



SN 2024dy: Dust Formation in a Long-lived Type II_n Supernova and Constraints on the Dust Mass

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Abstract

Type II_n supernovae (SNe) are a subclass of core-collapse SNe powered by interaction between the ejecta and the dense circumstellar material. Among them, long-lived Type II_n events are characterized by luminous, long-duration light curves with high radiative energy. Several cases of long-lived type II_n SNe exhibit substantial dust emission at late times. However, well-observed examples remain limited, and the details of their dust formation mechanisms remain poorly understood. Here we present photometric and spectroscopic observations of the Type II_n SN 2024dy in ultraviolet, optical, and near-infrared (NIR) wavelength for 500 days. SN 2024dy reached a peak magnitude of $M_r = -19.2$ mag with a total radiation energy of 1.9×10^{50} erg. An NIR excess emerged at late phases, and the spectral energy distribution modeling indicates the presence of carbon dust with temperatures of 1300–1800 K and masses of about $10^{-5} M_\odot$. The spectra features were typical of long-lived Type II_n SNe. The late time H α profile exhibits a strong suppression of the red wing, providing evidence for newly formed dust. Our results suggest that the derived dust mass above may be underestimated due to optical depth effects. SN 2024dy provides an important observational case for understanding dust formation in Type II_n SNe.

Unified Astronomy Thesaurus concepts: Supernovae (1668); Stellar mass loss (1613); Circumstellar matter (241)

Materials only available in the online version of record: data behind figures

1. Introduction

Massive stars with initial masses above $8\text{--}10 M_\odot$ end their lives as core-collapse supernovae (SNe). Among them, those showing narrow hydrogen emission lines in their spectra are classified as Type II_n, whose radiation is powered by shock interaction between the SN ejecta and the circumstellar material (CSM; E. M. Schlegel 1990; A. V. Filippenko 1997; N. Smith 2017). Type II_n SNe exhibit diversity in peak luminosity and light-curve timescales, which is generally interpreted as reflecting differences in preexplosion mass-loss histories of the progenitor (e.g., M. Kiewe et al. 2012; A. Nyholm et al. 2020; D. Hiramatsu et al. 2026).

Among these events, the luminous and longest-lived examples are often referred to as “long-lived” Type II_n SNe. These events are interpreted as explosions occurring within very massive CSM shells of a few solar masses (M. Fraser 2020, for a review). A prominent case is SN 2010jl, whose total radiated energy exceeds 10^{50} erg (C. Fransson et al. 2014), requiring an exceptionally large

explosion energy even under the assumption of efficient ejecta–CSM energy conversion. Polarimetric observations further reveal pronounced asymmetry, suggesting a geometrically complex shock structure and CSM distribution (F. Patat et al. 2011). Such asymmetry in the CSM has been proposed to significantly affect both the radiative efficiency and observed spectral properties of Type II_n SNe (A. Suzuki et al. 2019).

Furthermore, long-lived Type II_n SNe have emerged as key laboratories for studying dust formation in strongly interacting SN environments. Compared to the more common Type IIP SNe, Type II_n events more frequently exhibit luminous late-time near-infrared (NIR) and mid-infrared (MIR) emission, often implying dust masses that are 1 to 2 orders of magnitude larger (e.g., O. D. Fox et al. 2011; T. Szalai et al. 2021). Observationally, some events show pronounced NIR–MIR excesses accompanied by a progressive suppression of the red wing of H α on timescales of several hundred days (e.g., SN 2010jl; C. Fransson et al. 2014). These features are commonly interpreted as signatures of newly formed dust that selectively obscures the receding side of the emitting region (e.g., N. N. Chugai 2018).

However, the physical origin of the dust in Type II_n SNe remains debated. The observed blueshifted line profiles can be



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explained by continuous dust formation either in the SN ejecta or in the cool dense shell (CDS) formed between the forward and reverse shocks (e.g., N. Smith et al. 2009; C. Gall et al. 2014; A. Bevan et al. 2019). Alternatively, modeling of MIR spectral energy distributions (SEDs) suggests that a significant fraction of the emission may arise from preexisting dust located at radii larger than the forward shock (O. D. Fox et al. 2011). In addition, multiple dust components may coexist, and the relative contributions are difficult to distinguish observationally.

Recent theoretical models predict that 10^{-3} – $10^{-1} M_{\odot}$ of dust can form in the CDS of interacting SNe (A. Sarangi & J. D. Slavin 2022). This picture is also supported by long-term JWST/MIRI observations of Type IIn SN 2005ip, which have revealed continued dust accumulation over more than a decade after the explosion (M. Shahbandeh et al. 2025). Nevertheless, such estimates remain subject to significant uncertainties, particularly due to optical depth effects and the limited sensitivity of observations to cold dust at longer wavelengths.

In this context, adding another well-observed long-lived Type IIn SN is valuable both as an addition to the still limited sample of this rare class and as a test bed for dust-formation physics in strongly interacting SNe. However, well-observed examples remain scarce, and the structure, temporal evolution, and optical depth evolution of the dust-forming regions are still poorly constrained. Thus, detailed multiwavelength observations of new, well-characterized long-lived Type IIn SNe are therefore essential for advancing our understanding of dust-formation mechanisms and interaction physics in this subclass.

In this work, we present 500 days of ultraviolet (UV), optical, and NIR photometric and spectroscopic observations of SN 2024dy, a long-lived Type IIn SN exhibiting clear signatures of dust formation. The dataset covers both the infrared (IR) excess and the contemporaneous evolution of the H α line profile, allowing us to constrain the dust properties and give a stringent constraint on the dust mass. The structure of this paper is as follows. In Section 2, we describe the observations and data reduction. Section 3 presents the photometric results and Section 4 provides the spectroscopic results. In Section 5, we discuss the energy budget and the properties, of the dust emission. A summary of this paper is given in Section 6

2. Observations and Data Reduction

2.1. Discovery, Classification, and Extinction

SN 2024dy (also known as GOTO24lk, PS24qe, ZTF24aaabljq, Gaia24acc, and ATLAS24ada) was discovered by J. Tonry et al. (2024) on 2024 January 2 (MJD 60311.5) with 18.60 mag in orange band of the Asteroid Terrestrial-impact Last Alert System (ATLAS; J. L. Tonry et al. 2018). The last nondetection was obtained by the Zwicky Transient Facility (ZTF) on 2023 December 29 (MJD 60307.48), providing an upper limit of $m \geq 16.87$ mag in the g band. Just before this date, the Gravitational-wave Optical Transient Observer (GOTO) reported an upper limit of $m \geq 19.8$ mag in the GOTO L band (MJD 60307.05). Since the ZTF upper limit is relatively shallow, we adopt the GOTO upper limit as the final nondetection. In this paper, we take the midpoint between this GOTO nondetection and the first Gaia detection as the explosion date (2023 December 31, MJD 60309.2).

SN 2024dy was classified as a Type IIn SN at a redshift of $z = 0.0214$ by J. Wise et al. (2024), using a spectrum obtained with the Lick 3 m KAST spectrograph on 2024 January 8 (MJD 60317.55). Since the host galaxy of SN 2024dy is faint and its distance has not been published, we adopt $z = 0.0214$ as the redshift, derived from the narrow H α emission in the spectrum used for classification. This corresponds to a distance of 90.1 Mpc and a distance modulus of $\mu = 34.77$ (adopting $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{matter}} = 0.3$, and $\Omega_{\Lambda} = 0.7$, calculated with COSMOTOOL).¹¹ Throughout this paper, we adopt this value.

We adopted the Galactic extinction toward SN 2024dy to be $E(B - V)_{\text{MW}} = 0.026$ mag (E. F. Schlafly & D. P. Finkbeiner 2011). For the UV bands, we used the extinction law of M. H. Siegel et al. (2014) to estimate the extinction in each band. For the optical and NIR extinction corrections, we used the extinction law of J. A. Cardelli et al. (1989) with $R_V = 3.1$. As for the host galaxy extinction, no NaID absorption was detected in any of our spectra (see Section 4.1); thus, no additional correction was applied.

2.2. Ultraviolet, Optical, and Near-infrared Photometry

The photometric data presented in this paper are a combination of public archive data and those obtained by our observations.

Photometric observations in the gi band were conducted over 53 epochs (between MJD 60351.66 and 60808.46) with the OPTCAM mounted on the 1 m telescope at Iriki Observatory, starting immediately after the discovery. The OPTCAM data were reduced in a standard manner, using the OKUDA pipeline.¹² The photometry was carried out with the point-spread function (PSF) photometry using IRAF¹³ DAO-PHOT package (P. B. Stetson 1987). The photometric calibration was performed using the field stars from the Pan-STARRS Data Release 1 catalog (K. C. Chambers et al. 2016).

NIR observations were conducted over 40 epochs (between MJD 60322.67 and 60807.55) using kSIRIUS (T. Nagayama & H. Nakaya 2024) mounted on the 1.0 m telescope at the Iriki Observatory¹⁴ and HONIR (H. Akitaya et al. 2014) mounted on the 1.5 m Kanata telescope at the Higashi Hiroshima Observatory. The kSIRIUS data were analyzed in the same manner as those from OPTCAM: image reduction with the OKUDA pipeline followed by PSF photometry using DAO-PHOT. The HONIR data were reduced using standard procedures in IRAF, and PSF photometry was then performed. The calibration was performed using the stars from the Two Micron All Sky Survey catalog (M. F. Skrutskie et al. 2006).

For g and r band, we used data from ZTF (E. C. Bellm et al. 2019) obtained through the ALERCE explorer¹⁵ (F. Förster et al. 2021). Also, for the ATLAS oc bands, we used magnitude data obtained by using the ATLAS forced photometry server¹⁶ (A. N. Heinze et al. 2018; J. L. Tonry et al. 2018; K. W. Smith

¹¹ <http://www.bo.astro.it/~cappi/cosmotools>

¹² An image reduction Python-based pipeline developed for the data obtained with the 1 m telescope at Iriki Observatory.

¹³ Image Reduction and Analysis Facility (IRAF) distributed by the National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy under a cooperative agreement with the National Science Foundation.

¹⁴ <https://agarc.sci.kagoshima-u.ac.jp/about/>

¹⁵ <https://alerce.science/>

¹⁶ <https://fallingstar-data.com/forcedphot/>

et al. 2020). We binned the data into 1 day intervals and adopted only the data with $\geq 5\sigma$ detections.

UV and *UBV*-band photometric data were obtained from publicly available data from the Ultra-Violet Optical Telescope (UVOT) at the Neil Gehrels Swift Observatory (P. W. A. Roming et al. 2005). Aperture photometry was performed using the UVOT data analysis software package HEASoft,¹⁷ following standard procedures.

2.3. Optical Spectroscopy

Spectroscopic observations were carried out using two facilities. We obtained 10 epochs of data with the Hanle Faint Object Spectrograph Camera (HFOSC) mounted on the 2.0 m Himalayan Chandra Telescope (HCT) of the Indian Institute of Astrophysics over a period of approximately 400 days. The data were reduced using standard IRAF procedures. We also obtained four epochs of spectroscopic observations of SN 2024dy with the ARIES-Devasthal Faint Object Spectrograph and Camera (ADFOSC) on the Devasthal Optical Telescope (DOT). We reduced the data using standard IRAF tasks, which include preprocessing, extraction of the 1D spectrum, wavelength calibration, and flux calibration.

In addition, two spectra available on Transient Name Server (TNS; at 6 days: Lick 3 m KAST and 7 days: ESO New Technology Telescope (NTT)/EFOSC2) are also included in our analysis. The log of all spectroscopic observations is provided in Table 2.

3. Photometric Properties

3.1. Light-curve Evolution

SN 2024dy is one of the long-lived Type II_n SNe. Figure 1 shows the multiband light curves of SN 2024dy. For the following discussion, we define the period up to MJD 60497 (188 days) as Season 1, and that after MJD 60579 (270 days) as Season 2.

In the UV bands, a rapid decline is observed from the first epoch, and the UV colors become progressively redder with time. The rise is well sampled in the optical *g* through *i* bands, with particularly high-cadence coverage in the *o* band. Following E. O. Ofek et al. (2014), we model the early time *o*-band light curve using a t^2 prescription given by

$$F = F_{\max} \left(1 - \left[\frac{t - t_{\max}}{\Delta t} \right]^2 \right). \quad (1)$$

Here, $F_{\max}$ is the peak luminosity, $t_{\max}$ is the time of maximum light derived from the parabolic fit, and Δt is the time interval between zero luminosity and peak, corresponding to the rise time. The fit yields a peak time of $t_{\max} = 60347.54 \pm 0.15$ and a rise time of $\Delta t = 38.03 \pm 0.17$ days. The corresponding explosion date inferred from these values is $t_{\text{exp}} = 60309.51 \pm 0.23$, which is broadly consistent with the explosion date adopted in this study (MJD 60309.2).

The rise time of SN 2024dy places it among the subclass of Type II_n SNe with relatively long rise timescales identified in previous studies (see, e.g., A. Nyholm et al. 2020). Around maximum light, the optical light curves show an almost flat evolution. The time to reach peak brightness is longer in redder wavelengths, with the K_s band exhibiting a rise time of about 90 days.

The postpeak evolution is one of the most remarkable features of this object. In Season 1, after reaching peak, the *r* band showed a gradual decline at a rate of $0.0036 \text{ mag day}^{-1}$. The decline rate is found to be larger at shorter wavelengths (e.g., decline rate for *g* band is $0.0061 \text{ mag day}^{-1}$). In Season 2, when observations were resumed, the decline rate in the optical bands increased, while a rebrightening was observed in the NIR. During this period, the optical decline rate remained approximately constant, being $0.013 \text{ mag day}^{-1}$ in the *r* band and $0.013 \text{ mag day}^{-1}$ in the *g* band. In contrast, the NIR evolution was different: the *J*-band light curve exhibited a nearly flat evolution followed by a slow decline, whereas the K_s -band light curve showed a rebrightening around $t \sim 300\text{--}400$ days before transitioning to a nearly flat evolution.

3.2. Light-curve Comparison

Figure 2 compares the *r*-band light curve of SN 2024dy with the optical (*r* and *o* bands) light curves of several well-observed, luminous, long-lived Type II_n SNe, selected based on the long timescales. The comparison sample includes SN 2010jl (C. Fransson et al. 2014), SN 2015da (L. Tartaglia et al. 2020), SN 2017hcc (S. Moran et al. 2023), SN 2021adxl (S. J. Brennan et al. 2024), and SN 2021irp (T. M. Reynolds et al. 2025). Although SN 2021irp is not formally classified as a Type II_n SN, we include it here primarily because its light-curve morphology resembles that of SN 2024dy, with additional similarities in its late-time observational properties (further details are discussed in Section 4.2).

The optical rise time of SN 2024dy (38.03 ± 0.17 days) is somewhat shorter than those reported for SN 2015da (100 ± 3 days in the *R* band; L. Tartaglia et al. 2020) and SN 2017hcc (57 ± 2 days in the *o* band; S. Moran et al. 2023). Nevertheless, within the broader population of Type II_n SNe studied statistically, SN 2024dy would be classified as a subgroup with relatively long rise timescales (see, e.g., A. Nyholm et al. 2020). For SN 2010jl, SN 2021adxl, and SN 2021irp, the rise to peak brightness was not sufficiently captured, and therefore their rise times are not tightly constrained (see R. Stoll et al. 2011; S. J. Brennan et al. 2024; T. M. Reynolds et al. 2025). In Figure 2, we adopt the explosion dates reported in the respective references for each object.

The comparison objects selected in this study are characterized by their luminosities and long-lived light-curve evolution. However, their peak luminosities and behavior near peak exhibit a large diversity. The peak absolute magnitude of SN 2024dy is $M_r = -19.2$ mag, which is roughly consistent with the median *r*-band peak magnitude estimated from recent statistical Type II_n samples (see D. Hiramatsu et al. 2026). SN 2024dy is among the faintest in the comparison sample considered here, comparable to SN 2021irp at peak.

The decline rates among the comparison objects show notable similarities. SN 2010jl exhibits values of $\sim 0.001\text{--}0.007 \text{ mag day}^{-1}$ between 100 and 250 days in *r* band, and comparable decline rates are also seen in SN 2015da (*r* band, 100–600 days) and SN 2017hcc (*r* band, 230–280 days). These values are consistent with the decline rate of SN 2024dy in Season 1 (*r* band, $0.0036 \text{ mag day}^{-1}$). All of these decline rates are smaller than the ^{56}Co decay rate under the assumption of full gamma-ray trapping, as also mentioned by T. Nagao et al. (2025). An interesting feature is the difference in decline rates after

¹⁷ <https://heasarc.gsfc.nasa.gov/docs/software/heasoft/>

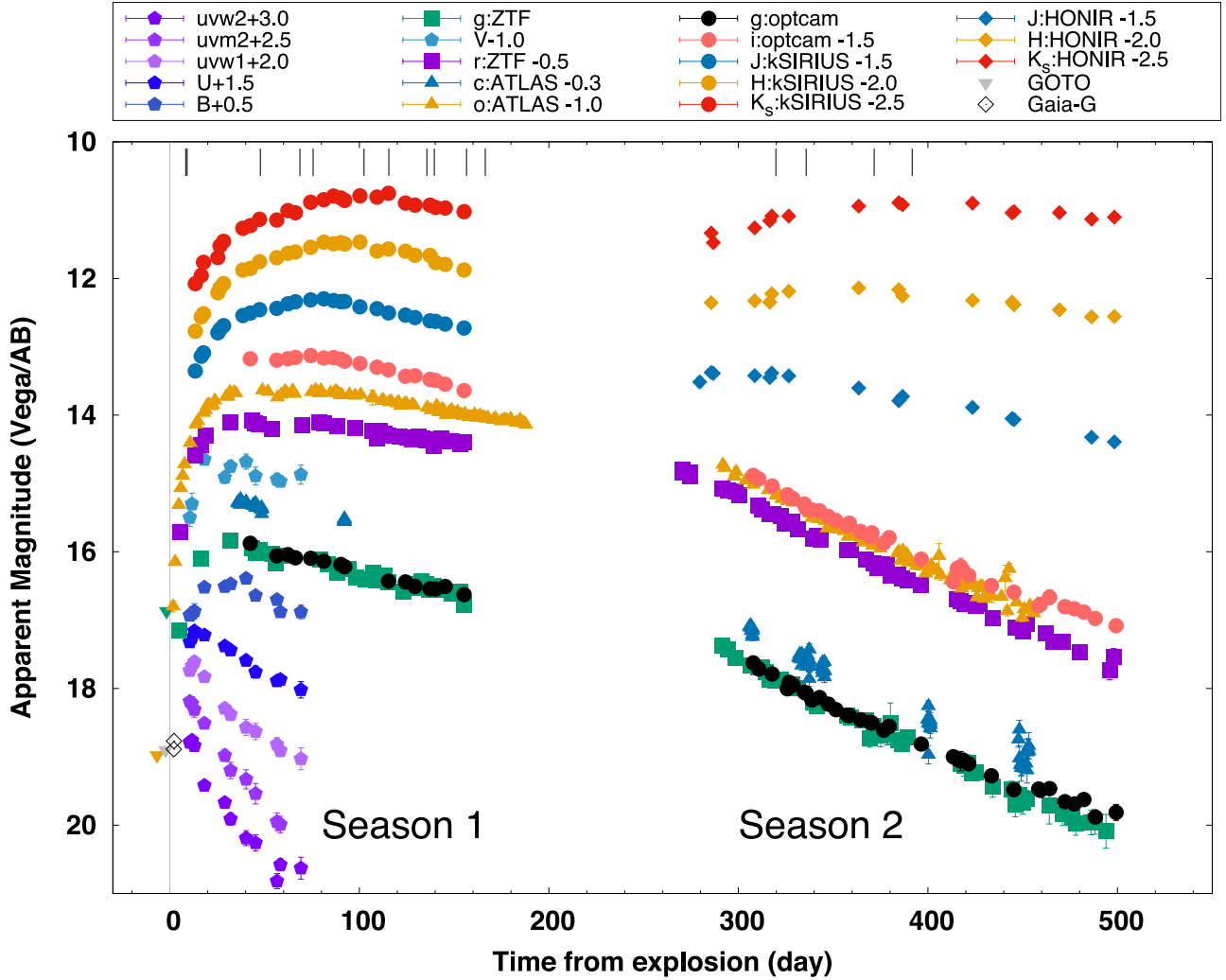


Figure 1. Multiband light curves of SN 2024dy. Each band is shifted in magnitude to distinguish them. The black lines at the top of this panel present the spectroscopic epoch. The gray line denotes the estimated explosion date (MJD 60309.2, defined in Section 2.1).

(The data used to create this figure are available in the [online article](#).)

~ 250 days. SN 2010jl, SN 2017hcc, and SN 2021adxl show an accelerated optical decline similar to that of SN 2024dy. In contrast, SN 2015da does not exhibit a clear acceleration during the same period, though the data coverage is relatively sparse. Among the objects showing accelerated declines, there is a diversity in the decline rates: SN 2021lrp shows the largest decline rate ($0.027 \text{ mag day}^{-1}$; T. M. Reynolds et al. 2025), whereas SN 2010jl shows the smallest ($0.0049 \text{ mag day}^{-1}$; C. Fransson et al. 2014).

3.3. Blackbody Fit and Pseudobolometric Luminosity

To investigate the NIR rebrightening observed in Season 2, we performed a two-component blackbody (BB) fit to the SED. Figure 3 shows examples of the BB fitting: a single-BB model for a Season 1 SED and a two-BB model for a Season 2 SED. The two-BB model is used as a phenomenological description to estimate the temperatures and BB radii of the optical and NIR components. The fit reveals a clear IR excess in Season 2, indicating the presence of a low-temperature component with $T \lesssim 3000 \text{ K}$. The results of the two-component BB fit are presented in Figure 4.

In Season 1, the SED was well reproduced by a single hot BB component with a temperature exceeding $10,000 \text{ K}$ at early times. The temperature decreased from $\sim 11,000$ to $< 6000 \text{ K}$ within the first ~ 100 days after the explosion. The inferred BB radius increased from $\sim 2.2 \times 10^{15}$ to $\sim 6.9 \times 10^{15} \text{ cm}$ in this period. Subsequently, the temperature became nearly constant, and the radius gradually decreased.

In Season 2, the observed SEDs were well reproduced by a two-component model consisting of a hot component dominating the optical emission ($\sim 8000 \text{ K}$) and a cool component dominating the NIR emission ($< 3000 \text{ K}$). The apparent increase in the temperature of the hot component between Seasons 1 and 2 should be interpreted with caution because the optical SEDs in Season 2 are constrained by fewer bands, resulting in relatively large uncertainties. A similar increase in the hot-component temperature was reported for SN 2010jl by C. Fransson et al. (2014), but its physical origin is not uniquely constrained by the present data. The temperature of the cool component decreased from approximately 3000 to 1800 K , while the radius increased from $\sim 1.1 \times 10^{16}$ to $\sim 3.1 \times 10^{16} \text{ cm}$. The origin of this cool component would be newly formed dust; more detail will be discussed in Section 5.4.1.

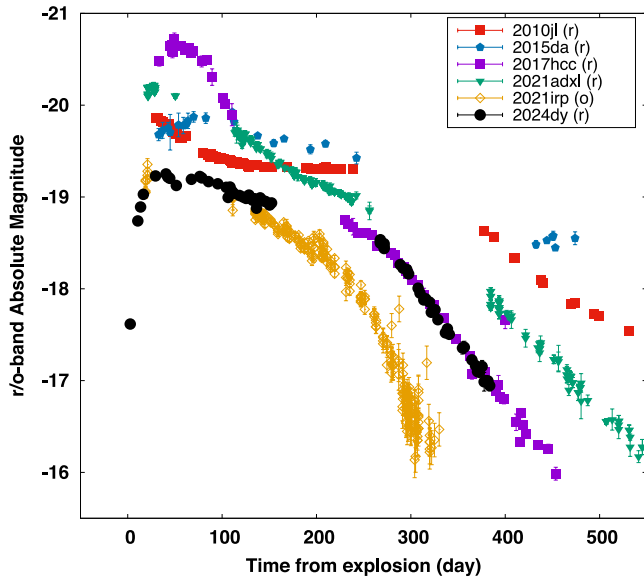


Figure 2. Comparison of the absolute-magnitude light curve of SN 2024dy with those of several long-lived Type II SNe: SN 2010jl (C. Fransson et al. 2014), SN 2015da (L. Tartaglia et al. 2020), SN 2017hcc (S. Moran et al. 2023), SN 2021adxl (S. J. Brennan et al. 2024), and SN 2021irp (o band; T. M. Reynolds et al. 2025). The explosion epochs and extinction corrections are adopted from the respective references.

We also derived the pseudobolometric luminosity by integrating the SEDs over wavelength using the trapezoidal assumption. To ensure consistency across all epochs, the pseudobolometric luminosity was constructed using only the bands with coverage from early to late phases. The resulting pseudobolometric light curve is shown in Figure 5 (black points). At early epochs where *i*-band data are unavailable, the pseudobolometric luminosities at these epochs are shown in gray. Because UV observations were obtained only at early phases, the UV–optical–NIR pseudobolometric light curve is shown only for the early epochs (purple). For comparison, we also plot the optical luminosity (blue points), obtained by integrating the flux in the *gri* bands, and the NIR luminosity (red points), obtained from the *JHK_s* bands. The lower panel of Figure 5 shows the temporal evolution of the optical and NIR fractions of the bolometric luminosity.

During Season 1, the UV–optical luminosity dominates and accounts for the majority of the total radiated energy. The peak luminosity of the UV–optical–NIR pseudobolometric light curve is estimated to be $\sim 1.6 \times 10^{43} \text{ erg s}^{-1}$ and the optical–NIR pseudobolometric light curve reaches a peak luminosity of $9.5 \times 10^{42} \text{ erg s}^{-1}$. The total radiated energy in the optical–NIR range inferred from the pseudobolometric light curve up to the end of Season 2 is estimated to be $1.9 \times 10^{50} \text{ erg}$.

From Season 2, the optical luminosity exhibits a rapid decline, whereas the NIR luminosity evolves more steadily. As a result, the relative contributions of the optical and NIR emission become reversed. The NIR fraction reaches $\sim 60\%$ at ~ 400 days after the explosion and increases to $\sim 80\%$ around 500 days (shown in lower panel of Figure 5).

4. Spectroscopic Properties

4.1. Spectroscopic Evolution

Figure 6 shows all the spectra of SN 2024dy we obtained. Two spectra obtained by other groups soon after the discovery

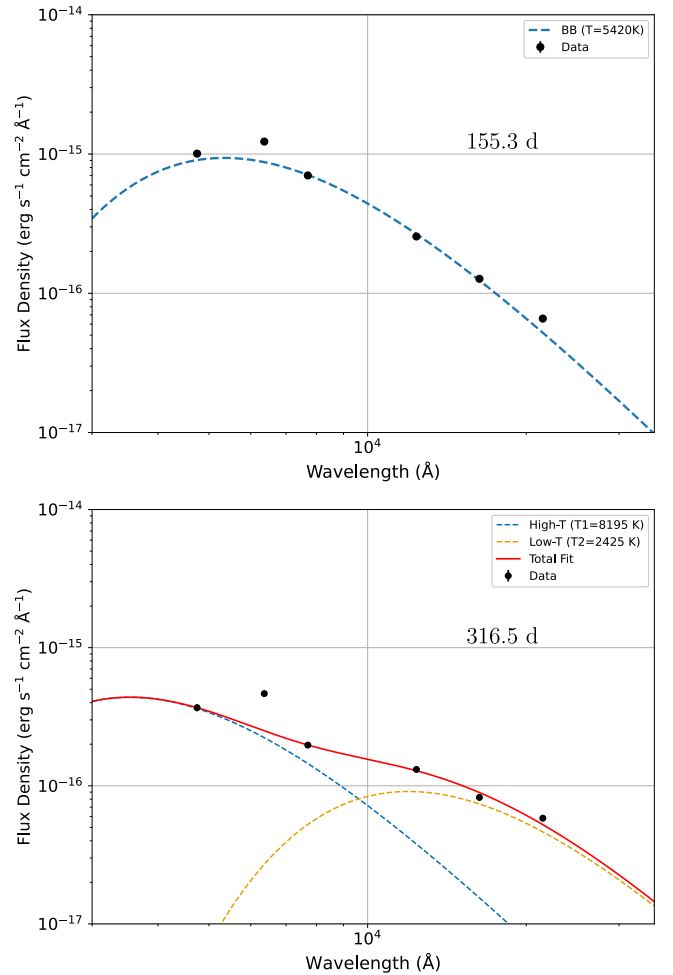


Figure 3. Examples of the SED fitting with BB models. The upper panel shows a single-BB fit to a Season 1 (155.3 days) SED, and the lower panel shows a two-BB fit to a Season 2 (316.5 days) SED. The observed SEDs are shown with filled circles. In the lower panel, the dashed lines represent the hot and cool BB components, and the red solid line shows their sum. The cool BB component accounts for the NIR excess observed in Season 2.

(available on TNS) are also shown at the top of Figure 6 (8 and 9 days). Several late-time spectra have been smoothed for clarity.

As in typical Type II SNe observed, the early spectra of SN 2024dy are characterized by a blue continuum together with prominent narrow (+intermediate) Balmer emission lines ($H\alpha$ $\lambda 6563$, $H\beta$ $\lambda 4861$, $H\gamma$ $\lambda 4340$, $H\delta$ $\lambda 4101$, and $H\epsilon$ $\lambda 3970$). Narrow He I $\lambda\lambda 5875$, 7065 and He II $\lambda 4685$ emission lines are also present shortly after the discovery. Around the He II $\lambda 4686$ line, a somewhat broad emission component is detected only in the earliest spectrum. This feature is likely to be C III $\lambda\lambda 4647$, 4650 and/or N III $\lambda\lambda 4634$, 4642 lines that are observed in very early spectra of Type II SNe (see, e.g., D. Khazov et al. 2016; O. Yaron et al. 2017). Unfortunately, there is a temporal gap between the first two spectra and the third spectrum. The third spectrum (47 days after the explosion) shows a very blue continuum. The He emission lines disappear and only the Balmer-series lines remain. In the spectra obtained after 102 days, a shallow absorption feature appears on the blue side of He I $\lambda 5876$. Also, the $H\alpha$ profile evolves from the early narrow and intermediate components into a profile that includes a broad emission component. The evolution of the $H\alpha$ profile is discussed in Section 4.3.

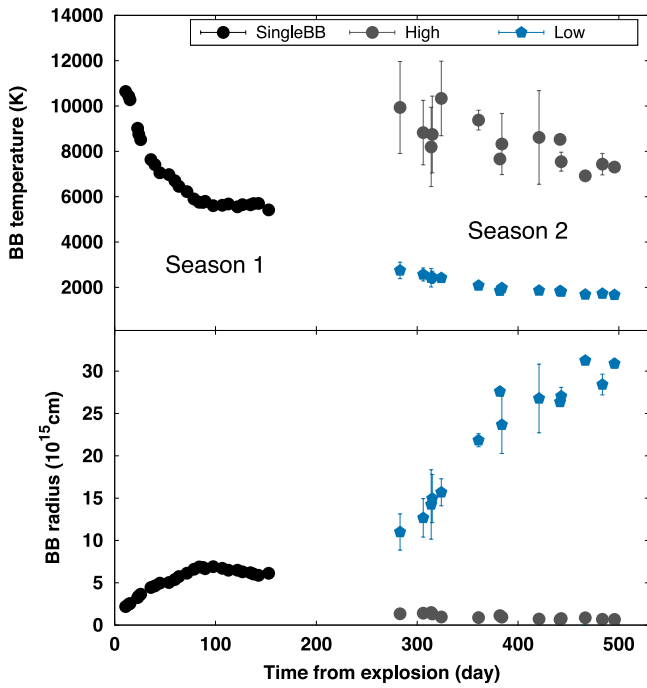


Figure 4. Temporal evolution of the temperature (top) and radius (bottom) obtained from the BB fits. Black, gray, and blue points represent the single-component, hot-component, and cool-component fits, respectively.

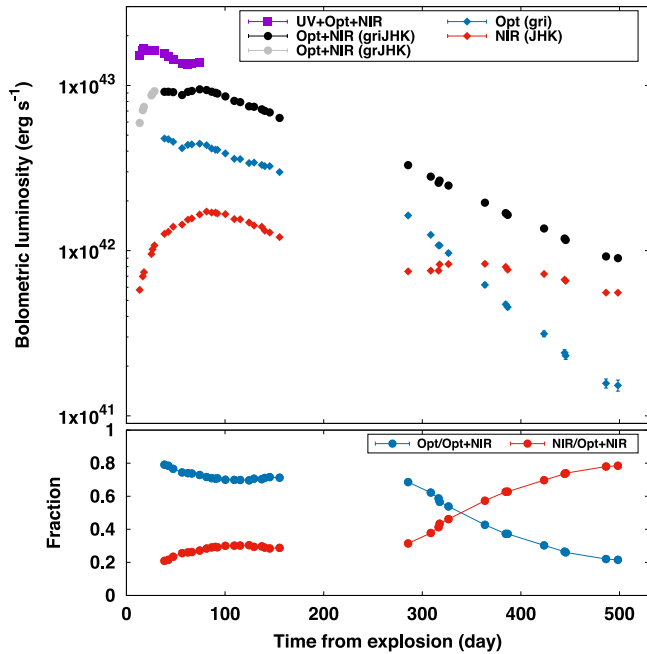


Figure 5. Upper panel: pseudobolometric light curve derived from the optical-NIR SEDs (black) and from the UV-optical-NIR SEDs (purple). The optical and NIR luminosities are also shown (blue and red, respectively). Epochs at early phases for which *i*-band data are unavailable are shown in gray. Lower panel: temporal evolution of the optical (*gri*) and NIR (*JHK_s*) contributions to the bolometric luminosity (*grJHK_s*).

(The data used to create this figure are available in the [online article](#).)

In Season 2 (>270 days), four spectra were obtained. Some of the spectra have low signal-to-noise ratio (S/N), and smoothing has been applied to improve their visibility. Except for the 335 days spectrum, the data are noisy, making it difficult to clearly identify features other than $H\alpha$ and $H\beta$.

Nevertheless, all spectra show a broad component in $H\alpha$, accompanied by an eroded red wing. In the highest-quality spectrum at 335 days obtained with the HCT, a shallow and extended absorption feature on the blue side of $He\ I\ \lambda 5875$ can be seen in addition to $H\alpha$ and $H\beta$. We also detect broad emission lines around $8500\ \text{\AA}$, which appear to correspond to the $Ca\ II\ NIR$ triplet ($\lambda\lambda 8498, 8542, 8662$).

4.2. Spectroscopic Comparison

In Figure 7, we compare representative spectra of SN 2024dy at different evolutionary phases with those of other long-lived Type II_n SNe. The comparison spectra were obtained from WISeREP, and the adopted redshift values follow those reported in the respective references given in the caption.

In the early phase (<50 days), SN 2024dy shows a significant similarity to SN 2010jl. The $H\alpha$ emission-line profiles in both objects are nearly identical, and both display wings that resemble symmetric Lorentzian. In addition to the $H\alpha$, narrow $He\ I$ and $He\ II$ emission lines were also observed. Apart from the Balmer series, no prominent additional spectral features are detected at this stage.

During the intermediate phase (50–170 days), more spectral features of SN 2024dy start to develop. As shown in Figure 7, SN 2024dy, SN 2010jl, and SN 2015da all develop asymmetric $H\alpha$ profiles, in contrast to the more symmetric shapes in the earlier phase. In this phase, the red side of the profile becomes increasingly suppressed, while the blue side remains extended. By contrast, SN 2017hcc shows a symmetric Lorentzian-like $H\alpha$ profile even at comparable epochs, highlighting the diversity of line-profile evolution among long-lived Type II_n SNe.

In the late phase (>300 days), the $H\alpha$ profile of SN 2024dy evolves further showing a close resemblance to that of SN 2021irp. Similarities are also found with the late-time spectral evolution of SN 2021acya, as discussed by I. Salmaso et al. (2025), particularly in the pronounced asymmetry of the Balmer-line profiles. A common property shared by SN 2024dy and all comparison objects is the persistent absence of nebular emission features typically observed in late-time spectra of ordinary Type II SNe (such as the $[O\ I]\ \lambda\lambda 6300, 6364$ doublet) even at later epochs.

4.3. Line-profile Evolution

One of the most notable features of SN 2024dy is the evolution of its $H\alpha$ profile. Figure 8 shows the expanded $H\alpha$ profiles, and Figure 9 presents the results of multicomponent Gaussian or Lorentzian fits for the spectra at several epochs. The fitting results for all the epochs are summarized in Table 3.

Figure 10 shows the temporal evolution of the $H\alpha$ and $H\beta$ luminosities, as well as the $H\alpha/H\beta$ ratio. The bottom panel indicates the expected Case B hydrogen recombination value ($H\alpha/H\beta \approx 3$; D. E. Osterbrock & G. J. Ferland 2006) with a black dashed line. During Season 1, the ratio remains close to ~ 3 , whereas in Season 2 it increases to significantly higher values.

The evolution of the $H\alpha$ line can be divided into three distinct phases. In the early phase (8–47 days), the profile consists of a combination of narrow Gaussian and intermediate-width Lorentzian. Such emission-line profiles are commonly observed in the early spectra of Type II_n SNe (e.g.,

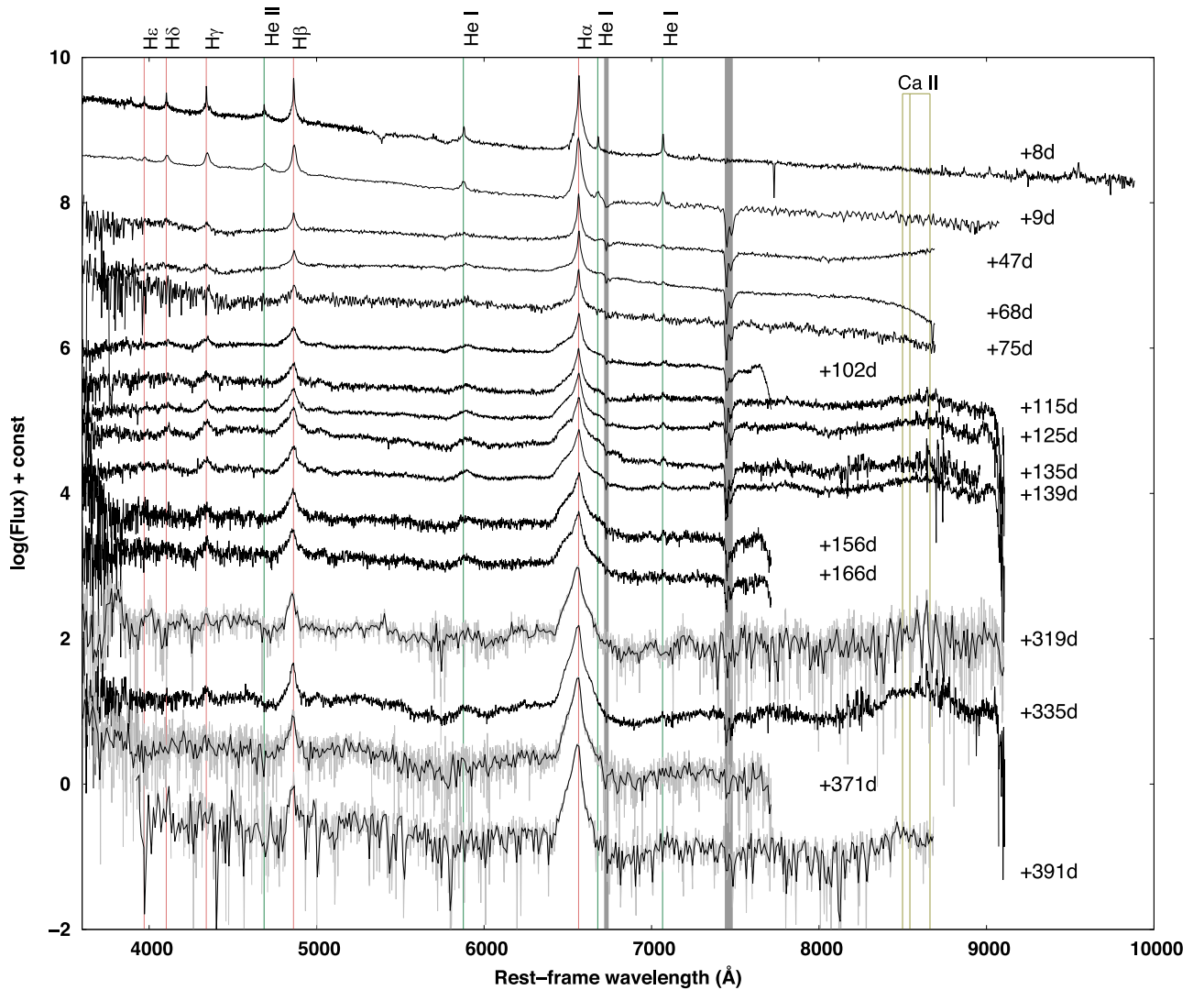


Figure 6. The spectra of SN 2024dy. The first two (upper side) spectra were published on TNS. The numbers indicate the days since the estimated explosion date. Several spectra obtained during Season 2 have been smoothed for clarity. The gray lines around 6800 and 7500 Å indicate the telluric absorption features, which are corrected in some spectra.

SN 2010jl; C. Fransson et al. 2014). The intermediate-width component shows a symmetric profile, with a Lorentzian FWHM of 1500–1800 km s⁻¹.

The narrow component has an FWHM of ~ 300 km s⁻¹ in the first spectrum, which has the highest spectral resolution among our spectra. The FWHM of the narrow Gaussian component measured in the 8 days spectrum is ~ 300 km s⁻¹. However, the spectral resolution of the Lick/Kast spectrum is estimated to be ~ 390 km s⁻¹ around H α . Therefore, this narrow component is not spectrally resolved, and the measured width should be regarded as an upper limit on the velocity of the unshocked CSM. The larger values measured at 9 and 47 days are also likely affected, or dominated, by the instrumental resolution at those epochs.

The second phase corresponds to the period from the peak to the end of Season 1 (68–166 days). During this phase, the intermediate-width component is better reproduced by a Gaussian profile, and a blueshifted broad component begins to emerge. The FWHM of this broad component is 7000–8000 km s⁻¹ and shows little evolution through the end of Season 1. The peak of the broad component also remains nearly constant at ~ -1000 km s⁻¹.

In the late phase from Season 2 onward, the H α profiles consistently exhibit a well-developed broad component and show a characteristic asymmetry caused by the suppression of the red wing. This line asymmetry becomes more apparent when comparing the blue and red sides of the profile, as shown in Figure 11, where the blue side has been reflected across the rest wavelength. In the 335 days spectrum, which has the highest S/N in Season 2, a similar shape may be present in the H β profile.

5. Discussion

5.1. Energy Source

The Season 1 spectra of SN 2024dy are dominated by narrow hydrogen emission lines, indicating interaction between the H-rich CSM and the SN ejecta (see Section 4). The light curves exhibit a relatively slow rise (~ 38 days), which is also consistent with interaction with a dense CSM. The timescale can be explained by the photon diffusion timescale through an optically thick CSM. In addition, the observed timescales and peak luminosity clearly place SN 2024dy within the subclass of long-lived Type II_n SNe.

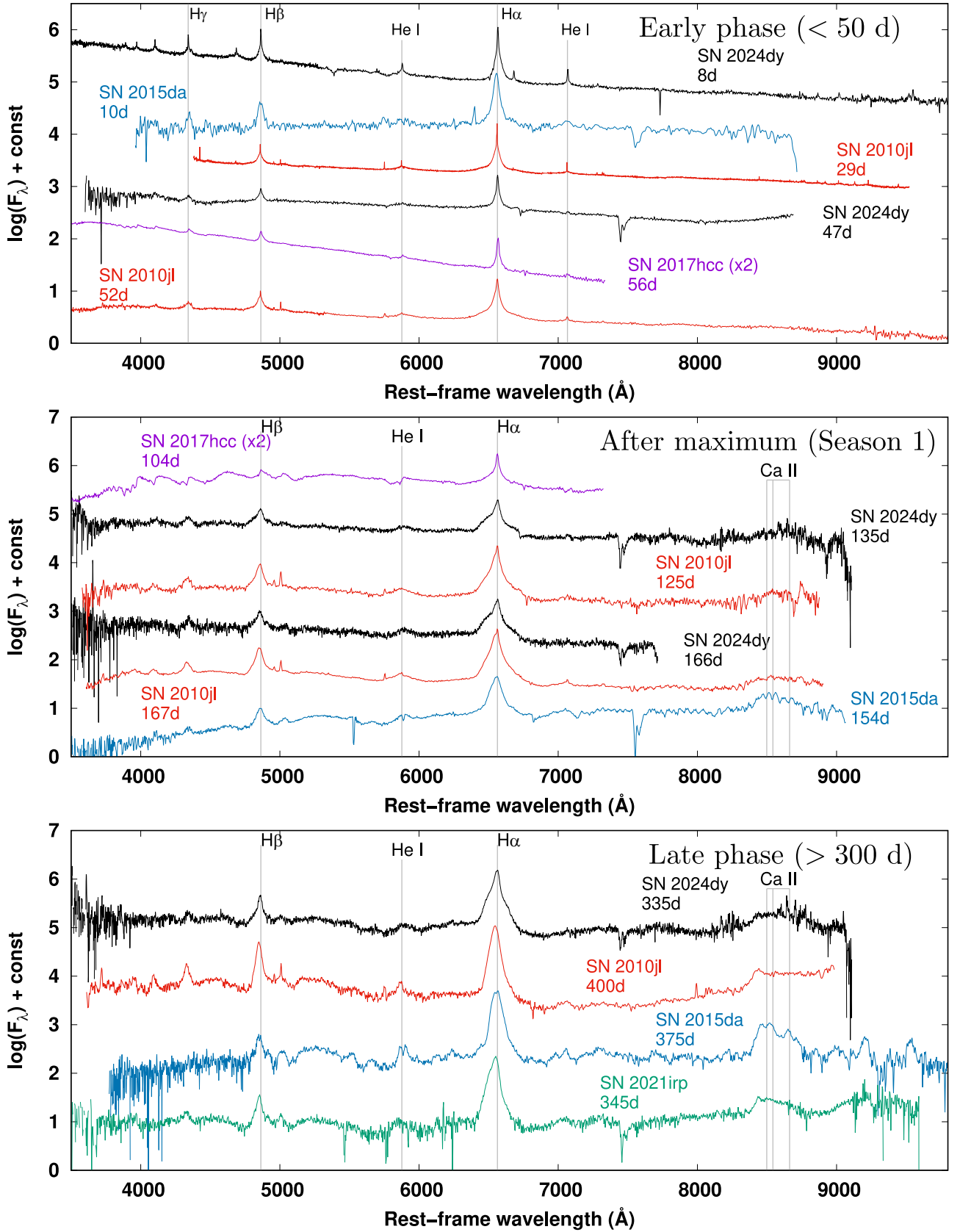


Figure 7. Comparison between the spectra of SN 2024dy and those of other long-lived Type IIc SNe. Top panel: early phase (<50 days). Middle panel: postpeak phase (50 days to the end of Season 1). Bottom panel: late phase (>300 days). The redshifts for SN 2010jl, SN 2015da, SN 2017hcc, and SN 2021irp were adopted from the literature cited below: C. Fransson et al. (2014), L. Tartaglia et al. (2020), S. Moran et al. (2023), and T. M. Reynolds et al. (2025). For visual clarity, the spectrum of SN 2017hcc was plotted as $2\log(F) + \text{const}$ and is labeled as “SN 2017hcc (x2).”

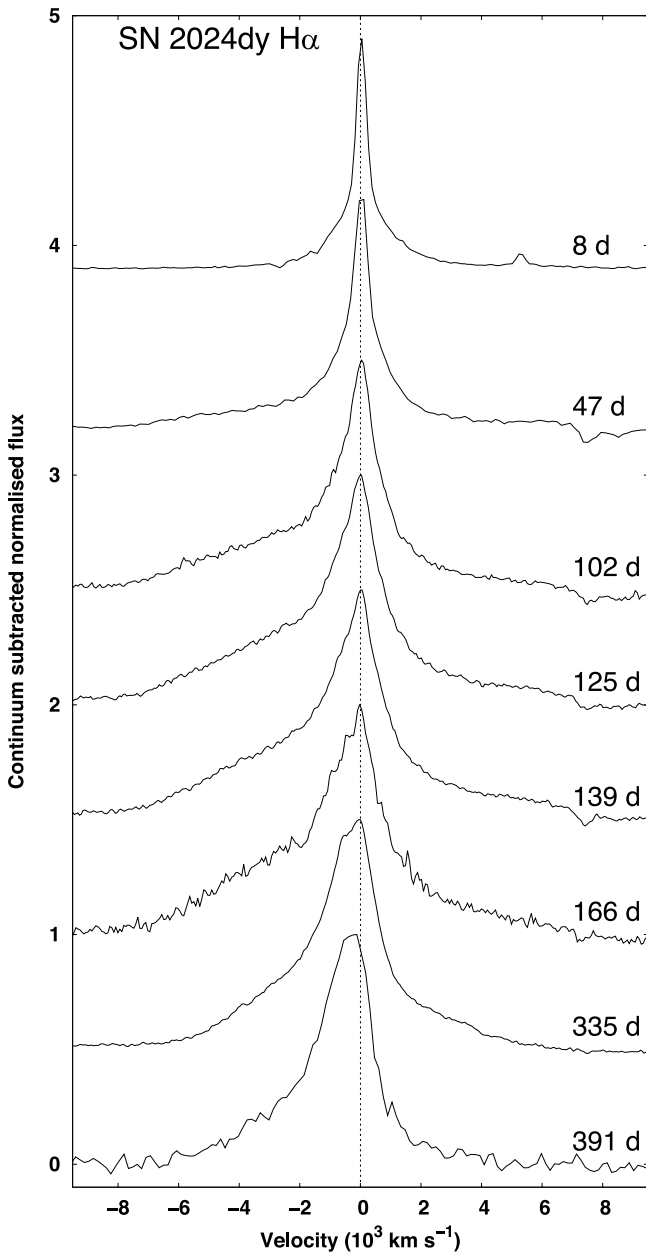


Figure 8. Evolution of the H α emission line. The continuum has been subtracted, and each profile is normalized to the peak of the narrow component.

Assuming that luminosity of the ejecta–CSM interaction is fed by energy at the shock front, the progenitor’s mass-loss rate can be estimated using the relation given by N. N. Chugai & I. J. Danziger (1994):

$$\dot{M} = \frac{2L}{\epsilon} \frac{v_w}{v_{\text{SN}}^3}. \quad (2)$$

Here, $\dot{M}$ denotes the mass-loss rate of the progenitor star, and ϵ represents the efficiency with which the kinetic energy of the shock is converted into radiative energy. Following previous studies, we adopt a value of $\epsilon = 0.3$ in this work (e.g., T. J. Moriya et al. 2013). For the wind velocity of the CSM v_w , we adopt a steady wind velocity typical of luminous blue variables, $v_w \sim 100 \text{ km s}^{-1}$ (N. Smith 2017). For the velocity of the SN ejecta v_{SN} , we adopt an expansion velocity of

$v_{\text{SN}} = 7700 \text{ km s}^{-1}$ inferred from the temporal evolution of the BB radius. The peak luminosity is estimated to be $1.6 \times 10^{43} \text{ erg s}^{-1}$ from the pseudobolometric light curve obtained by integrating the SED from the UV, optical (g , r , and i) and NIR (J , H , and K_s ; see Section 3.3).

From these values, the mass-loss rate is estimated to be $0.037 M_{\odot} \text{ yr}^{-1}$. This value is consistent in order of magnitude with the mass-loss rates inferred for other Type IIn SNe (10^{-3} – $10^{-1} M_{\odot} \text{ yr}^{-1}$ for some interacting SNe; I. Salmaso et al. 2025). Although this value represents a lower limit, the mass-loss rate estimated for SN 2024dy is relatively small compared to those of the comparison objects. For SN 2010jl, a mass-loss rate of $\gtrsim 0.1 M_{\odot} \text{ yr}^{-1}$ has been inferred (C. Fransson et al. 2014), which is an order of magnitude higher than our estimate for SN 2024dy. Similarly, a mass-loss rate for SN 2015da is estimated to be 0.6 – $0.7 M_{\odot} \text{ yr}^{-1}$ (L. Tartaglia et al. 2020), and that for SN 2017hcc is $0.12 M_{\odot} \text{ yr}^{-1}$ (B. Kumar et al. 2019), both of which are substantially larger than that of SN 2024dy. Since the luminosity produced by CSM interaction is approximately given by Equation (2) (e.g., T. J. Moriya et al. 2013), it is natural that, for SN 2024dy, whose peak radiated energy is lower by an order of magnitude, a relatively modest mass-loss rate of $\dot{M} \sim 10^{-2} M_{\odot} \text{ yr}^{-1}$ is inferred. Nevertheless, this value still falls within the regime of a dense CSM.

It should be noted that the mass-loss rate derived above is subject to uncertainty, particularly due to assumptions about the geometry of the CSM. Luminous Type IIn events such as SN 2015da (L. Tartaglia et al. 2020; N. Smith et al. 2024) require very high mass-loss rates, corresponding to several solar masses of CSM when interpreted under the assumption of spherical symmetry. However, SN 2015da also shows evidence for pronounced asymmetry (N. Smith et al. 2024), indicating that the true geometry of the CSM remains poorly constrained. In this context, SN 2024dy exhibits a shorter rise time than SN 2015da, which may reflect differences in the line-of-sight distribution of the CSM. Nevertheless, the present observations do not provide meaningful constraints on the degree of CSM asymmetry for either event. We therefore assume a spherically symmetric CSM distribution for simplicity.

An evaluation of the energy budget indicates that SN 2024dy radiated a total energy of $\sim 2 \times 10^{50} \text{ erg}$. This value is of the same order of magnitude as the total radiated energy of $5.8 \times 10^{50} \text{ erg}$ estimated for SN 2010jl (C. Fransson et al. 2014). The total radiated energy from CSM interaction correlates with the total mass of the CSM swept up by the shock (T. J. Moriya et al. 2013). Therefore, if the luminosity is indeed dominated by CSM interaction, a comparable total radiated energy suggests a similar CSM mass. In this context, the combination of a comparable total radiated energy and a lower peak luminosity in SN 2024dy favors a scenario of “moderate interaction,” in which the CSM has a lower density but is distributed over a more spatially extended structure, resulting in a total CSM mass consistent with that inferred for SN 2010jl (several solar masses).

5.2. Origin of the Line-profile Evolution

In Type IIn SNe and other strongly interacting SNe, many studies have reported that emission-line profiles evolve toward systematically blueshifted and asymmetric shapes. In many cases, the early time line profiles are nearly symmetric and

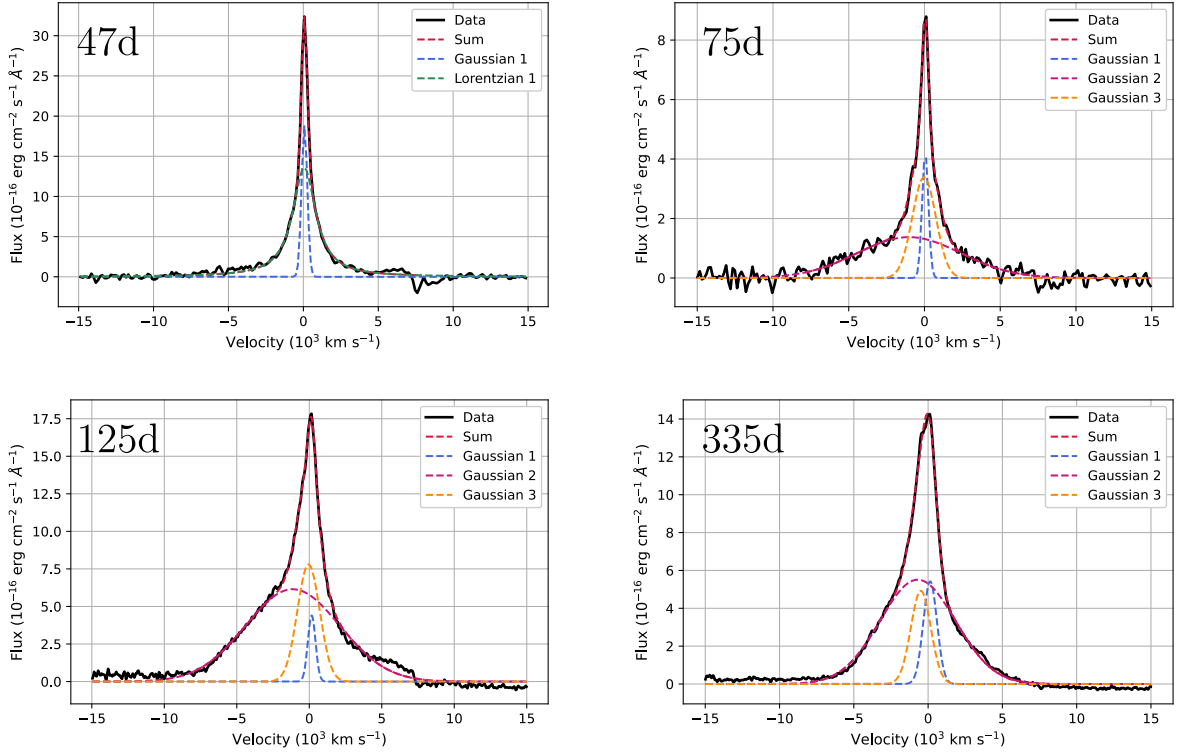


Figure 9. Fits to the $H\alpha$ line profiles at 47, 75, 135, and 335 days. The 47 days profile is modeled with a combination of a Gaussian and a Lorentzian component, while the later epochs are fitted using multiple Gaussian components.

