



Panchromatic JWST Observations and Models of the Dim Type Iax Supernova SN 2024vjm at 200 days

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Abstract

We report JWST spectra and photometry of the underluminous Type Iax supernova (SN Iax) 2024vjm obtained 202.8 rest-frame days postexplosion. The spectrum exhibits a rich set of forbidden lines from low-ionization, intermediate-mass, and iron-group elements, notably the [Ni II] 6.64 μm resonance line, which is a direct indicator of stable nickel. Strong CO and SiO emission is detected alongside a warm dust continuum; the spectral properties are consistent with preexisting rather than newly formed dust. Synthetic spectra were computed with the generalized stellar atmospheres code PHOENIX using simplified ejecta models. The models reproduce the overall spectral energy distribution and the molecular emission features reasonably well, but substantially underestimate the strength of the mid-infrared atomic forbidden lines, leaving the synthetic spectrum dominated by molecular emission. Experiments in which the molecular opacity is suppressed do not recover the forbidden lines; instead, the emission peak migrates to Co and Fe transitions near 2 μm . We attribute this discrepancy to poorly constrained collisional rates and possibly to an excess of iron group material in the current ejecta models. A prominent feature at 12.8 μm is not well accounted for by the [Ne II] 12.81 μm line, indicating that the 12.8 μm feature may be largely due to [Fe III]. The presence of CO, SiO, and stable nickel together with the nondetection of neon places tight constraints on the total ejecta mass and the nucleosynthetic yields of SN Iax progenitor systems.

Unified Astronomy Thesaurus concepts: Type Ia supernovae (1728); Radiative transfer (1335)

1. Introduction

Type Iax supernovae (SNe Iax) are a not-uncommon subclass of thermonuclear supernovae (R. J. Foley et al. 2013). The overall rate of SNe Iax is $\sim 5\%$ – 15% of the Type Ia supernovae (SNe Ia) rate (S. Srivastav et al. 2024; D. D. Desai et al. 2026). SNe Iax are easily distinguishable from the primary class by their relatively

faint light curves and the low expansion velocities observed in their spectra (see S. W. Jha 2017, for a review).

SNe Iax have i -band maxima (i_{max}) that range from about -18.5 mag for SN 2012Z to $i_{\text{max}} \approx -13.7$ mag for SN 2024vjm. SNe Iax are typically divided into three categories based upon their peak brightness (S. W. Jha 2017). Dim SNe Iax have $i_{\text{max}} > -15.5$ mag; other examples include SN 2008ha, SN 2010ae, and 2019gsc (R. J. Foley et al. 2009; M. D. Stritzinger et al. 2014; L. Tomasella et al. 2020). Intermediate brightness SNe Iax have $i_{\text{max}} > -18.0$ mag; examples include SN 2005hk, SN 2019muj, SN 2022xlp, SN 2024pxl, and SN 2025qe (M. M. Phillips et al. 2007; D. K. Sahu et al. 2008; B. Barua et al. 2021; D. Bánhidi et al. 2025; M. R. Magee et al. 2025; M. Singh et al. 2026, W. B. Hoogendam et al. 2025). Bright SNe Iax have $i_{\text{max}} < -18$ mag; members of the bright class include SN 2002cx, SN 2012Z, SN 2014dt, and SN 2024bfu

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(W. Li et al. 2003; M. D. Stritzinger et al. 2015; M. Singh et al. 2018; M. R. Magee et al. 2025).

A variety of models have been proposed to explain the origins of SNe Iax. One model is a close binary system consisting of a C+O+Ne white dwarf (WD) with a helium donor companion star (X. Meng & P. Podsiadlowski 2014; M. Fink et al. 2014; M. Kromer et al. 2015; C. Feldman et al. 2023). Helium accretion induces thermonuclear burning in the primary, that is, a deflagration, but the WD primary fails to fully disrupt, resulting in a bound remnant. This model is known as the failed deflagration model. Another model is the merger of an O+Ne WD with a C+O WD, producing a failed deflagration of the C+O WD, ejecting a very small amount of mass, producing an event that is even dimmer than SN 2024vjm (R. Kashyap et al. 2018). Finally, the pulsating delayed detonation of a near-Chandrasekhar-mass ($M_{\text{Ch}} \sim 1.4M_{\odot}$) WD (M. D. Stritzinger et al. 2015) may also explain SNe Iax.

SNe Iax are quite diverse in peak luminosity, which is expected to vary with progenitor system and explosion mechanism. The failed deflagration models of C+O+Ne WDs tend to produce enough ^{56}Ni to power the explosion; however, their ejecta mass $0.01 < M_{\text{ejecta}} < 0.1 M_{\odot}$ and kinetic energies $10^{48} < E_{\text{KE}} < 10^{49}$ erg are too low (C. Feldman et al. 2023) and hence the models do not fit the postmaximum light curve evolution. The merger of an O+Ne WD and a C+O WD discussed above produces extremely faint and fast light curves; this failing may be alleviated by more massive O+Ne primaries (R. Kashyap et al. 2018). It has been argued (S. Neopane et al. 2022), that WD mergers naturally produce highly magnetized, uniformly rotating WDs that contract and spin up, leading to both: near- M_{Ch} deflagration to detonation transition (A. M. Khokhlov 1991a, 1991b; D. Arnett & E. Livne 1994a, 1994b; P. Hoefflich et al. 1995; P. Höflich 1995; J. C. Wheeler et al. 1995; P. Hoefflich & A. Khokhlov 1996; A. Y. Poludnenko et al. 2019) producing normal SNe Ia; and pure deflagrations leading to SNe Iax. The merger models of S. Neopane et al. (2022) result in central detonations, unlike what is found in JWST studies of normal bright SNe Ia (J. M. DerKacy et al. 2023, 2024; C. Ashall et al. 2024; L. A. Kwok et al. 2026).

All the failed deflagration models described above leave behind a bound remnant. Late-time observations of SN 2012Z revealed a flux excess between 500 and 400 days (C. McCully et al. 2022). M. Schwab et al. (2026) extended the baseline to 2500 days with the Hubble Space Telescope (HST), concluding that the excess is due to a bound remnant. SN 2014dt showed early dust signatures (O. D. Fox et al. 2016), but lacked enough data to pinpoint the dust's origin. It could well be that dust is produced, but with different compositions, for example: carbonates in dim; silicates in intermediate; and iron dust in bright SNe Iax.

2. SN 2024vjm

SN 2024vjm was discovered on 2024 September 13 (MJD 60566) by the BlackGem telescope (H. Tranin et al. 2024) with a q -band apparent magnitude of 18.8 (q is a wide-band 420–720 nm filter; P. J. Groot et al. 2024). The supernova is located in the nearby galaxy NGC 6744, at an estimated distance of 9.4 Mpc (G. S. Anand et al. 2021; E. A. Zimmerman et al. 2026). SN 2024vjm is the closest SN Iax ever discovered.²² SN 2024vjm

Table 1

Basic Observational Parameters of SN 2024vjm Used in This Work

Parameter	Value	Source
R.A.	19 ^h 09 ^m 25 ^s .780	(1)
Decl.	−63°50′01″.7532	(1)
T_{exp} (MJD)	60565.6 ± 1.0	(2)
$M_{o,\text{max}}$ (mag)	~−13.8	...
z	0.0028	(1)
Distance (Mpc)	9.39 ± 0.43	(3,4)
μ (Mpc)	29.86 ± 0.01	(3,4)
$E(B - V)_{\text{MW}}$ (mag)	0.038 ± 0.02	(5)
$E(B - V)_{\text{Host}}$ (mag)	0	
Host	NGC 6744	(1)

References. (1) <https://www.wis-tns.org/object/2024vjm>, (2) L. A. Kwok et al. (2025b), (3) G. S. Anand et al. (2021) (4) E. A. Zimmerman et al. (2026), (5) E. F. Schlafly & D. P. Finkbeiner (2011).

is also the dimmest, with $i_{\text{max}} \sim -13.7$ mag (E. A. Zimmerman et al. 2026). The Asteroid Terrestrial-impact Last Alert System (ATLAS J. L. Tonry et al. 2018) light curve implies a value of $M_{o,\text{peak}} = -13.6 \pm 0.4$ mag and $t_{\text{peak}} \sim \text{MJD } 60575.6$. We take the time of B_{max} as $t_{B_{\text{max}}} = \text{MJD } 60572.3$ and the rise time as 6.6 days, corresponding to $t_{\text{exp}} = \text{MJD } 60565.6$ (E. A. Zimmerman et al. 2026). The foreground reddening to NGC 6744 is $A_V = 0.118$ mag or $E(B - V) = 0.038$ (E. F. Schlafly & D. P. Finkbeiner 2011). Since SN 2024vjm is on the edge of a near face-on galaxy, we neglect any reddening due to the host.

SN 2024vjm was observed by JWST ~+12 days after peak with NIRSpec and the Mid-Infrared Instrument/Medium Resolution Spectrometer (MIRI/MRS; L. A. Kwok et al. 2025b). With the use of MIRI/MRS, their spectrum extends from $0.9 \lesssim \lambda \lesssim 20 \mu\text{m}$. They identify [Mg II] 4.76 μm , [Mg II] 9.71 μm , [Ne II] 12.81 μm , and O I 2.76 μm , which they attribute to unburned material. They find that the ejecta is well mixed, indicating a deflagration and that the spectra are well fit with failed deflagration models, but that they require extra emission in the mid-infrared (MIR), which points to a bound remnant.

We obtained Director's Discretionary Time to observe SN 2024vjm at around 200 days through program JWST-GO-9231 (PI: Baron; E. Baron et al. 2025b). The purpose of this program is to obtain near-infrared (NIR) and MIR spectroscopic and photometric data to probe line formation, the formation of molecules, and the formation of dust in SN 2024vjm. Table 1 provides the basic observational parameters of SN 2024vjm adopted in this work.

3. Observations and Data Reduction

3.1. JWST Spectra

Spectroscopic observations were obtained at 196.6 days past maximum (196.1 days in the rest frame, which we will use throughout) using the fixed slit with the Near Infrared Spectrograph (NIRSpec) and the MIRI low-resolution spectrometer (LRS). This produced continuous spectral data from ~0.7 to 14 μm . The resolving power of these observations is ~1000 for NIRSpec and ~100 for MIRI/LRS. All data were reduced using the JWST pipeline version 1.18.0 (H. Bushouse et al. 2025) and CRDS context `jwst_1371.pmap`. A log of the spectral observations can be found in Table 2.

²² Despite SN 2022xlp's smaller redshift, SN 2024vjm's distance is 9.4 ± 0.4 Mpc, while SN 2022xlp's distance is 22.1 Mpc (D. Bánhidí et al. 2025).

Table 2
Log of the JWST Spectral Observations

Parameter	Value
NIRSpec Spectral Observations	
Mode	Fixed slit
T_{obs} (MJD)	60768.86/60768.94
Rest-frame phase wrt B_{max} (days)	+196.1
Rest-frame phase wrt explosion (days)	202.8
Slit	S400A1
Subarray	SUBS400A1
Grating filter	G140M-F070LP/G235M-F170LP/ G395M-F290LP
Exp time (s)	238.44/331.92/378.66
Groups per integration	50/70/80
Integrations per exp.	1/1/1
Total dithers	3/3/3
Total integrations	3/3/3
Readout pattern	NRSRapid
MIRI Spectral Observations	
Mode	LRS
T_{obs} (MJD)	60768.94/60769.09
Rest-frame phase (days)	+196.1
Groups per integration	100
Integrations per exp.	20
Exposures per dither	1
Total dithers	2
Total exp. time (s)	11,205.61

3.2. JWST Imaging

We obtained simultaneous imaging of SN 2024vjm in the JWST MIRI filters F1500W, F1800W, and F2100W. The data were reduced using the same method described in K. Medler et al. (2025). Point-spread function (PSF) photometry was performed using a custom Python notebook built on the WebbPSF-based `space_phot` package (M. D. Perrin et al. 2014). We select the PSF width to minimize residuals in the fit, accounting for the expected wavelength-dependent broadening. For each dither in which SN 2024vjm is detected, we average the individual flux measurements and estimate the photometric uncertainty from the standard deviation across the dithers. A log of the photometric observations is presented in Table 3.

3.3. Spectral Energy Distribution

Figure 1 shows the resulting spectral energy distribution (SED) including both the spectroscopy and photometry. The underlying continuum appears to roughly conform to a blackbody-like shape, with significant emission from a few forbidden lines, spread throughout the wavelength region including the [Ca II] 0.73 μm , the [Ni II] 6.64 μm line, the [Ar II] 6.9 μm line, the [Co II] 10.52 μm line, and the [Fe III] 12.84 μm line. There is also clear emission from both the CO fundamental and first overtone bands as well as from the SiO first overtone. This is, to our knowledge, the first clear detection of CO and SiO in SNe Iax or SNe Ia. In the case of the peculiar 2003fg-like SN LSQ14fmg, E. Y. Hsiao et al. (2020) speculated that a steep drop in the light curve about a month postmaximum was due to the formation of CO and the cooling it provides, but there was no spectroscopic

Table 3
The Photometry Obtained with JWST

Filter	Obs. Date (MJD)	Exp. Time (s)	Phase ^a (days)	Magnitude (Mag)
F1500W	60769.09/60769.12	1110.0	+196.83	19.64 $\pm$ 0.01
F1800W	60769.12/60769.20	1744.4	+196.91	19.78 $\pm$ 0.02
F2100W	60769.12/60769.20	4191.4	+196.91	20.18 $\pm$ 0.02

Note.

^a Rest-frame days with respect to B_{max} MJD 60572.29.

confirmation of the presence of CO. CO has been observed in numerous core collapse events including SNe 1987A, 2023ixf, and 2024ggi (D. H. Wooden et al. 1993; K. Medler et al. 2025; T. Mera et al. 2026) and SiO has been observed in SNe 2004et and 2024ggi (R. Kotak et al. 2009; T. Mera et al. 2026). Dust has been observed to form in SN 2018cvt (L. Wang et al. 2024), but SN 2018cvt is an SN Ia circumstellar medium, a rare subclass of SNe Ia, and also in the 2003fg-like SN 2022pul (L. A. Kwok et al. 2024; M. R. Siebert et al. 2024; J. Johansson 2026, in preparation). Spitzer detected a MIR excess in the SN Iax 2014dt about 1 yr postexplosion (O. D. Fox et al. 2016). This has been interpreted as due to newly formed dust, preexisting dust, or a bound remnant (R. J. Foley et al. 2016; O. D. Fox et al. 2016; T. Szalai et al. 2019). In neither SN 2018cvt nor SN 2022pul was molecule formation of either CO or SiO observed. In SN 2024vjm, the long-wavelength ($15 < \lambda < 21 \mu\text{m}$) photometry does not show any evidence for significant emission from cold ($T \lesssim 500 \text{ K}$) dust.

E. A. Zimmerman et al. (2026) present extensive light curve coverage of SN 2024vjm, but we present additional photometry. Figure 2 shows the light curve of SN 2024vjm obtained by ATLAS and by the Precision Observations of Infant Supernova Explosions (POISE; C. Burns et al. 2021). From the ATLAS o -band light curve, we find that $t_{o, \text{max}} = \text{MJD } 60575.6$, $o_{\text{max}} = 16.5 \text{ mag}$, and $o_{\text{max}} = -12.9 \text{ mag}$ correcting for foreground extinction. The time of maximum light in the o band and our adopted explosion time lead to a rise time in the o band of 11 days, with the o -band light curve peaking ~ 4 days after the B -band light curve.

Using the (to be made public) tool QuickID (E. Baron 2026, in preparation), Figure 3 shows line identifications. QuickID uses the database of P. A. M. van Hoof (2018) and simple line strength criteria, chosen by the user to narrow down the possible line IDs. No modeling is done, and thus, the line IDs are tentative. We identify forbidden and permitted lines. We find lines due to intermediate-mass elements [Ca II], [Ar II], [Ar III], and iron group elements [Fe II], [Fe III], [Co II], [Co III], and [Ni II]. It is possible that there is a feature due to [Ne II], but as discussed below, we do not find strong evidence to support that identification.

Figure 4 shows the strong lines of both the intermediate-mass elements and the iron group elements in velocity space. The [Ca II] doublet is resolved, as are the strong components of the Ca IR triplet, indicating low ejecta velocities. The centroid and velocity width obtained from Gaussian fits to the features are shown in Table 4. The argon lines are broader with widths around 3000 km s^{-1} , while the iron group elements are narrower with widths around 1500 km s^{-1} . However, the argon lines are not flat topped so the argon is not confined to a shell. This analysis shows that the ejecta of SN 2024vjm is “almost

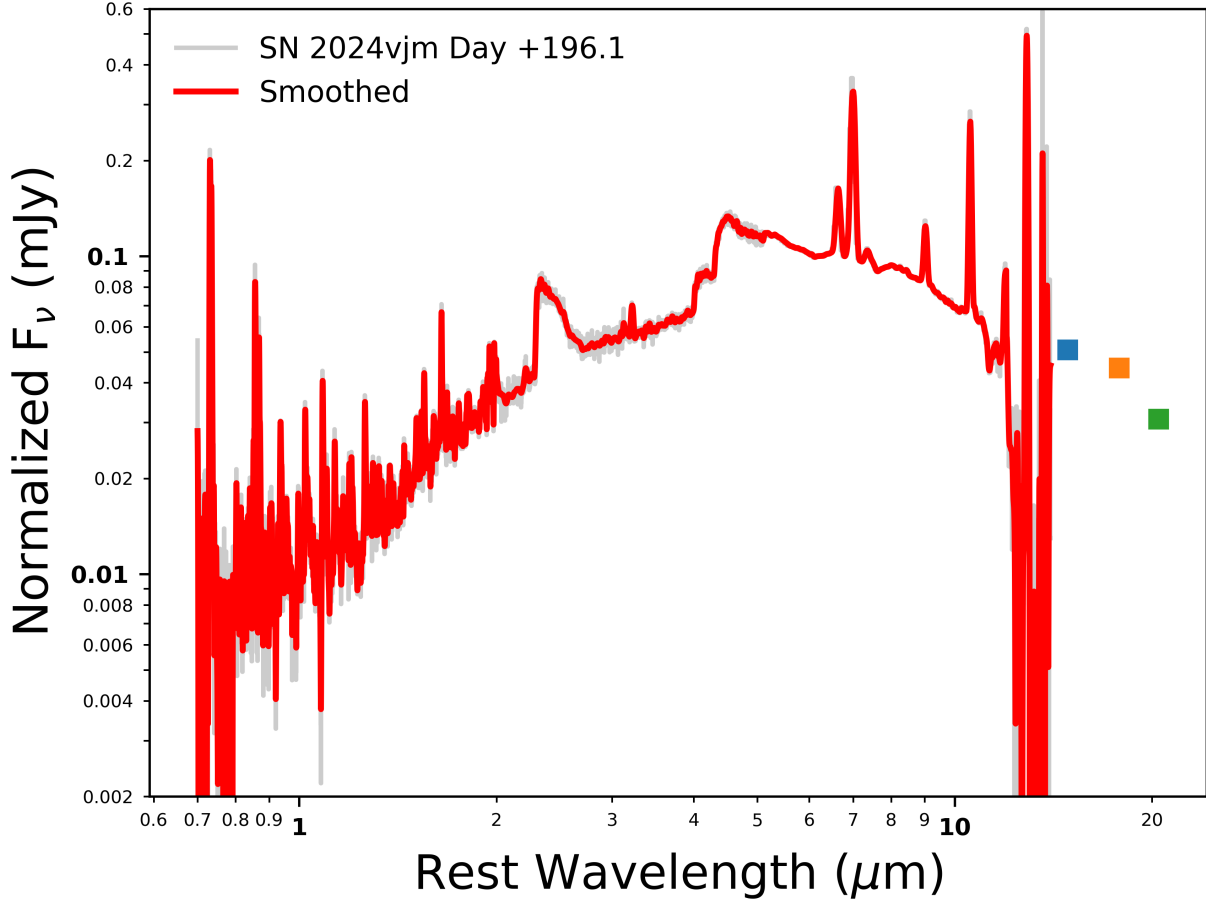


Figure 1. SED of SN 2024vjm. The raw and smoothed Day +196.1 SN 2024vjm JWST spectrum plus the day 196.9 JWST photometry (shown by squares).

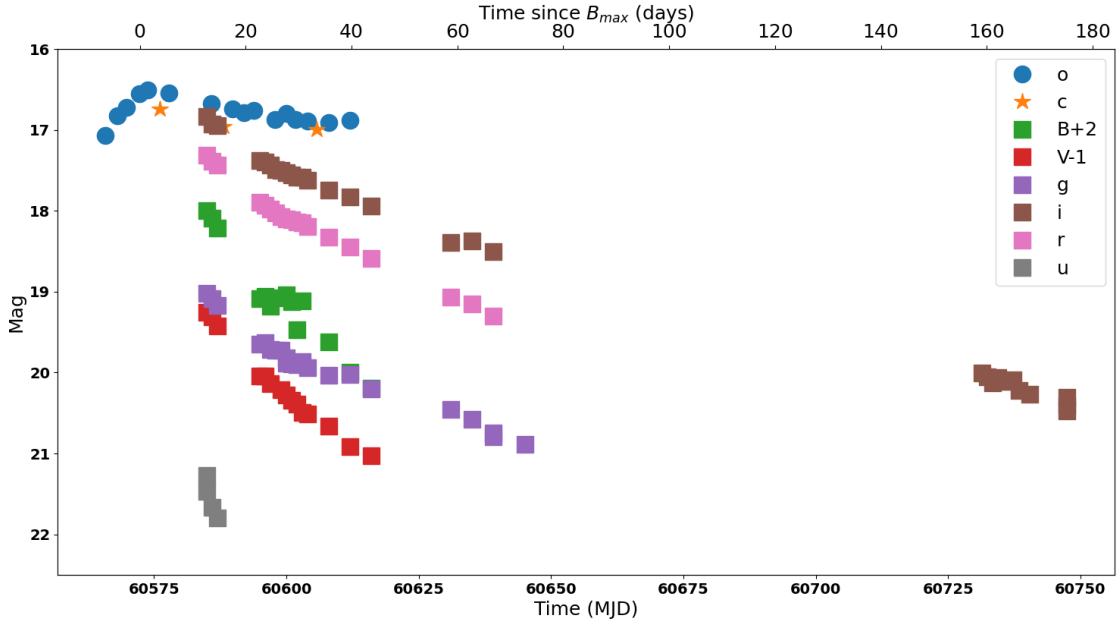


Figure 2. The SN 2024vjm light curve obtained by ATLAS and POISE.

fully mixed” or “almost radially stratified.” As noted above, the line IDs of Figure 3 do not take line blending into account; thus, in the absence of detailed models, it is not possible to draw strong conclusions about the velocity extent of the broader lines. However, both the identifications of [Ca II] and

the Ca II IR triplet are solid. These calcium features show rather symmetric profiles in velocity space, while the [Co II] feature shows a slight redshift. Since the [Co II] line is a resonance line, it should be relatively immune to line blending; the shift could be due to the density and ionization profile, or it

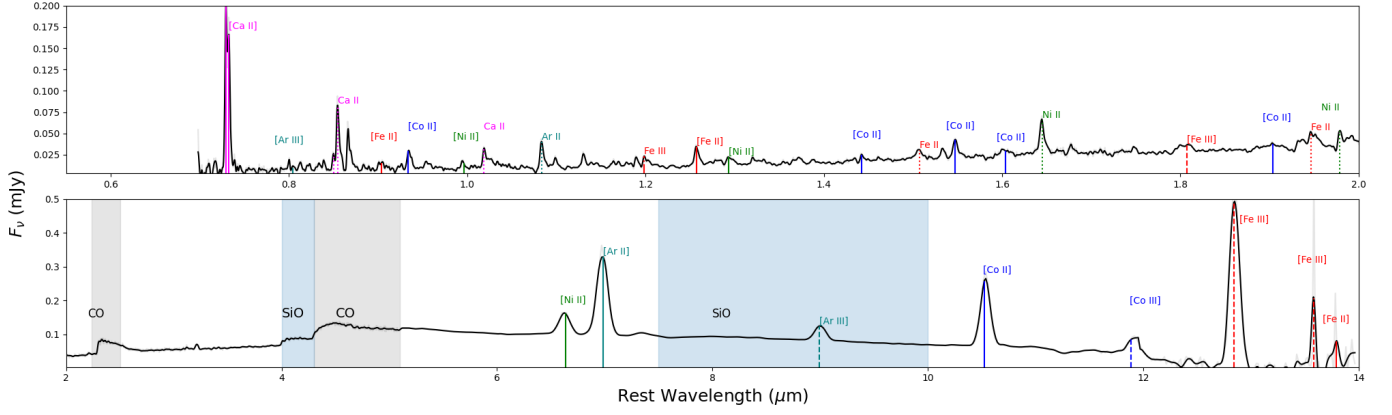


Figure 3. The observed Day +196.1 SN 2024vjm JWST spectrum, with tentative line identifications. The CO and SiO fundamental and first overtone bands are shaded (A. M. Heras et al. 1999).

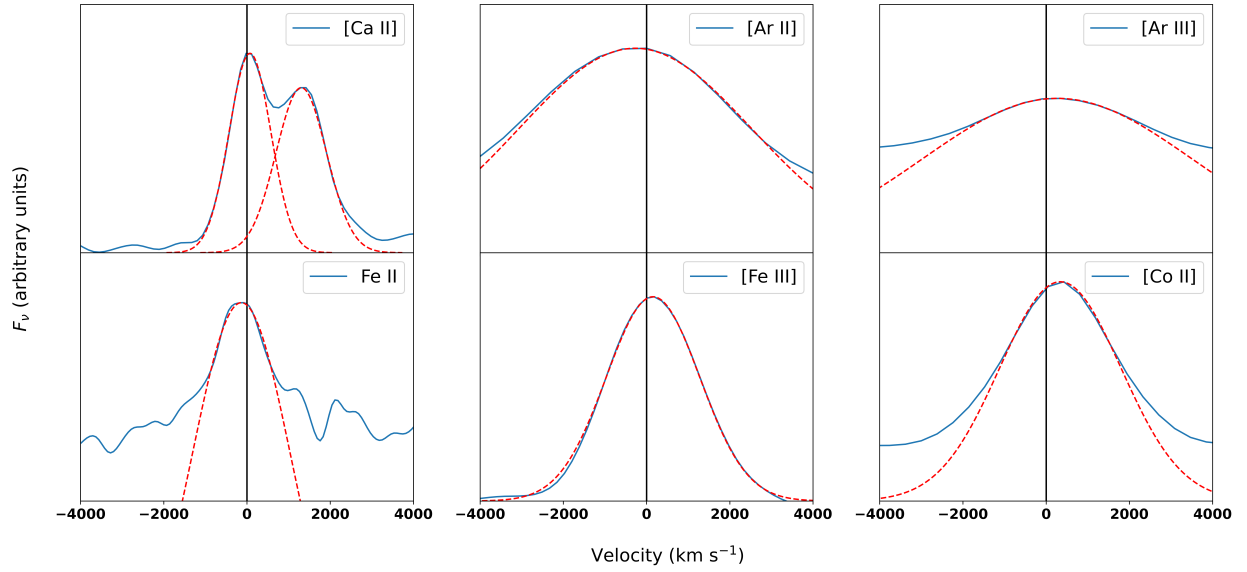


Figure 4. The strong intermediate-mass element lines (top row) and iron group element lines (bottom row). The blue lines are the data and the red dashed lines are a Gaussian fit to the feature. The argon lines are broader and somewhat more asymmetric in velocity space with red or blueshifts. The [Ca II] doublet is resolved, as is the Ca IR triplet. [Ca II] shows a very symmetric line shape, while the [Fe III] has a small redshift and the [Co II] line has a more marked redshift. The Gaussian fit results are shown in Table 4.

Table 4
Widths and Central Velocities of Lines Shown in Figure 4

Feature	Rest Wavelength (vacuum)	Center (km s ⁻¹)	Width (km s ⁻¹)
[Ca II]	0.7291 μm	70	500
[Ca II]	0.7293 μm	30	540
[Ar II]	6.985 μm	-270	2800
[Ar III]	8.991 μm	270	3200
Fe II	1.507 μm	-140	1200
[Fe III]	12.841 μm	150	1100
[Co II]	10.522 μm	340	1500

could be due to a true asymmetry in the elements produced in later-stage burning, and the calcium could be primordial. The narrow width and near-zero redshift of both components of the [Ca II] doublet are interesting. It seems unlikely that the calcium emission is from below that of the iron group elements, suggesting that calcium originates in a wind external to the ejecta. An ~ 500 km s⁻¹ wind is not a feature of models

for the formation of SNe Iax. M. R. Siebert et al. (2023) found extremely narrow [Ca II] with a width of around 200 km s⁻¹, in the 2003fg-like SN 2020hvf (as well as other 2003fg-like SNe), which they attributed as due to the wind from the intact companion star. They also found a broad [Ca II] feature from the ejecta.

4. Spectral Comparison

Figure 5 shows a suite of SNe Ia (including SNe Iax) that have been observed by JWST. All phases are with respect to the *B*-band maximum. The 1991bg-like SN 2022xkq spectrum obtained at day +130 (J. M. DerKacy et al. 2024), is earlier than that of SN 2024vjm, while SNe 2021aefx (days +323, +417 J. M. DerKacy et al. 2023; C. Ashall et al. 2024), 2022gy (day +337), and 2022aaq (day +207) (L. A. Kwok et al. 2025a) are normal SNe Ia. While the ions that make up the spectra of both the SNe Ia and SNe Iax are similar, the difference in the nature of the spectra between the SNe Ia and SN 2024vjm is striking. Not only are the features in SNe Ia much broader than those present in SN 2024vjm, but their

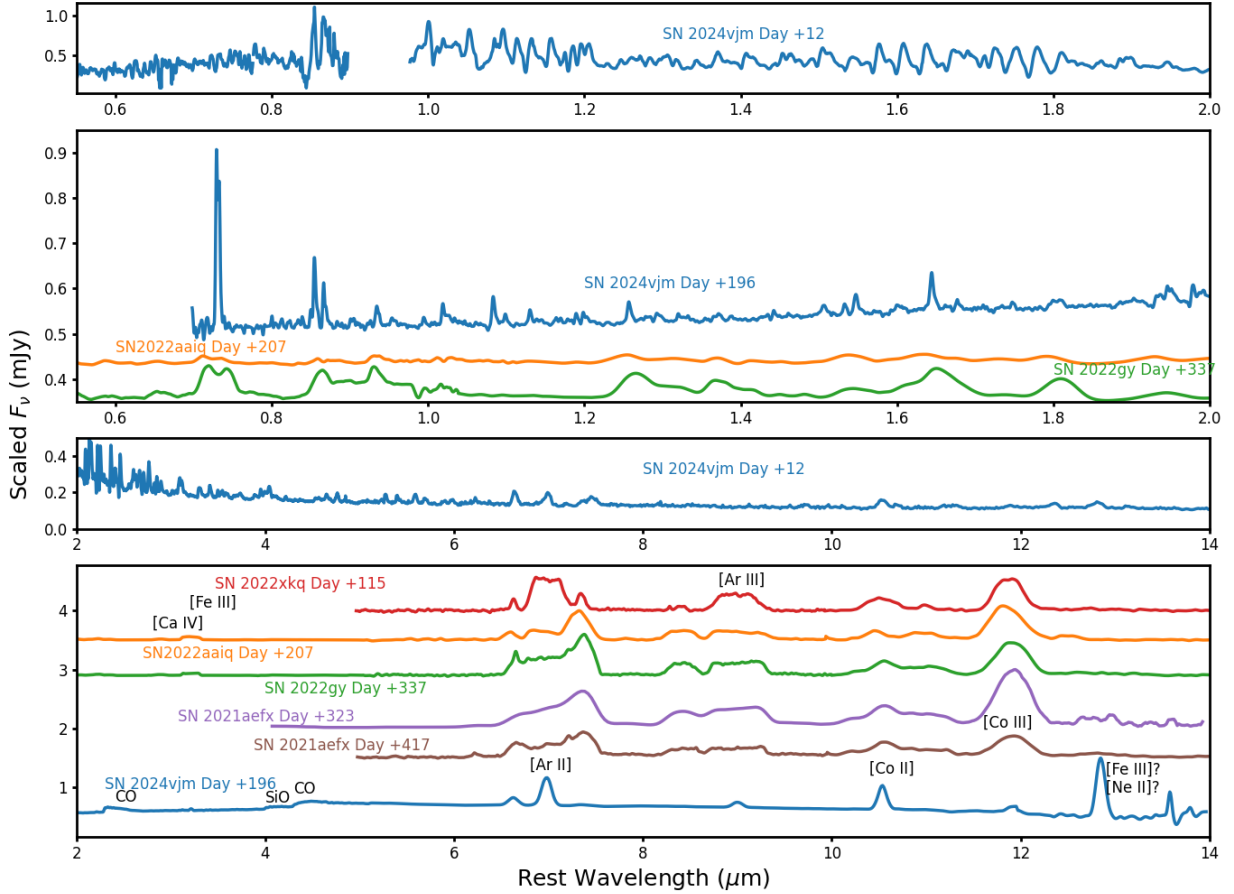


Figure 5. The observed Day +196.1 SN 2024vjm JWST spectrum plotted against other SNe Ia at similar epochs that have also been observed by JWST. The data for SN 2022xkq are from J. M. DerKacy et al. (2024) as rereduced by L. A. Kwok et al. (2025a), the data for SNe 2022aaig and 2022gy are from L. A. Kwok et al. (2025a), and the data for SN 2021aefx are from C. Ashall et al. (2024). The thin panels show SN 2024vjm at Day +12 (L. A. Kwok et al. 2025b).

relative strengths are quite different. Whereas the dominant feature in the NIR for SNe 2022gy and 2022aaig is due to a blend of [Ca IV] and [Fe III] (L. A. Kwok et al. 2025a), in SN 2024vjm it is due to CO. Both the normal SNe 2022gy and 2022aaig and SN 2024vjm show a flat feature in the wavelength range $\approx 4\text{--}4.2\ \mu\text{m}$, attributed to [Ca IV] by L. A. Kwok et al. (2025a). However, given the low temperature required for the formation of CO, it seems unlikely that this feature is due to such a highly ionized species, at least in the case of SN 2024vjm (see Section 7 for a discussion of this particular feature). Moving further to the red, [Ar II] is prominent in both SN 2024vjm and SN 2022xkq, whereas [Ar III] forms a prominent flat-topped feature in the normal SNe Ia, but is a relatively narrow symmetric feature in SN 2024vjm. The same pattern continues to the red, where in the SNe Ia the strongest feature is the [Co III] resonance line at $11.88\ \mu\text{m}$, but in SN 2024vjm it is the [Co II] $10.52\ \mu\text{m}$ resonance line that dominates over the higher ionization [Co III] line. Interestingly, further to the red, the SNe Ia lack the feature at $12.8\ \mu\text{m}$ seen in SN 2024vjm, which is likely due to the [Fe III] $12.84\ \mu\text{m}$ line, but could be due to the [Ne II] $12.81\ \mu\text{m}$ resonance line.

5. Dust Emission

There is a strong indication of an underlying dust continuum present in SN 2024vjm. Figure 6(a) shows our best-fit blackbody to the SN 2024vjm SED, giving a temperature of $T_{\text{BB}} \approx 1400\ \text{K}$. With only a single epoch, it is not possible to ascertain whether

this dust is newly formed or preexisting. However, a simple estimate of the dust radius gives $R_d = 2.1 \times 10^{16}\ \text{cm}$ (M. Shahbandeh et al. 2025), whereas the ejecta, even moving at a velocity of $10,000\ \text{km s}^{-1}$ would have only reached a radius of about $1.7(10,000/v_{\text{max}}(\text{km s}^{-1})) \times 10^{16}\ \text{cm}$, where v_{max} is the true maximum ejecta velocity. As noted in M. Shahbandeh et al. (2025), this radius estimate is for the optically thin case and provides a minimum radius for the dust. That means the dust may reside in a shell with a larger radius, but if the radius of the shell were any smaller, the dust would become optically thick. This suggests, but does not prove that the dust is preexisting rather than newly formed.

To go a little deeper, we calculated a simple optically thin dust model. The observations were masked to remove the molecular emission. This gives a fit with two graphite components at $T \sim 500$ and $\sim 1250\ \text{K}$ and a total dust mass of $M_{\text{dust}} = 2.41 \times 10^{-4}\ M_{\odot}$. Figure 6(b) shows the best-fit model compared to the SN 2024vjm SED, including the photometry points. Clearly, the more physical fit shown in Figure 6(b) gives significantly smaller residuals to the dust continuum than the simple blackbody assumption of Figure 6(a). Figure 6(c) shows the SED with this dust continuum removed. It is this SED that we will compare to models.

6. Models

In order to go beyond the line identifications, we consider some simple models of SNe Iax. While the favored model for

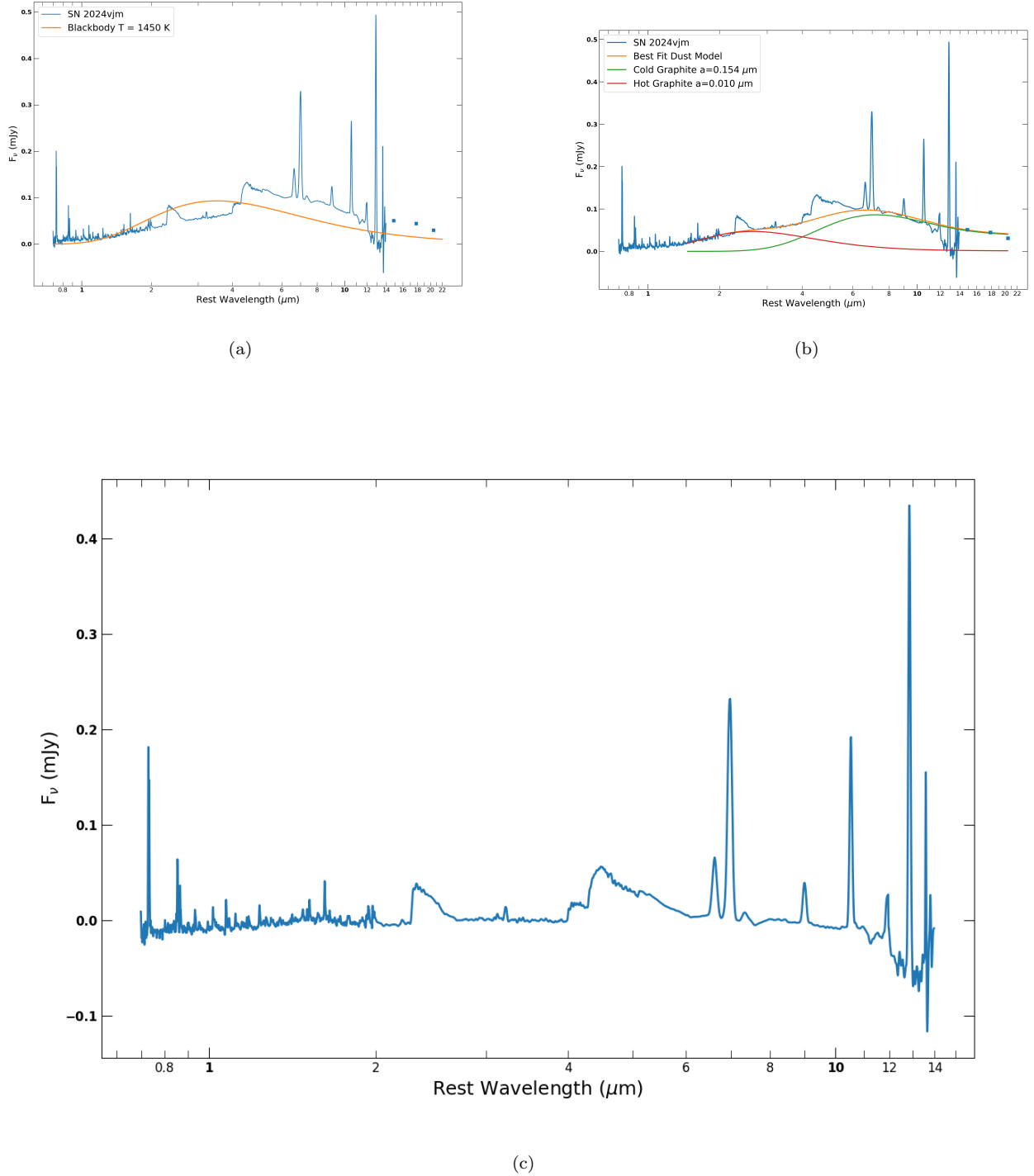


Figure 6. (a) The observed Day +196.1 SN 2024vjm JWST spectrum plotted against the best-fit blackbody. (b) The observed Day +196.1 SN 2024vjm JWST spectrum plotted against the best-fit dust model. The two components of the model, consisting of cold, $0.15 \mu\text{m}$ and hot, $0.01 \mu\text{m}$ graphite, are also shown. (c) The observed Day +196.1 SN 2024vjm JWST spectrum with the best fit dust model (b) removed.

SNe Iax is the failed deflagration model, leaving a bound remnant, radially stratified models such as the pulsating delayed detonation (M. D. Stritzinger et al. 2014) have also been considered. Therefore, we consider both radially stratified and fully mixed models. For the radially stratified model, we consider a modified version of the W7 model (K. Nomoto et al. 1984, 1986), and for the fully mixed model, N1def (M. Fink et al. 2014). Both W7 and N1def are the result of pure deflagrations, but W7 has radially stratified abundances,

which makes it suitable for our purposes. W7 has a long history of being used as a template for SNe Ia (for example, see D. J. Jeffery et al. 1992; F. Thielemann 2007; P. A. Mazzali et al. 2014; C. Ashall et al. 2016; C. Cain et al. 2018; L. J. Shingles et al. 2020; C. McCutcheon et al. 2022; M. R. Magee et al. 2024) and N1def is specifically constructed as a model of faint SNe Iax (M. Fink et al. 2014). We modified W7, taking its abundance and density distributions without modification, but reducing the total mass and velocity extent. In order to distinguish this model from

W7 itself, we refer to it henceforth as W7-Iax. A similar approach of modifying the kinetic energy, nickel mass, and total mass of W7 was taken for modeling the light curve of the SN Iax 2005hk (D. K. Sahu et al. 2008).

To compare the models to data, we use the PHOENIX/1D generalized stellar atmosphere code (P. H. Hauschildt & E. