission of SNe IIn can provide further observational constraints on the CSM properties, once the responsible emission mechanism is identified. To disentangle which of the emission mechanisms is more important for the IR excess at late-time spectral energy distributions (SEDs) of SNe IIn, it is crucial to follow the temporal evolution of the IR light curves from early- to late-time (Szalai et al. 2018).

Because the photometric and spectral properties of SNe IIn inevitably reflect the CSM formed by stellar mass-loss episodes of the progenitor stars several hundreds of years before the SN explosions, close examination of SNe IIn enables observational probing of the final stages in the evolution of massive stars (e.g., Smith et al. 2017, and references therein). In this paper, we report the discovery of an SN 1988Z-like SN IIn KISS15s found in a low-mass star-forming galaxy at redshift $z = 0.038$ over the course of the Kiso Supernova Survey (KISS). We present 800 days of broadband optical light curves and optical spectra of KISS15s. KISS15s has been continuously detected in archival Near-Earth Object Wide-field Infrared Survey Explorer (NEOWISE) W1- and W2-band MIR data since $\sim 7$ days after the first optical detection. Thus, NEOWISE data enable one to follow the dust IR emission light curves of KISS15s from the very early epochs.

The remainder of this paper is organized as follows. Section 2 describes the photometric and spectroscopic observations for KISS15s. Section 3 presents detailed analyses of the broadband light curves and emission line profiles and comparisons of the observed properties with known SNe IIn in the literature. In Section 4, we discuss implications for the progenitor and CSM properties of KISS15s derived from analyses of the light curves and spectra. Conclusions are summarized in Section 5.

2. Observations and Data Reduction

We describe the optical-IR broadband photometric observations for KISS15s in Section 2.1, which includes optical data from Kiso/KisoWide Field Camera (KWFC; Section 2.1.1), SkyMapper (Section 2.1.2), Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Section 2.1.3), Mayall/Kitt Peak Ohio State Multi-Object Spectrograph (KOSMOS; Section 2.1.4), and Blanco/DECam (Section 2.1.5), and IR data from WISE/NEOWISE (Section 2.1.6) and Nayuta/NIC (Section 2.1.7). In Section 2.2, we describe optical spectroscopic data from Nayuta/Line Imager and Split Spectrograph (LISS; Section 2.2.1) and ARC3.5 m/Dual Imaging Spectrograph (DIS; Section 2.2.2). Finally, we provide an estimate of the dust extinction inside of the host galaxy in Section 2.3.

Throughout the paper we assume a Wilkinson Microwave Anisotropy Probe 3-year Lambda cold dark matter cosmology with $\Omega_L = 0.73$, $\Omega_M = 0.27$, and $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$ (Spergel et al. 2007). Barycentric corrections for time and radial velocity were applied using barycorr (Eastman et al. 2010; Wright & Eastman 2014; Kanodia & Wright 2018). The modified Julian date (MJD) time stamp is expressed as the barycentric MJD (using the barycentric dynamical timescale).

2.1. Broadband Photometry

2.1.1. Discovery and Follow-up Photometry with Kiso/KWFC

KISS15s was discovered on 2015 September 18.78 UT (MJD = 57283.78) as a $g \sim 19.6$ mag transient (Figure 1) during the KISS (Morokuma et al. 2014), using the 1.05 m KisoSchmidt
Telescope located at Kiso Observatory in Japan; the telescope is equipped with a 2\,\texttimes\,2 WFC (the KWFC; Sako et al. 2012). KISS has performed g-band observations for selected sky regions within the Sloan Digital Sky Survey (SDSS) Legacy Survey region (York et al. 2000), and searched for optical transients through the point-spread function (PSF)–matched image subtraction technique, using SDSS g-band mosaic images as the reference frames (see Morokuma et al. 2014, for details of the KISS pipeline). Re-examination of the previous KWFC images revealed KISS15s detection in the image obtained on 2015 September 11.63 UT (MJD = 57276.63), although the PSF profile of KISS15s was partially affected by bad pixels in this first detection image. After the discovery of KISS15s, we carried out follow-up imaging observations with the Kiso/KWFC for g-, r-, and i-bands.

We noticed that KISS15s is identical to an optical transient, PS15bva, independently discovered by the Pan-STARRS Survey for Transients (Kaiser et al. 2010). The discovery date of PS15bva by Pan-STARRS is 2015 August 30 (MJD = 57264.56), 12 days earlier than the first discovery by KISS. No spectroscopic follow-up observation for KISS15s = PS15bva has been reported. This work presents the first spectroscopic classification of this object.

KISS15s is located at \( \alpha = 03^\text{h}08^\text{m}31^\text{s}640, \delta = -00^\circ50\arcmin55\arcsec \) (J2000)\(^9\), 0\arcmin53 west, and 3\arcmin05 north of the center of the star-forming galaxy SDSS J030831.67-005005.6 (KISS15s) and SDSS J030831.67-005006.8,\(^10\) at a redshift of \( z = 0.03782 \) measured by the SDSS. Although the SDSS database assigns a redshift of \( z = 0.03794 \) for a point-source object on the northeast side of SDSS J030831.67-005008.6 (Figure 1), this object is probably a foreground Galactic star with an SDSS spectrum contaminated by emission lines from SDSS J030831.67-005008.6. Because KISS15s is located on the edge of the extended structure of SDSS J030831.67-005008.6, we identify SDSS J030831.67-005008.6 as the host galaxy of KISS15s. Follow-up spectroscopy for KISS15s (described in Section 2.2) confirms that the redshift of KISS15s is consistent with the redshift of this galaxy. A luminosity distance \( d_L \) and distance modulus (DM) of the host galaxy corrected for the Virgo infall + Great Attractor + Shapley supercluster local flow is \( d_L = 156 \text{ Mpc} \) and DM = \( m-M = 35.97 \text{ mag} \), respectively.\(^11\) The angular–spatial size scale is 0.720 kpc/\( £\), thus, the galactocentric offset of KISS15s is \( \sim 2.23 \text{ kpc} \). The Galactic extinction toward KISS15s was obtained from the NASA/IPAC Extragalactic Database (NED) as \( E(B-V) = 0.053 \text{ mag} \) (Fitzpatrick 1999; Schlafly & Finkbeiner 2011); \( A_g, A_r, A_i, A_z, A_{\text{UK}}, \text{and} A_k = 0.255, 0.199, 0.137, 0.102, 0.076, 0.043, 0.027, \text{and} \ 0.018 \text{ mag} \), respectively. The Galactic extinction coefficients of WISE W1- and W2-bands are \( A_{W1} = 0.011 \) and \( A_{W2} = 0.007 \text{ mag} \), according to the Fitzpatrick (1999) extinction curve.

The KISS data reduction pipeline only provides rough estimates of the \( g \)-band magnitude of the transients. To extract the \( g \)-, \( r \)-, and \( i \)-band photometric measurements of KISS15s, we reanalyzed the KISS imaging data, starting from the raw FITS files. Each of the KISS Kiso/KWFC images was obtained with an exposure time of 180 s without dithering. After applying an overscan, bias, and pixel-flat and illumination-flat corrections (see Kokubo 2016, for details of the KWFC data reduction), the images were processed by \texttt{SExtractor} (Bertin & Arnouts 1996) to produce aperture photometry catalogs of field stars around KISS15s. For each image, the aperture diameter size was set to twice the seeing full width at half maximum (FWHM) size to maximize the signal-to-noise ratio (S/N) of the photometric measurements and minimize the effects of systematic centering errors (e.g., Mighell 1999). Then the photometric zero-point of each image was determined by taking a 3σ-clipping weighted average of the differences between the instrumental magnitudes in the \texttt{SExtractor} catalog and the SDSS magnitudes of field stars retrieved from the SDSS Stripe 82 database (see the appendix of Annis et al. 2014).

Then template matching and image subtraction were applied to the KWFC images, using WCSRemap and High-order Transform of PSF and Template Subtraction (HOTPANTS) version 5.1.10 software, written by A. Becker\(^14\) (Becker 2015). SDSS Stripe 82 deep coadd images, constructed by Annis et al. (2014) from all imaging data obtained on or before 2005 December 1 (York et al. 2000; Frieman et al. 2008), were used as pre-SN template (=reference) images. The SDSS Stripe 82 coadd images are much deeper and have higher resolution than KWFC images (a 50% completeness limit for point sources of 23.6, 24.6, 24.2, 23.7, and 22.3 mag for the \( u \), \( g \), \( r \), \( i \), and \( z \)-bands, respectively, with a median seeing size of \( \sim 1.1\)′′; Annis et al. 2014). WCSRemap was used to produce astrometrically remapped reference images that aligned exactly with individual KWFC images. Then HOTPANTS was used to align the PSF and flux scale of the reference image with those of the KWFC image. \texttt{SExtractor} aperture photometry for KISS15s was applied to the subtracted KWFC images. It should be noted that because the host galaxy light is almost completely removed from the subtracted KWFC images, the photometric measurements of KISS15s derived here, as described, are free from contamination of the underlying host galaxy flux.

Finally, photometric measurements obtained with the same filter each day were combined by taking a weighted mean. Table 1 presents the \( g \)-, \( r \)-, and \( i \)-band measurements for KISS15s from the Kiso/KWFC image subtraction photometry; Figure 2 shows the light curves corrected for Galactic extinction.

### 2.1.2. Early Photometry Obtained with the SkyMapper Survey

SkyMapper is a fully automated 1.3 m optical telescope at Siding Spring Observatory in Australia (Scalzo et al. 2017). First Data Release (DR1.1) of the SkyMapper Southern Survey (Wolf et al. 2018)\(^15\) contains \( u \)-, \( g \)-, \( r \)-, \( i \)-, and \( z \)-band imaging data at the position of KISS15s obtained on MJD = 56899.78 (2014 August 30), 56902.77 (2014 September 2), 57234.78 (2015 July 31), and 57262.75 (2015 August 28).

First, we searched for cataloged photometry data at the position of KISS15s in the SkyMapper photometry table.

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\(^{9}\) https://star.pst.qub.ac.uk/p1ifrheepi/psdb/

\(^{10}\) The record is available at the Open Supernova Catalog (Guillochon et al. 2017): https://sne.space/sne/PS15bva/

\(^{11}\) KISS15s is recorded in the Gaia public data release 2 (Gaia Collaboration et al. 2018) as source_id = 3265523970849514880 at a sky coordinate \( \alpha = 47°13′17″, \delta = -0°38′49″ \); however, the Gaia sky position determination of KISS15s may be affected by the underlying host galaxy light.

\(^{12}\) http://skyserver.sdss.org/dr12/en/tools/explore/Summary.aspx?id=1237663783144259952

\(^{13}\) \( d_L \) and \( m-M \) were taken from the NASA/IPAC Extragalactic Database (NED).

\(^{14}\) https://github.com/acbecker/hotpants

\(^{15}\) DR1 includes only images from the Shallow Survey; http://skymapper.anu.edu.au/data-release/dr1/; 10.4225/41/593626ad5674.
To further check whether KISS15s was detected in much earlier SkyMapper images and to carry out difference image photometry, we downloaded 600" × 600" SkyMapper cut-out images centered on KISS15s. HOTPANTS image subtraction was applied to the SkyMapper images, with SDSS Stripe 82 coadd images as a reference. Then, using the Python module Photutils (Bradley et al. 2017), we applied forced aperture photometry for the difference images with the circular aperture centered on the sky coordinate of KISS15s. Magnitude zero points were calculated by comparing measured instrumental magnitudes of field stars around KISS15s with the SDSS magnitudes. Finally, photometric measurements of each filter obtained on the same day were binned by taking weighted averages.

Table 2 reports the >3σ detection SkyMapper photometry data points for KISS15s. We found that KISS15s was barely detected in r-, i-, and z-band images on 2015 July 31 (Figure 3). Only a single exposure per each filter was obtained at this epoch, in which the exposure times were 40, 5, 5, 10, and 20 s for u-, g-, r-, i-, and z-bands, respectively. KISS15s was not detected in u- and g-band images obtained on the same day, giving magnitude 5σ lower limits of u > 18.09 mag and g > 17.88 mag. The SkyMapper’s first detection date is earlier than the first detection by KISS survey data by 42 days; thus, SkyMapper provides the earliest optical photometry data of KISS15s.

On SkyMapper’s second detection date, 2015 August 28, KISS15s was detected in r-, i-, and z-bands, but not in u- and g-bands, giving magnitude 5σ lower limits of u > 18.69 mag and g > 18.98 mag. At this epoch, two exposures were obtained per each filter; the total exposure times were 80, 10, 10, 20, and 40 s for u-, g-, r-, i-, and z-bands, respectively. The last nondetection by SkyMapper observations was 2014 September 2, roughly 1 yr before the first detection date of 2015 July 31.

SkyMapper r-, i-, and z-band photometry data of KISS15s are shown in Figure 2, along with Kiso/KWFC data.

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Table 1

| MJD          | Date     | mag. | Error in mag. | Band |
|--------------|----------|------|---------------|------|
| 57276.636    | 2015 Sep 11 | 19.65 | 0.08          | g    |
| 57283.784    | 2015 Sep 18 | 19.61 | 0.06          | g    |
| 57308.679    | 2015 Oct 13 | 19.69 | 0.06          | g    |

Note. Galactic extinction is uncorrected.

(This table is available in its entirety in machine-readable form.)

Table 2

| MJD          | Date     | mag. | Error in mag. | Band |
|--------------|----------|------|---------------|------|
| 57234.7870   | 2015 Jul 31 | 18.11 | 0.32          | r    |
| 57234.7873   | 2015 Jul 31 | 17.72 | 0.20          | i    |
| 57234.7877   | 2015 Jul 31 | 17.55 | 0.27          | z    |
| 57262.7524   | 2015 Aug 28 | 18.65 | 0.23          | r    |
| 57262.7527   | 2015 Aug 28 | 18.61 | 0.15          | i    |
| 57262.7531   | 2015 Aug 28 | 18.15 | 0.10          | z    |

Note. Galactic extinction is uncorrected.
Figure 3. SkyMapper i-band reference-subtracted images at the position of KISS15s. The position of KISS15s determined by the KWFC observations is marked by a circle. The images are 2 × 2-binned for clarity.

2.1.3. Pan-STARRS i-band Photometry

The Pan-STARRS 3πm Survey detected KISS15s as of 2015 August 30 (referred to as PS15bva in the Pan-STARRS Survey for Transients database). Given that single-exposure Pan-STARRS images are not publicly available, we retrieved Pan-STARRS photometry data of KISS15s directly from the Open Supernova Catalog (Guillochon et al. 2017). Transient photometry was performed on difference images, using reference images created by stacking frames in each band between 2010 and 2012.\(^{16}\) KISS15s was imaged in i- and w-bands, in which the i-band is similar to that of the SDSS system and the w-band is approximately a g + r + i-band (Tonry et al. 2012). Table 3 lists the Pan-STARRS i- and w-band photometry data of KISS15s, where multiple photometry data obtained within a day are binned by taking the weighted average. The i- and w-band light curves are shown in Figure 2. In the figure, the i-band magnitude is corrected for the Galactic extinction of \(A_i = 0.102\) mag; however the w-band magnitude is not corrected, because the extinction estimate for the w-band is uncertain.

### Table 3

| MJD    | Date     | AB mag. | Error in mag. | Band |
|--------|----------|---------|---------------|------|
| 57264.5795 | 2015 Aug 30 | 18.34   | 0.02          | i    |
| 57319.4943 | 2015 Oct 24 | 18.53   | 0.01          | i    |
| 57320.4304 | 2015 Oct 25 | 18.51   | 0.01          | i    |
| 57354.4335 | 2015 Nov 28 | 18.69   | 0.08          | i    |
| 57341.3750 | 2015 Nov 15 | 18.97   | 0.02          | w    |
| 57343.4161 | 2015 Nov 17 | 18.93   | 0.02          | w    |
| 57363.3764 | 2015 Dec 07 | 19.02   | 0.01          | w    |
| 57387.3352 | 2015 Dec 31 | 19.20   | 0.01          | w    |
| 57693.4538 | 2016 Nov 01 | 20.05   | 0.11          | w    |
| 57697.4347 | 2016 Nov 05 | 19.94   | 0.02          | w    |
| 58054.5265 | 2017 Oct 28 | 21.18   | 0.06          | w    |
| 58099.3644 | 2017 Dec 12 | 21.42   | 0.22          | w    |

Note. Galactic extinction is uncorrected.

### Table 4

| MJD    | Date     | AB mag. | Error in mag. | Band |
|--------|----------|---------|---------------|------|
| 57959.454 | 2017 Jul 25 | 21.78   | 0.10          | g    |
| 57959.456 | 2017 Jul 25 | 20.31   | 0.02          | r    |
| 57959.459 | 2017 Jul 25 | 21.46   | 0.05          | i    |

Note. Galactic extinction is uncorrected.

2.1.4. Mayall 4 m/KOSMOS Optical Photometry

We obtained single epoch g-, r-, and i-band photometry for KISS15s with the Mayall 4 m Telescope in KOSMOS imaging mode (Martini et al. 2014) on 2017 July 25 UT (MJD = 57959.5). KOSMOS was used with a 2k4k E2V charge-coupled device (CCD) with a pixel scale of 0.292 pixel\(^{-1}\). The exposure time for each band was 180 s. The seeing condition on the observing night was ~5 pixel = 1.5.

Mayall/KOSMOS images were analyzed in the same way as the Kiso/KWFC data, using HOTPANTS and aperture photometry. The Mayall/KOSMOS image subtraction photometry of KISS15s is summarized in Table 4. The Mayall/KOSMOS g- and i-band data are well below the power-law extrapolation of the Kiso/KWFC and SkyMapper photometry data (Figure 2). The significant drop in optical continuum emission indicates that the heating sources of the continuum emission region, which may be the innermost part of KISS15s, lose most of their kinetic energy (see Section 3.1.1 for details).

Mayall/KOSMOS r-band photometry shows an excess compared to g- and i-band data, and has a consistent brightness with the last Kiso/KWFC r-band observation. The apparent r-band excess relative to the g- and i-bands is probably due to flux contamination from a persistently strong H\(\alpha\) emission line (Section 2.2). It should be noted that the Mayall/KOSMOS r-band filter transmission is relatively enhanced at wavelengths around \(\lambda_{\text{obs}} \sim 6800\) Å compared to that of the original SDSS r-band filter (adopted by the Kiso/KWFC). The enhanced H\(\alpha\) emission line EW at later epochs (Section 2.2) and the enhanced filter response can explain the r-band excess. We note that a similar r-band excess relative to the other bands due to the

\(^{16}\) https://star.pst.qub.ac.uk/ps1threepi/psdb/
contamination of the strong H\textalpha{} emission line was also observed in luminous type IIn SN 2010jl (Fransson et al. 2014).

2.1.5. Blanco 4 m/DECam Optical Photometry

KISS15s was serendipitously detected in g-, r-, and z-band images obtained through the DECam Legacy Survey (DECaLS DR7; Dey et al. 2018).\textsuperscript{17} DECaLS uses a 3 deg$^2$ FoV prime focus optical imager DECam, which is mounted on the Blanco 4 m telescope at Cerro Tololo Inter-American Observatory and includes 62 2k4k CCDs at 0.′263 pixel$^{-1}$ resolution. The g-, r-, and z-band images of KISS15s were obtained on 2017 November 11–12, 2017 September 17, and 2015 November 28, respectively. Two images were obtained per each filter at detector positions of S28 and N29 (see e.g., Shaw 2015); the exposure times of g-, r-, and z-band images were 80 and 166 s, 65 and 58 s, and 85 and 88 s, respectively. The seeing FWHMs were ∼3.3–4.6 pixels, corresponding to 0.′9–1.′2.

We downloaded the images and associated inverse-variance maps from the DECam Legacy Survey web page. The DECaLS images were analyzed in the same way as Kiso/KWFC data, using HOTPANTS and g-, r-, and z-band references created from SDSS Stripe 82 data. Aperture photometry for the reference-subtracted images was performed using Photutils. The DECaLS image subtraction photometry of KISS15s is summarized in Table 5, where a weighted average of the two photometric measurements for each filter is reported. As shown in Figure 2, the DECaLS g-band measurement confirms a faster rate of decline at the late epochs (≥600 days since discovery) compared to the slower temporal evolution at the early epochs.

As with Mayall/KOSMOS r-band photometry (Section 2.1.4), DECaLS r-band photometry also shows an excess, compared to g- and i-band Mayall/KOSMOS data in late epochs. The DECam r-band filter transmission is relatively enhanced at wavelengths around $\lambda_{\text{obs}} \approx 6800$ Å compared to the original SDSS r-band filter. Thus, the apparent r-band excess of the DECaLS measurement is probably due to flux contamination from the strong H\textalpha{} emission line.

2.1.6. NEOWISE W1- and W2-band Infrared Photometry

The NEOWISE reactivation mission has been scanning the entire sky, using a space-based infrared telescope in the MIR wavelength range, specifically W1 (3.4 μm) and W2 (4.6 μm) bands, since late 2013 as an extension of the original mission, the WISE All-Sky Survey (Wright et al. 2010; Mainzer et al. 2014). The NEOWISE survey visits each sky region roughly twice per year (each visit consists of 9–16 exposures) and thus is useful for examining the long-term MIR light curve evolution of astronomical transients. In this work, we used the NEOWISE 2018 Data Release, which includes all W1- and W2-band images and associated photometry catalogs acquired before the end of 2017.

First, we searched for a point source at the position of KISS15s in the NEOWISE-R Single Exposure (L1b) Source table available at the NASA/IPAC Infrared Science Archive, and found that KISS15s was detected in a NEOWISE W1-band single exposure image obtained on 2015 August 5 (MJD = 57239.47; frame id = 62453b177), KISS15s has continuously been detected since the first detection both in the W1- and W2-bands. The first detection of KISS15s by NEOWISE was 1 month prior to the first detection by Kiso/KWFC (Section 2.1.1), and ∼7 days after the detection by SkyMapper (Section 2.1.2).

Then we examined whether KISS15s appeared in WISE/NEOWISE images by creating a coadded image for each visit for each band, using an online version of the WISE/NEOWISE Coadder ICORE (Masci & Fowler 2009; Masci 2013).\textsuperscript{18} Images of 0.′03 × 0.′03 (at 1′0 pixel$^{-1}$) coadded intensity and standard deviation at the position of KISS15s were created for each band for each NEOWISE visit (∼10 exposures per visit). Images with a qual_frame>=5, a moon separation angle >20°, and ssa_sep (distance from South Atlantic Anomaly edge) > 0° were used as input. A simple area weighting was used for its interpolation, converting the native input pixel scale of 2″75 pixel$^{-1}$ to the output pixel scale of 1″0 pixel$^{-1}$ (Section 7 of Masci 2013). Aside from the NEOWISE data, W1- and W2-band images obtained during the epochs of the WISE all-sky survey (in 2010–2011; ∼40 exposures) were coadded into W1- and W2-band referenced images, respectively; then the reference images were subtracted from the single visit coadd images to create difference images. The residual background in the difference image was estimated by taking a median of the pixel fluxes, and the estimated residual background was subtracted from the difference image.

Figure 4 shows the WISE/NEOWISE reference and difference images at the position centered on KISS15s. No signal was detected in the difference images before the NEOWISE visit on 2015 August 5. Since then, KISS15s has appeared continuously as a point source. We can see that the W2-band fluxes were barely detected in 2015 August (at the ∼3.4σ level). Aperture photometry was applied to the difference images using Photutils, in which a fixed standard circular aperture with 8″/25 radius centered on the sky coordinate of KISS15s was used. The same aperture photometry was also applied to the associated variance images to estimate the photometric errors of the aperture fluxes. To account for the spatial correlation of pixel noise, the photometric errors of the aperture fluxes derived from the photometry of the variance map were inflated by a factor of 2.75 (equating to the ratio of the input to output pixel scale; section 13 of Masci 2013). To determine the magnitude zero points, first we downloaded 0.′3 × 0.′3 ALLWISE W1- and W2-band images around KISS15s and measured the circular aperture instrumental magnitudes of field stars. The mean difference between the instrumental and Vega magnitudes of field stars cataloged in the ALLWISE point source catalog was calculated as a magnitude zero-point for each of the W1- and W2-bands. The magnitude offsets between Vega and AB magnitude systems were taken from Jarrett et al. (2011) as $m_{\text{W1,AB}} = m_{\text{W1,Vega}} + 2.699$ mag and $m_{\text{W2,AB}} = m_{\text{W2,Vega}} + 3.339$ mag.

\begin{table}[t]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
MJD & Date & AB mag. & Error in mag. \tabularnewline
\hline
57354.148 & 2015 Nov 28 & 18.35 & 0.01 \tabularnewline
58013.384 & 2017 Sep 17 & 20.62 & 0.02 \tabularnewline
58068.701 & 2017 Nov 11 & 22.63 & 0.19 \tabularnewline
\hline
\end{tabular}
\caption{Blanco/DECam DECaLS Photometry of KISS15s}
\end{table}

\textsuperscript{17} Specifically, the DECam Legacy Survey of the SDSS Equatorial Sky (PI: D. Schlegel and A. Dey); http://legacysurvey.org/.

\textsuperscript{18} http://irsa.ipac.caltech.edu/applications/ICORE/
The bottom panel of Figure 2 shows the W1- and W2-band difference image photometry light curves of KISS15s after 2015 August 5 (Table 6). Interestingly, the W1- and W2-band MIR fluxes increased over time from 2015 to 2017, as opposed to the optical light curves that have steadily decreased since discovery (Figure 2). The late-time excess emission at IR wavelengths observed in SNe IIn are commonly interpreted as new dust formation in the CDS region, or as dust IR echoes from the CSM (e.g., Stritzinger et al. 2012; Fransson et al. 2014; Sarangi et al. 2018).}

Table 6

| Mid. MJD | Mid. Date | AB mag. | Error in mag. | Band |
|----------|-----------|---------|---------------|------|
| 57241.5  | 2015 Aug 7| 18.52   | 0.14          | W1   |
| 57411.8  | 2016 Jan 24 | 18.41  | 0.12          | W1   |
| 57607.1  | 2016 Aug 7 | 17.50   | 0.06          | W1   |
| 57773.6  | 2017 Jan 20 | 17.17  | 0.04          | W1   |
| 57971.2  | 2017 Aug 6 | 17.12   | 0.05          | W1   |

| Mid. MJD | Mid. Date | AB mag. | Error in mag. | Band |
|----------|-----------|---------|---------------|------|
| 57241.5  | 2015 Aug 7| 18.94   | 0.32          | W2   |
| 57411.8  | 2016 Jan 24 | 18.18  | 0.15          | W2   |
| 57607.1  | 2016 Aug 7 | 17.42   | 0.10          | W2   |
| 57773.6  | 2017 Jan 20 | 17.03  | 0.06          | W2   |
| 57971.2  | 2017 Aug 6 | 16.94   | 0.06          | W2   |

Note. Galactic extinction is uncorrected.

The W1- and W2-band images obtained during the run were shifted and added to generate a final image using SWARP (Bertin et al. 2002).

We performed two-dimensional fitting of the KISS15s and the host galaxy to derive the NIR magnitudes of KISS15s. We first modeled the PSFs of the coadded J-, H-, and Ks-band images by fitting three Gaussians to a simultaneously imaged nearby field star, 2MASS J03083221-0050320. Then, each of the NIR images of KISS15s + foreground star + host galaxy were fitted with a model composed of two PSFs for KISS15s, the foreground star, and one inclined exponential disk for the host galaxy. The magnitude zero points of the NIR images were determined by comparing the 2MASS point source magnitudes (Skrutskie et al. 2006) and PSF-fitting instrumental magnitude measurements for five nearby field stars simultaneously imaged with KISS15s. The Vega magnitudes were converted into AB magnitudes using offsets between AB and Vega magnitude systems of 0.91, 1.39, and 1.85 mag for J-, H-, and Ks-bands, respectively (Blanton & Roweis 2007). The PSF fitting was performed using IDL routine MPFIT2DFUN,19 developed by Craig B. Markwardt; multi-component model fitting was performed using GALFIT (Version 3.0.5; Peng et al. 2002).

Figure 5 shows the best-fitting GALFIT model of J-, H-, and Ks-band images. The PSF magnitudes of KISS15s are summarized in Table 7. KISS15s is brighter in the longer wavelength bands, suggesting that the NIR bands are

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19 https://www.physics.wisc.edu/craigm/idl/down/mpfit2dfun.pro
dominated by the same host dust component revealed by NEOWISE W1- and W2-band photometry.

2.2. Optical Spectroscopy

2.2.1. Nayuta/LISS Very-low-resolution Spectroscopy

Following the Kiso/KWFC discovery of KISS15s on 2015 September 18.78 UT, we carried out optical spectroscopy measurements for rapid classification of the transient on 2015 September 19.7 UT (MJD = 57284.7) with the 2.0 m Nayuta telescope, using an optical spectrograph, LISS (Hashiba et al. 2014). LISS employs a back-illuminated fully depleted-type Hamamatsu 2k1k CCD. We used a grism with a linear dispersion of 12.4 Å pixel$^{-1}$ and a 2$''$/0 width long-slit to obtain a very-low-resolution optical spectrum for KISS15s. The observed-frame wavelength range was 4000–10,000 Å, and the total on-source exposure time was 65 minutes. The spatial scale of LISS is 0.244 pixel$^{-1}$, and the instrumental broadening is estimated to be $\sigma_r \sim 30$ Å. The slit direction was set to a position angle (PA) of 158.5° to align the slit spatial direction to the semimajor axis of the host galaxy.20 The spectra were extracted using an aperture size of 2"×44.

The spectrophotometric standard star G191-B2B was observed for the flux calibration. Because the atmospheric extinction coefficients (mag/airmass values as a function of wavelength) at NHAO are not well constrained, we did not apply the airmass correction for the KISS15s spectrum. The airmass values during the observations were 1.320–1.248 for KISS15s and 1.530–1.518 for G191-B2B; thus, the bluest part of the KISS15s spectrum may be overestimated by ~0.1 mag relative to the reddest part. Data reduction, including overscan, bias, flat correction, cosmic ray rejections with the use of L.A. Cosmic (lacospec; van Dokkum 2001), and wavelength and flux calibrations, were carried out using IRAF. The LISS spectrum was corrected for telluric absorption features in the wavelength ranges of 6800–6890 Å and 7600–7630 Å (O$_2$ bands) by dividing the KISS15s spectrum by the normalized combined spectrum of the standard star. The spectrum was corrected for Galactic extinction using the Fitzpatrick (1999) extinction curve.

