



SN 2017egm: A Helium-rich Superluminous Supernova with Multiple Bumps in the Light Curves

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Abstract

When discovered, SN 2017egm was the closest (redshift $z = 0.03$) hydrogen-poor superluminous supernova (SLSN-I) and a rare case that exploded in a massive and metal-rich galaxy. Thus, it has since been extensively observed and studied. We report spectroscopic data showing strong emission at around He I $\lambda 10830$ and four He I absorption lines in the optical. Consequently, we classify SN 2017egm as a member of an emerging population of helium-rich SLSNe-I (i.e., SLSNe-Ib). We also present our late-time photometric observations. By combining them with archival data, we analyze high-cadence ultraviolet, optical, and near-infrared light curves spanning from early pre-peak (~ -20 days) to late phases ($\sim +300$ days). We obtain its most complete bolometric light curve, in which multiple bumps are identified. None of the previously proposed models can satisfactorily explain all main light-curve features, while multiple interactions between the ejecta and circumstellar material (CSM) may explain the undulating features. The prominent infrared excess with a blackbody luminosity of $10^7\text{--}10^8 L_{\odot}$ detected in SN 2017egm could originate from the emission of either an echo of a pre-existing dust shell or newly formed dust, offering an additional piece of evidence supporting the ejecta–CSM interaction model. Moreover, our analysis of deep Chandra observations yields the tightest-ever constraint on the X-ray emission of an SLSN-I, amounting to an X-ray-to-optical luminosity ratio $\lesssim 10^{-3}$ at late phases ($\sim 100\text{--}200$ days), which could help explore its close environment and central engine.

Unified Astronomy Thesaurus concepts: [Supernovae \(1668\)](#)

Supporting material: data behind figures, machine-readable tables

1. Introduction

Thanks to the rise of wide-field time-domain surveys, a rare class of supernovae (SNe) that are $\sim 2\text{--}3$ mag more luminous than normal SNe have been revealed in the past one and a half

decades, known as the superluminous supernovae (SLSNe; see a recent review by Gal-Yam 2019). As with normal SNe (Filippenko 1997), SLSNe are categorized into two classes based on their spectra around maximum light: hydrogen-poor (SLSNe-I) and hydrogen-rich events (SLSNe-II; Gal-Yam 2019).

Since the discovery of the first SLSN-I over 15 yr ago (SN 2005ap; Quimby et al. 2007), more than 100 such events have been found, and identifications of diverse properties among

them have motivated subclassifications. Subclasses with rapidly and slowly evolving light curves have been proposed (Gal-Yam 2012; Inserra et al. 2018; Quimby et al. 2018), but whether clear divisions can be made is debated (e.g., Nicholl et al. 2017b; Lunnan et al. 2018). Spectroscopically, their early-time spectra often show a characteristic W-shaped feature near 4200 Å produced by a pair of broad absorption features associated with O II (Quimby et al. 2011). SLSNe-I have long been linked to SNe-Ic due to their similarities in post-peak spectra and a lack of both H and He (Pastorello et al. 2010; Quimby et al. 2011). During the past few years, several SNe initially classified as SLSNe-I have been found with He spectral features. PTF10hgi shows both H and He lines (Quimby et al. 2018), and is followed by a small sample of He-rich SLSNe-I classified as SLSNe-Ib from the Zwicky Transient Facility (ZTF; Yan et al. 2020). However, the studies of SLSNe-Ib still lack high-quality multiwavelength photometric and spectroscopic observations covering the early phase to the late stages.

The mechanisms powering SLSNe-I remain elusive (Moriya et al. 2018; Gal-Yam 2019). Several possible mechanisms beyond the conventional means such as radioactive decay of ^{56}Ni have been proposed to explain their extreme radiative power, including energy injection from a rapidly rotating, highly magnetic neutron star (e.g., Kasen 2010; Woosley 2010), the interaction of the SN ejecta with circumstellar material (CSM; e.g., Chevalier & Irwin 2011; Chatzopoulos et al. 2013; Sorokina et al. 2016), and the pair-instability mechanism (e.g., Heger & Woosley 2002; Gal-Yam et al. 2009). Magnetar models are often invoked in fitting the light curves. However, some observational evidence already indicates that the magnetar model cannot be the only process affecting the luminosity and morphology for SLSNe-I, and multiple processes may contribute to the optical emission. For example, the light-curve undulations and sometimes prominent post-peak bumps seen in some SLSNe-I light curves cannot be explained by a simple magnetar model (e.g., Nicholl et al. 2016; Yan et al. 2017a, 2017b; Anderson et al. 2018; Lunnan et al. 2020). The CSM interaction model offers a natural explanation for the bumps and fluctuations in light curves (e.g., Blinnikov 2017; Inserra et al. 2017; Moriya et al. 2018), but the absence of relatively narrow emission lines in the spectra of most SLSNe-I is often regarded as a major issue for the CSM model.

Gaia17biu/SN 2017egm (with a redshift $z = 0.03063$) was discovered by the Photometric Science Alerts Team of the Gaia mission on 2017 May 23 (UT dates are used throughout this paper) and subsequently classified as an SLSN-I (Dong et al. 2017); it was the closest SLSN-I discovered by then. In contrast to the typical dwarf and metal-poor host galaxies for SLSNe-I, its host galaxy, NGC 3191, is massive (Dong et al. 2017) and has a mean metallicity near solar (Nicholl et al. 2017a; Bose et al. 2018; see also spatially resolved observations by Chen et al. 2017; Izzo et al. 2018). Its pre-peak near-ultraviolet (NUV) to optical colors (Bose et al. 2018) are similar to those of Gaia16apd (Kangas et al. 2017) and among the bluest observed for an SLSN-I, while its peak luminosity ($M_g = -21$ mag) is substantially lower than that of Gaia16apd. Moreover, SN 2017egm holds the tightest upper limit of radio luminosity among SLSNe-I (Bose et al. 2018). The sharp peaks in the light curves of SN 2017egm are shown to be well fitted by ejecta–CSM interaction (CSI) models, but are difficult to explain by only a magnetar or radioactive decay of

^{56}Ni (Wheeler et al. 2017). Hosseinzadeh et al. (2022) also concluded that SN 2017egm cannot be explained well by the magnetar model alone, given the multiple bumps in its extended post-peak light curve.

As one of the closest SLSNe-I and having extensive multiwavelength observations, SN 2017egm appears to be an ideal target for further detailed studies, which may help us understand the explosion mechanism of SLSNe-I. In this paper, we present the most complete photometric and spectroscopic analysis of SN 2017egm, taking our observational data and all public data together. We present the observations and data reduction in Section 2. In Section 3, we analyze its light curves and spectra, and we classify it as an SLSN-Ib and compare it to other SLSNe-I. Section 4 presents a discussion and our conclusions. In this work, we adopt a luminosity distance of $D_L = 138.7 \pm 1.9$ Mpc assuming a standard Planck cosmology (Planck Collaboration et al. 2016).

2. Observations and Data

Multiband photometry from UV to mid-infrared (MIR) wavelengths, as well as optical spectra spanning ~ 300 days since the discovery of SN 2017egm, were taken by us or gathered from publicly available archives. Here we describe the relevant observations and data reduction. In addition, analysis of the four epochs of Chandra visits is presented for the first time.

2.1. Ground-based Optical and Near-infrared Photometry

We obtained late-time multiband images with a set of ground-based instruments. Optical data in the *BVgriz* bands were taken with 0.6 m telescopes at Post Observatory (PO) at the Sierra Remote Observatories (SRO; CA, USA), the 2.0 m Las Cumbres Observatory Global Telescope network (LCOGT), the 2.0 m Liverpool Telescope (LT) at La Palma, and the ALFOSC mounted on the 2.6 m Nordic Optical Telescope (NOT). The *JHK* near-infrared (NIR) images were obtained with the NIR Camera mounted on the NOT (NOTCam) and the NIR Wide-Field Camera mounted on the United Kingdom Infrared Telescope (UKIRT).

We found that the transient signals associated with SN 2017egm were undetectable after ~ 360 days in all of our optical and NIR images. Thus, we generate the reference images with these late-stage data, which are dominated by host-galaxy emission around the position of SN 2017egm. All photometric measurements were performed on the difference images, which are obtained by subtracting the reference image from a current science image by matching the point-spread function (PSF). Specifically, we used HOTPANTS (Becker 2015) for image subtraction. Before subtraction, we removed cosmic rays and aligned the images using Astrometry.net. Most instruments have good references with high signal-to-noise ratios (S/Ns) and Gaussian-like PSF profiles, so the subtractions were conducted directly with their corresponding references. However, the quality of the final-epoch LT image did not satisfy the requirement for a reference image owing to clouds; thus, the 2.0 m LCOGT reference images were adopted instead.

After image subtraction, PSF photometry was performed on the difference image with the Photutils package (Bradley et al. 2022) of Astropy (Astropy Collaboration et al. 2022) for the optical and NIR data. The photometric data were calibrated

using PS1 standards (Chambers et al. 2016) in the field of view with Pan-STARRS color-term corrections (Tonry et al. 2012) applied for the Johnson *BV* filters and Sloan Digital Sky Survey *griz* filters, and the *JHK* NIR data were calibrated using Two Micron All Sky Survey standards. Swift/UVOT and optical *griz* photometric data were calibrated for the AB magnitude system and BVJHK for the Vega magnitude system.

We reprocessed early-time optical data observed by the above-mentioned instruments and presented by Bose et al. (2018) for consistency according to the same procedure in this work. The phases in the paper are given in the rest frame of SN 2017egm, and the reference epoch is set to be the *g*-band peak at JD = 2,457,926.3.

2.2. Swift/UVOT Photometry

UV images were obtained with the Neil Gehrels Swift Observatory (hereafter Swift) with the Ultraviolet Optical Telescope (UVOT). The Swift/UVOT data covered ~ 140 days of NUV data after discovery, which provided good sampling for a blue bump before the NUV became undetectable (see Figure 1). The Swift/UVOT photometry was measured with the UVOT-SOURCE task in the `Heasoft` package using $5''$ apertures after subtracting the galaxy background using a Swift/UVOT image taken on 2018 June 26 (+360 days). It was placed in the AB magnitude system (Oke & Gunn 1983), adopting the revised zero-points and sensitivity from Breeveld et al. (2011) as done in the previous work analyzing the early-time UVOT data (Bose et al. 2018). All of the photometric data are presented in Table 1.

2.3. Archival MIR Data

The Wide-field Infrared Survey Explorer (WISE) conducted a full-sky survey at 3.4, 4.6, 12, and 22 μm (labeled as W1–W4, respectively) from 2010 February to August (Wright et al. 2010). The solid hydrogen cryogen used to cool the W3 and W4 instruments was depleted later and placed in hibernation in 2011 February. WISE was reactivated and renamed NEOWISE-R in late 2013, using only W1 and W2, to search for asteroids that could pose potential impact hazards to Earth (Mainzer et al. 2014). Up to 2021 December, the NEOWISE survey has visited every region of the sky 16 times every six months, with an average of 12 single exposures within each epoch (typically within one day).

Previous works show that the IR echoes (UV/optical light absorbed and re-radiated in the IR by dust) of optical transients are detectable on timescales of months to years while the intraday variability is negligible (e.g., Jiang et al. 2016, 2021; Sun et al. 2022). To acquire high-S/N measurements, we choose to perform photometry on the time-resolved WISE/NEOWISE coadds, and each coadd per band per epoch is produced by stacking exposures within typically ~ 1 day intervals (Meisner et al. 2018).²⁵

2.4. X-Ray Observations

Four epochs of X-ray observations of SN 2017egm (PI R. Margutti) were obtained with the Chandra X-ray Observatory on 2017 June 26 (24 ks exposure), 2017 September 17 (25 ks), 2017 November 9 (25 ks), and 2018 May 21 (24 ks); they correspond to +4, +85, +136, and +323 days since the optical peak. We processed the Chandra data with CIAO (v.4.14)

using the latest calibration files (v.4.9.6). The Level-2 event files were recreated by the script of `chandra_repro`. SN 2017egm is not detectable at any individual epoch. Then we analyzed the stacked images of all four epochs with a total exposure time of 96.9 ks, still yielding a nondetection. Assuming a power-law spectrum with photon index $\Gamma = 2$ and Galactic column density $N_{\text{H}} = 1.08 \times 10^{20} \text{ cm}^{-2}$, the inferred 3σ unabsorbed flux upper limit is $8.4 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 0.5–10 keV band, corresponding to $1.9 \times 10^{39} \text{ erg s}^{-1}$ at the distance of SN 2017egm. Alternatively, if we assume a thermal emission, e.g., a blackbody with temperature of $kT = 1 \text{ keV}$, the inferred unabsorbed flux upper limit is $7 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$, corresponding to a luminosity of $1.8 \times 10^{39} \text{ erg s}^{-1}$.

The nondetection from the deep Chandra observations gives the most stringent constraint on the X-ray emission of an SLSN-I to date. Figure 2 shows this limit compared with a large sample of X-ray observations of other SLSNe-I from Margutti et al. (2018). The X-rays from SN 2017egm could be heavily absorbed by CSM, i.e., a neutral hydrogen column density of $N_{\text{H}} = 10^{24} \text{ cm}^{-2}$ will lead to a nondetection of intrinsic X-ray luminosity of $10^{41} \text{ erg s}^{-1}$.

2.5. Spectroscopic Observations

Optical spectra from +84 to +261 days were obtained using the Kast Spectrograph mounted on the 3 m Shane telescope at Lick Observatory (CA, USA; Miller & Stone 1993), the Double Spectrograph for the Palomar 200 inch Hale telescope (P200), the MODS1 multiobject double spectrographs mounted at the Large Binocular Telescope Observatory (LBT), and the OSIRIS instrument located in the Gran Telescopio CANARIAS (GTC). We also obtained spectra of SN 2017egm in the NIR at +105 days using the Aerospace Corporation’s Visible and Near-Infrared Imaging Spectrograph (VNIRIS) mounted on the Shane telescope and +143 days using the Spex medium-resolution spectrograph (0.7–5.3 μm ; Rayner et al. 2003) on the NASA Infrared Telescope Facility (IRTF). All of the spectra except for the one observed with LBT/MODS were taken at or near the parallactic angle to minimize differential slit losses caused by atmospheric dispersion (Filippenko 1982). Regarding the LBT observation, the slit width was $1''$ and the slit position angle was set to the default 0° (north–south), which corresponds to a parallactic angle of 146° at the start of observation. However, due to a low airmass (~ 1.0) and short exposure time (600 s), the effect of differential atmospheric refraction should be small (see Filippenko 1982). The LBT/MODS data were processed with the `modsCCDRed` program (Pogge 2019) and the `MODSIDL` pipeline (Croxall & Pogge 2019). The raw measurements of SpeX data were converted to absolute flux using the `Spextools` software package (Vacca et al. 2003; Cushing et al. 2004). The VNIRIS data were processed using software customized for VNIRIS and written in the Interactive Data Language (Rudy et al. 2021). All of the other spectra were reduced and calibrated using standard procedures in IRAF.²⁶ See a summary of our late-time spectra in Table 2.

²⁵ <https://portal.nersc.gov/project/cosmo/temp/ameisner/neo8>

²⁶ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

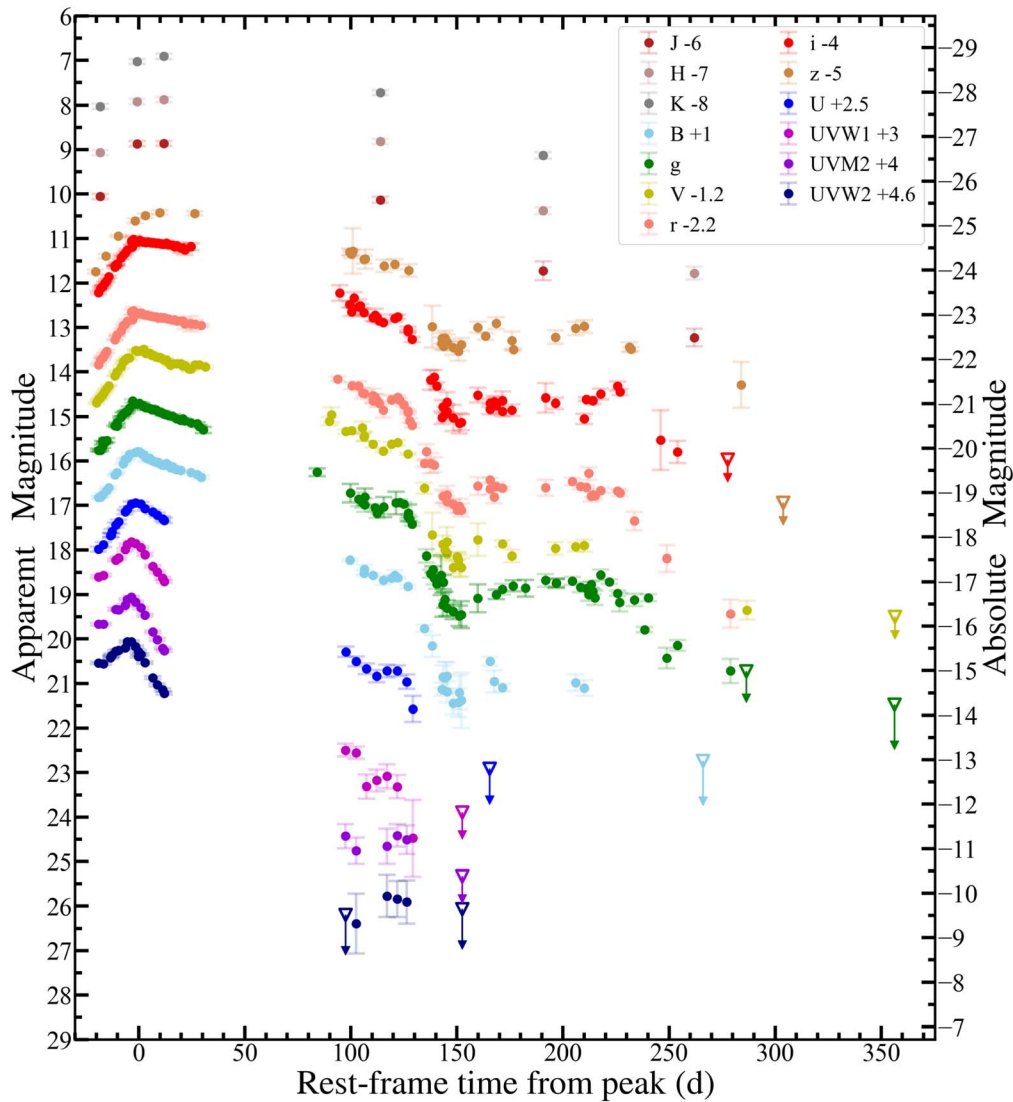


Figure 1. Multiband light curves of SN 2017egm from NUV to NIR with Galactic extinction corrected. The light curves are shifted vertically at various offsets for different bands for display. The reference epoch is set to be the g -band peak at $\text{JD} = 2,457,926.3$. All optical light curves show a rapid descent during 120–150 days and multiple bumps distinctly. The hollow triangles with downward arrows represent upper limits of the corresponding bands.

3. Analysis and Results

3.1. Photometric and Color Evolution

All light curves are shown in Figure 1, including our data presented in this work along with early-phase data from Bose et al. (2018) and late-phase gri data published by Hosseinzadeh et al. (2022). The magnitudes are corrected for Galactic extinction ($R_V = 3.1$ and $E(B - V) = 0.0097 \pm 0.0005$ mag; Schlafly & Finkbeiner 2011) following Bose et al. (2018) and K -corrections based on the optical spectra.

During ~ 2 weeks following the season gap ($\sim +30$ – 100 days), the light curves are in a relatively smooth decline, which appears to extend the post-peak linear decline in magnitude prior to the gap. The post-peak decline rate of SN 2017egm is one of the slowest among SLSNe-I (Bose et al. 2018), but its peak luminosity ($M_{g,\text{peak}} \approx -21$ mag) is close to the mean for SLSNe-I, defying the empirical correlation reported by Inserra & Smartt (2014) that the more slowly declining SLSNe-I tend to be more luminous.

At $\sim +115$ days, the optical light curves show a small bump in all bands, followed by a rapid decline (~ 2 mag) at

$\sim +130$ – 150 days. Meanwhile, the U -band light curve also exhibits a bump followed by possibly an even more rapid drop of NUV fluxes given the nondetection around $+150$ days. The bump is reminiscent of that found in SN 2015bn (Nicholl et al. 2016), which was more pronounced in the bluer bands. A sharp decline in all bands a few months after the peak is an expected common feature for the ejecta–CSM interaction model, and this occurs when the shock wave reaches the outer edge of the extended envelope with no more material ahead, with no source of radiation energy remaining (Sorokina et al. 2016). Interestingly, there is a second bump at $\sim +150$ – 240 days, which is most clearly seen in the g -band light curve. The second bump appears nearly flat, and the variations are particularly small in redder bands, suggesting an extra power supply, such as CSM interaction.

As shown by Bose et al. (2018), the UV-to-optical color ($uvw2 - r$) evolution near the peak of SN 2017egm is similar to that of Gaia16apd (Kangas et al. 2017), which starts with a very blue color and becomes redder rapidly as the SN cools. By contrast, the optical color evolution is much less dramatic (see the top panel of Figure 3). We compare the $g - r$ color

Table 1
Photometry of SN 2017egm

MJD	Phase ^a (days)	<i>B</i> (mag)	<i>g</i> (mag)	<i>V</i> (mag)	<i>r</i> (mag)	<i>i</i> (mag)	<i>z</i> (mag)	Telescope ^b /Inst.	Source ^c
57,904.90	−20.28	...	...	...	...	...	16.74 ± 0.04	LT	Bose et al. (2018)
57,905.18	−20.01	...	...	15.89 ± 0.02	...	...	...	PO	Bose et al. (2018)
57,906.20	−19.02	15.82 ± 0.04	15.76 ± 0.03	15.81 ± 0.02	16.03 ± 0.02	16.21 ± 0.03	...	PO	Bose et al. (2018)
...
58,213.37	279.02	...	20.72 ± 0.27	...	21.63 ± 0.32	>20.96	...	KeplerCam	Hosseinzadeh et al. (2022)
58,218.46	283.96	...	...	...	...	...	19.29 ± 0.51	LT	This work
58,221.20	286.62	...	>20.73	20.55 ± 0.21	...	...	...	PO	This work
58,238.90	303.79	...	...	...	...	...	>21.45	AF	This work
58,293.20	356.48	...	>21.48	>20.70	...	...	...	PO	This work
MJD	Phase ^a (days)	<i>J</i> (mag)	<i>H</i> (mag)	<i>K</i> (mag)	Telescope ^b /Inst.	Source			
57,906.94	−18.30	16.06 ± 0.06	16.07 ± 0.06	16.03 ± 0.06	NC	Bose et al. (2018)			
57,924.96	−0.82	14.87 ± 0.06	14.92 ± 0.06	15.03 ± 0.06	NC	Bose et al. (2018)			
57,937.90	11.74	14.86 ± 0.06	14.88 ± 0.06	14.91 ± 0.06	NC	Bose et al. (2018)			
58,043.24	113.95	16.13 ± 0.07	15.82 ± 0.06	15.72 ± 0.06	NC	This work			
58,122.26	190.62	17.72 ± 0.21	17.38 ± 0.08	17.13 ± 0.07	NC	This work			
58,195.62	261.80	19.23 ± 0.20	18.78 ± 0.14	...	UKIRT	This work			
MJD	Phase ^a (days)	UVU (mag)	UVW1 (mag)	UVM2 (mag)	UVW2 (mag)	Telescope ^b /Inst.	Source		
57,906.32	−18.90	15.48 ± 0.05	15.60 ± 0.03	15.67 ± 0.03	15.94 ± 0.03	UVOT	Bose et al. (2018)		
57,908.69	−16.60	15.38 ± 0.05	15.56 ± 0.03	15.66 ± 0.03	15.96 ± 0.03	UVOT	Bose et al. (2018)		
57,912.07	−13.32	15.18 ± 0.05	...	...	15.82 ± 0.03	UVOT	Bose et al. (2018)		
...		
58,058.91	129.15	19.07 ± 0.29	21.48 ± 0.86	...	...	UVOT	This work		
58,083.36	152.88	...	>20.90	>21.34	>21.47	UVOT	This work		
58,096.30	165.43	>20.42	...	...	...	UVOT	This work		

Notes.