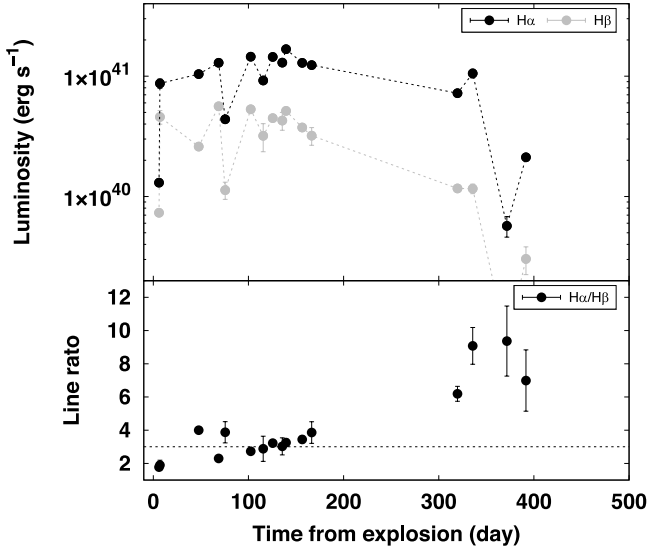


Figure 10. Upper: evolution of the $H\alpha$ (black) and $H\beta$ (gray) line luminosities. Lower: temporal evolution of the $H\alpha/H\beta$ flux ratio. The expected Case B recombination value ($H\alpha/H\beta \approx 3$) is indicated by the dashed line.

characterized by Lorentzian wings produced by electron scattering. Pronounced blueshifts develop at later epochs, particularly in the intermediate-width component originating from postshock CDS (e.g., SN 2010jl and SN 2015da; N. Smith et al. 2012, 2024; L. Tartaglia et al. 2020). Such line-profile asymmetries do not necessarily reflect intrinsic geometric asymmetries in the CSM, but may instead arise from selective suppression of emission from the receding side. Two main mechanisms are often invoked to explain this behavior (although they are not mutually exclusive). One is geometric

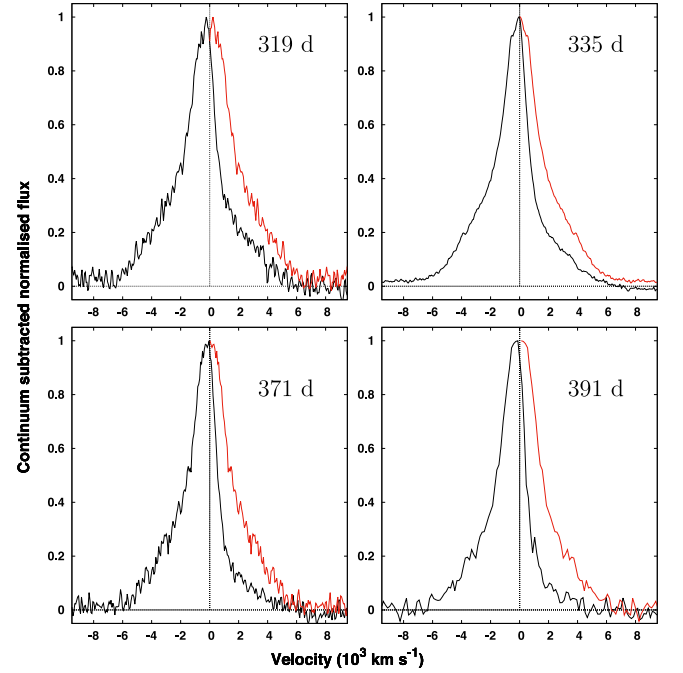


Figure 11. $H\alpha$ profiles in Season 2, with the blue side reflected onto the red side across the rest wavelength. The reflected profiles are shown in red, and the rest wavelength is indicated by a black dashed line.

obscuration, in which the visibility of the emitting regions depends on the viewing angle, and the interaction region and/or the unshocked CSM is optically thick. The other is obscuration by newly formed dust within the SN ejecta or the CDS, which selectively absorbs the redshifted emission. The latter dust-formation scenario is strongly supported by its association with independent observational signatures, such as

a rapid decline in optical luminosity and the emergence of an IR excess, as exemplified by events such as SN 2006jc (e.g., S. Mattila et al. 2008).

The line-profile asymmetry observed in SN 2024dy during the phase after its peak (68–166 days, as shown in Figures 8 and 9) is not consistent with the canonical signatures of dust formation. During this epoch, the blue side of the $H\alpha$ emission-line profile extends to velocities of up to $\sim 8000 \text{ km s}^{-1}$, whereas the red side is clearly more limited in velocity extent. However, neither accelerated optical fading nor the accompanying NIR excess is observed. The absence of these observational signatures suggests that dust is not the dominant cause of the line profile at this phase.

Assuming that the $H\alpha$ -emitting region is distributed in a shell-like structure and that an optically thick region (e.g., the interaction region or dense CSM) exists interior to it, the asymmetric line profile observed in SN 2024dy at this phase can be naturally explained. In this scenario, emission from the near side of the shell is observed with little attenuation, whereas emission from the far side is obscured by the optically thick interior region, resulting in a systematic suppression of the redshifted (receding) component. Consequently, an asymmetric profile characterized by a selective deficit on the red side is produced.

In contrast, the blueshifted Lorentzian profile formed via electron scattering in a radiatively accelerated CSM, as discussed for SN 2010jl (C. Fransson et al. 2014), produces a largely symmetric broadening with a shifted peak. Such a profile cannot account for the one-sided suppression of the red wing observed in SN 2024dy. Consistently, the observed line profile is better reproduced by a Gaussian component than by an intermediate-width Lorentzian (see Section 4.3). Therefore, the line asymmetry in this object is more plausibly attributed to geometrical obscuration by optically thick material rather than to a blueshift caused by radiative acceleration.

In Season 2, the asymmetric line profile is likely caused by dust absorption. The NIR excess detected in SN 2024dy emerges at the beginning of Season 2, coincident with the epoch at which the asymmetry in the $H\alpha$ profile becomes pronounced. The temporal correspondence between these phenomena strongly suggests that the $H\alpha$ profile in Season 2 results from the selective obscuration of the receding emission by newly formed dust. We therefore here examine whether the observed line profile can be explained by dust absorption, and defer further discussion of the dust origin and mass to Sections 5.3 and 5.4.

Figure 11 presents an enlarged view of the $H\alpha$ line profiles observed during Season 2, in which the blue side of the profile relative to the rest wavelength is reflected and overplotted onto the red side (red line). The asymmetry at this phase is characterized by an apparent attenuation affecting only the red side of the profile, with little suppression near the rest wavelength with no pronounced blueshift of the line peak. Using the reflected blue side profile as a reference, we estimated the fraction of flux lost on the red side. Specifically, for the red-side profile shown in Figure 11, we integrated the flux over the velocity range of $0\text{--}5000 \text{ km s}^{-1}$ and computed the ratio relative to the corresponding integrated flux on the blue side. For the final spectrum obtained at 391 days, we find that the integrated flux on the red side is approximately 50% of that on the blue side. This ratio remains nearly

constant throughout Season 2, showing no significant temporal evolution at all epochs in Season 2.

5.3. Dust as the Origin of Infrared Excess

An IR excess observed from the NIR to MIR is one of the characteristic features of Type II_n SNe. Two primary origins have been widely discussed: (1) heating of preexisting circumstellar (CS) dust by the SN radiation (IR echo), and (2) newly formed dust that condenses in the SN environment after explosion. If the dust is newly formed, it would condense either within the SN ejecta (e.g., T. Kozasa et al. 1989; D. H. Wooden et al. 1993) or in the CDS in postshock gas lying in between the forward and reverse shocks (e.g., A. Sarangi & J. D. Slavin 2022; N. Smith et al. 2024). From a large Spitzer Space Telescope sample of Type II_n SNe, O. D. Fox et al. (2011) found that many objects exhibit a late-time IR excess, which is interpreted as emission from preexisting CS dust heated by the SN. In contrast, for long-lived Type II_n events such as SN 2010jl, SN 2005ip, and SN 2015da, dust formation in the CDS on timescales of several hundred days after explosion has been suggested, producing significant observational signatures including enhanced IR emission and asymmetric emission-line profiles (e.g., C. Gall et al. 2014; A. Sarangi et al. 2018; N. Smith et al. 2024). In the following section, we discuss the origin of the IR excess observed in SN 2024dy from two perspectives: an IR echo and dust formation.

5.3.1. Infrared Echo

First, we discuss whether the IR excess observed during Season 2 in SN 2024dy can be attributed to an IR echo. The BB radius of the cool component estimated in Section 3.3 is $\sim 10^{16} \text{ cm}$ and shows a gradual increase over time. This radius should be regarded as a lower limit on the emitting radius. If this component originates from preexisting circumstellar dust present at the time of explosion, it must correspond to dust that survived sublimation by the SN radiation. The dust sublimation radius can be estimated by following O. D. Fox et al. (2011):

$$r_{\text{evap}} = \left(\frac{L_{\text{peak}}}{16\pi\sigma T_{\text{evap}}^4 \langle Q \rangle} \right)^{1/2}. \quad (3)$$

Here, T_{evap} is the dust sublimation temperature and $\langle Q \rangle$ is the Planck-averaged absorption coefficient of the dust. In this case, assuming a dust sublimation temperature of $\sim 1900 \text{ K}$ for carbon dust and a peak SN luminosity of $\sim 10^{43} \text{ erg s}^{-1}$, the dust sublimation radius is estimated to be $r_{\text{evap}} \sim 1.5 \times 10^{17} \text{ cm}$.

The dust sublimation radius, $r_{\text{evap}} \sim 1.5 \times 10^{17} \text{ cm}$, corresponds to a light-travel time of ~ 58 days. Therefore, if the NIR excess were produced by an IR echo from preexisting dust located near this radius, the emission could in principle begin at relatively early phases. Interpreting the onset of the NIR excess at ~ 300 days as an IR echo would naively suggest a characteristic dust-shell radius of $R \sim ct \sim 7.8 \times 10^{17} \text{ cm}$. However, a detached CSM dust distribution with $R \gg r_{\text{evap}}$ is not itself implausible, since preexisting dust may reside in a shell or cavity formed by previous mass loss. In addition, the onset of an echo from the near side of a CSM shell can occur earlier than the full light-crossing time of $2R/c$. Thus, these geometrical considerations alone do not rule out an IR-echo

scenario. The main difficulty with this interpretation is that the onset of the NIR excess coincides with the accelerated optical fading and the red-wing attenuation of $H\alpha$, both of which are more naturally associated with newly formed dust. We therefore disfavor an IR-echo scenario from preexisting dust as the dominant origin of the observed NIR excess.

5.3.2. Dust Formation

We now consider a scenario in which the observed IR excess originates from newly formed dust. As summarized in Sections 3 and 4, SN 2024dy exhibits several key observational signatures: (i) an accelerated decline in the optical luminosity (Figures 1 and 5), (ii) a rise in the NIR luminosity accompanied by a clear NIR excess (Figure 4), and (iii) a suppression of the red wing in line profiles, most prominently in $H\alpha$ (Figures 8 and 11). These features become particularly pronounced during Season 2, and all of them can be naturally explained by the formation of newly formed dust (N. Smith et al. 2012).

The increase in the optical decline rate from Season 1 to Season 2 suggests the emergence of additional obscuration along the line of sight. This is consistent with attenuation by newly formed dust. In this scenario, the absorbed optical radiation is reemitted in the IR, which naturally explains the rise in the NIR luminosity. The suppression of the red wing in the $H\alpha$ profile provides further evidence of dust formation, as similar evolution has been reported in other long-lived Type II_n SNe (e.g., N. N. Chugai 2018; N. Smith et al. 2024; T. M. Reynolds et al. 2025).

Although T. M. Reynolds et al. (2025) discuss the possibility that red-wing attenuation may result from occultation by an optically thick photosphere, this explanation appears unlikely for SN 2024dy in Season 2. If photospheric occultation were responsible, the attenuation would be expected to weaken as the photosphere recedes. However, the $H\alpha$ profiles in Figure 10 show no clear temporal decrease in the suppression, favoring dust formation as the dominant origin of the Season 2 asymmetry.

Furthermore, as shown in the lower panel of Figure 9, the higher $H\alpha/H\beta$ ratio during Season 2 is also consistent with wavelength-dependent attenuation expected from dust absorption. Although the Balmer decrement can be influenced by several other physical processes, such as high optical depth, collisional excitation, or deviations from Case B recombination, this trend provides additional support for the dust-formation scenario.

When these observational characteristics are considered together, they strongly support the presence of newly formed dust in SN 2024dy.

The suppression of the red wing of the late-time $H\alpha$ profile indicates selective attenuation of the receding side emission along the line of sight, which is a well-known observational signature associated with dust formation. Previous studies have interpreted red-wing suppression differently depending on the location of dust formation. For example, N. N. Chugai (2018) compared radiative transfer models with the $H\alpha$ profile of SN 2010jl and argued that dust confined solely to the CDS could not reproduce the observed asymmetry. In contrast, N. Smith et al. (2024) found in SN 2015da that the broad component remains largely symmetric, while only the intermediate-width component becomes asymmetric; together with a flux deficit near zero velocity, this favored the CDS as

the dust-formation site. Consistent with this view, numerical calculations by L. Dessart et al. (2025) demonstrate that CDS dust can produce similar line-profile asymmetries.

The $H\alpha$ profile of SN 2024dy exhibits characteristics intermediate between these cases. Although red-wing suppression is pronounced, little or no flux deficit appears near zero velocity (Figure 11), suggesting selective attenuation of the receding emission only. Such a morphology can be reproduced by dust located either within the SN ejecta or in the CDS, provided that the dust distribution is asymmetric or clumpy. Therefore, the line profile alone does not uniquely constrain the dust-formation site.

The spectral evolution suggests that ejecta dust is unlikely to dominate the observed NIR emission. An additional important constraint is that, at least until the middle of Season 2, the spectra do not show clear ejecta-origin features such as nebular lines (e.g., O I $\lambda\lambda 6300, 6364$). This suggests that the photosphere remains embedded within the CSM and that the SN ejecta are not yet exposed. Under such conditions, even if dust were forming within the ejecta, its thermal emission would not be expected to dominate the observed NIR luminosity. It is therefore difficult to attribute the NIR excess detected during Season 2 solely to ejecta dust.

These considerations suggest that dust formation in the CDS is the more plausible scenario for SN 2024dy. SN 2024dy shows evidence that strong interaction persists up to late phases (~ 500 days), implying that the CDS formed in the interaction region provides a favorable environment for dust formation over an extended period.

5.4. Estimation of Dust Mass

5.4.1. Spectral Energy Distribution Modeling

In some previously observed Type II_n SNe, IR emission attributed to dust has been reported (e.g., SN 2005ip: O. Fox et al. 2009; SN 2010jl: C. Fransson et al. 2014; SN 2014ab: T. J. Moriya et al. 2020; SN 2017hcc: S. Moran et al. 2023). In particular, SN 2010jl exhibited an IR excess caused by dust emission in its SED from an early phase. The NIR excess observed in SN 2024dy in Season 2 (see Section 3.3) is also likely to originate from newly formed dust, similar to these cases.

Here, we modeled the cool component of the SED with dust emission calculated from dust-emission models. The dust emission is described by

$$F_{\lambda,\text{dust}} = \frac{M_{\text{dust}} B_{\lambda}(T_{\text{dust}}) \kappa_{\lambda}(a)}{D^2}, \quad (4)$$

where M_{dust} is total dust mass, $B_{\lambda}(T_{\text{dust}})$ is the BB emission at the dust temperature T_{dust} , $\kappa_{\lambda}(a)$ is the mass absorption coefficient for the dust grains of radius a as derived from Mie theory, and D is the distance to the emission source. We investigated the temporal evolution of the dust temperature and mass that best reproduces the observed SED. The models (see K. S. Kawabata et al. 2007, for details) assume optically thin dust emission, with two possible compositions: amorphous carbon (“BE” soot case from F. Rouleau & P. G. Martin 1991) and astronomical silicates (B. T. Draine 1985). We assume a single grain size of $0.01 \mu\text{m}$, and explore dust masses in the range 10^{-6} – $10^{-3} M_{\odot}$. Dust emission is calculated for temperatures between 500 and 1900 K in steps of 10 K.

For each pair of T_{dust} and M_{dust} , we constructed a BB + dust model by adding a hot BB component to the precomputed dust-emission SED. The temperature and radius of the hot BB component were treated as free parameters and optimized by least-squares fitting. We then calculated χ^2 for each BB + dust combination and adopted the model with the minimum χ^2 as the best-fit solution.

Figure 12 presents the SEDs at representative epochs, including the final epoch of Season 1 and two epochs from Season 2. A single-BB component reproduces the Season 1 SED well (as discussed in Section 3.3). For the Season 2 epochs, the observed NIR excess is well explained by adding a dust-emission component, modeled as carbon dust, to the BB emission. The r band is excluded from the fitting because it is contaminated by $H\alpha$ emission. Through Season 2, the flux of the BB component (dominating the optical region) declines with time, while the NIR dust emission remains nearly constant, with its peak gradually shifting toward longer wavelengths.

Table 1 summarizes the temporal evolution of the dust temperature and mass inferred from dust-emission models assuming carbon grains. At the beginning of Season 2, the dust temperature is estimated to be ~ 1800 K, then the temperature decreases to ~ 1350 K over the subsequent ~ 200 days. These temperatures are well below the typical sublimation temperature of carbon dust (~ 1900 K; e.g., E. Dwek 1985). In contrast, fitting the data with silicate compositions yields temperatures that exceed the silicate sublimation temperature (~ 1500 K; e.g., E. Dwek 1985) at many epochs, rendering such models physically implausible. Therefore, we conclude that the dust responsible for the observed NIR excess is likely dominated by carbon grains rather than silicates.

5.4.2. Effects of Optical Depth on Dust-mass Estimates

In Section 5.4.1, we applied dust-emission models to the NIR excess and estimated the temperature and mass of the dust. However, these estimates may not capture the total amount of dust that formed. In this section, we discuss why the inferred dust mass may be an underestimate of the total dust mass produced in SN 2024dy.

Figure 13 shows the time evolution of the dust mass we estimated for SN 2024dy in Section 5.4.1 (black points). Similarly, we show for comparison the time evolution of dust masses estimated under the assumption of carbon grains for several other Type II SNe, including SN 2010jl (A. Sarangi et al. 2018), SN 2015da (L. Tartaglia et al. 2020), and SN 2021irp (T. M. Reynolds et al. 2025). As is clear from this comparison, the dust mass inferred for SN 2024dy is noticeably smaller than the estimates for other objects with similar characteristics. In the following, we consider whether the dust mass in SN 2024dy could be underestimated, while noting that similar systematic effects may also affect the dust-mass estimates for the comparison objects.

E. Dwek et al. (2019) pointed out that the apparent increase in dust mass with time can arise from the decreasing IR optical depth of expanding, optically thick ejecta, rather than from slow dust formation. In this picture, most of the dust may form rapidly at early phases, but only a fraction of its IR emission can escape. As the ejecta expand and the optical depth decreases, a larger fraction of formed dust becomes observable, producing an apparent increase in the inferred dust mass approximately following $M_{\text{dust,obs}} \propto t^2$. Thus, a small dust

mass inferred at early epochs does not necessarily imply inefficient dust formation; rather, it may simply reflect the fact that the bulk of the dust in the inner, optically thick regions has not yet become observable. As shown in Figure 13, the relation $M_{\text{obs}} \propto t^2$ (black dot line) appears to reproduce the time evolution of the dust mass estimated for SN 2024dy remarkably well. This suggests that the inferred value of $\sim 10^{-5} M_{\odot}$ represents only the mass of the “apparently optically thin” dust, rather than the total amount of dust that was actually formed.

We also note that an additional possibility is the presence of cooler dust that would not be detectable in the NIR. In several dust-forming SNe such as SN 2010jl, the presence of an additional, cooler dust component ($T_{\text{dust}} \lesssim 1000$ K) has been suggested from MIR observations (e.g., O. D. Fox et al. 2011). However, our NIR data are not sensitive to such low-temperature dust emission, and we cannot place meaningful constraints on its presence or absence. A detailed investigation of this component is therefore beyond the scope of this paper.

These considerations imply that it is difficult to infer the amount of optical extinction directly from the dust masses estimated through the NIR emission. We therefore also estimated the dust mass responsible for the observed optical attenuation by evaluating the degree of optical fading, and compared this value with the dust masses inferred from the NIR excess. We estimated the optical depth τ required to reproduce two observational constraints: the suppression of the red wing in the $H\alpha$ profile and the accelerated decline of the optical pseudobolometric light curve.

From the flux deficit in the red wing of the last spectrum at 391 days (Section 5.2), we derived $\tau \sim 0.9$. As an independent estimate, we compared the optical and optical + NIR pseudobolometric light curves in Figure 5. During Season 1 (~ 100 –280 days), these two light curves show similar decline rates after a vertical scaling. At 391 days, however, the optical luminosity is lower by a factor of ~ 2 –3 relative to the expected value extrapolated from the decline of Season 1. This corresponds to an additional fading of $\Delta m \sim 0.9$ –1.1 mag, or $\tau \sim 0.8$ –1.0. These two independent estimates are broadly consistent, suggesting an optical depth of order $\tau \sim 0.9$ during Season 2.

The optical depth is defined as

$$\tau = \int \kappa \rho dr. \quad (5)$$

Assuming a thin dust shell with mass $M_{\text{dust,abs}}$ at radius r and thickness Δr , the density is written as

$$\rho \sim \frac{M_{\text{dust,abs}}}{4\pi r^2 \Delta r}. \quad (6)$$

Substituting this into Equation (5), we obtain

$$\tau \sim \kappa \rho \Delta r \sim \frac{\kappa M_{\text{dust,abs}}}{4\pi r^2}. \quad (7)$$

This expression can be rearranged to give the dust mass in terms of the optical depth. We rewrite Equation (7) as

$$M_{\text{dust,abs}} = \frac{4\pi r_{\text{BB}}^2}{\kappa} \tau. \quad (8)$$

Here, $M_{\text{dust,abs}}$ denotes the dust mass contributing to the absorption, and r_{BB} is the BB radius estimated from the SED fitting, which also provides a lower limit on the radial extent of the dust-emitting region. Therefore, the dust mass derived

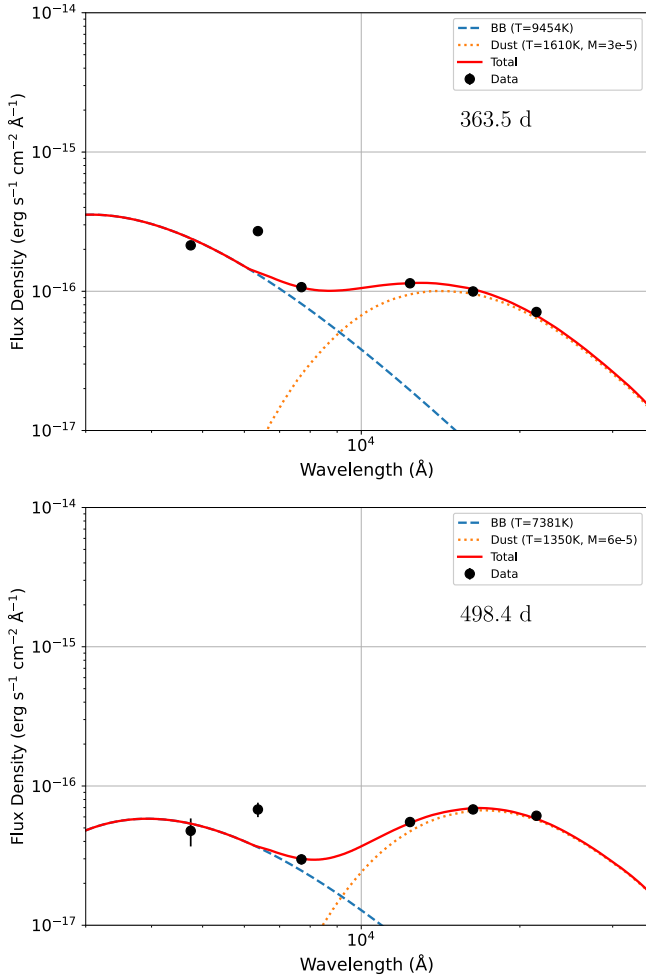


Figure 12. BB and dust component fits to the SED at representative epochs. These panels present selected epochs from Season 2, where the SEDs are modeled with a combination of a BB component and carbon dust emission (orange dashed lines). The red solid lines indicate the total model SED. The r band is excluded from the fitting due to contamination from $H\alpha$ emission.

Table 1

Estimated Carbon Dust Temperature (T_{dust}) and Dust Mass (M_{dust}) at Each Epoch

MJD	Epoch (days)	T_{dust} (K)	M_{dust} ($M_{\odot}$)
60594.8	285.6	1840^{+25}_{-14}	$(1.0^{+0.1}_{-0.2}) \times 10^{-5}$
60617.8	308.6	1880^{+20}_{-15}	$(1.0^{+0.7}_{-0.1}) \times 10^{-5}$
60625.7	316.5	1640^{+9}_{-17}	$(2.0^{+0.3}_{-0.1}) \times 10^{-5}$
60626.8	317.6	1680^{+17}_{-9}	$(2.0^{+0.1}_{-0.1}) \times 10^{-5}$
60635.8	326.6	1710^{+11}_{-13}	$(2.0^{+0.2}_{-0.1}) \times 10^{-5}$
60672.7	363.5	1610^{+9}_{-11}	$(3.0^{+1.2}_{-0.1}) \times 10^{-5}$
60693.8	384.6	1460^{+7}_{-10}	$(5.0^{+1.3}_{-0.5}) \times 10^{-5}$
60695.8	386.6	1510^{+10}_{-4}	$(4.0^{+0.4}_{-0.2}) \times 10^{-5}$
60732.7	423.5	1450^{+5}_{-3}	$(5.0^{+0.5}_{-0.4}) \times 10^{-5}$
60753.6	444.4	1430^{+6}_{-4}	$(5.0^{+0.4}_{-0.5}) \times 10^{-5}$
60754.7	445.5	1430^{+2}_{-10}	$(5.0^{+0.5}_{-0.4}) \times 10^{-5}$
60795.5	486.3	1390^{+5}_{-2}	$(5.0^{+1.1}_{-0.2}) \times 10^{-5}$
60807.6	498.4	1350^{+8}_{-2}	$(6.0^{+1.3}_{-0.3}) \times 10^{-5}$

Note. The uncertainties correspond to the projected ranges of the 1σ confidence region in the chi-squared values for varying T_{dust} and M_{dust} .

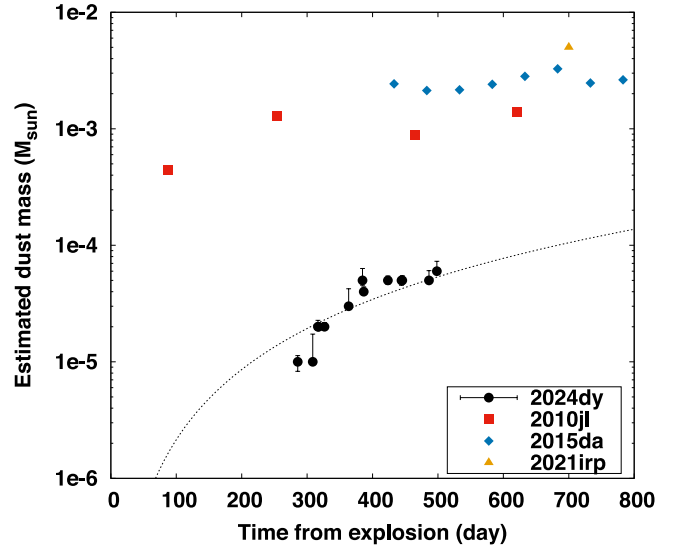


Figure 13. Temporal evolution of the dust mass inferred for SN 2024dy (black points), derived from the NIR excess assuming optically thin emission from hot dust (Section 5.4.1). For comparison, the dust-mass estimates for SN 2010jl (A. Sarangi et al. 2018), SN 2015da (L. Tartaglia et al. 2020), and SN 2021irp (T. M. Reynolds et al. 2025), all assuming carbon dust, are also shown. The black dotted line indicates an arbitrarily scaled $M_{\text{dust,obs}} \propto t^2$ relation expected from the evolution of the effective emitting surface of optically thick dust, as discussed by E. Dwek et al. (2019), and is shown for illustrative purposes only. The systematically lower dust mass inferred for SN 2024dy and its apparent consistency with the t^2 trend suggest that the derived dust mass may represent a lower limit rather than the total amount of dust formed.

using r_{BB} should be regarded as a lower limit. The parameter κ is the dust absorption coefficient, for which we adopt a representative value of $\kappa \sim 30,000 \text{ cm}^2 \text{ g}^{-1}$ at the wavelength of $H\alpha$ (F. Rouleau & P. G. Martin 1991). Using Equation (8), the dust mass required to account for the optical attenuation is estimated to be $M_{\text{dust,abs}} \geq 1.6 \times 10^{-4} M_{\odot}$. This value is approximately an order of magnitude larger than the dust mass inferred from the SED fitting at the same epoch. We also note that this estimate focuses only on the dust responsible for the absorption, and thus represents a lower limit on the total dust mass that was actually formed. Additional dust may remain undetected owing to geometric asymmetry or other effects.

These results imply that the NIR emission traces only a fraction of the dust actually formed at ~ 400 days, indicating that a substantial amount of the newly formed dust remained missing from our view. This estimate is also consistent with the fact that the estimated dust mass from SED is well reproduced by the $M_{\text{dust,obs}} \propto t^2$ relation proposed by E. Dwek et al. (2019), as discussed above. A similar argument has been made for many Type IIP SNe (e.g., S. Tinyanont et al. 2019), indicating the need for more systematic NIR–MIR studies of Type IIn SNe as well.

From these considerations, we conclude that the dust masses derived from the SED fitting represent only the “visible” dust component and trace only a fraction of the dust responsible for the optical attenuation. In addition, cooler dust may also be present but remains unconstrained by our NIR data. Therefore, the dust masses estimated in this work should be regarded as lower limits to the total amount of dust formed in SN 2024dy.

6. Summary and Conclusions

In this study, we present UV–optical–NIR photometric and spectroscopic observations of the Type IIn SN 2024dy, obtained over a period of approximately 500 days. Below, we summarize the key results and discussions presented in this study.

(1) SN 2024dy is a long-lived Type IIn monitored for nearly 500 days in the optical and NIR. Its peak magnitude is $M_r \simeq -19.2$ mag, consistent with the typical luminosity of this class. The rise time was 38 days, placing it toward the longer end of the distribution of Type IIn SNe.

(2) After the solar conjunction, the Season 2 light curves exhibit a marked change in evolution. In the optical bands, the decline rate increases by a factor of about 4 compared to Season 1, whereas the NIR bands became nearly flat or showed signs of rebrightening.

(3) The Season 2 SEDs show a pronounced NIR excess, which is well reproduced by a two-component BB consisting of a hot component with $T \sim 6 \times 10^3$ – 10^4 K and a cooler component with $T < 3000$ K. The pseudobolometric light curve peaks at 1.6×10^{43} erg s^{−1}, and the total radiated energy over 500 days is 1.9×10^{50} erg. During Season 2, the ratio $L_{\text{NIR}}/L_{\text{opt}}$ increases steadily with time.

(4) The early time spectra are dominated by Balmer emission lines and a blue continuum, both characteristic of strong CSM interaction in Type IIn SNe, and several He lines are also detected. After its peak, a blueshifted component appears in H α , and by Season 2 the line evolves into an asymmetric profile with a suppressed red wing, indicative of dust obscuration. Throughout the entire monitoring period, no clear ejecta-origin features emerge, suggesting that strong CSM interaction persists to the late phases.

(5) The mass-loss rate inferred from the peak luminosity is $0.037 M_{\odot} \text{ yr}^{-1}$. Although this value is somewhat lower than those of comparison objects, the comparable total radiated energy suggests that SN 2024dy was surrounded by a CSM mass similar to that of the comparison events, likely distributed over a more extended and lower-density region.

(6) Assuming the NIR excess arises from optically thin dust emission, the inferred carbon dust temperature decreases from 1800 to 1300 K, while the dust mass increases to $(1\text{--}6) \times 10^{-5} M_{\odot}$. The temperatures rule out silicate grains, indicating that carbon dust is the dominant component.

(7) The properties of the observed dust emission cannot be explained by an IR echo and instead point to newly formed dust. The data do not allow us to uniquely identify the formation site, and distinguishing between the inner ejecta and the CDS is challenging with the present observations. The dust mass estimated from the SED modeling is significantly smaller

than the mass estimated from the attenuation of H α , implying that a substantial fraction of the newly formed dust is either buried in an optically thick region or exists as cooler dust that is not detectable at NIR.

Long-lived Type IIn SNe such as SN 2024dy remain rare, and their physical nature is still not well understood. Future facilities, including Vera C. Rubin Observatory (Ž. Ivezić et al. 2019), are expected to provide increasing opportunities to monitor such events over timescales exceeding 1000 days (e.g., W. V. Jacobson-Galán et al. 2025; M. Shahbandeh et al. 2025). Expanding the sample of these long-lived interacting SNe will be essential for developing a more complete understanding of the physics of CSM interaction.

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Data Availability

The photometric data and pseudobolometric luminosities used in this work are available as data behind the relevant figures. The data files are provided in CSV format, together with Read Me files describing the file contents, column definitions, units, magnitude systems, telescopes, instruments, and data sources. The spectra will be uploaded to WISEREP.

Appendix A Observation Log

In this appendix, we present a summary of the spectroscopic observations used in this study. Table 2 provides the observational log, including the observation date, phase, instrument, wavelength coverage, exposure time, and resolution for each epoch.

Table 2
Log of Spectroscopic Observations of SN 2024dy

Date (YYYYMMDD)	MJD	Phase (days)	Telescope + Instrument	Spectral Range (Å)	Exposure Time (s)	Resolution
20240216	60356.9	47.7	DOT + ADFOSC	3500–7100	600	700
20240308	60377.8	68.6	DOT + ADFOSC	3500–7100	900	700
20240315	60384.8	75.6	DOT + ADFOSC	3500–7100	600	700
20240411	60411.6	102.4	HCT + HFOSC	3800–8000	2400	~500
20240424	60424.7	115.5	HCT + HFOSC	3800–8000	1800	~500
20240504	60434.7	125.5	HCT + HFOSC	3800–8000	2400	~500
20240514	60444.8	135.6	HCT + HFOSC	3800–8000	2700	~500
20240518	60448.7	139.5	HCT + HFOSC	3800–8000	2700	~500
20240604	60465.7	156.5	HCT + HFOSC	3800–8000	1050	~500
20240614	60475.6	166.4	HCT + HFOSC	3800–8000	1800	~500
20241114	60628.9	319.7	HCT + HFOSC	3800–8000	3600	~500
20241130	60644.9	335.7	HCT + HFOSC	3800–8000	2700	~500
20250105	60680.8	371.6	HCT + HFOSC	3800–8000	3600	~500
20250125	60700.8	391.6	DOT + ADFOSC	3500–7100	2700	700

Appendix B

Result of Line Fitting

Table 3 summarizes the parameters obtained from the $H\alpha$ line-profile fitting shown in Figure 9.

Table 3
Full Width at Half-maximum Measurements of the $H\alpha$ Line Profile of SN 2024dy

Epoch (days)	Gaussian 1 (km s ⁻¹)	Gaussian 2 (km s ⁻¹)	Gaussian 3 (km s ⁻¹)	Lorentzian (km s ⁻¹)
8.4	346.7 ± 7.4	...	...	1643.7 ± 46.4
9.1	785.2 ± 70.5	...	...	1580.0 ± 209.4
47.7	455.4 ± 16.9	...	...	1865.2 ± 83.9
68.6	443.5 ± 15.7	8067.0 ± 278.5	1804.6 ± 61.9	...
75.6	490.9 ± 28.6	8076.5 ± 315.4	1825.3 ± 88.2	...
102.4	564.4 ± 24.6	7282.5 ± 79.9	1822.3 ± 41.1	...
115.5	443.1 ± 22.7	6647.5 ± 87.4	1778.5 ± 38.8	...
125.5	626.0 ± 36.5	7637.5 ± 68.6	1810.9 ± 41.3	...
135.6	585.8 ± 50.6	7598.9 ± 83.9	1752.3 ± 45.9	...
139.5	565.8 ± 39.6	7881.1 ± 81.0	1839.7 ± 43.9	...
156.5	379.5 ± 55.4	6818.9 ± 80.0	1658.8 ± 45.2	...
166.4	449.1 ± 52.5	7084.3 ± 79.9	1731.3 ± 43.3	...
319.7	719.5 ± 82.7	6097.7 ± 80.1	1514.8 ± 67.2	...
335.7	1083.0 ± 94.2	5975.0 ± 46.9	1578.0 ± 166.7	...
371.6	964.0 ± 212.7	5067.4 ± 86.8	1415.8 ± 301.9	...
391.6	779.5 ± 114.3	4934.4 ± 127.6	1554.2 ± 75.0	...

Note. Each epoch is given in days since the estimated explosion date (MJD 60309.2). The first three spectra are well reproduced by a combination of a narrow Gaussian component and an intermediate Lorentzian component.

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