Finally, the absolute flux of the LISS spectrum was scaled to match the Galactic extinction-corrected $i$-band magnitude of KISS15s obtained from broadband photometry. We chose the $i$-band as the reference wavelength band, because the $r$-band is less affected by the H$\alpha$ emission line and blue continuum emission from the star-forming host galaxy than the $g$- and $r$-bands. To perform the spectrophotometry, we first interpolated the $i$-band magnitude of KISS15s at the epoch of Nayuta/LISS spectroscopy from the $i$-band broken-line light-curve model (Figure 2; see Section 3.1.1 for details). Then the filter-convolved $i$-band magnitude of the raw LISS spectrum was calculated using Speclite.21 The spectrophotometric scaling factor was calculated from the difference between the broadband and spectroscopic $i$-band magnitudes.

Figure 6 presents the Nayuta/LISS spectrum of KISS15s. Based on the redshift information ($z = 0.03782$) of the host galaxy SDSS J030831.67-005008.6 taken from the SDSS database, a strong, resolved broad emission line at the observed wavelength of $\lambda_{obs} \sim 6800$ Å can readily be identified as the H$\alpha$ emission line related to KISS15s. The H$\beta$ emission line, He I emission line ($\lambda$5876), and Ca II IR triplet ($\lambda\lambda$8498, 8542, 8662) are also barely detectable in the Nayuta/LISS spectrum with a consistent redshift. Thus, the Nayuta/LISS spectrum confirms that KISS15s actually belongs to the galaxy SDSS J030831.67-005008.6. The broad H$\alpha$ line does not show any P Cygni features, as is the case for other SNe IIn.

2.2.2. ARC3.5 m/DIS Low- and High-resolution Spectroscopy

At later epochs, we obtained three low-resolution spectra and two high-resolution spectra for KISS15s using the DIS mounted on the ARC3.5 meter telescope at the Apache Point Observatory (APO). DIS is a dual channel imaging spectrograph, composed of a Marconi CCD42-20-0-310 on the blue side and an E2V CCD42-20-1-D21 on the red side.22 Table 7 lists the log of the ARC3.5 m/DIS observations of KISS15s.

The first epoch ARC3.5 m/DIS low-resolution optical spectrum of KISS15s was obtained on 2015 December 2 UT (MJD = 57358.2). A standard low-resolution grating setup of B400/R300 for blue/red channels, 1 × 1 on-chip binning, and a 2.0" long-slit were used. The spatial scales were 0.400 pixel$^{-1}$ and 0.42 pixel$^{-1}$ for the blue and red channels, respectively. The total exposure time was 45 minutes (three exposures of 15 minutes each), and the slit direction was set to PA = 158.5°.

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20 PA = 0° corresponds to the north–south, PA increasing from north toward east.

21 https://github.com/dkirkby/speclite. Spectral response curves of SDSS (Doi et al. 2010) and WISE (Wright et al. 2010) filters are included in the Speclite module.

22 https://www.apo.nmsu.edu/arc35m/Instruments/DIS
A spectrophotometric standard star GD50 was also observed on the same day for the flux calibration.

The second epoch ARC3.5 m/DIS low-resolution spectrum was obtained on 2016 January 30 UT (MJD = 57417.1), using the same instrumental setup as the first observation, except for the use of a 1''5 width long-slit and 2 × 1 binning. The observation may have been affected to some extent by cirrus clouds.

The third epoch ARC3.5 m/DIS spectrum was obtained on 2016 February 12 UT (MJD = 57430.1) using a high-spectral resolution mode: 0''9 width long-slit, 1 × 1 binning, a no-order sorting filter, and B1200/R1200 gratings. The B1200 and R1200 grisms were tilted in their housings so that the target wavelengths (5040 Å and 6800 Å, respectively) were located toward the center of the detector. As summarized in Table 8, the instrumental broadening of the high-resolution mode was evaluated to be $\sigma_{\text{inst}} \sim 20$ km s$^{-1}$ in the H$\alpha$ emission wavelength region of KISS15s. The total exposure time was about 74 minutes, and the slit direction was set to PA = 158°5.

The spectrophotometric standard star GD50 was observed on the same day for flux calibration.

The fourth epoch ARC3.5 m/DIS spectrum was obtained on 2016 October 4 (MJD = 57665.4), using both low- and high-spectral resolution modes and the same instrumental configurations as the previous observations. The total exposure times were 60 and 67.6 minutes for the low- and high-resolution spectroscopy mode, respectively; however, cloudy weather conditions prevented us from achieving the planned S/N objective.

Data reduction of ARC3.5 m/DIS spectra was carried out using IRAF. Simple aperture extraction was performed, in which the extraction aperture was set to ~2''4 to minimize flux contamination from the host galaxy. The relative airmass correction was applied using the APO atmospheric extinction coefficients compiled by J. Davenport. All spectra were corrected for Galactic extinction using the Fitzpatrick extinction curve, under the assumption of $R_V = 3.1$.

The sensitivity functions derived from the data of the spectrophotometric standard stars obtained on the first (low-resolution) and third (high-resolution) DIS observation epochs were used for the flux calibration. Note that due to the differences in the grism tilt angles between observations runs, the fourth epoch blue-channel DIS spectrum could not be accurately calibrated. For each DIS spectrum, we corrected for telluric absorption features in the wavelength ranges of 6860–6890 and 7600–7630 Å (O II bands) by dividing the KISS15s spectrum by a continuum-normalized spectrophotometric standard star spectrum.

Finally, the absolute flux scales of DIS spectra were calibrated by spectrophotometry. Because the i-band is less affected by blue continuum emission from the star-forming host galaxy (Section 4.1) and the strong emission lines compared to g and r-bands, we used the broken-line i-band light-curve model (Figure 2; see Section 3.1.1) as the reference magnitude for spectrophotometry measurements. High-resolution mode spectra did not cover a sufficient wavelength range; thus, we applied spectrophotometry only to low-resolution mode spectra. Specifically, the observed spectra were convolved with the SDSS i-band filter transmission curve using Specfit; the spectrophotometric calibration factor for each spectrum was derived from the ratio of the i-band power-law fitted flux and the filter-convolved flux.

Figure 6 shows low-resolution ARC3.5 m/DIS spectra. At early epochs, the DIS spectra showed consistent spectral features with the lower-resolution Nayuta/LISS spectrum. The broad H$\alpha$, H$\beta$, and Ca II IR triplet emission lines are clearly visible. In addition, an intermediate-velocity width component can be identified on top of the broad H$\alpha$ emission line in both DIS and Nayuta/LISS spectra. The broad component ($\sigma_{\text{FWHM}} \sim 14,000$ km s$^{-1}$) had weakened considerably by 2016 October 4; however, the intermediate component ($\sigma_{\text{FWHM}} \sim 2000$ km s$^{-1}$) retained its high luminosity during the observations.

Several narrow emission lines (e.g., [O II]$\lambda$3727, H$\beta$, [O III]$\lambda$4959, 5007, and H$\alpha$) are also clearly visible in the DIS spectra. As discussed in Section 3.2.1, these narrow components are probably due to the emission from extended H II regions in the host galaxy and thus are not directly related to the SN explosion of KISS15s. As for the narrow component, the different slit widths and variable seeing conditions during

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Figure 6. Nayuta/LISS very-low-resolution spectrum and ARC3.5 m/DIS spectra of KISS15s. The ARC3.5 m/DIS spectra obtained on 2015 December 2016 January 30, and October 4 are scaled by factors of 10, 100, and 1000 in flux, respectively. The observation dates since the first detection date (MJD = 57234) are indicated at the left-band side. The Galactic extinction is corrected. The wavelengths of H$\beta$ and H$\alpha$ emission lines are indicated by dotted vertical lines, assuming a redshift of $z = 0.03782$. Arbitrarily scaled blackbody spectra with a temperature of $T_{\text{BB}} = 4000$ and 6000 K are also shown. The Galactic extinction-corrected spectra of KISS15s shown in this figure are available.

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23 http://astronomy.nmsu.edu:8000/apo-wiki/wiki/DIS
The slit direction is set to PA due to defocusing of the spectrograph. For the spectra obtained on 2016 October 4, we assume shown in this figure are available.

In Figure 6, blackbody spectra with temperatures of observed on 2016 October 4 suffer from complex instrumental broadening. The multi-component Hα emission line profile of KISS15s revealed by the ARC3.5 m/DIS confirms that this object is an SN IIn with strong ejecta-CSM interaction. Particularly, the long-duration optical continuum light curves, IR emission excess, and complex spectral properties of KISS15s all suggest that KISS15s belongs to the "1988Z-like" subclass of SNe IIn (e.g., Stritzinger et al. 2012; Taddia et al. 2013; Smith et al. 2017).

2.3. Note on the Dust Extinction in the Host Galaxy

In previous studies, the strengths of the equivalent widths (EWs) of interstellar Na I D λ5889,5895 absorption lines have often been used as the host galaxy extinction estimator for SNe through the relation of \( E(B-V)_{\text{host}} = 0.16 \times \text{EW(Na I D)} \) (Taddia et al. 2013; Turatto et al. 2003). In the DIS spectrum of KISS15s, no clear absorption feature from Na I D is detected. However, it should be noted that the EW measurements of Na I D absorption lines are claimed to provide poor constraints on reddening (Poznanski et al. 2011). Moreover, circumstellar dust related to the progenitor activity of KISS15s and newly formed dust in the ejecta-CSM interaction region may not be traced by gas absorption lines. Therefore, the possibility of the presence of substantial dust extinction for the optical emission of KISS15s cannot readily be ruled out.
One estimate of the amount of dust extinction can be obtained by matching the KISS15s spectrum to those of other SNe II in a similar kind. As pointed out in Section 2.2.2, the long-duration optical light curves and the broad emission line profile of KISS15s are very similar to SN 1988Z (and its analogues), a typical SN II with strong ejecta–CSM interactions (e.g., Turatto et al. 1993; Aretxaga et al. 1999; Stritzinger et al. 2012; Smith et al. 2017). Figure 8 compares the DIS spectrum of KISS15s obtained on 2015 December 2 (+124 days since SkyMapper’s first detection) to a +115 days spectrum of SN 1988Z downloaded from WISEREP (Yaron & Gal-Yam 2012). In the same figure, we also plotted a DIS spectrum of KISS15s corrected for putative host galaxy dust extinction, on the assumption of Small Magellanic Cloud (SMC)–like extinction ($R_V=2.93$; Pei 1992) with $E(B-V)_{\text{host}} = 0.6$ mag

\begin{equation}
E(B-V)_{\text{host}} = 0.6 \text{ mag}
\end{equation}

in the host galaxy of KISS15s. We find that the overall spectral shape of KISS15s well matches that of SN 1988Z when the SMC–like extinction correction is applied. Figure 8 shows that the spectral shape of the dereddened continuum of KISS15s can reasonably be explained by a single blackbody of $T_{BB} = 9000 \text{ K}$.

In this work, we assumed that KISS15s is actually affected by the host galaxy extinction of $E(B-V)_{\text{host}} = 0.6$ mag. The extinction is either due to interstellar dust in the host galaxy or circumstellar dust around KISS15s. $E(B-V)_{\text{host}} = 0.6$ mag corresponds to the observed-frame extinction of $A_g_{\text{host}}, A_{g,\text{host}}, A_{r,\text{host}}, A_{i,\text{host}}, A_{g,\text{host}}$, and $A_{W2,\text{host}}=0.79, 2.07, 2.2, 1.8, 3, 1.3, 1.4, 0.8, 0.7, 0.28$, and $0.052$ mag, respectively, on the assumption of the $R_V=2.93$ SMC–like extinction curve of Pei (1992). This implies that the intrinsic emission of KISS15s is several magnitudes brighter than the observed spectrum, and that KISS15s is intrinsically a luminous SN ($M_K = m_K - DM - A_V - A_{V,\text{host}} \simeq -18.8$ mag at MJD = 57234; see Figure 2), which is 1 mag brighter than SN 1988Z ($M_K \sim -18$ mag; Turatto et al. 1993) at around the discovery epoch.

3. Analyses

3.1. Broadband Light Curves

In this subsection we examine the details of the temporal evolution of the optical and IR luminosity of KISS15s, and compare the properties with those of other 1988Z-like SNe IIn.

3.1.1. Optical Light Curves

The $g$- and $i$-band measurements at early epochs (MJD $< 57800$) revealed that the optical light curves of KISS15s showed a slow decline for $\sim 500$–$600$ days since the first detection by SkyMapper at MJD = 57234 (Figure 2). After that, KISS15s experienced a rapid decline in luminosity, as discussed in Section 2.1.4. Although the $r$- and $z$-bands are contaminated by strong Hα and Ca II IR triplet emission, respectively, the $g$- and $i$-band fluxes are dominated by optical continuum emission.

If the $g$-band luminosity light curve at MJD $< 57800$ is assumed to be a power law,

\begin{equation}
L_g \propto t^\alpha,
\end{equation}

the observed magnitude can be expressed as

\begin{equation}
g = c_g - 2.5\alpha \log(MJD - MJD_0),
\end{equation}

where $\alpha$ is the power-law index in Equation (2), $c_g$ is the $g$-band magnitude at MJD = MJD$_0$ + 1, and MJD$_0$ is a model parameter corresponding to the SN explosion date. By fitting Equation (3) to the Galactic extinction-corrected $g$-band light curve of KISS15s at MJD $< 57800$, we obtain $c_g = 17.29 \pm 0.76$ mag, $\alpha = -0.45 \pm 0.11$, and MJD$_0 = 57209.2^{+22.4}_{-56.1}$. MJD$_0 = 57209.2$ corresponds to 2015 July 6, which implies that the explosion date of KISS15s is probably 1 month before the first detection by SkyMapper on MJD = 57234. The best-fit power-law model is shown in Figure 2.

Next, to evaluate the temporal evolution of the $g-i$ color, we constructed broken-line light-curve models for the $g$- and $i$-bands as follows. First, the light curve was divided into three parts (MJD $< 57450$, 57450 $< MJD < 57800$, and 57800 $< MJD$), and a linear regression line was fitted separately to each. At MJD $< 57450$, linear regression lines for the $g$- and $i$-band magnitude light curves were calculated as the light-curve model. At MJD $< 57450 < 57800$, the $g$-band light curve was modeled by a linear regression line of $g$-band data between MJD = 57400 and 57800. In the same way, the $g$-band light curve at 57800 $< MJD$ was modeled by a linear regression line of the two late-time $g$-band measurements from Mayall/KOSMOS and Blanco/DECam. Given that $i$-band data are too sparse to directly estimate $g-i$ color at MJD $> 57450$, we simply assumed a constant $g-i$ color fixed to an average value evaluated from the data between MJD = 57420 and 57450. The Galactic extinction-corrected $g-i$ color at MJD $< 57450$ was evaluated as $g-i = 0.67 \pm 0.03$ mag; we assumed that this color remained constant at MJD $> 57450$:

\begin{equation}
g-i = 0.67 \pm 0.03 \text{ mag (MJD} > 57450).\end{equation}

The best-fit linear light-curve models are shown in Figure 2. The $r$-band shows a clear excess relative to the $g$- and $i$-band.
The slow time evolutions of the optical light curves suggest that the CSM interaction is the dominant source of the optical luminosity of KISS15s (rather than the radioactive decay of \(^{56}\)Ni and \(^{58}\)Co), similar to other SNe IIn. The rapid decline in luminosity in late epochs (>600 days since discovery) implies that the volume of the continuum emission region begins to suddenly decrease at this epoch. Figure 10 compares the absolute magnitude optical light curves of KISS15s with other 1988Z-like SNe IIn.\(^{25}\) In Figure 10, the magnitudes are corrected for the host galaxy dust extinction of \(E(B-V)_{\text{host}} = 0.6\) mag and the corresponding \(g-i\) color temperature were calculated; the \(g-i\) blackbody color as a function of blackbody temperature was calculated using Speclite and assuming a source redshift of \(z = 0.03782\). Then the temperatures of the \(g-i\) colors of KISS15s were searched. Figure 9 shows the \(g-i\) color temperature as a function of time, along with the uncertainty due to broken-line-light-curve modeling. On the assumption of a SMC-like host galaxy extinction of \(E(B-V)_{\text{host}} = 0.6\) mag, the \(g-i\) color of KISS15s at MJD > 57450 becomes

\[
T_{BB,\text{opt}} = 13,000 \text{ K} \pm 600 \text{ K} \quad (\text{MJD} > 57450),
\]

as shown in Figure 9.