^a Rest-frame time (days) relative to the epoch of the *g*-band peak brightness.

^b The abbreviations of telescope/instrument used are as follows: LT—2.0 m Liverpool Telescope; PO—0.6 m telescopes of Post Observatory; LCOGT—Las Cumbres Observatory Global Telescope Network; AF—ALFOSC mounted on 2.0 m NOT telescope; KeplerCam—KeplerCam mounted on 1.2 m telescope at Fred Lawrence Whipple Observatory; NC—NotCAM IR imager on 2.0 m NOT telescope; UKIRT—NIR Wide-Field Camera mounted on the United Kingdom Infrared Telescope; UVOT—Ultraviolet Optical Telescope on board the Swift satellite.

^c We have reprocessed the data with the source of Bose et al. (2018) using the same procedure with this work.

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

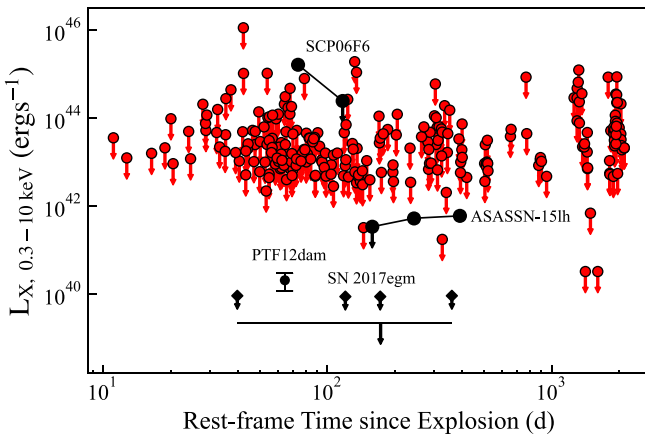


Figure 2. X-ray observations of SN 2017egm along with other SLSNe-I from Margutti et al. (2018) spanning the phase range ~ 10 –2000 days since explosion. Upper limits for SN 2017egm are shown as black diamonds, other upper limits are shown as red circles, and detections or possible detections for SCP 06F6 (Barbary et al. 2009), PTF12dam (Nicholl et al. 2013) and ASASSN-15lh (Dong et al. 2016) are shown as black circles. Black horizontal line with arrows is the SN 2017egm average weighted by exposure time. The explosion time of SN 2017egm is estimated as the time of its first detection.

evolution of SN 2017egm with that of other well-observed SLSNe-I and find it is most similar to SN 2015bn (see the bottom panel of Figure 3) during all available phases. They both show less evolution than others. Their optical colors are roughly constant near the peak with $g - r \approx r - i \approx -0.2$ mag, and they become gradually redder until $\sim +100$ days. After $\sim +100$ days, the $g - r$ color curve of SN 2017egm appears to flatten out, probably because of multiple bumps and the strong, varying emission-line features in the corresponding wavelength regimes.

3.2. Pseudo-bolometric Light Curve

The densely sampled multiband light curves of SN 2017egm allow us to analyze its spectral energy distributions (SEDs) at different epochs. We use the `PhotoFit` package (Soumagnac et al. 2020) to fit the blackbody temperature (T_{bb}), luminosity (L_{bb}), and effective radius (R_{bb}). The fitting results are given in Table 3. The blackbody model fits the SEDs well near maximum light. The observing cadence after +150 days in *B* and *V* is sparse except for the *g* band; thus, we interpolate the *g*-band light curve to match with the *BV* epochs. We require at

Table 2
Summary of Late-time Spectroscopic Observations of SN 2017egm

UT date	JD – 2,458,000	Phase ^a (days)	Exp. Time (s)	Airmass	Telescope /Instrument
2017-09-16.50	13.00	84.0	900	2.9	P200/DBSP
2017-09-27.54	24.04	94.8	2100	1.9	Shane/Kast
2017-10-08.50	35.00	105.5	720	1.5	Shane/AeroSpOpIR
2017-10-19.55	46.05	116.2	1200	1.3	Shane/Kast
2017-10-25.54	52.04	122.0	2100	1.3	Shane/Kast
2017-10-30.47	56.97	126.8	900	1.3	P200/DBSP
2017-10-30.54	57.04	126.9	3000	1.2	Shane/Kast
2017-11-16.58	74.08	143.4	2965	1.3	IRTF/Spex
2017-11-21.50	79.00	148.2	1980	1.1	Shane/Kast
2017-12-12.48	99.98	169.0	3600	1.1	Shane/Kast
2017-12-18.50	106.00	174.4	3600	1.0	Shane/Kast
2017-12-28.43	115.93	184.0	3 × 1000	1.1	P200/DBSP
2018-01-13.50	132.00	199.6	3600	1.0	Shane/Kast
2018-03-14.29	191.79	257.6	600	1.0	LBT/MODS
2018-03-17.99	195.49	261.2	2 × 1800	1.1	GTC/OSIRIS

Note.

^a Rest-frame time (days) relative to the epoch of the *g*-band peak brightness.

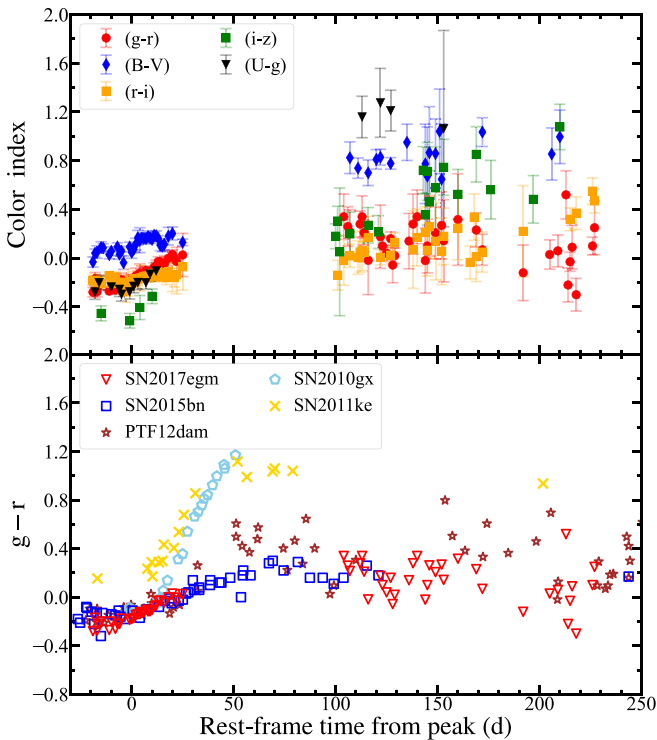


Figure 3. Optical color evolution of SN 2017egm. Top: evolution of a selection of optical colors. Bottom: comparison of rest-frame $g - r$ color with that of other well-observed SLSNe-I.

least three photometry bands in the fitting. We do not use the NIR *JHK* data in the single blackbody fitting, and their analysis is shown in next section.

In Figure 4, we show the temporal variations of inferred blackbody parameters and compare them with those of PTF12dam (Nicholl et al. 2013), Gaia16apd (Kangas et al. 2017), and SN 2015bn (Nicholl et al. 2016). SN 2017egm evolves in temperature like Gaia16apd but with smaller radii and luminosities. The total observed radiation energy is close to

7.8×10^{50} erg. Distinct from the smooth decline in the other three, the bolometric light curve of SN 2017egm features several slope changes, including high temperature initially with a steady cooling, a small bump followed by a steep decline, and then a late-time broad bump accompanied by rising temperature. It is worth noting that the late-time bolometric light curves at $\gtrsim 150$ days, which exhibited variations including a broad bump, were synthesized without NUV photometry. Thus, the derived blackbody parameters were less certain than those at earlier phases. However, such a multitude of variations with complicated characteristics suggests that it may have undergone multiple physical processes, which can hardly be explained by a simple magnetar or ^{56}Ni decay model.

Recent work suggests that the undulations and late-stage bumps appear to be a common phenomenon among SLSNe-I (Inserra et al. 2017; Chen et al. 2023; Hosseinzadeh et al. 2022). There are two main interpretations. One attributes them to the temporal variation of the central engine, which could be modulated by photon diffusion in the ejecta, or the change in opacity that causes the variations in photospheric emission (see discussions in Hosseinzadeh et al. 2022 and references therein). The other mechanism invokes the CSI model, in which the ejecta–CSM interaction is an effective process to convert mechanical energy into thermal emission. In the case of SN 2017egm, the latter scenario seems to be preferable. First, Wheeler et al. (2017) find that the linear rise and decline around the sharp peak of SN 2017egm can be well explained by the CSI model but are difficult to fit with the magnetar model, and they also expected that the late-time light curves could discriminate between the two models. The magnetar model (Vurm & Metzger 2021; Hosseinzadeh et al. 2022) has significant issues in fitting the bumps. We discuss the models further in Section 4.

3.3. MIR Excess and Dust Emission

The NEOWISE survey visited the sky region of SN 2017egm every six months since 2014 and acquired a total of 14 epochs of observations. The images at the first

Table 3
Best-fit Blackbody Parameters

Phase ^a (days)	Temperature T_{bb} (10^3 K)	Radius R_{bb} (10^{15} cm)	Luminosity L_{bb} ($\text{Log}_{10}(\text{erg s}^{-1})$)
-19.02	17.36 ± 0.15	1.18 ± 0.01	43.95 ± 0.03
-18.05	17.03 ± 0.13	1.22 ± 0.01	43.95 ± 0.02
-17.08	16.45 ± 0.14	1.32 ± 0.02	43.96 ± 0.03
-16.11	16.24 ± 0.11	1.37 ± 0.01	43.97 ± 0.03
-15.39	16.13 ± 0.12	1.43 ± 0.02	43.99 ± 0.02
-10.29	15.29 ± 0.10	1.79 ± 0.02	44.10 ± 0.02
-8.35	14.86 ± 0.09	1.95 ± 0.02	44.12 ± 0.02
-7.38	14.53 ± 0.09	2.09 ± 0.02	44.14 ± 0.02
-6.40	14.39 ± 0.08	2.17 ± 0.02	44.16 ± 0.02
-5.42	14.77 ± 0.10	2.15 ± 0.03	44.20 ± 0.02
-4.45	14.53 ± 0.09	2.26 ± 0.03	44.21 ± 0.02
-1.55	13.63 ± 0.09	2.55 ± 0.03	44.20 ± 0.02
-0.57	13.40 ± 0.07	2.61 ± 0.02	44.19 ± 0.02
0.40	12.95 ± 0.06	2.70 ± 0.02	44.17 ± 0.01
1.37	12.73 ± 0.06	2.79 ± 0.03	44.16 ± 0.02
2.34	12.68 ± 0.06	2.71 ± 0.02	44.13 ± 0.01
3.31	12.12 ± 0.09	2.95 ± 0.05	44.13 ± 0.02
4.28	12.03 ± 0.06	2.91 ± 0.03	44.10 ± 0.02
5.26	11.80 ± 0.05	2.95 ± 0.03	44.08 ± 0.02
6.22	11.63 ± 0.06	2.94 ± 0.03	44.05 ± 0.02
7.19	11.34 ± 0.06	3.05 ± 0.03	44.04 ± 0.02
8.16	11.18 ± 0.05	3.07 ± 0.03	44.02 ± 0.02
9.13	11.02 ± 0.06	3.11 ± 0.03	44.01 ± 0.02
10.10	10.83 ± 0.05	3.19 ± 0.03	44.00 ± 0.02
11.07	10.79 ± 0.06	3.14 ± 0.03	43.98 ± 0.02
11.97	10.58 ± 0.06	3.22 ± 0.03	43.97 ± 0.01
12.04	10.57 ± 0.08	3.22 ± 0.05	43.96 ± 0.03
13.98	10.07 ± 0.18	3.42 ± 0.08	43.93 ± 0.06
15.91	10.24 ± 0.14	3.29 ± 0.08	43.92 ± 0.06
17.85	9.88 ± 0.13	3.38 ± 0.08	43.89 ± 0.05
19.79	9.86 ± 0.12	3.41 ± 0.07	43.89 ± 0.04
20.76	9.73 ± 0.11	3.49 ± 0.07	43.88 ± 0.05
21.73	9.72 ± 0.10	3.44 ± 0.06	43.87 ± 0.04
24.65	9.57 ± 0.08	3.47 ± 0.05	43.86 ± 0.04
27.56	9.41 ± 0.08	3.48 ± 0.10	43.83 ± 0.06
28.53	9.34 ± 0.07	3.46 ± 0.12	43.81 ± 0.07
29.50	8.94 ± 0.12	3.70 ± 0.14	43.79 ± 0.09
99.65	6.35 ± 0.10	3.51 ± 0.12	43.15 ± 0.04
103.55	5.97 ± 0.08	3.98 ± 0.14	43.16 ± 0.05
106.83	6.15 ± 0.13	3.39 ± 0.17	43.07 ± 0.07
111.30	6.11 ± 0.14	3.33 ± 0.19	43.04 ± 0.07
115.17	6.58 ± 0.13	2.78 ± 0.12	43.01 ± 0.04
121.96	6.20 ± 0.11	3.17 ± 0.13	43.03 ± 0.05
126.82	6.91 ± 0.10	2.38 ± 0.07	42.96 ± 0.03
128.75	6.59 ± 0.14	2.34 ± 0.11	42.87 ± 0.04
135.50	5.78 ± 0.34	2.17 ± 0.30	42.57 ± 0.16
137.45	6.45 ± 0.70	1.54 ± 0.35	42.47 ± 0.19
139.35	5.72 ± 0.51	1.87 ± 0.39	42.43 ± 0.22
140.41	5.81 ± 0.35	1.69 ± 0.22	42.36 ± 0.13
143.41	5.07 ± 0.35	1.92 ± 0.28	42.24 ± 0.12
144.38	5.36 ± 0.34	1.72 ± 0.22	42.24 ± 0.11
145.35	5.22 ± 0.42	1.68 ± 0.32	42.17 ± 0.20
148.26	4.78 ± 0.39	1.95 ± 0.40	42.15 ± 0.26
151.17	5.17 ± 0.55	1.61 ± 0.39	42.12 ± 0.22
152.13	6.30 ± 1.37	0.99 ± 0.43	42.04 ± 0.28
159.85	6.02 ± 1.23	1.42 ± 0.59	42.28 ± 0.29
165.63	7.19 ± 0.63	1.03 ± 0.17	42.31 ± 0.13
167.57	7.85 ± 1.06	0.82 ± 0.20	42.26 ± 0.21
168.54	7.44 ± 1.02	0.91 ± 0.22	42.26 ± 0.18
171.45	7.89 ± 0.93	0.82 ± 0.16	42.27 ± 0.21
204.45	9.46 ± 1.02	0.62 ± 0.11	42.34 ± 0.26
208.33	9.20 ± 1.06	0.63 ± 0.12	42.31 ± 0.28
211.00	7.32 ± 0.40	0.99 ± 0.09	42.30 ± 0.10

Table 3
(Continued)

Phase ^a (days)	Temperature T_{bb} (10^3 K)	Radius R_{bb} (10^{15} cm)	Luminosity L_{bb} ($\text{Log}_{10}(\text{erg s}^{-1})$)
212.04	6.34 ± 0.48	1.26 ± 0.17	42.26 ± 0.12
213.21	7.96 ± 0.65	0.85 ± 0.11	42.31 ± 0.16
214.02	8.47 ± 0.76	0.72 ± 0.11	42.28 ± 0.17
215.04	5.58 ± 0.53	1.54 ± 0.30	42.22 ± 0.11
217.79	7.22 ± 1.40	0.96 ± 0.30	42.25 ± 0.28
225.75	7.67 ± 0.66	0.86 ± 0.14	42.26 ± 0.12
233.55	6.90 ± 1.36	0.89 ± 0.32	42.11 ± 0.23
248.99	7.19 ± 1.45	0.59 ± 0.26	41.83 ± 0.28

Note.

^a Rest-frame time (days) relative to the epoch of the g -band peak brightness. Data after +148 days were fitted without UV limit.

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

NEOWISE epoch are used as references since they were observed securely before the SN explosion. We then perform image subtraction with HOTPANTS and PSF photometry on the difference images following Jiang et al. (2021). We take the epochs displaying $>3\sigma$ detection at the position of SN 2017egm in at least one band as robust MIR excess (see the light curve in Figure 5). The excesses are clearly detectable at +137, +292, and +492 days after the g -band peak. SN 2017egm remained luminous in the optical band at +137 and +260 days, indicating a non-negligible contribution from the Rayleigh–Jeans tail of the optical blackbody. Therefore, we try to fit the overall optical–NIR–MIR SEDs with double-blackbody functions for these two epochs (see Figure 5). The fitting results show that the MIR excesses are mainly dominated by the blackbody component peaked in the MIR, which can be naturally attributed to reprocessed dust emission. The dust blackbody temperatures at the three epochs are 520 ± 70 , 565 ± 83 , and 827 ± 45 K with luminosities of (3.54 ± 1.50) , (3.89 ± 2.01) , and $(1.65 \pm 0.40) \times 10^{41}$ erg s⁻¹, respectively (see Table 4 for the fitting results). The last epoch has a significantly bluer W1 – W2 color and subsequently higher inferred blackbody temperature than the previous two epochs, suggesting that the dust might be heated up while the SN luminosity decreased. Our measurements of the W1 and W2 excesses are consistent with those found by Sun et al. (2022), but they did not infer blackbody parameters of dust emission owing to a lack of contemporaneous optical data.

The origin of dust in SLSNe remains poorly explored until very recently. Chen et al. (2021) has concluded that the prominent IR excess detected after +230 days in SN 2018bsz can only be well explained by newly formed dust within the SNe ejecta after careful analysis. Moreover, Sun et al. (2022) performed a systematic study of the MIR light curves of 10 SLSNe at $z < 0.12$, including SN 2017egm, and suggested that the MIR excess of SN 2017egm may also be explained by the newly formed dust model like SN 2018bsz, owing to their similarities. One notable characteristic that makes SN 2017egm distinct from other slowly declining SLSNe-I is the rapid drop in luminosity that occurred between +120 and +150 days, which is reminiscent of the sudden drop starting at +98 days observed in SN 2018bsz. However, as claimed by Chen et al. (2021), the drop is yet likely due to the ejecta transitioning to the nebular phase rather than dust extinction, although robust

Table 4
Blackbody Fitting Results for Epochs with MIR Data

Phase ^a (days)	$T_{\text{IR,bb}}$ (K)	$R_{\text{IR,bb}}$ (10^{15} cm)	$L_{\text{IR,bb}}$ (10^{41} erg s ⁻¹)	$T_{\text{Opt,bb}}$ (K)	$R_{\text{Opt,bb}}$ (10^{15} cm)	$L_{\text{Opt,bb}}$ (10^{41} erg s ⁻¹)
+137	520 ± 70	82.1 ± 12.0	3.54 ± 1.50	7100 ± 500	1.2 ± 0.2	25.30 ± 9.70
+292	565 ± 83	73.1 ± 14.7	3.89 ± 2.01	4800 ± 420	1.5 ± 0.5	5.51 ± 2.08
+492	827 ± 45	22.2 ± 2.5	1.65 ± 0.40	...	...	...

Note.

^a Rest-frame time (days) relative to the epoch of the g-band peak brightness.

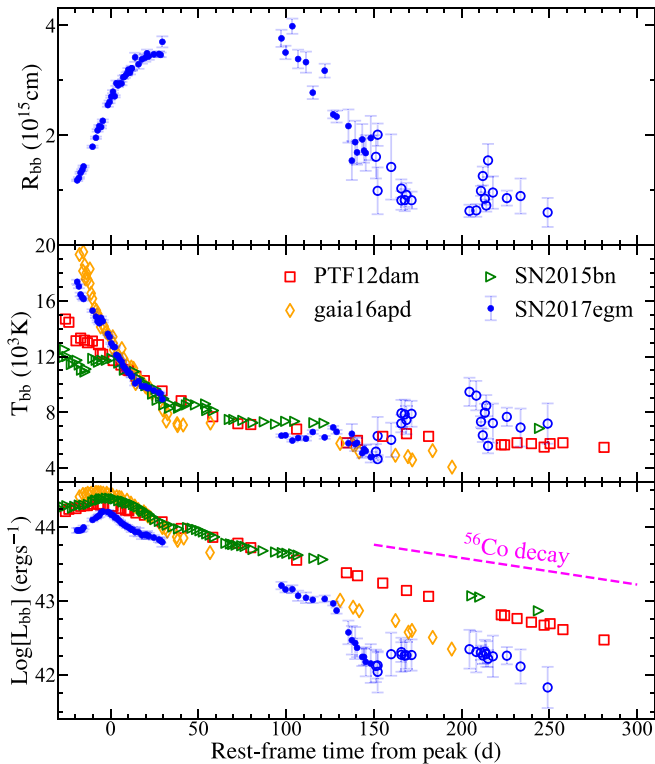


Figure 4. Evolution of the blackbody radius (top panel), temperature (middle panel), and luminosity (bottom panel) of SN 2017egm. The evolution of three other well-observed SLSNe-I (PTF12dam (red squares), SN2015bn (green triangles), and Gaia16apd (orange diamonds)) is overplotted for comparison. The open symbols denote that the blackbody fitting is performed without NUV photometry.

evidence for dust formation appears later (see also Pursiainen et al. 2022). Actually, an IR echo of a proper pre-existing spherical dust shell can equally reproduce the observed MIR emission. Note that $R_{\text{bb,IR}}$ is around $(7.3\text{--}8.2) \times 10^{16}$ cm, which is much larger than $R_{\text{bb,Opt}}$ ($\sim 10^{15}$ cm) in our double-blackbody fits at both epochs. The IR emission comes much further out than the region of ejecta, and thus the excess may be dominated by pre-existing dust emission. It is worthwhile to note that the inferred dust temperature shows a rising trend albeit with large errors, which is unusual in the echo scenario. Nevertheless, an asymmetric dust bubble shell, i.e., the shell on the far side is closer to the SNe than that in our line of sight, can produce such a trend. In spite of this, we cannot definitively exclude a dust formation process at later epochs, particularly considering a higher blackbody temperature and smaller radius for the third MIR epoch (+492 days, see Table 4), which may represent the dust formed during ejecta–CSM collision. In fact, the newly formed and pre-existing dust could work

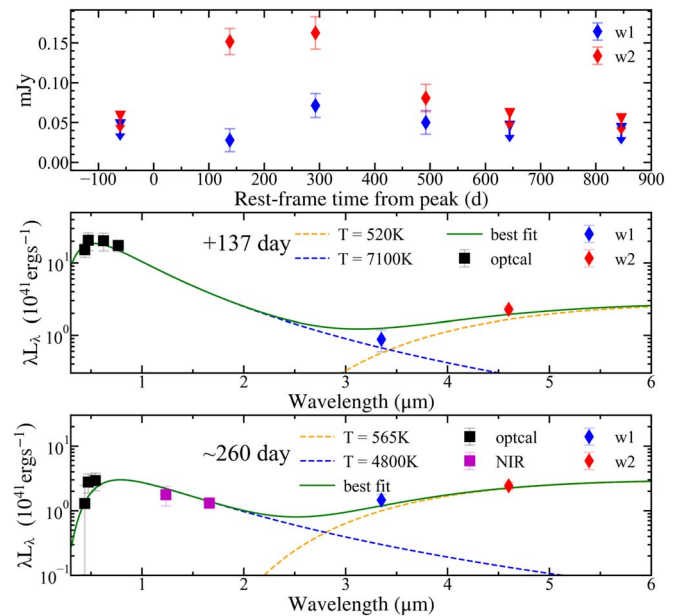


Figure 5. MIR light curves of SN 2017egm and the double-blackbody fitting of the UV–optical–IR SEDs. Top panel: W1 ($3.4 \mu\text{m}$, blue diamonds) and W2 ($4.6 \mu\text{m}$, red diamonds) light curves of SN 2017egm measured from the NEOWISE survey, in which the triangles mark the 3σ upper limits. Middle and bottom panels: SED fitting at +137 and +260 days. Two blackbody components are required to account for the overall SED, which is peaked at optical and MIR bands, respectively.

(The data used to create this figure are available.)

simultaneously, as has been demonstrated in SN 2006jc (Mattila et al. 2008) and some other SNe II (e.g., Pozzo et al. 2004; Meikle et al. 2007).

3.4. Spectroscopic Analysis

The optical spectra are presented chronologically in Figure 6, with notable O I, Ca II, and Mg I emission lines marked. For ~ 200 days after the peak, its blue continuum faded rapidly, and in contrast, the emission-line features evolve slowly. We identify the lines by comparing with other SLSNe-I (Nicholl et al. 2016, 2019; Kangas et al. 2017; Quimby et al. 2018).

Two NIR spectra are presented in Figure 7. There is a strong feature around the region of He I $\lambda 10830$ at +105 days. There was controversy in the past over the identification of He I $\lambda 10830$ in SLSNe-I spectra. The proposed He I $\lambda 10830$ in the spectra of SN 2012il (Inserra et al. 2013) was later found to be a broad emission feature redshifted by $\sim 1500 \text{ km s}^{-1}$ relative to $\lambda 10830$, and may instead be blueshifted nebular Pa γ emission (Quimby et al. 2018). In our case, the feature around

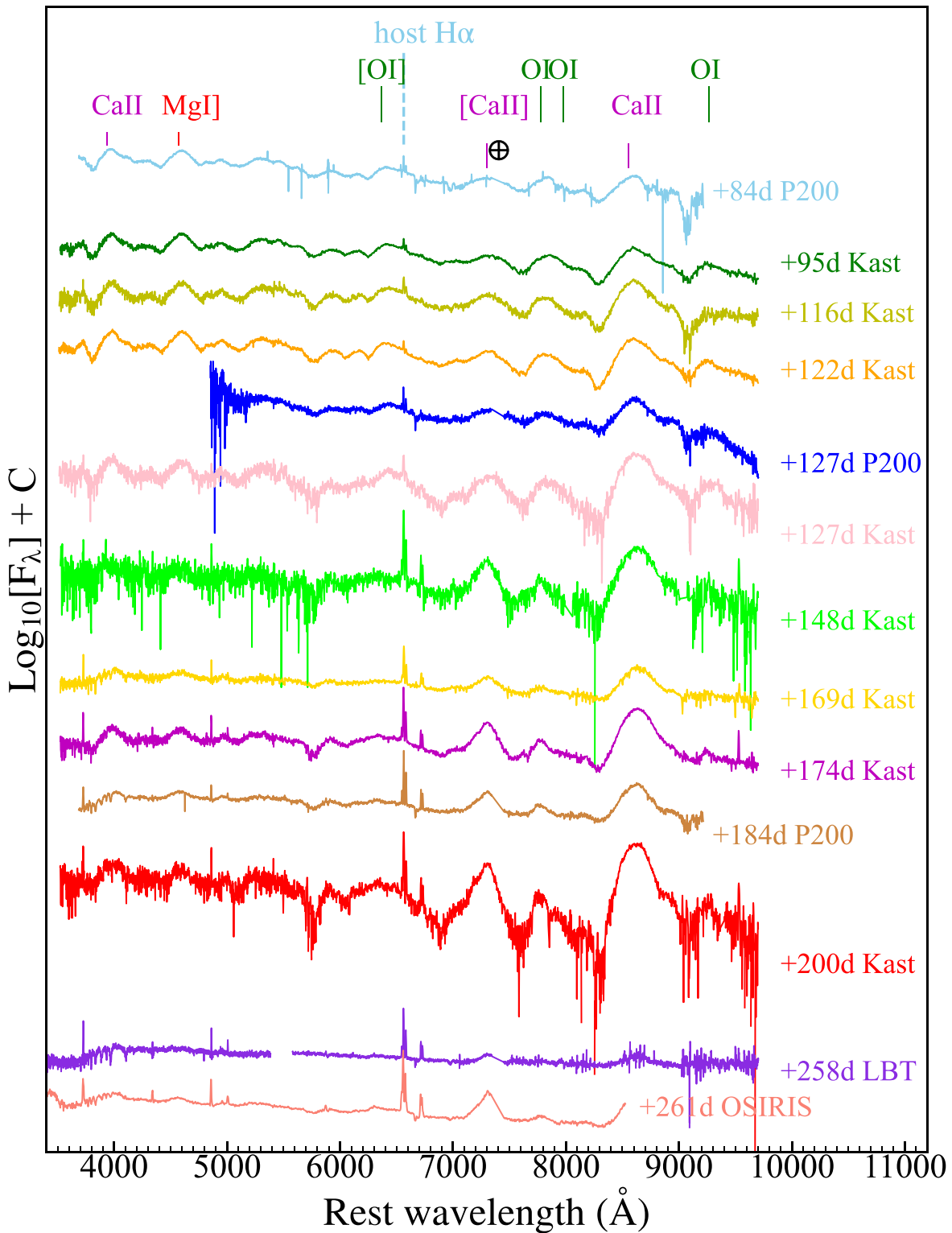


Figure 6. Rest-frame spectral evolution of SN 2017egm. Strong O I, Ca II, and Mg I] $\lambda 4571$ features are marked by different colors at the top. The \oplus symbol marks the positions of the strongest telluric absorption bands, which have been masked. Each spectrum is labeled by the instrument employed and the rest-frame phase from maximum light. The data used to create this figure are made available digitally.

(The data used to create this figure are available.)

10830 Å at +105 days also shows a strong P Cygni profile with a velocity of ~ -8000 km s $^{-1}$, which is similar to SN 2019hge, the only other SLSN-I with He I 1.08 μ m, so it cannot be a nebular Pa γ line. The nondetection of He I at ~ 2.05 μ m might

be simply due to the low S/N, since it is generally much weaker than He I $\lambda 10830$ (Yan et al. 2020). Interestingly, the He I feature faded rapidly with the detection of a weak emission line at +143 days. On the other hand, it is worthwhile to note

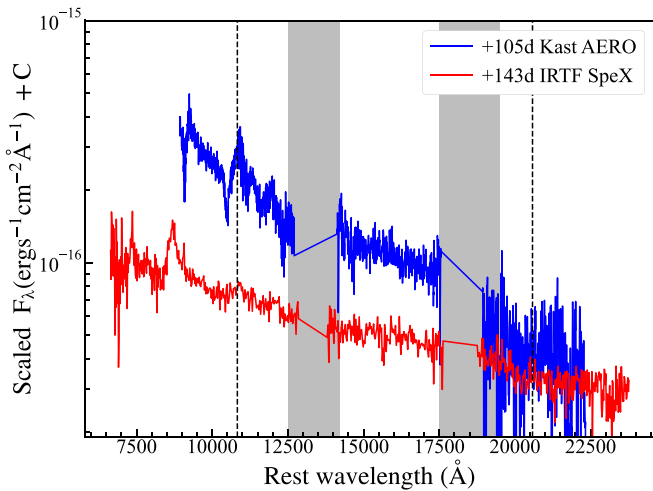


Figure 7. NIR spectra at two epochs. The prominent He I line $\lambda 10830$ is detected at +105 days. Strong telluric and unreliable regions in the spectra are masked out. The dashed lines mark the rest-frame wavelengths of He I lines at 10830 and 20586 Å. The data used to create this figure are made available digitally.

(The data used to create this figure are available.)

that there is no significant He I $\lambda 10830$ in the early-time NIR spectra (-2.7 and -0.5 days) according to Bose et al. (2018), indicating that the He I could be short-lived.

Yan et al. (2020) reported six He-rich SLSNe-Ib from the ZTF Phase-I SLSN-I sample, suggesting that the key to identifying He-rich events is the presence of multiple He features. We cross-check our optical spectra for He features. In Figure 8, we compare the spectra of SN 2017egm at $\sim +100$ days with the well-studied SLSN-Ic SN 2015bn in detail. Four He I absorption lines (He I $\lambda\lambda 5876, 6678, 7065, 7281$) are detected in SN 2017egm with a velocity of -7000 km s $^{-1}$. He I $\lambda 5876$ is the strongest of the four, with a deep absorption feature that could be caused by possible contamination from Na I $\lambda 5890$. The other three lines are weaker, while the He I $\lambda 7065$ absorption is well isolated. Since the four He I lines are detected in multiple spectra of SN 2017egm between +95 and +127 days, the existence of helium is firmly established. Further comparisons between SN 2017egm and other known SLSNe-Ib are presented in the next section.

3.5. Spectroscopic Evolution

Apart from the strong W-shaped O II absorption features at 3700–4500 Å, the early-stage spectra of SN 2017egm are mostly devoid of other prominent features, while heavily blended metallic lines start to appear at $\sim +26$ days (Bose et al. 2018; see their Figure 6 for details). Some common line features in SLSNe-Ic are identified, such as a few Fe II lines and Na I D at 4900–5600 Å, the Ca II $\lambda 3750$, the Ca II $\lambda\lambda 3934, 3969$ H&K doublet, the Ca II $\lambda\lambda 8498, 8542, 8662$ NIR triplet, and O I $\lambda 7774$. At +84 days, the spectrum is full of strong, blended lines and P Cygni profiles, with also a strong Mg I $\lambda 4571$ line, which usually emerges at $\gtrsim 30$ days post-peak (Inserra et al. 2013; Nicholl et al. 2016). Other prominent features identified are also shown in Figure 8 and compared with those in SN 2015bn. The Fe II lines between 4200 and 5000 Å, including contributions from Mg II, become stronger in the high-quality +95 days spectrum, in which the previously

dominant O II lines become weaker and finally disappear as the ejecta cool and these species recombine. At the same time, the strengths of [O I] $\lambda\lambda 6300, 6364$, Na I $\lambda 5890$, and the calcium lines increase substantially. The Ca II $\lambda 3750$ is weaker than the prominent Ca II $\lambda\lambda 3934, 3969$ H&K doublet in both early-time (+26 days; Bose et al. 2018) and late-time (up to +127 days, see Figure 6) spectra. There is an unidentified line at ~ 6100 Å, and a similar line seen for SN 2015bn was interpreted as a possibly detached, high-velocity component of Si II (Nicholl et al. 2016). The asymmetric O I $\lambda 7774$ line profile may be contaminated by Mg II $\lambda\lambda 7877, 7896$. By +148 days, the blue continuum has faded, and thus the features at the blue end (< 6000 Å; e.g., Mg I $\lambda 4571$, Ca II $\lambda\lambda 3969, 3750$, and a few Fe II lines), which were previously overwhelmed by the continuum, become quite visible. It is notable that the inferred velocity of He I $\lambda 10830$ (-8000 km s $^{-1}$) is larger than that of the optical He I lines (-7000 km s $^{-1}$). A similar velocity difference was also found in SN 2019hge (Yan et al. 2020; see their Figure 1 for optical He I lines at -6000 km s $^{-1}$ and their Figure 2 for He I $\lambda 10830$ at -8000 km s $^{-1}$), which was attributed to either the difference in excitation levels of the NIR and optical lines or the He I $\lambda 10830$ being blended with a possible blueshifted C I $\lambda 10691$ line.

The He I $\lambda 10830$ fades concurrently in the +143 days NIR spectra (see Figure 7) as the He I $\lambda\lambda 7065, 7281$ appears to fade in the +148 days optical spectra (see Figure 9 for the zoomed-in view of the spectra normalized to [Ca II] $\lambda 7300$). Curiously, the apparent fading in He I happens concurrently when the light curve drops rapidly to a local minimum. Interestingly, He I slightly emerges again at +200 days, coinciding with the second bump in the light curve. If the He I features and the light curve indeed coevolve, it could indicate that the source of nonthermal emission needed to produce the He I features (see, e.g., Yan et al. 2020) may also power the optical emission. We note that the above-mentioned interpretation is complicated by the possible blending of the [Ca II] $\lambda 7300$ line with oxygen features (Nicholl et al. 2019). We also note that the He I $\lambda 5876$ feature is always present in most optical spectra, though it is heavily blended with Na I $\lambda 5890$. Most line velocities can be well fitted by a broad Gaussian and the line velocities decline slowly. For instance, the velocity of [Ca II] $\lambda 7300$ drops from 10,900 km s $^{-1}$ (+95 days) to 8000 km s $^{-1}$ (+200 days).

The features described above are common for slowly declining Type Ic SLSNe, so we try to compare the spectral evolution of SN 2017egm with that of PTF12dam and SN 2015bn in Figure 10. However, SN 2017egm differs greatly from the other two objects at early phases; for example, the O II absorption features disappear faster and the O I $\lambda 7774$ is weaker near the time of peak brightness. Their later evolution is similar except for the presence of strong absorption features at 5876 Å as well as other weaker He I lines in SN 2017egm.

Yan et al. (2020) classified SN 2019hge as an SLSN-Ib based on its NIR spectrum and the other five events as good SLSN-Ib/Iib candidates. Here we compare the optical spectra of SN 2017egm with those of SN 2019hge and PTF10hgi (Figure 11). SN 2019hge is redder with strong Si II $\lambda 6355$, C II $\lambda 6580$, and He I at an early phase, while these features are weaker or absent in SN 2017egm at similar epochs. Similar to SN 2017egm, the He I in SN 2019hge appeared most prominently when the temperature was relatively low ($T_{\text{bb}} \sim 7000$ – 8000 K) but were suppressed at higher temperature in the earlier phases (Yan et al. 2020). The He I

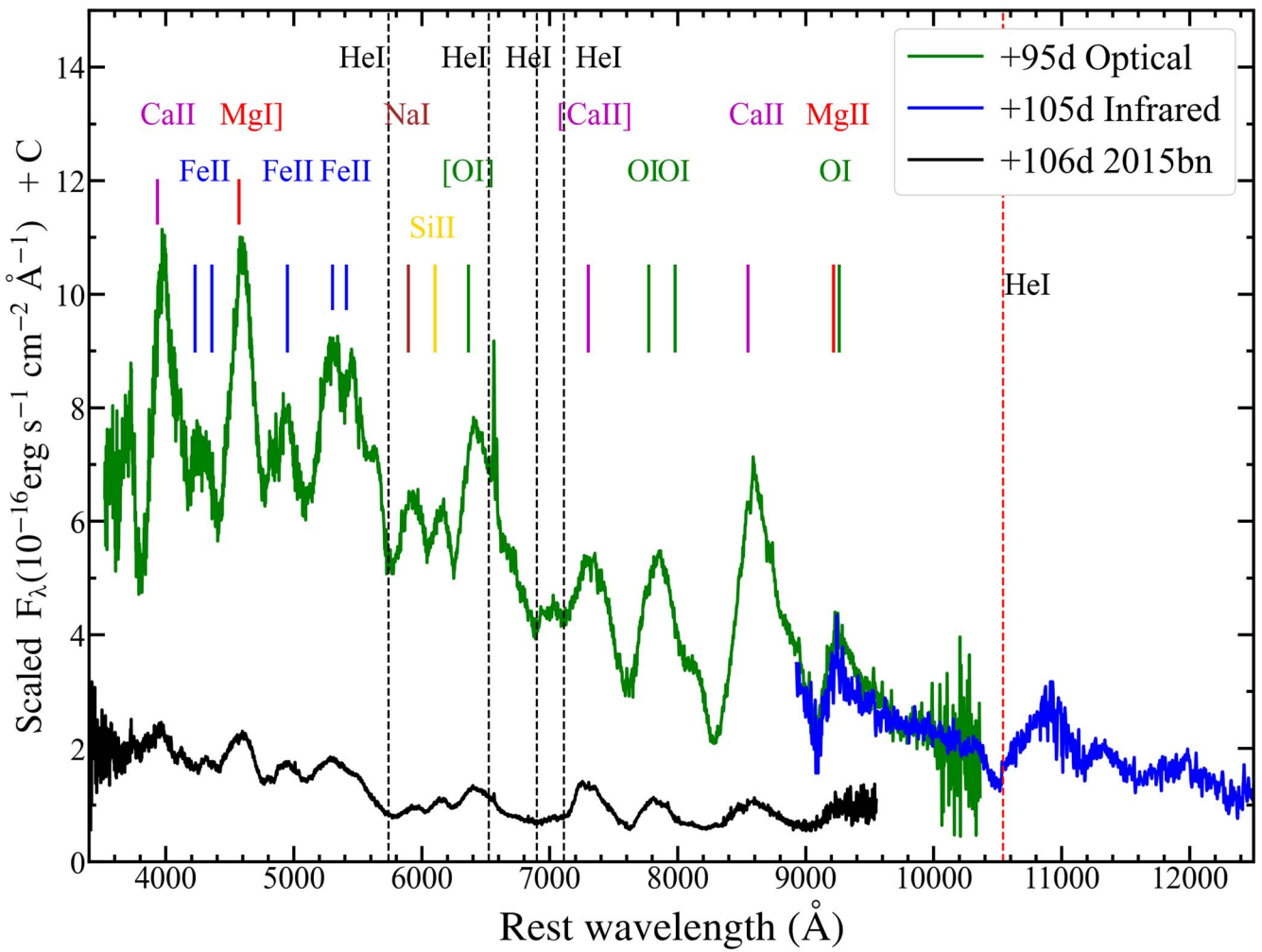


Figure 8. Optical spectrum of SN 2017egm at +95 days post-maximum and NIR spectrum at +105 days. The optical spectrum of SLSN-Ic SN 2015bn at +106 days is plotted for comparison. The identified lines are labeled by different colors at the top. The dashed lines mark the locations of He I $\lambda\lambda 5876, 6678, 7065,$ and 7281 , with a velocity of -7000 km s^{-1} (black) and He I $\lambda 10830$ with a velocity of -8000 km s^{-1} (red).

absorption features of SN 2017egm, with a velocity of around -7000 km s^{-1} , are similar to both SN 2019hge and PTF10hgi at late phases. Other nebular-phase features of those objects are similar to those in SLSNe-Ic. Meanwhile, the light curves of the SLSNe-Ib in the ZTF sample (see Figure 12) show blue bumps, strong undulations, and mostly relatively low peak luminosities in comparison with SLSNe-Ic (Chen et al. 2023). Interestingly, with a peak luminosity $M_r \approx -21$ mag, SN 2017egm is the most luminous among the known SLSNe-Ib, while the peak magnitudes M_r of other SLSNe-Ib/IIb are all dimmer than -20.5 . As discussed earlier, the sharp peak of SN 2017egm may suggest a constant-density CSM shell ($s=0$), as previously noted by Chatzopoulos et al. (2013) and Wheeler et al. (2017). Chen et al. (2023) also concluded that three SLSNe-Ib strongly prefer the CSM+Ni model over the magnetar model. However, none of the SLSNe-Ib shows narrow nebular emission-line features indicative of ejecta-CSM interaction like in SNe-Ibn or SNe-IIIn.

4. Summary and Discussion

We have conducted a comprehensive photometric and spectroscopic analysis of SN 2017egm, a hydrogen-poor SLSN that exploded in the rare environment of a massive and metal-rich galaxy, and we identify it as the closest SLSN-Ib found to

date. The main results obtained from our analysis are summarized below.

1. The long-term multiband light curves of SN 2017egm spanning ~ 300 days have a sharp peak, rapid decline, and multiple late-time bumps, but the object can be broadly categorized into the subclass of slowly evolving SLSNe-I according to the luminosity and color evolution near peak brightness.
2. The spectra of SN 2017egm resemble those of SLSNe-Ic except for the presence of strong He I $\lambda 10830$ emission and multiple optical He I absorption lines. Given the presence of these helium features, we classify SN 2017egm as an SLSN-Ib, which is a rare yet accumulating subpopulation of SLSNe-I (Yan et al. 2020).
3. SN 2017egm is one of a handful of SLSNe-I with a significant IR excess ($L_{\text{IR}} \approx 10^8 L_{\odot}$) indicative of dust echoes from pre-existing dust or emission from newly formed dust (Sun et al. 2022).
4. SN 2017egm was not detectable in each of the four-epoch Chandra observations or even in the stacked images. This yields the tightest constraint on the X-ray emission of an SLSN-I to date, with a 3σ upper limit of $1.9 \times 10^{39} \text{ erg s}^{-1}$ in the $0.5\text{--}10 \text{ keV}$ range.

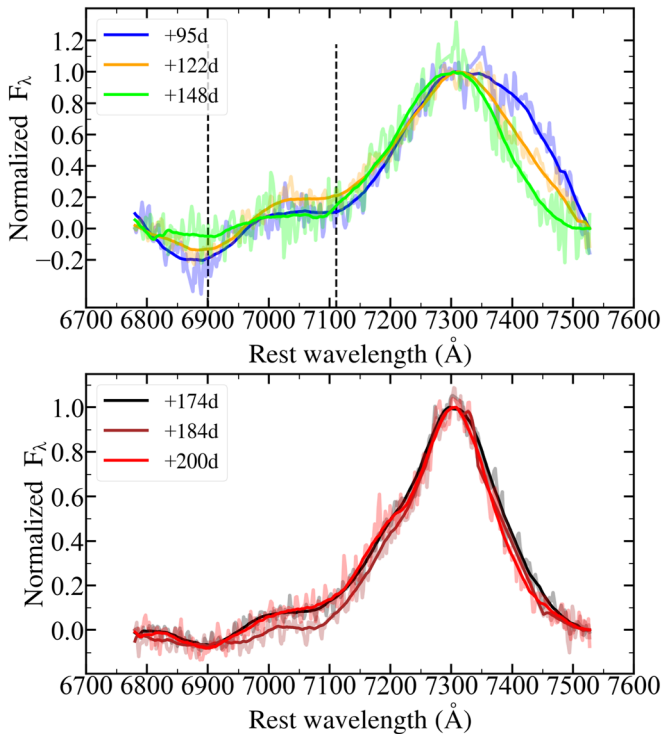


Figure 9. The He I $\lambda\lambda 7065, 7281$ evolution of SN 2017egm. All spectra, with continuum subtracted, have been smoothed using the Savitzky–Golay filtering algorithm and normalized to [Ca II] $\lambda 7300$. All spectra are overlaid onto the original spectral data, which are in the same color. The dashed vertical lines mark He I $\lambda\lambda 7065, 7281$, with a velocity of -7000 km s^{-1} .

The observational features discussed above serve as the most complete characterization of SN 2017egm to date in terms of the unprecedented temporal and wavelength coverage. Before this work, several models were proposed to account for the observations of SN 2017egm, and its light curve seems more likely to be explained by CSM interaction (Wheeler et al. 2017; Hosseinzadeh et al. 2022). On the basis of our more complete characterization, we try to further explore this scenario with TigerFit (Chatzopoulos et al. 2016; Wheeler et al. 2017) assuming a hybrid model by combining radioactive decay with a constant density (camrads0) or a wind-like density (csmrads2) profile (Chatzopoulos et al. 2013). The best-fit model has an ejecta mass of $10.7 M_\odot$ and a ^{56}Ni mass of $0.15 M_\odot$, colliding with a CSM with mass of $2.7 M_\odot$.

So far, no simple models, including our best-fit one or others (Wheeler et al. 2017; Hosseinzadeh et al. 2022), can reproduce the bolometric light curve of SN 2017egm satisfactorily (see Figure 13). The model powered solely by radioactive decay is not viable because it requires substantially more ^{56}Ni than that allowed by the ejecta mass. The magnetar-only model needs a rather smaller ejecta mass, but it fails to reproduce the peak light-curve profile (Wheeler et al. 2017; see their Table 1 for the parameters) and late-time fluctuations. The model will release a total energy significantly exceeding the observed value, even counting in the reprocessed energy radiated in the MIR, which is yet too low to compensate for the sharp drop in optical luminosity (see Figure 13). The CSM model with a constant-density shell could fit the sharp peak well, but a single ejecta–CSM interaction model is inadequate to produce the multiple bumps seen in SN 2017egm.

Liu et al. (2018) has shown that a multiple ejecta–CSM interaction model can fit the undulating bolometric light curve of iPTF15esb, which displays two prominent peaks and a plateau. In their scenario, the appearance of late-time broad $\text{H}\alpha$ emission can be naturally interpreted as the ejecta running into a neutral H shell (Yan et al. 2017a). Massive stars could experience mass losses in the form of eruptions in the final stage of their lives (Vink 2022), and the progenitors of SNe could sometimes expel two or more shells and/or episodic winds. Furthermore, the steep decline ($\sim 0.1 \text{ mag day}^{-1}$) in SN 2017egm is expected in the CSM interaction scenario (Sorokina et al. 2016).

Thus, these observations of light curves may indicate the existence of extended and multiple CSM shells or CSM clumps at different radii around SN 2017egm. The ejecta–CSM interactions could be the sources of the nonthermal excitation needed to produce the He I lines (see, e.g., Yan et al. 2020), so this might explain why the He I features appear to coevolve with the late-time light curve as shown in Figure 9. Similar coevolution of light curve and spectra was seen in the case of hydrogen-rich SN 1996al, which was attributed to CSM interaction (Benetti et al. 2016). One major sign from interaction with the CSM is broad emission lines from shocked photoionized ejecta (see, e.g., Blinnikov 2017), and the “hump” near He I $\lambda 7065$ in spectra from +174 to +200 days (see the bottom panel of Figure 9) may suggest the existence of such features blended by the strong Ca II lines. Detailed modeling will be needed to further model the data and explore the underlying mechanism, but this is beyond the scope of this work.

A common issue with the interpretation in terms of ejecta–CSM interaction for SLSNe-I is the lack of narrow emission lines expected from the photoionized CSM. A hydrogen-deficient CSM can lead to nondetection of Balmer lines, but the lack of emission from other elements could remain problematic. However, Chatzopoulos et al. (2013) suggested that the absence of narrow emission lines in the optical spectra of SLSNe-I does not necessarily argue against CSM interaction. In that scenario, emission due to CSM interaction may appear as a blue continuum, which has been observed in the $\lesssim +200$ days spectra of SN 2017egm with an H-deficient CSM. They argued that the intermediate-width emission such as [O I] $\lambda\lambda 6300, 6364$ and O I $\lambda 7774$ features found in SN 2007bi could be evidence for CSM interaction (Gal-Yam et al. 2009). In fact, Nicholl et al. (2019) noticed a suggested narrow core of [O I] $\lambda 6300$ in the late-time spectra of SN 2017egm, and their latest spectrum at 353 days had the clearest indication of such a core. Our late-time spectra (~ 200 days) show similar profiles (see the bottom panel of Figure 14), albeit wider than the profile in their 353 days spectrum. Interestingly, like the He I features, the [O I] feature also changes significantly during the drastic light-curve evolution. Its primary peak was considerably redshifted before +122 days (see the top panel Figure 14), and the line profiles of [O I] $\lambda\lambda 6300, 6364$ change considerably after the light curve drops rapidly. Since detailed, non-LTE radiation hydrodynamics models of H-poor CSM interaction models are not available, the nature of these lines and their formation sites await further investigation.

We have shown that the color and spectral evolution of SN 2017egm are broadly similar to those of other SLSNe-I such as SN 2015bn and also SLSN-Ib SN 2019hge except for He I lines, yet they have substantial differences in light-curve

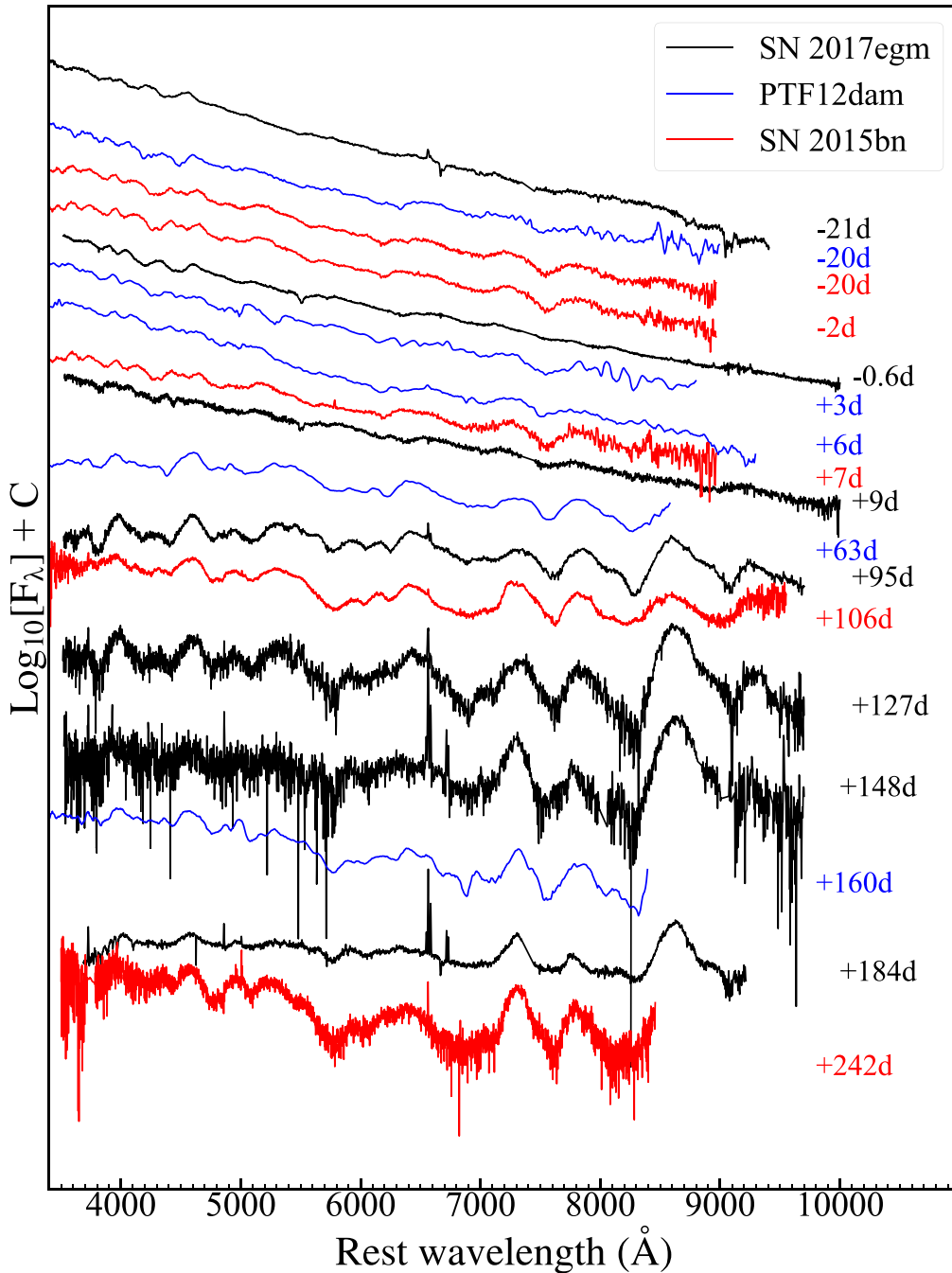


Figure 10. The comparison of optical spectra between SN 2017egm and some other slowly declining Type Ic SLSNe at similar phases, including PTF12dam (Nicholl et al. 2013) and SN 2015bn (Nicholl et al. 2016). Their spectroscopic evolution is nearly identical.

evolution. Previous spectroscopic observations of SLSNe-I have not captured the drastic spectral change in the bumpy phase and thus offered us few clues to the light-curve evolution (Hosseinzadeh et al. 2022). However, our high-S/N spectra obtained at different bumpy phases of SN 2017egm suggest clearly not only the variations in continuum flux but also significant changes in spectroscopic profiles, potentially shedding new light on the formation of lines in the ejecta.

In addition, the X-ray and MIR observations may offer useful insights into SN 2017egm. SN 2017egm holds the tightest X-ray upper limit among SLSNe-I, which might provide strict constraints on the subparsec environment and properties of central engines in SLSNe-I (see, e.g.,

Chevalier & Fransson 2003; Levan et al. 2013; Huang & Li 2018; Margutti et al. 2018; Moriya et al. 2018; Vurm & Metzger 2021). Our deepest X-ray observations in SLSNe-I rule out the densest environments typical of eruptions of luminous blue variable and Type II_n SNe (Margutti et al. 2018), but the parameter space of SN 2017egm ($L_X < 10^{40}$ erg s⁻¹ and X-ray-to-optical luminosity ratio $L_X/L_{\text{Opt}} \lesssim 10^{-3}$) is almost an entirely uncharted territory to explore. Andrews & Smith (2018) invoked the possibility that strong CSM interaction is hidden behind the ejecta over a wide range of viewing angles to explain the absence of narrow emission lines and X-ray emissions in the case of the peculiar iPTF14hls, and it may be of interest to consider similar scenarios for SLSNe-Ib

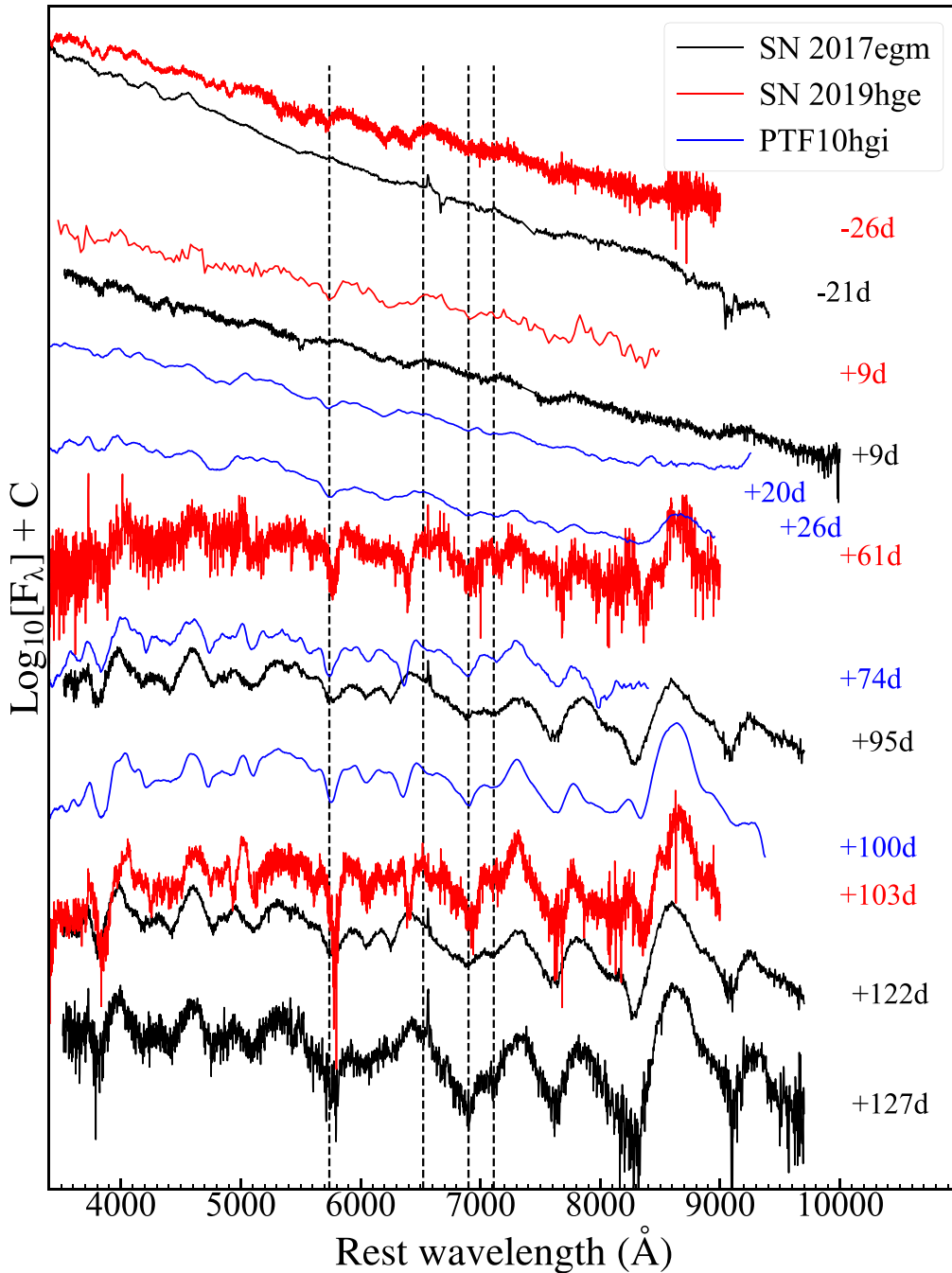


Figure 11. Comparison of optical spectra of SN 2017egm and other well-studied SLSNe-Ib/Iib, SN 2019hge (Yan et al. 2020) and PTF10hgi (Quimby et al. 2018), at similar phases. The dashed lines mark the locations of He I $\lambda\lambda 5876, 6678, 7065, \text{ and } 7281$, with a velocity of -7000 km s^{-1} .

in the context of CSM interactions. On the other hand, the detection of an unambiguous dust emission has not been reported in SLSNe until very recently (Chen et al. 2021; Sun et al. 2022), and SN 2017egm belongs to the population with clear evidence of pre-existing dust or dust formation. The MIR echo agrees nicely with the ejecta–CSM interaction model, and reveals a new promising method to probe the subparsec environment of SLSNe.

In the upcoming golden era of wide-field time-domain surveys, such as the Legacy Survey of Space and Time (Ivezic et al. 2019) with the Rubin Observatory and the Wide-Field Survey Telescope (Lin et al. 2022), SLSNe are expected to soon be discovered at a high rate. SN 2017egm, as a rare SLSN

studied in great detail, will serve as a valuable case for comparison and be re-evaluated statistically in the context of large samples.

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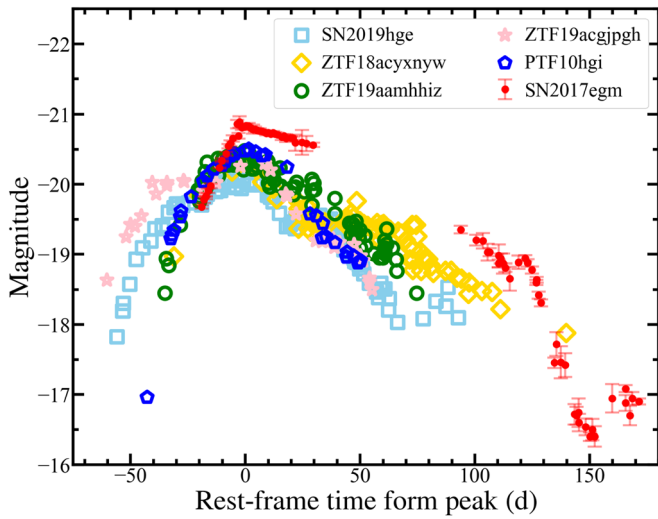


Figure 12. The r -band light curves of five SLSNe-Ib/IIb with well-sampled observations.

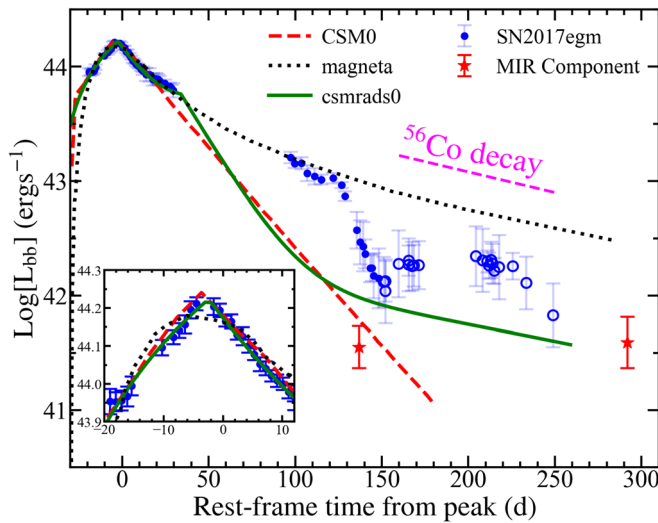


Figure 13. The bolometric light curve is plotted together with the best-fit `csmrads0` model and a previous CSM0/magnetar model from Wheeler et al. (2017). The inset shows a zoomed-in view around the peak.

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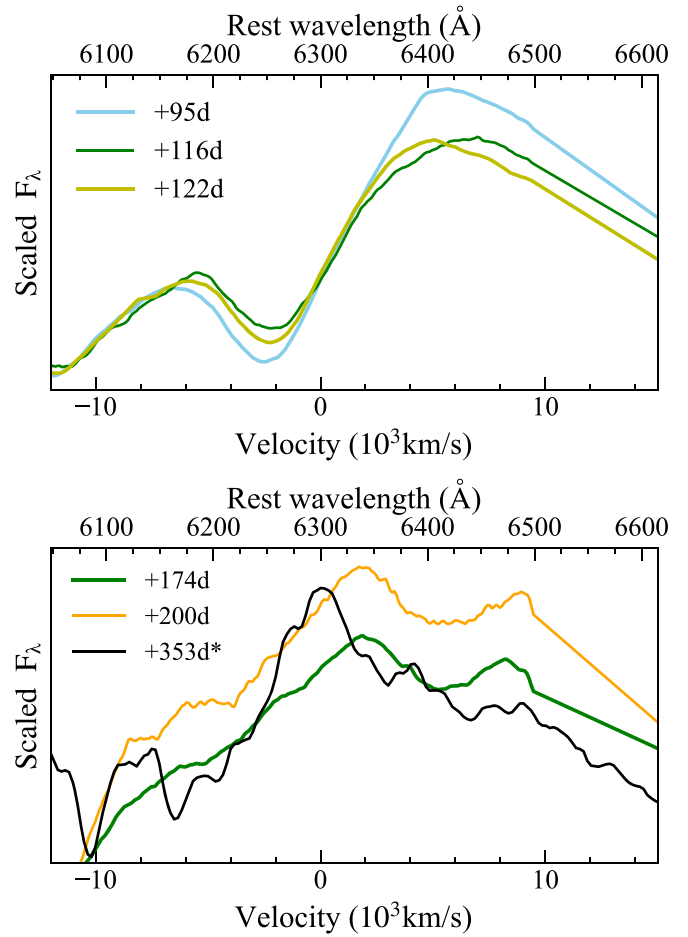


Figure 14. Observed [O I] $\lambda\lambda 6300, 6364$ features. Top panel: the considerably redshifted features of [O I] $\lambda\lambda 6300, 6364$ before 122 days. Bottom panel: a suggested narrow core near 6300 \AA in late-time spectra was previously reported by Nicholl et al. (2019; a spectrum at +353 days from Nicholl et al. 2019 is marked by * in the legend). Our late-time spectra show similar profiles, while the widths of the profiles in our +174 and +200 days spectra are broader than that of the +353 days spectrum from Nicholl et al. (2019). The spectra are smoothed using the Savitzky–Golay filtering algorithm and have been continuum-subtracted and converted to velocity space. The strong host-galaxy $H\alpha$ emission was masked.

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