The 3–4 \(\mu\)m IR emission of SNe IIn can readily be identified as hot dust thermal emission (Smith et al. 2009; Fox et al. 2010; Maeda et al. 2013; Gall et al. 2014; Szalai et al. 2018). Graphite/silicate dust grains sublimate at temperatures of \(T_{\text{sub}} = 1400–1800 \text{ K}\) (e.g., Guhathakurta & Draine 1989; Baskin & Laor 2018), and the 3–4 \(\mu\)m IR emission corresponds to dust thermal emission close to the dust sublimation temperature. Figure 11 compares the \(W_1\) and \(W_2\) band light curves of KISS15s, with several years of Spitzer/IRAC band 1 (3.6 \(\mu\)m) and band 2 (4.5 \(\mu\)m) light curves for other SN 1988Z-like SNe IIn (SN 2005ip, SN 2006jd, and SN 2010jl) taken from the literature. Compared to the Spitzer/IRAC sample of SNe IIn, NEOWISE data of KISS15s enable the temporal evolution of the IR emission to be followed from the very early epochs (~7 days after the first detection). The peak IR luminosity of KISS15s is similar to that of other SN 1988Z-like SNe IIn, suggesting that the IR emission mechanism in KISS15s is identical to them.

As for SN 2010jl, although the significant IR excess above the extrapolated UV-optical emission at <1 yr since discovery is most likely due to the IR echo of the initial flash of the SN by preexisting dust in the CSM (Sarangi et al. 2018), the late-time IR emission associated with dust-induced increasingly blue-shifted line profiles are due to new dust formation in the CDS (Andrews et al. 2011; Maeda et al. 2013; Gall et al. 2014; Stoll et al. 2011; Fransson et al. 2014; Montya 2014); the same scenario may be the case for the optical luminosity drop observed in KISS15s.

3.1.2. IR Light Curves

\begin{itemize}
  \item Discovery dates of SN 1988Z (Turatto et al. 1993), SN 2005ip, SN 2006jd (Stritzinger et al. 2012), SN 2010jl (Stoll et al. 2011), and KISS15s (this work) are MJD = 47507.5, 53679.16, 54020.54, 55478.64, and 57234, respectively.
\end{itemize}

\(^{25}\) Discovery dates of SN 1988Z (Turatto et al. 1993), SN 2005ip, SN 2006jd (Stritzinger et al. 2012), SN 2010jl (Stoll et al. 2011), and KISS15s (this work) are MJD = 47507.5, 53679.16, 54020.54, 55478.64, and 57234, respectively.
Szalai et al. 2018). As discussed later, the first W1- and W2-band data points of KISS15s (at 7.5 days since discovery) are consistent with the Rayleigh–Jeans tail of the optical blackbody emission, as evidenced by the blue W1 – W2 color. We found that the W1- and W2-band dust thermal emission light curves of KISS15s increase smoothly, without any early-phase excess at <1 yr, as opposed to SN 2010jl. The smooth IR light curves of KISS15s indicate that the early-phase IR echo is unimportant for KISS15s and that the IR emission is mainly from newly formed dust in the CDS, suggested as the origin of hot dust thermal emissions of other SNe IIn (e.g., Fox et al. 2010, 2011; Maeda et al. 2013; Gall et al. 2014; Fransson et al. 2014).

Figure 12 shows the temporal evolution of the W1 – W2 color temperature of the IR emission component of KISS15s at 177.5, 373.1, 539.6, and 737.2 days since discovery, where the W1 – W2 blackbody colors of various temperatures were calculated using Speclite, assuming asource redshift of z = 0.03782. Here, we also assumed that the flux contribution from the Rayleigh–Jeans tail of the optical blackbody emission is not significant at these epochs, and the observed W1 – W2 color was directly used to calculate the color temperature. The W1 – W2 color of KISS15s shows little time variation, and the color temperature remains almost constant during the observations at ~1200 K. The weighted average of the W1 – W2 color temperature is

$$T_{BB,IR} = 1190 \text{ K} \pm 60 \text{ K}. \quad (6)$$

It should be noted that dust grains formed inside of SN ejecta observed in type II-P SNe generally have dust temperatures of at most several hundreds of Kelvin (Szalai et al. 2018); thus, the persistently high dust temperature of KISS15s can definitely be attributed to the newly formed dust grains in the CDS, as observed in other SNe IIn. The estimated dust temperature is slightly lower than the sublimation temperature of silicate and graphite grains ($T_{sub} = 1400$ and 1800 K, respectively; e.g., Baskin & Laor 2018), indicating that both of these dust grain species are likely contributors to the IR continuum emission of KISS15s.

In contrast to the increasing IR light curves, the optical light curves of KISS15s decrease over time during the observations. Figure 13 presents the g-, r-, W1-, and W2-band spectral energy distribution (SED) of KISS15s at the epochs of the NEOWISE observations (indicated as the days since discovery, defined as MJD–57234). The optical points are interpolated by the broken-line light-curve models shown in Figure 2. The photometry data are dereddened by assuming SMC-like dust extinction in the host galaxy of E(B – V)$_{host}$ = 0.6 mag. Optical + IR blackbody model spectra, composed of an optical blackbody with temperature $T_{BB, opt}$ estimated from the g – i color (Figure 9) and IR blackbody with temperature $T_{BB,IR} = 1190$ K (Figure 12), are also shown.
IR blackbody model spectrum for the SED of each epoch is also shown, where the time-dependent optical blackbody temperature is from Figure 9; the IR blackbody is assumed to have a constant temperature of $T_{BB,IR} = 1190$ K and is scaled to the $W2$-band magnitudes. As for the continuum emission, the IR emission increases as the optical emission fades, and the $3-4 \mu m$ IR luminosity is comparable to the optical luminosity at about 2 yr after the discovery. This observation is consistent with the suggestion that new dust formation in the SN environment is enhanced several hundreds of days after the SN explosion (e.g., Gall et al. 2014; Sarangi et al. 2018).

Figure 13 shows that after the correction of $E(B-V)_{host} = 0.6$ mag, the earliest-phase IR luminosities (7.5 days since discovery) can fully be attributed to Rayleigh–Jeans tail emission in the optical blackbody emission of $T_{BB} = 7400$ K (see Figure 9). This provides additional evidence that KISS15s is heavily reddened by SN-related/unrelated dust in the host galaxy. In addition, the non-detection of the IR blackbody component at the earliest phase (7.5 days since discovery) excludes the possibility of a large IR flux contribution from IR echoes of the SN shock breakout radiation by preexisting dust in close proximity to KISS15s at this epoch.

Figure 14 presents the IR broadband SED from Nayuta/NIC $J$-, $H$-, and $K_s$-band data on 2017 December 21–22 (784.9 days since discovery) and from NEOWISE $W1$- and $W2$-band data on 2017 August 5–6 (737.2 days since discovery; same as those shown in Figure 13) are also shown for comparison. The photometry data are corrected for the host galaxy extinction of $E(B-V)_{host} = 0.6$ mag. The dotted lines are the same blackbody model shown in Figure 13 (737.2 days).

The constant temperature and the increasing luminosity indicate that the surface area of the dust thermal emission region is expanding. Figure 15 shows the integrated IR blackbody luminosity as a function of observation epoch, $L_{BB,IR}(t)$, calculated from the $W2$-band magnitudes of KISS15s by assuming a constant blackbody temperature of $T_{BB,IR} = 1190$ K. If we assume that the dust distribution is approximated as a homogeneous thin shell, the blackbody radius can be defined as (Fox et al. 2010, 2011)

$$r_{BB,IR}(t) = \left( \frac{L_{BB,IR}(t)}{4\pi\sigma_B T_{BB,IR}^4} \right)^{1/2}$$

$$= 14.4 \text{lt-day} \times \left( \frac{L_{BB,IR}(t)}{2 \times 10^{42} \text{ erg s}^{-1}} \right)^{1/2} \times \left( \frac{T_{BB,IR}}{1190 \text{ K}} \right)^{-2} \text{ yr},$$

where $\sigma_B$ is Stefan–Boltzmann’s constant and $r_{BB,IR}(t)$ is increasing over time. The numerical calculation results of $r_{BB,IR}(t)$ are shown in the middle panel of Figure 15. Note that the actual dust radius can be a few times larger than $r_{BB,IR}$ if the dust distribution is inhomogeneous. The bottom panel of Figure 15 shows the expansion velocities of the IR blackbody radius, $v_{dust}$. Two definitions of the velocities are possible: one is

$$v_{dust} = \frac{r_{BB,IR}(t)}{t} = \frac{r_{BB,IR}(\text{MJD})}{\text{MJD} - \text{MJD}_0},$$

and the other is

$$v_{dust} = \frac{dr_{BB,IR}(t)}{dt} \approx \frac{\Delta r_{BB,IR}(\text{MJD})}{\Delta \text{MJD}}.$$

where the former represents the hypothetical linear velocity required for the dust shell to reach $r_{BB,IR}(t)$ at a given $t$, and the latter is the dust shell velocity between two adjacent epochs. We assume an explosion date of MJD$_0 = 57209.2$ (Section 3.1.1) with Equation (8).

It should be noted that the derived $r_{BB,IR}(t)$ is more than an order of magnitude smaller than the light-crossing distance since the SN explosion of KISS15s (MJD$_0 \sim 57209.2$; Section 3.1.1). This suggests that the IR echo model is not the main source of the late-phase NIR excess emission. The estimated dust shell velocity $v_{dust}$ is consistent with the ejecta and/or shock front velocities inferred from the velocity width of broad/intermediate Hα emission line components (see Sections 4.3 and 4.4), suggesting that the dust grains are located in the proximity of the ejecta-CSM interaction region or CDS. These results, the late-time IR excess, the hot dust temperature, and the inferred expansion velocity, are consistent with the scenario that the hot dust thermal emission of KISS15s is due to newly formed dust grains in the CDS.

To examine whether the dust grains can really be formed against the strong UV-optical radiation field around the SN, we can compare the derived dust shell size estimate with a
The dust sublimation radius \( r_{\text{sub}} \) within which the dust grains are completely sublimated due to intense UV-optical radiation from the SN. The dust sublimation radius is given as

\[
\frac{r_{\text{sub}}}{L_{\text{abs}} T_{\text{eff}}^{-1/2}} \sim Q_{\text{UV}}^{-1/2} Q_{\text{IR}}^{-1/2} \frac{1}{16 \pi \sigma_\text{B} T_{\text{sub}}^4},
\]

where \( Q_{\text{UV}} \) and \( Q_{\text{IR}} \) are the Planck-averaged UV-optical absorption and IR emission efficiencies of the dust grains, respectively, and \( L_{\text{abs}} \) is the SN UV-optical luminosity absorbed by the dust. Because graphite grains have a higher sublimation temperature than silicate grains, here we consider the case of the graphite sublimation radius defined by \( T_{\text{1800 sub}} = 1800 \text{K} \). As described previously, we can approximate \( Q_{\text{UV}} \sim Q_{\text{IR}} \sim 1 \) on the assumption of a large dust grain size (e.g., Fox et al. 2010). We can expect that the UV-optical luminosity of KISS15s is always, at most, on the order of \( L_{\text{BB,opt}} \approx 10^{43} \text{erg s}^{-1} \) (Figure 15).

Thus, \( r_{\text{sub}} = 7.1 \text{ lt-day} \left( \frac{L_{\text{BB,opt}}}{10^{43} \text{erg s}^{-1}} \right)^{1/2} \left( \frac{T_{\text{sub}}}{1800 \text{K}} \right)^{-2} \).
which indicates that the dust grains can indeed exist at the inferred location of $r_{BB,IR}$.

On the assumption of single-size dust grains and that the dust grains are mostly optically thin to IR emission, the total dust mass $M_d$ required to produce the observed IR emission can be estimated as (e.g., Smith & Gehrz 2005)

$$M_d = \left( \frac{a}{3 \sigma_b \langle Q_{IR} \rangle T_d} \right) L_{BB,IR}. \quad (12)$$

where $\rho$ is the mass density of the dust grain. Substituting the mass density of a graphite grain ($\rho = 2.25 \text{ g cm}^{-3}$), a grain size of $a = 0.5 \mu m$, a dust temperature of $T_d = 1190 \text{ K}$, $L_{BB,IR} = 2 \times 10^{42} \text{ erg s}^{-1}$ (Figure 15), and $\langle Q_{IR} \rangle \sim 1$ into Equation (12), we obtain

$$M_d \approx 3 \times 10^{-4} M_\odot \left( \frac{a}{0.5 \mu m} \right) \left( \frac{T_d}{1190 \text{ K}} \right)^{-4} \left( \frac{L_{BB,IR}}{2 \times 10^{42} \text{ erg s}^{-1}} \right). \quad (13)$$

It should be noted that the estimated total mass of the newly formed large dust grains is consistent with that observed in SN 2010jl (Gall et al. 2014). The derived value sets a lower limit of the total dust mass if the dust IR emission is self-shielded. The dust grains radiating $\sim 3 \mu m$ IR emission will undergo rapid radiative cooling. Therefore, KISS15s may currently harbor a cool dust component of a mass of $\gg 3 \times 10^{-4} M_\odot$, which may be detected by future follow-up observations at MIR and longer wavelengths.

3.1.3. Bolometric Luminosity

An estimate of a bolometric luminosity light curve can be obtained from blackbody fitting for optical and IR data points, as described in Sections 3.1.1 and 3.1.2. Because the IR blackbody component of KISS15s can naturally be attributed to the newly formed dust in the ejecta-CSM interaction region (rather than IR echoes from preexisting dust), the bolometric luminosity is estimated to be the sum of optical and IR blackbody components (Fransson et al. 2014). Here we define the pseudo-bolometric luminosity as the sum of the optical and IR blackbody luminosities, $L_{bol} = L_{BB,OPT} + L_{BB,IR}$, which can be calculated from the best-fit blackbody models shown in Figure 13.

Figure 16 shows the temporal evolution of the optical and IR blackbody luminosities and the pseudo-bolometric luminosity of KISS15s. The power-law index of the optical luminosity is $L_{BB,OPT} \propto t^{-0.23}$ on the assumption of MJD$_0 = 57209.2$ (Section 3.1.1). The relative luminosity contribution of the IR luminosity relative to the optical luminosity becomes stronger at later epochs; consequently, the optical + IR pseudo-bolometric luminosity shows slower temporal evolution compared to the optical luminosity. The power-law index of the pseudo-bolometric luminosity light curve is given by

$$L_{bol} \propto t^{-0.16} \quad (14)$$

at $< 600$ days since discovery.

After the rapid decline in the optical luminosity at $> 600$ days, the pseudo-bolometric luminosity accordingly decrease suddenly, as the IR luminosity remains nearly constant at these epochs. This behavior of the bolometric luminosity evolution indicates that the sudden decrease in optical luminosity is not due to dust extinction by newly formed dust; instead, this behavior supports a scenario in which the intrinsic weakening of the ejecta-CSM interaction causes accelerated fading of the optical luminosity, as described in Section 3.1.1 (see Maeda et al. 2013; Moriya 2014).

The peak luminosity of KISS15s is estimated to be $L_{peak} \sim 1.0 \times 10^{43} \text{ erg s}^{-1}$, and the total radiated energy at the first 600 days is roughly $\sim 4.0 \times 10^{50} \text{ erg}$. This estimate indicates that KISS15s is one of the most luminous SNe IIn discovered in the local universe so far, comparable to the luminous ($L_{peak} \sim 3.0 \times 10^{43} \text{ erg s}^{-1}$) type IIn SN 2010jl (Fransson et al. 2014). In the case of SN 2010jl, if the observed luminosity is assumed to be solely powered by $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ radioactive decay, it requires an unreasonably large $^{56}\text{Ni}$ mass of $M_{56\text{Ni}} \sim 3.4 M_\odot$ (see Moriya et al. 2013, for details). From the same discussion, the required $^{56}\text{Ni}$ mass to account for the luminosity observed in KISS15s is $M_{56\text{Ni}} \sim 1.1 M_\odot$. Although the $^{56}\text{Ni}$ mass production over $1 M_\odot$ may be possible with the SNe of massive stars (e.g., Umeda & Nomoto 2008), a more natural explanation for the high luminosity, as well as the persistent light curves even after the decay time of $^{56}\text{Co}$ ($T_{56\text{Co}} = 111.3 \text{ days}$; Nadyozhin 1994), is that KISS15s is powered by the strong ejecta-CSM interaction, as is the case for other luminous SNe IIn.

3.2. Emission Line Properties

3.2.1. Spectral Profile of the H$\alpha$ Emission Line

Figure 17 compares the spectral properties of H$\alpha$ and H$\beta$ emission lines of the DIS low-resolution spectrum obtained on 2015 December 2. It is clear that the H$\beta$ and H$\alpha$ emission lines have nearly identical spectral profiles, and both of them have broad ($\lambda_{FWHM} \sim 14,000 \text{ km s}^{-1}$), intermediate ($\lambda_{FWHM} \sim 2000 \text{ km s}^{-1}$), and narrow ($\lambda_{FWHM} < 100 \text{ km s}^{-1}$) components. It should be noted that the He I emission lines and the H$\gamma$ emission line also have similar line profiles (Figure 8), although the H$\gamma$ emission line luminosities are much weaker than the H$\beta$ and H$\alpha$ emission lines. As shown in Figure 18 (see also Figure 8), the optical spectral properties of KISS15s are similar to type IIn SN 1988Z and other SN 1988Z-like subclasses of SN IIn (see, e.g., Stathakis & Sadler 1991; Pastorello et al. 2002; Miller et al. 2010; Stritzinger et al. 2012).

To quantitatively evaluate the line widths and line intensities of the H$\alpha$ emission, we fitted multi-component Gaussian models to Nayuta/LISS and ARC3.5 m/DIS spectra in the spectral region around the H$\alpha$ emission line. The line profile fitting was performed using the Python version of MPFIT (Markwardt 2009). Nayuta/LISS and ARC3.5 m/DIS low-resolution spectra were fitted in an observed-frame wavelength range of $\lambda_{obs} = 5860-7440 \text{ Å}$, and the ARC3.5 m/DIS high-resolution spectra were fitted at $\lambda_{obs} = 6240-7310 \text{ Å}$.

First, the DIS low- and high-resolution spectra were fitted by three Gaussians (broad, intermediate, and narrow) and a single power-law model. The Nayuta/LISS very-low-resolution spectrum was fitted by two Gaussians and a single power-law model, because the spectral resolution of Nayuta/LISS is lower than the velocity width of the intermediate component; thus,
the narrow component is mixed with the intermediate component. The measurement uncertainties of the model parameters were evaluated by 10,000 trials of Monte Carlo resampling, where 10,000 mock spectra were generated by adding Gaussian flux noise to the original spectrum using the calculated flux density errors. Figure 19 shows the profiles of the H\(\alpha\) emission of KISS15s. The best-fit model spectra and the fitting residuals are also shown in the same figure, and the best-fit model parameters are tabulated in Table 9. The fitted models mostly explain the observed emission line profiles, except for a blueshift excess component at \(v \sim -5000\ \text{km s}^{-1}\), as indicated in Figure 17.

Next, we performed another model fitting to the H\(\alpha\) profiles by adding an additional Gaussian component to account for the blueshift excess component. Figure 20 shows the same H\(\alpha\) emission line profiles as Figure 19, but fitted by the refined model with the additional Gaussian blueshift excess component. The best-fit parameters of the four Gaussians model are tabulated in Table 10. The best-fit model shown in Figure 20 reasonably reproduces the observed line profiles, and the fitting residuals no longer show any signature of remaining spectral components. We also tried to model the line profiles with additional Gaussian absorption of the broad component, instead of the additional Gaussian emission component, but no reasonable fitting was achieved. This analysis suggests that the apparent asymmetry of the entire H\(\alpha\) line profile of KISS15s is not due to absorption of broad or intermediate emission lines by opaque gases or dusts located in the ejecta-CSM interaction region (as suggested for other SNe IIn by, e.g., Smith et al. 2009; Fox et al. 2011; Smith et al. 2012b; Taddia et al. 2013; Fransson et al. 2014; Chevalier & Fransson 2017). Instead, the observed line profile of KISS15s is most likely due to the presence of an additional blueshifted symmetric intermediate Gaussian emission component with respect to the symmetric narrow, intermediate, and broad Gaussians, which may be related to the inhomogeneity of the CSM distributions (Smith et al. 2015; Andrews et al. 2016). There is no evidence of Lorentzian-like broad wing components in the observed line profiles of KISS15s, suggesting that the electron scattering in optically thick ejecta-CSM regions is not relevant in KISS15s (see, e.g., Smith et al. 2010; Fransson et al. 2014; Borish et al. 2015; Huang & Chevalier 2018). Considering the better fitting for the observed spectra compared to the three Gaussians model, here we focus on the fitting results from the “additional Gaussian model” or the four Gaussians model (Table 10 and Figure 20).
The narrow emission line component is partially resolved in the DIS high-resolution spectrum obtained at MJD $= 57430.1$ ("DIS high 1" in Tables 9 and 10). The rest-frame velocity FWHM ($\text{FWHM}_{\text{rest}}$) can be estimated from the observed-frame line width ($\sigma_{\text{obs}}$), the instrumental broadening width ($\sigma_{\text{inst}}$), and the source redshift $z$ as

$$\text{FWHM}_{\text{rest}} = 2\sqrt{2\ln 2} \frac{\sigma_{\text{obs}}^2 - \sigma_{\text{inst}}^2}{1 + z}.$$  \hspace{1cm} (15)
Substituting \( \sigma_{\text{obs}} = 47.2 \text{ km s}^{-1} \) and \( \sigma_{\text{inst}} = 20.8 \text{ km s}^{-1} \) taken from Tables 10 and 8, respectively, to Equation (15), the rest-frame velocity FWHM of the narrow component of KISS15s is evaluated as FWHM\(_{\text{rest,n}} = 114.8 \text{ km s}^{-1} \). It should also be noted that the H\(\alpha\) line flux of the narrow component is \( \sim 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \), which is roughly in agreement with the host galaxy H\(\alpha\) line flux measured from the SDSS spectrum (see Section 4.1 for details). Therefore, although it is still possible that there is a flux contribution to the narrow line from the unshocked CSM photoionized by strong radiation from KISS15s, we can assume that the observed narrow emission line component predominantly comes from the foreground/background H II regions in the host galaxy that may not directly be related to the SN explosion event of KISS15s. We put a rough upper limit on the velocity width of the undetected narrow emission line component from the CSM formed by the progenitor’s stellar wind as FWHM\(_{w} \lesssim 100 \text{ km s}^{-1} \), which means that \( v_{w} \lesssim 100 \text{ km s}^{-1} \) on the assumption of \( v_{w} \simeq \text{FWHM}_{w} \) (e.g., Taddia et al. 2015; see Section 4.4 for further discussion).

Figure 21 shows the temporal evolution of the rest-frame velocity width FWHM (FWHM\(_{\text{rest}}\); Equation (15)) and the velocity shift relative to the systemic redshift of \( z = 0.03782 \) of the decomposed H\(\alpha\) emission line components of KISS15s. The velocity width of the broad component gradually decreases as a function of time from FWHM \( \sim 14,000 \text{ km s}^{-1} \) to \( \sim 10,000 \text{ km s}^{-1} \), and the velocity shift only shows weak variability. It is interesting to note that the velocity widths of the intermediate and blueshift excess components are consistent with each other, suggesting that the two components are produced by the same emission mechanism. The line-of-sight velocity of the two intermediate-width components are, however, very different: the velocity shift of the intermediate component decreases from \( \sim 0 \text{ km s}^{-1} \) to about \( -500 \text{ km s}^{-1} \); on the other hand, that of the blueshift component increases from about \( -6000 \text{ km s}^{-1} \) to about \( -4500 \text{ km s}^{-1} \). The coexistence of these two emission line components implies that the emission region has a spherically asymmetric geometry, which may be related to the inhomogeneous structure of the CSM produced by the intrinsic non-spherically symmetric progenitor’s stellar wind (see Section 4.3 for further discussion; Borish et al. 2015; Smith 2017, and references therein).

Figure 22 presents the light curves of the decomposed H\(\alpha\) emission line luminosities. The broad emission line luminosity monotonically decreases, as with the power-law luminosity evolution of the optical continuum light curve. The similarity of the luminosity evolution between the broad H\(\alpha\) line and optical continuum implies that the broad emission line component and optical continuum emission are powered by the same energy source, which may be the ingoing and/or outgoing intense radiation from the ejecta-CSM interaction region (e.g., Chugai & Danziger 1994; Chevalier & Fransson 2017). The intermediate and blueshifted components show different temporal evolutions with each other, as well as with the broad component. The luminosity of the intermediate component increases during the observations, which may imply that the volume of the ejecta-CSM interaction region is increasing. On the other hand, the blueshift component becomes weaker at the last epoch of the spectroscopic observation, suggesting that this component is produced from a separate region from where the intermediate component emerges.

### 3.2.2. Other Spectral Features

In addition to HeI\(\lambda 5876\), the HeI\(\lambda 7065\) emission line is clearly visible in the KISS15s spectra (Figure 8), and it seems to have at least two spectral components with intermediate \( (\sim 2000 \text{ km s}^{-1}) \) and narrow \( (<300 \text{ km s}^{-1}) \) line widths. The broad emission bump at wavelengths of \( \lambda_{\text{rest}} \sim 8600 \text{ Å} \) is probably due to a blend of broad O\(\lambda 8446\).

KISS15s shows prominent broad emission line features of the Ca II IR triplet (\( \lambda \lambda 8498, 8542, 8662 \)), as is also observed in several other SNe IIn, such as SN 1988Z (e.g., Turatto et al. 1993). Blended Ca II IR triplet emission shows a temporal evolution similar to that of the H\(\alpha\) emission line, although the detailed spectral decomposition is difficult due to insufficient spectral coverages of our data and blending of multiple broad/intermediate lines of Ca II and probably O\(\lambda 8446\).
The strong, broad/intermediate Ca II triplet emission with no associated P Cygni absorption feature must be emitted by the same region as that with the strong Hα emission line (i.e., the CDS and/or photoionized ejecta; Chugai & Danziger 1994; Dessart et al. 2016). The origin of the broad bump at the wavelengths of $\lambda_{\text{rest}} \sim 7300$ Å in KISS15s spectra is unclear, but it may be due to a blend of broad lines of He I and Ca II and several forbidden lines (e.g., Graham et al. 2014; Smith et al. 2017). The flux excess in the wavelength range of $\lambda_{\text{rest}} < 5700$ Å generally observed in spectra of SNe IIn, which is composed of a blend of Fe II and several other emission lines (Stathakis & Sadler 1991; Stritzinger et al. 2012), is not observed or is significantly weaker in KISS15s compared to SN 1988Z (Figure 8).

4. Discussion

4.1. Host Galaxy Properties

The host galaxy of KISS15s, SDSS J030831.67-005008.6, was imaged by the SDSS Legacy Survey, and the central
Figure 21. Rest-frame intrinsic velocity width and the velocity shift of the decomposed broad, intermediate, and blueshift excess Gaussian components of the Hα line profile of KISS15s, as a function of observed time. The velocity widths of the intermediate and blueshift components are unresolved in the Nayuta/LISS and are omitted from the plot.

Table 10

Best-fit Gaussian Model for the Hα Line Profile with a Blue-shift Excess Component

| Parameter Name | LISS | DIS Low 1 | DIS Low 2 | DIS Low 3 | DIS High 1 | DIS High 2 |
|----------------|------|-----------|-----------|-----------|------------|------------|
| Date           | 2015 Sep 19 | 2015 Dec 2 | 2016 Jan 30 | 2016 Oct 4 | 2016 Feb 12 | 2016 Oct 4 |
| Days Since Discovery | 50.7 days | 124.2 days | 183.1 days | 431.4 days | 196.1 days | 431.4 days |
| Norm. ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$) | 9.72 ± 0.07 | 5.20 ± 0.01 | 3.61 ± 0.02 | 2.52 ± 0.02 | 2.90 ± 0.06 | 0.70 ± 0.03 |
| Index | 0.36 ± 0.07 | 1.13 ± 0.03 | 0.72 ± 0.08 | 0.00 ± 0.11 | −0.06 ± 0.24 | 0.47 ± 0.54 |
| $\sigma_{obs,b}$ (km s$^{-1}$) | 6427.16 ± 158.91 | 6076.60 ± 44.98 | 5922.66 ± 100.59 | 4355.02 ± 191.32 | 6526.60 ± 198.63 | 4201.36 ± 283.85 |
| $\lambda_{obs,b}$ (Å) | 6795.94 ± 3.11 | 6795.87 ± 1.17 | 6802.42 ± 2.18 | 6798.58 ± 2.94 | 6804.27 ± 3.14 | 6811.12 ± 5.70 |
| Flux$_{b}$ ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$) | 3685.78 ± 107.11 | 2174.53 ± 22.13 | 1669.75 ± 33.36 | 796.34 ± 34.03 | 1482.86 ± 44.84 | 330.64 ± 24.83 |
| $\sigma_{obs,i}$ (km s$^{-1}$) | 1420.75 ± 84.34 | 971.30 ± 12.54 | 1012.55 ± 15.51 | 998.11 ± 14.29 | 1070.06 ± 13.36 | 904.97 ± 18.84 |
| $\lambda_{obs,i}$ (Å) | 6816.41 ± 1.48 | 6813.15 ± 0.19 | 6805.61 ± 0.28 | 6804.06 ± 0.23 | 6802.07 ± 0.24 | 6803.46 ± 0.39 |
| Flux$_{i}$ ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$) | 677.10 ± 62.69 | 726.85 ± 9.45 | 853.24 ± 15.79 | 1223.74 ± 26.65 | 951.19 ± 16.34 | 417.99 ± 12.97 |
| $\sigma_{obs,\Delta}$ (km s$^{-1}$) | ... | 140.48 ± 4.06 | 121.09 ± 4.59 | 140.88 ± 49.27 | 47.20 ± 1.30 | 102.97 ± 14.33 |
| $\lambda_{obs,\Delta}$ (Å) | ... | 6812.98 ± 0.08 | 6810.72 ± 0.10 | 6813.57 ± 1.56 | 6809.51 ± 0.03 | 6812.96 ± 0.17 |
| Flux$_{\Delta}$ ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$) | ... | 120.79 ± 3.83 | 109.74 ± 4.45 | 14.78 ± 5.01 | 99.93 ± 2.36 | 29.34 ± 3.20 |
| $\sigma_{obs,\Delta add}$ (km s$^{-1}$) | ... | 1405.69 ± 79.96 | 1069.12 ± 57.61 | 762.90 ± 123.95 | 1145.75 ± 49.37 | 749.03 ± 399.18 |
| $\lambda_{obs,\Delta add}$ (Å) | 6675.12 ± 9.46 | 6679.37 ± 1.90 | 6692.49 ± 1.30 | 6714.40 ± 2.89 | 6695.31 ± 0.96 | 6714.74 ± 5.04 |
| Flux$_{\Delta add}$ ($10^{-17}$ erg s$^{-1}$ cm$^{-2}$) | 95.13 ± 35.07 | 108.08 ± 9.93 | 158.10 ± 12.25 | 44.83 ± 10.84 | 215.18 ± 12.51 | 14.89 ± 8.61 |

Note. Same as Table 9. Subscript “add” denotes the additional blue-shifted component. The intermediate and blueshifted components in the LISS spectrum are unresolved and assumed to have the same velocity width.

The region was observed spectroscopically through the SDSS 3 arcsec fiber spectrograph (York et al. 2000). Three spectra obtained at different epochs are available in the SDSS database. We used the spectrum taken at MJD = 52264 (which has the highest S/N among the three spectra) in the analyses that follow. Note that the emission lines detected in the SDSS spectrum of SDSS J030831.67-005008.6 are unresolved, and the velocity width is constrained to $\sigma \lesssim 70$ km s$^{-1}$.

According to the outputs of the SDSS photo pipeline, the light profile of SDSS J030831.67-005008.6 is best fit by a pure exponential model. The host galaxy $g$- and $r$-band absolute magnitude is $M_g = −17.01 ± 0.02$ and $M_r = −17.18 ± 0.02$ mag, and the $u−r$ color is $1.46 ± 0.13$ mag (corrected for Galactic extinction), which are typical values of a “blue cloud” star-forming galaxy (e.g., Schawinski et al. 2014). The effective radius of the exponential profile model $r_e$ is $4.73 ± 0.07$ (3.1 ± 0.1 kpc) in the $r$-band. Figure 23 shows a BPT diagram (Baldwin et al. 1981) of SDSS J030831.67-005008.6, where the Galactic extinction-corrected line intensities are calculated from SDSS spectroscopy pipeline outputs (sp2line). Based on the BPT classification, this galaxy is a low-metallicity star-forming galaxy. The SDSS spectroscopy pipeline outputs indicate that the stellar mass of this galaxy is $\log(M_*/M_\odot) = 8−9$ (Kauffmann et al. 2003; Tremonti et al. 2004). The luminosity-metallicity relation (Equation (1) of Lee et al. 2006) suggests that this galaxy is metal-poor ($12+\log O/H \sim 8.1 ± 0.4$; see also Aartsen et al. 2015). Alternatively, the Galactic extinction-corrected line intensity ratio analyses

http://www.sdss.org/dr12/algorithms/magnitudes/
The line luminosities evaluated from the spectro-photometrically calibrated low-resolution spectra are shown. The host galaxy extinction of $E(B-V)_{host} = 0.6$ mag is corrected. For comparison, an arbitrary-scaled power-law of $L_{\text{H}\alpha,\text{opt}} \propto r^{-0.23}$ (Equation (14)) is also shown. The right panel compares the time evolution of the Hα line luminosity of KISS15s with those of other SN 1988Z-like SNe, SN 1988Z (Aretxaga et al. 1999), SN 2005ip, SN 2006jd (Stritzinger et al. 2012), and SN 2010Ji (Jencson et al. 2016).

The SDSS spectrum of the host galaxy shows strong recombination lines, such as Hα, Hβ, and [O III] emission lines, from the HII regions in the galaxy. The SDSS spectroscopy pipeline indicates that the narrow Hα emission line flux from the central 3 arcsec region of the galaxy is $I_{\text{H}\alpha,\text{host}} = 7.39 (\pm 0.15) \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, and its equivalent is EW $= 116.1 \pm 2.4$ Å.

The star formation rate (SFR) estimated from the Hα emission line luminosity of the host galaxy, $L_{\text{H}\alpha,\text{host}} = 4\pi d_L^2 I_{\text{H}\alpha,\text{host}} = 2.17 (\pm 0.04) \times 10^{39}$ erg s$^{-1}$, is (Kennicutt et al. 1994; Kennicutt 1998)

$$\text{SFR}(\text{H}\alpha) = 7.9 M_\odot \text{yr}^{-1} \times \left( \frac{L_{\text{H}\alpha,\text{host}}}{10^{42} \text{erg s}^{-1}} \right)$$

$$\simeq 0.02 M_\odot \text{yr}^{-1}.$$  

As already pointed out in Section 3.2.1, it should be noted that this Hα flux is comparable to that observed in the DIS spectra of KISS15s as the narrow Hα component—namely, $\sim 1 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. Considering the local variation in Hα luminosity within the galaxy, it is possible that the narrow Hα flux in the KISS15s spectrum is mostly from star-forming (HII) regions in the host galaxy and is not directly related to the SN event. The other narrow emission lines of [O III] and [S II] observed in the KISS15s spectrum are probably also due to flux contributions from the HII regions in the host galaxy (see the cases of SN 1987F and SN 2006qq; Filippenko 1989; Taddia et al. 2013).

Generally speaking, the low-metallicity environment suggests that the dust content of the host galaxy is small. The Balmer decrement of the SDSS spectrum of SDSS J030831.67-005008.6 is Hα/Hβ $\sim 3.24 \pm 0.31$ (Galactic extinction corrected). This value is only slightly larger than the Case B Hα/Hβ ratio of 2.86 for an electron density of $n = 100$ cm$^{-3}$ and electron temperature $T_e = 10^4$ K (e.g., Osterbrock 1989; Brinchmann et al. 2004; Domínguez et al. 2013). The Balmer decrement of $\sim 3.24$ implies that the host galaxy extinction, if any, is $E(B-V)_{host} \sim 0.12$ mag (assuming SMC-like extinction and $R_V = 2.93$), which is much smaller than the host galaxy extinction inferred from the KISS15s spectrum ($E(B-V)_{host} \sim 0.6$ mag; Section 2.3).

The explosion site of KISS15s, which is located at the edge of the host

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28 HII-CHI-mistry Version 3.0: http://www.iaa.es/cpm/HII-CHI-mistry.html.
galaxy, could be much deeper inside the dust lane of the galactic disk or embedded in a dusty nebuLa and thus more heavily obscured, as inferred in Section 2.3. It is also possible that KISS15s is affected by CSM dust. A promising candidate progenitor of SNe IIn would be the luminous blue variables (LBVs; Gal-Yam & Leonard 2009; Dwarkadas 2011); observationally circumstellar environments of LBVs are preferentially dusty (Umana et al. 2012).

The comoving volume within the redshift of SDSS J030831.67-005008.6 is 0.0143 Gpc$^3$. The volumetric rate of the CC SNe at the local universe is estimated to be $\sim 0.7 \times 10^{-4}$ SN Mpc$^{-3}$ yr$^{-1}$ (e.g., Li et al. 2011a). SNe IIn comprise roughly 7% of the entire CC SNe population (Li et al. 2011b; Smith et al. 2011a; Shivvers et al. 2017). From these values, we can estimate that SNe IIn are occurring at a rate of $\sim 70$ yr$^{-1}$ out to the redshift of SDSS J030831.67-005008.6 (at the comoving distance of 150 Mpc; see also Fox et al. 2010). Considering the limiting magnitudes and the sky coverage of the KISS survey ($\sim 300$ deg$^2$), the event rate of $\sim 70$ yr$^{-1}$ is consistent with the fact that a handful of SNe IIn within 150 Mpc (including the 1988Z-like KISS15s) had been discovered in 4 years’ worth of survey data (see Morokuma et al. 2014). It also indicates that 1988Z-like SNe IIn are common among the total population of SNe IIn (e.g., Taddia et al. 2015).

4.2. Energy of the Optical Continuum Emission

Eruptions of LBVs produce $M > -16$ mag optical transients with similar optical spectra to SNe IIn, referred to as SN impostors (e.g., Van Dyk et al. 2000; Maund et al. 2006; Smith et al. 2011b; Smith 2014; de Jaeger et al. 2015). If the host galaxy extinction is assumed to be zero, KISS15s may possibly be identified as an SN impostor, in terms of its faintness of the optical continuum emission ($M_B \sim -16.6$ mag at the peak epoch; Figure 2). However, as discussed in Sections 2.3 and 3.1.2, there is strong evidence of the host galaxy extinction of $E(B-V)_{\text{host}} \sim 0.6$ mag; thus, the intrinsic peak absolute magnitude of KISS15s is estimated to be $M_B \sim -18.8$ mag (Figure 10). According to the luminosity function of SNe IIn compiled by Richardson et al. (2014), the inferred intrinsic absolute magnitude of KISS15s is consistent with the typical magnitude range of SNe IIn ($M_B = -15.81$ to $-21.25$ mag in the $2\sigma$ range; the mean is $M_B = -18.53$ mag). Moreover, KISS15s shows strong broad and intermediate emission lines in the optical spectra and late-time hot dust thermal emission, both of which are difficult to explain without the strong shock interaction between SN ejecta and dense CSM. These observational properties suggest that KISS15s is not an SN impostor but rather is a true SN event.

Since its discovery, the optical continuum emission of KISS15s has shown a slow temporal evolution up to $\sim 600$ days followed by a sudden decrease, with a faster rate of decline rate in late epochs (Sections 3.1.1 and 3.1.3). The long-duration optical continuum emission of SNe IIn is undoubtedly the result of strong ejecta-CSM interactions (Chevalier 1981; Schlegel 1990; Smith 2017). If we assume that the event duration is solely determined by the outer extent of the dense CSM (e.g., Smith 2014), the long duration of $t_{\text{duration}} \sim 600$ days of the KISS15s light curve may imply that the progenitor star of KISS15s had experienced continuous mass loss by extreme stellar winds blowing for

$$t_{\text{wind}} \sim \frac{v_e}{v_w} \times t_{\text{duration}}$$

$$\approx 82 \text{ yr} \left(\frac{v_e}{2000 \text{ km s}^{-1}}\right) \times \left(\frac{v_w}{40 \text{ km s}^{-1}}\right)^{-1} \left(\frac{t_{\text{duration}}}{600 \text{ days}}\right)$$

before the SN explosion, where $v_w$ and $v_e$ denote the stellar wind velocity and the ejecta-CSM shock velocity, respectively (Smith 2017; Smith et al. 2017). Here we adopt typical values for SNe IIn. The long-duration light curves, corresponding to the centuries of massive stellar winds before the SN explosion, are commonly observed in 1988Z-like SNe IIn (Figure 10); however, the physical mechanism driving such stellar winds in the final stage of stellar evolution is unclear (Shiode & Quataert 2014; Smith 2014; Smith et al. 2017; Yaron et al. 2017, and references therein). As already mentioned in Sections 3.1.1 and 3.1.3, the sudden luminosity drop observed in KISS15s at $\sim 600$ days after first detection may possibly be interpreted as a signature of the shock wave exit from the dense CSM (as suggested for the luminosity evolution of SN 2010jl; Fransson et al. 2014; Moriya et al. 2014; Dessart et al. 2015).

As discussed in Section 3.1.3, the power-law index of the time evolution of the bolometric light curve of KISS15s is $\alpha = -0.16$ (Equation (14)). Comparing this value to a simple interaction model that relates the power-law index of the time evolution of the bolometric light curve $\alpha$ to that of the density radial profile of the expanding SN ejecta $\rho_e \propto r^{-n}$ and the stellar wind CSM of $\rho_{\text{CSM}} \propto r^{-\eta}$ as (e.g., Moriya et al. 2013, 2014; Fransson et al. 2014; Ofek et al. 2014)

$$\alpha = \frac{6s - 15 + 2n - ns}{n - s},$$

we obtain $n = 21$ in the case of a steady stellar mass loss, $s = 2$. This power-law index is steeper than the values expected for the SN ejecta density structure of red supergiants (RSGs; $n \approx 12$) and Wolf–Rayet stars (n $\approx 10$; e.g., Chevalier & Fransson 1994; Matzner & McKee 1999; Moriya et al. 2013, 2014; Ofek et al. 2014). Instead, if we assume $n$ to be in the range of $n = 10–12$, the CSM density slope $s$ can be constrained to be $s = 1.6–1.8$, suggesting that the mass-loss rate was nearly steady but gradually decreased as the progenitor got closer to the time of explosion (Moriya et al. 2014). In conclusion, the photometric light curve of the continuum emission of KISS15s is consistent with the scenario that KISS15s is an SN IIn in which the continuum luminosity (at least after the time of discovery) is powered by the strong interaction between SN II ejecta and the CSM formed by centuries of nearly steady mass-loss episodes of the progenitor star before the SN explosion.

4.3. CSM Properties of KISS15s: Temporal Variation in the Emission Line Profile

The line-of-sight velocity of KISS15s (the bottom panel of 21) shows complex behaviors. Focusing on the intermediate component, the velocity shift decreases from 0 to $-500$ km s$^{-1}$. An increase in the blueshift velocity of an intermediate-width emission line component in SNe IIn is interpreted either as increasing extinction of the red wing by newly formed dust (Maeda et al. 2013; Gall et al. 2014) or as radiative acceleration of
the line emission regions due to the intense radiation from inner regions (Fransson et al. 2014). In the case of KISS15s, the emission line profile of the intermediate component remains consistent with a symmetric Gaussian while the velocity shift changes. The persistently symmetric line profile disagrees with the expectation from the dust extinction model and supports the scenario that the time evolution of the velocity shift is probably due to the radiative acceleration of the line-emitting region. Contrary to the intermediate emission line, the blueshift excess component of KISS15s shows deceleration since discovery, due to the radiative acceleration of the line-emitting region.

The emission line profile of KISS15s largely resembles those of 1988Z-like SNe IIn (Figure 18). It has been suggested that the broad and intermediate-velocity components in the SN 1988Z-like SNe IIn can be interpreted as two distinct line-emitting regions, where the former is related to the unshocked expanding ejecta and the latter to the shocked ejecta/CSM (or CDS) regions. The line velocity widths are determined by a combination of bulk motion of the line-emitting region, electron scattering broadening, and so forth, and it is uncertain which physical mechanisms are dominantly responsible for producing the observed emission line velocity widths. The intermediate and blueshifted excess emission line components have similar velocity widths but have a relative velocity shift of about $\sim 5000 \text{ km} s^{-1}$ (Section 3.2.1). This suggests that two separate shocked regions may have propagated through the non-spherically symmetric CSM, in which the large velocity shift component corresponds to emission from a high velocity ejecta-CSM shock propagating through a more rarified CSM region toward the observer (e.g., Chugai & Danziger 1994; Fox et al. 2010; Smith et al. 2012a).

Interestingly, similar blueshifted excess emission with a velocity shift of about $\sim 5000 \text{ km} s^{-1}$ (decelerated from $\sim 5500$ to $\sim 4000 \text{ km} s^{-1}$) was detected in the helium lines of SN 2010jl; however, in the case of SN 2010jl, blueshifted excess emission is not detected in the hydrogen lines (Fransson et al. 2014; Borish et al. 2015). Borish et al. (2015) attributed this blueshifted emission component to photoionized ejecta in which hydrogen is underabundant, expanding into a CSM region of relatively small density toward the observer. In the case of KISS15s, the blueshifted component is clearly detected in the hydrogen lines and has a consistent Gaussian profile with the central component (Section 3.2.1). Thus, the blueshifted excess in KISS15s is interpreted as photoionized hydrogen-abundant CSM material located in the high velocity ejecta-CSM interaction region.

In the literature, it is generally assumed that the shock front velocity $v_\text{f}$ is on the order of the velocity width of the intermediate component (Kiewe et al. 2012; Taddia et al. 2013)—that is, $v_\text{f} \sim v_\text{i} \sim 2000 \text{ km} s^{-1}$ for KISS15s. In addition, an estimate of an upper limit on $v_\text{i}$ can be derived from the line-of-sight velocity shift of the blueshifted excess emission component, $v_\text{i} \lesssim 5000 \text{ km} s^{-1}$ (see Section 3.2.1 for details). Adopting $t_\text{duration} = 600$ days, the expanding shock reaches $r_s = v_\text{f} \times t_\text{duration} \sim 4 \text{ lt-day}$. The inferred values of the shock front velocity $v_\text{f}$ and the radial extent $r_s$ are comparable to the IR blackbody expansion velocity $v_\text{bb,IR}$ and the IR blackbody radius $r_\text{bb,IR}$ (Equations (9) and (7), respectively), which further supports the scenario that the hot dust thermal emission probed by the W1- and W2-band observations is produced by newly formed dust in the ejecta-CSM interaction region or CDS.

The velocity width of the broad emission line decreases from $\sim 14,000$ to $\sim 10,000 \text{ km} s^{-1}$ (Figure 21). Although the line-broadening mechanism, and consequently the origin, of the broad emission lines are unclear, the extreme broadness suggests that the broad line emission region is related to the inner part of the ejecta-CSM system of KISS15s, in which a high gas temperature and a large bulk motion of the gas can be expected. Assuming that the velocity width reflects the thermal motion of free electrons, the decreasing velocity width indicates that the temperature of the broad emission line region rapidly decreases by a factor of two during our observations, due to radiative cooling or adiabatic expansion.

### 4.4. Progenitor Mass-loss Rate

Assuming a steady stellar wind CSM ($s = 2$; Section 4.2), the progenitor mass-loss rate $M$ just before the SN explosion can be related to the bolometric luminosity via a kinetic-to-radiation conversion efficiency factor $\epsilon < 1$, as

$$\dot{L}_\text{bol} = \epsilon \frac{dE_{\text{kin}}}{dt} = \frac{1}{2} \epsilon \frac{M}{v_\text{w}^3}, \quad (18)$$

where $E_{\text{kin}}$ denotes the kinetic energy of the thin shocked shell, and $\epsilon$ is usually assumed to be in a range of 0.1–0.5 (Moriya et al. 2013, 2014; Moriya & Maeda 2014; Ofek et al. 2014). As reference values, we adopt $\epsilon = 0.3$ and $v_\text{w} \sim v_\text{i} \sim 2000 \text{ km} s^{-1}$ (Section 4.3). The absence of the narrow P Cygni absorption in the APO/DIS high-resolution spectra ($\sigma_\text{inst} = 20.8 \text{ km} s^{-1}$; Section 2.2.2) may provide a constraint on the stellar wind velocity of KISS15s as $v_\text{w} \lesssim (\text{FWHM}_{\text{inst}}/(1+z)) = 47.2 \text{ km} s^{-1}$; hence, we adopt $v_\text{w} = 40 \text{ km} s^{-1}$ (e.g., $v_\text{w} = 40 \text{ km} s^{-1}$ is assumed in the case of SN 2005ip by Smith et al. 2017).

As shown in Section 3.1.3, the pseudo-bolometric luminosity of KISS15s at $\sim 600$ days since discovery is roughly $\dot{L}_\text{bol} \sim 0.8 \times 10^{43} \text{ erg} s^{-1}$ (Figure 16), giving a mass-loss rate estimate of

$$M \simeq 0.4 \, M_\odot \, \text{yr}^{-1} \left( \frac{\dot{L}_\text{bol}}{0.8 \times 10^{43} \text{ erg} s^{-1}} \right) \times \left( \frac{v_\text{w}}{40 \, \text{ km} s^{-1}} \right) \left( \frac{\epsilon}{0.3} \right)^{-1} \left( \frac{v_\text{i}}{2000 \, \text{ km} s^{-1}} \right)^{-3}. \quad (19)$$

The observed duration of $t_\text{duration} \sim 600$ days for KISS15s indicates that the amount of shocked CSM around KISS15s at the epoch of our last spectroscopic observation on 2016 October 4 is (Fransson et al. 2014)

$$M_\text{shocked \, CSM} = \frac{v_\text{i}}{v_\text{w}} \frac{M}{t_\text{duration}} \sim 35 \, M_\odot \left( \frac{\dot{L}_\text{bol}}{0.8 \times 10^{43} \text{ erg} s^{-1}} \right) \times \left( \frac{\epsilon}{0.3} \right)^{-1} \left( \frac{v_\text{i}}{2000 \, \text{ km} s^{-1}} \right)^{-2} \times \left( \frac{t_\text{duration}}{600 \, \text{days}} \right). \quad (20)$$

Instead, in the literature, it is usually assumed that the luminosity of the intermediate Hα line (denoted as $L_{\text{Hα}}$) is
proportional to the bolometric luminosity $L_{\text{bol}}$ and thus is a
good indicator of $L_{\text{bol}}$ (e.g., Salamanca et al. 1998; Kiewe et al.
2012; Taddia et al. 2013; de Jaeger et al. 2015). $L_{\text{H}_\alpha}$ can be
written as

$$L_{\text{H}_\alpha} = \frac{1}{2} \epsilon_{H\alpha} \frac{M}{v_w} \nu_\alpha^3,$$  \hspace{1cm} (21)

where $\epsilon_{H\alpha}$ represents the efficiency of the conversion of the
dissipated kinetic energy into the $H\alpha$ luminosity in the shock
wave. Note that at most only half of the total radiation
contributes to the ionization of the shell, $\epsilon_{H\alpha}$ is less than 0.5
(Salamanca et al. 1998). For KISS15s, the intermediate $H\alpha$
emission line luminosity in late epochs, corrected for the host
galaxy extinction of $E(B - V)_{\text{host}} = 0.6$ mag, is $L_{H\alpha} \sim 1 \times 10^{41}$ erg s$^{-1}$ (Figure 22). To make the mass-loss rate values
between Equations (18) and (21) consistent with each other,
$\epsilon_{H\alpha}$ must be much smaller than $\epsilon$—that is,

$$\frac{\epsilon_{H\alpha}}{\epsilon} = \frac{L_{H\alpha}}{L_{\text{bol}}} = 0.013 \left(\frac{L_{H\alpha}}{1.0 \times 10^{41} \text{ erg s}^{-1}}\right) \left(\frac{L_{\text{bol}}}{0.8 \times 10^{43} \text{ erg s}^{-1}}\right)^{-1}.$$  \hspace{1cm} (22)

The low value of $\epsilon_{H\alpha}$ probably reflects a low conversion
efficiency from the ionizing continuum to the $H\alpha$ emission line
due to thermalization of the $H\alpha$ line inside the dense CSM
(e.g., Fransson et al. 2014). In the case of $\epsilon = 0.3$, $\epsilon_{H\alpha}$ becomes
0.004, which is an order of magnitude smaller than the
canonical value of $\epsilon_{H\alpha} = 0.05$ usually assumed in the literature
(e.g., Salamanca et al. 1998; Taddia et al. 2013).

It should be kept in mind that these estimates strongly
depend on the assumed parameters. The mass-loss rate estimate
based on the provided equations is uncertain in that the wind
velocity $v_w$ is not observationally constrained for KISS15s, and
continuum and emission line luminosities $L_{\text{bol}}$ and $L_{H\alpha}$ are
time-variable. The assumption that the velocity width of the
intermediate $H\alpha$ emission line represents the shock velocity $v_s$
may be an oversimplification, and the mass-loss rate estimate of
KISS15s becomes much smaller ($M \sim 0.1 M_\odot$ yr$^{-1}$) if we
instead adopt a higher value of $v_s = 3000$ km s$^{-1}$, as inferred
for SN 2010jl (Ofek et al. 2014). Moreover, the provided
equations assume spherically symmetric CSM distributions;
thus, the mass-loss rate estimate is subjected to uncertainties
depending on the inhomogeneities of the CSM (e.g., Fransson et al.
2014).

The mass-loss rate of KISS15s estimated with Equation (19) is
largely on the upper bound of those measured in other SNe IIn
(e.g., Kiewe et al. 2012; Taddia et al. 2013; Moriya et al.
2014). For example, using Equation (19) and adopting $\epsilon = 0.3$,
the mass-loss rate of the highly luminous SN 2010jl is estimated to be
$M \sim 0.4 M_\odot$ yr$^{-1}$ (Fransson et al. 2014).\footnote{Fransson et al.
(2014) implicitly assumed $\epsilon = 1$ when deriving $M = 0.11 M_\odot$
yr$^{-1}$ as a mass-loss rate estimate for SN 2010jl (see Equations
(9) and (11) of Fransson et al. 2014).

Such a high progenitor mass-loss rate is three to four orders
of magnitude higher than typical values for RSGs, and is
consistent with those expected for eruptive mass loss of LBVs
(e.g., Kiewe et al. 2012; Taddia et al. 2013; Smith 2014;
Goldman et al. 2017). However, as noted by Taddia et al.
(2013), we should not take the rough mass-loss rate estimate}
described above as conclusive evidence for the LBV progenitor
channel for SNe IIn. According to studies of local environ-
ments of SNe IIn in their host galaxies, SNe IIn generally do
not trace star-forming regions in the host galaxies, suggesting
that the majority of SN IIn events are not related to the most
massive stars such as LBVs (e.g., Habergham et al. 2014;
Kuncarayakti et al. 2018). Moreover, as mentioned in
Section 4.2, the long duration of several hundreds of days of
the light curves of KISS15s implies that the high progenitor
mass-loss rates are sustained at least for decades before the SN
explosions. Similar enhanced mass loss for $\sim 1000$ yr before
core collapse (i.e., well before Ne, O, or Si burning phases)
may also explain the continuous strong CSM interaction in
other SN 1988Z-like SNe IIn, such as SNe 2005ip and 1988Z
(Smith et al. 2017). These observations suggest that there must
be unresolved mechanisms that trigger the large persistent
mass loss at the final stage of the massive star evolution, other
than the eruptive mass loss observed in LBVs and RSGs (e.g.,
Moriya et al. 2014; Smith et al. 2017).

Physical mechanisms enhancing the mass-loss from RSGs
several decades before the explosion are currently not uniquely
identified (e.g., Shiode & Quataert 2014; Smith & Arnett 2014;
Woosley 2017). Further long-term observations of SNe IIn will
provide important information about the mass-loss mechanisms
in the late stage of massive star evolution.

\subsection*{4.5. Model of the Emission Regions of KISS15s}

The observations of the emission line profile and the light
curves of KISS15s provide constraints on the geometry of its
emission regions. Figure 24 summarizes the proposed picture
of the ejecta-CSM interaction region of KISS15s, based on a
toroidal CSM geometry model (Chugai & Danziger 1994;
Mauerhan et al. 2014; Smith et al. 2015; Smith 2017). As
mentioned in Sections 3.2 and 4.3, such a CSM density
distribution formed by the wide-angle bipolar stellar wind can
result in the inhomogeneous expanding ejecta distribution and
produce multiple velocity components in the $H\alpha$ emission line
(discussed later). It should be noted that although the model
illustrated in Figure 24 employs a bipolar outflow-like
geometry, we do not exclude the possibility of one-sided
asymmetry (see, e.g., Fransson et al. 2014).

The broad emission lines (FWHM $\sim 14,000$ km s$^{-1}$) are
probably produced from unshocked ejecta, which is ionized by
high-energy ingoing radiation from the reverse shock (e.g.,
Chugai & Danziger 1994; Chevalier & Fransson 2017). As
shown in Figure 22, the continuum luminosity shows a similar
decaying rate with the broad $H\alpha$ emission line, suggesting
that the continuum emission may possibly be powered by the same
energy source with a broad emission line, and the emission
regions of the broad emission line and optical continuum are
cospatial (e.g., Smith 2017).

The intermediate emission line component can be produced from
the shocked CSM/ejecta or CDS ionized by the intense
radiation from the forward or reverse shocks (e.g., Smith et al.
2017, and references therein). The blueshifted intermediate
emission line component has a consistent velocity width of
$\sim 2000$ km s$^{-1}$ with the intermediate emission line at
the systemic redshift, suggesting that the physical conditions
between the two emission regions should be similar to each
other; nevertheless, the line-of-sight velocity is different by
The observed narrow emission lines are probably dominated by the emission from H\textsc{ii} regions in the host galaxy, which may not be directly related to KISS15s. Nevertheless, the present observations do not rule out the possibility of a narrow emission line flux contribution from the unshocked CSM photoionized by the SN emission.

Apparently, the proposed toroidal CSM distribution is not a unique solution. Another possible scenario to explain the blueshifted H\textalpha intermediate-width emission line component is to consider the (one-sided) jet structure of SN ejecta. To account for the triple-peak H\textalpha emission line (composed of central emission line and \(\sim10,000\,\text{km}\,\text{s}^{-1}\) blueshifted and redshifted H\textalpha emission lines) observed in SN 2010ip, Smith et al. (2012a) proposed a model in which a two-sided supernova jet, inclined relative to the observer, passes through initially spherically symmetric CSMs and produces two shocked regions with blue- and redshifted velocities. It should be noted that the triple-peak H\textalpha emission line profile in SN 2010ip is quite different from the double-peak intermediate line profile observed in KISS15s, and the velocity shift is also more modest in KISS15s (\(\sim-5000\,\text{km}\,\text{s}^{-1}\)); thus, there is no need to employ the jet structure other than the inhomogeneous expansion due to the aspherical CSM structure in the case of KISS15s.

Further multi-wavelength monitoring observations at optical, IR, X-ray, and radio wavelengths should reveal the details of the ejecta-CSM interaction regions in KISS15s.

5. Conclusions

We report the discovery of KISS15s, which is confirmed to be an SN 1988Z-like SN IIn. The host galaxy of KISS15s is a low-mass (\(M_* = 10^{8.3-9} M_\odot\)), low-metallicity (12 + log O/H = 7.873 \pm 0.385), star-forming galaxy at \(z = 0.038\). Spectral comparisons with SN 1988Z suggest that it is suffering from host galaxy extinction of \(E(B-V)_{\text{host}} = 0.6\,\text{mag}\) on the assumption of an SMC-like extinction curve.

We modeled the H\textalpha emission line profile by combining four symmetric Gaussians of narrow, intermediate, blueshifted intermediate, and broad velocity width components. While the blueshift velocities of the narrow, intermediate, and broad components relative to the systemic redshift of \(z = 0.038\) are smaller than about \(-1000\,\text{km}\,\text{s}^{-1}\), the blueshifted intermediate component shows a large blueshift of about \(-5000\,\text{km}\,\text{s}^{-1}\). The fitting results reveal the FWHMs of broad, intermediate, and narrow components of \(\lesssim 1000\), \(\sim2000\), and \(\sim14,000\,\text{km}\,\text{s}^{-1}\), respectively, and the intermediate and blueshifted intermediate-velocity components have consistent velocity widths with respect to the others. The narrow H\textalpha emission line component is most likely dominated by emission from the interstellar medium (H\textsc{ii} regions) in the host galaxy. However, it is still possible that there is a flux contribution from an unshocked CSM around KISS15s, which is photoionized by strong radiation from KISS15s. The intermediate H\textalpha line luminosity has increased monotonically since the discovery of KISS15s, which implies that the ejecta-CSM interaction is still ongoing, at least during the observations presented in this work.

In the \(\lesssim600\) days since discovery, the optical continuum emission has decreased monotonically. By contrast, the hot dust IR continuum emission peaking at \(\sim3\,\mu\text{m} (T_{\text{BB,IR}} = 1190\,\text{K})\) has increased over time since discovery, suggesting that new dust grains are continuously being formed in the CDS. The increasing IR luminosity indicates that the IR blackbody expansion velocity
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is $v_{\text{dust}} \sim 1000$–$6000$ km s$^{-1}$ (Figure 15), which is close to the velocity widths and/or velocity shifts of the H$\alpha$ emission line components, suggesting that the hot dust thermal emission is actually due to newly formed dust in the CDS and is not due to the IR echo by preexisting dust in the CSM. Unlike the other SNe IIn associated with IR excess emission due to the newly formed dust at the CDS (e.g., SN 2005ip, 2006jd, and 2010jl), the intermediate H$\alpha$ emission line profile of KISS15s shows no evidence of late-time blueshifted asymmetry, which implies that the geometric configuration of the line-emitting region and dust-forming region in the CDS is different among SNe IIn.

The bolometric luminosity of KISS15s (calculated from the sum of the optical and IR blackbody luminosities) roughly follows a power-law luminosity evolution of $L \propto t^{-0.16}$. The power-law decline of the luminosity can naturally be explained by the interaction between the ejecta and the mostly steady stellar wind (Section 4.2).

The coexistence of the intermediate H$\alpha$ emission line components with large blueshift and at roughly systemic redshift indicates that the ejecta-CSM interaction region of KISS15s has a non-spherical, inhomogeneous spatial distribution. We propose a toroidal CSM geometry model where the ejecta expanding through the rarified CSM region can have a higher velocity than that through the dense CSM, producing the blueshifted intermediate component. The broad emission line may be produced from unshocked ejecta ionized by the intense radiation from the ejecta-CSM interaction region or CDS.

The progenitor mass-loss rate inferred from the bolometric luminosity is $M \sim 0.4 M_\odot$ yr$^{-1}$ ($v_w/40$ km s$^{-1}$), where $v_w$ is the observationally unconstrained wind speed of the CSM, suggesting that the progenitor of KISS15s was a RSG star or an LBV that had experienced a large mass-loss in the centuries before the explosion. The comparison between the bolometric continuum luminosity and intermediate-width H$\alpha$ emission line luminosity indicates that the kinetic-to-radiation conversion efficiency for the H$\alpha$ emission is roughly 100 times smaller than that for the bolometric luminosity.

Future follow-up observations of KISS15s at optical, IR, radio, and X-ray wavelengths will provide insight into the late-time evolution of dust formation in KISS15s and more detailed constraints regarding the CSM geometry.

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Software: IRAF, Astropy (Astropy Collaboration et al. 2018), EXExtractor (Bertin & Arnouts 1996), HOTPANTS (Becker 2015), barycorpy (Kanodia & Wright 2018), MPFIT (Markwardt 2009), GALFIT (Peng et al. 2002).

Appendix A
Instrumental Line Profiles of ARC3.5 m/DIS
Red-arm Spectra

Figure 25 presents the ARC3.5-m/DIS red-arm R300 and R1200 arc lamp spectra obtained on the same nights with KISS15s observations. The instrumental line profile at the first three epochs is well reproduced by a single Gaussian function; \( \sigma_{\text{inst}} \) obtained by a single Gaussian fitting for these arc lamp spectra at \( \lambda_{\text{obs}} = 6900–7100 \) Å are listed in Table 8.

In the last epoch (2016 October 4), the instrumental profiles of both R300 and R1200 were significantly affected by an additional broad-width wing component, although the instrumental settings were nearly the same as those used in previous observations. This peculiar instrumental profile is not seen in the DIS blue-arm data (Table 11). DIS red-arm spectra sometimes exhibit complex instrumental broadening profiles (Baldassare et al. 2016). Figure 26 shows the results of a double Gaussian fitting for R300 and R1200 arc lamp spectra obtained on 2016 October 4. The line profile is reasonably reproduced by the double Gaussian model, in which the narrow core shows widths that are consistent with previous observations; the widths of the broad wing are several times broader than the narrow core. This double Gaussian profile may be due to a slight defocusing of the internal focus of the red-arm spectrograph.\(^{30}\) Table 8 shows the widths of both the narrow and broad components. The broad component dominates the flux of the total line profile; therefore, we assumed \( \sigma_{\text{inst}} = \sigma_{\text{inst}}(b) \) for the spectra obtained on 2016 October 4.

Although the complex instrumental line profile makes the narrow component fitting uncertain, it does not affect the fitting results for the intermediate and broad line components because the intrinsic velocity widths of these components are at least several times larger than those associated with instrumental broadening.

\(^{30}\) https://www.apo.nmsu.edu/arc35m/Instruments/DIS/#5
Figure 25. ARC3.5 m/DIS red-arm arc lamp spectra at $\lambda = 6250$–$6750$ Å obtained at different epochs. On 2016 October 4, the instrumental profile was significantly contaminated by a broad base, which may be due to improper setting of the internal focus of the DIS spectrograph.

Figure 26. Double Gaussian spectral profile model for ARC3.5 m/DIS red-arm arc lamp R300 and R1200 spectra obtained on 2016 October 4. The line width of the narrow cores is consistent with the instrumental resolution. The additional broad component is probably due to the defocusing of the spectrograph.
Appendix B

Profile Fitting for the Hβ Line

The observed spectra in the wavelength range of the Hβ emission line have a lower S/N than the Hα emission line, as shown in Figure 17. The broad component is barely seen in the Hβ profile, and the blueshifted intermediate component clearly detected in Hα emission line profiles (Section 3.2.1) is not seen in the Hβ profile.

We modeled the Hβ emission line profiles as for the Hα emission line analyzed in Section 3.2.1 (Table 10). The observed-frame central wavelength and the velocity width of the broad Hβ line were constrained from the broad Hα wavelength fitting result for each spectrum at each epoch. The blueshifted intermediate component was not included in the fitting. For the LISS spectrum, the unresolved intermediate Hβ and narrow [O III] lines were assumed to have the same width, and the flux ratio and the central wavelength ratio of the [O III] doublet lines were fixed to 1:3 and 4959:5007, respectively.

Figure 27 shows the profiles of the Hβ+[O III] emission of KISS15s. The best-fit model spectra and the fitting residuals are also shown in the same figure, and the best-fit model parameters are tabulated in Table 12. Note that the broad Hβ component is not detected (<1σ) in the last epoch DIS low-/high-resolution spectra, as indicated by the bold font in Table 12. Figure 28 compares the temporal evolutions of the rest-frame line FWHM and the velocity shift of the intermediate Hβ and Hα lines, where the Hβ line widths are converted into intrinsic values using Equation (15); the instrumental broadening factors are listed in Table 11. The velocity widths and the velocity shifts of Hβ and Hβ intermediate components are consistent with each other within the error designated, suggesting that the temporal variation in the Balmer emission line profiles are not solely due to the chromatic extinction of newly formed dust in the CDS region.

Table 11
Instrumental Broadening $σ_{\text{inst}}$ in the Hβ Spectral Region of Nayuta/LISS and ARC3.5 m/DIS Blue-Arm

| MJD     | Date      | Inst.-Grating | $σ_{\text{inst}}$ (km s$^{-1}$) |
|---------|-----------|---------------|-------------------------------|
| 57284.7 | 2015 Sep 19 | LISS-very low | 1720                          |
| 57358.2 | 2015 Dec 2  | DIS-B400/R300 | 173.5                         |
| 57417.1 | 2015 Jul 31 | DIS-B400/R300 | 134.1                         |
| 57665.4 | 2016 Oct 4  | DIS-B400/R300 | 178.5                         |
| 57430.1 | 2016 Feb 12 | DIS-B1200/R1200 | 56.4                      |
| 57665.4 | 2016 Oct 4  | DIS-B1200/R1200 | 35.5                      |

Note. The velocity width of the instrumental line profile $σ_{\text{inst}}$ at the Hβ wavelength region is evaluated by single Gaussian model fittings for arc lamp spectra in the wavelength ranges of $λ_{\text{obs}} = 5200–6000$ Å (two lines) for LISS and $λ_{\text{obs}} = 4600–5100$ Å (three lines) for the DIS blue-arm.
Figure 27. Same as Figure 19, but for Hβ+[O III] emission line profiles on 2015 September 19 (Nayuta/LISS), 2015 December 2, 2016 January 30, and 2016 October 4 (ARC3.5 m/DIS blue-arm low-resolution). The bottom two panels are for high-resolution DIS spectra.
Figure 28. Comparisons of the rest-frame intrinsic velocity width and the velocity shift of the decomposed intermediate Gaussian component of Hβ and Hα line profiles of KISS15s, as a function of observed time. The velocity width of the intermediate component is unresolved in the Nayuta/LISS and is omitted from the plot.

Table 12
Best-fit Gaussian Model for the Hβ Line Profile without the Blueshift Excess Component

| Parameter Name       | LISS       | DIS Low 1  | DIS Low 2  | DIS Low 3  | DIS High 1 | DIS High 2 |
|----------------------|------------|------------|------------|------------|------------|------------|
| Date                 | 2015 Sep 19| 2015 Dec 2 | 2016 Jan 30| 2016 Oct 4 | 2016 Feb 12| 2016 Oct 4 |
| Days Since Discovery | 50.7 days  | 124.2 days | 183.1 days | 431.4 days | 431.4 days | 431.4 days |
| Norm. (10⁻¹⁷ erg s⁻¹ cm⁻² A⁻¹) | 8.42 ± 0.17 | 4.34 ± 0.02 | 3.07 ± 0.03 | 2.81 ± 0.02 | 4.27 ± 0.10 | 2.40 ± 0.10 |
| Index                | −0.14 ± 0.38| 0.27 ± 0.08 | 0.71 ± 0.17 | 0.64 ± 0.14 | 0.33 ± 0.38 | −0.84 ± 0.61 |
| Flux (10⁻¹⁷ erg s⁻¹ cm⁻²) | 112.66 ± 319.06 | 126.76 ± 13.01 | 142.20 ± 18.66 | −30.90 ± 13.68 | 187.99 ± 48.25 | −46.10 ± 43.01 |
| σ_{obs, i} (km s⁻¹) | 2686.27 ± 1116.26 | 961.88 ± 56.06 | 971.78 ± 71.37 | 1041.09 ± 63.18 | 989.29 ± 76.22 | 1230.31 ± 149.90 |
| λ_{obs, i} (Å)        | 5034.68 ± 7.00  | 5044.17 ± 0.83 | 5038.24 ± 1.77 | 5038.71 ± 0.82 | 5036.31 ± 1.32 | 5041.49 ± 1.41 |
| Flux (10⁻¹⁷ erg s⁻¹ cm⁻²) | 310.68 ± 229.86 | 73.74 ± 4.45  | 56.67 ± 6.18  | 111.15 ± 7.89 | 114.68 ± 10.25 | 112.13 ± 18.27 |
| σ_{obs, n} (km s⁻¹)   | 145.20 ± 5.83  | 134.40 ± 7.27 | 169.42 ± 6.27 | 69.97 ± 3.71  | 45.23 ± 3.54  | 16.51 ± 1.45  |
| λ_{obs, n} (Å)        | 5045.32 ± 0.24 | 5046.05 ± 0.27 | 5047.15 ± 0.23 | 5045.29 ± 0.08 | 5046.15 ± 0.08 | 5046.15 ± 0.08 |
| Flux (10⁻¹⁷ erg s⁻¹ cm⁻²) | 5178.06 ± 14.71 | 5146.52 ± 0.26 | 5147.11 ± 0.31 | 5148.44 ± 0.33 | 5146.56 ± 0.14 | 5148.08 ± 0.10 |
| λ_{obs,[OIII]4959} (Å) | 56.84 ± 27.57  | 15.08 ± 1.22  | 16.16 ± 1.74  | 16.06 ± 1.53  | 22.37 ± 1.94  | 12.70 ± 1.35  |
| Flux_{[OIII]4959} (10⁻¹⁷ erg s⁻¹ cm⁻²) | 5196.09 ± 0.11 | 5197.15 ± 0.15 | 5198.26 ± 0.16 | 5196.60 ± 0.07 | … | … |
| λ_{obs,[OIII]5007} (Å) | 45.23 ± 1.70  | 50.94 ± 2.67  | 50.25 ± 2.18  | 57.48 ± 2.85  | … | … |
| Flux_{[OIII]5007} (10⁻¹⁷ erg s⁻¹ cm⁻²) | … | … | … | … | … | … |

Note. The fitting parameters are a normalization and a spectral index of the power-law continuum, observed-frame velocity widths, observed-frame central wavelengths, and integrated fluxes for the broad, intermediate, and narrow components. However, note that the line width and the central wavelength of the broad component are fixed to those constrained from the Hα line profile fitting (Table 10). The Hβ and [O III]4959/5007 narrow components are assumed to have the same line width. The broad component is undetected in late-time spectra, as indicated by bold fonts. The observation epochs of LISS, DIS low 1, DIS low 2, DIS low 3, DIS high 1, and DIS high 2 are MJD = 57284.7, 57358.2, 57417.1, 57665.4, 57430.1, and 57665.4, respectively. The DIS high-resolution spectra are not spectro-photometrically calibrated; thus, the flux values suffer from absolute flux calibration uncertainties.
Figure 29 presents the Balmer decrements of the broad, intermediate, and narrow Hα components from the fitting results (Tables 10 and 12). We can see that the Balmer decrements of the broad and intermediate components are larger than the canonical case $B$ value of $H_\alpha/H_\beta \sim 3$ (Osterbrock 1989) at least $\sim 100$ days since discovery, even after correcting for the putative SMC-like dust extinction of $E(B-V)_{\text{host}} = 0.6$ mag. The steep Balmer decrement is often observed in SNe IIn.

The steep Balmer decrement calculated from the luminosity ratios $H_\alpha/H_\beta$ of the broad, intermediate, and narrow velocity width components. Only spectro-photometrically calibrated LISS and low-resolution DIS data are used. The host galaxy extinction of $E(B-V)_{\text{host}} = 0.6$ mag is corrected. The broad $H_\alpha$ component in the final epoch DIS data, and the narrow $H_\alpha$ component in the final epoch DIS data is significantly affected by complex instrumental broadening, as discussed in Appendix A; thus, these data are excluded from the plot.

Figure 29

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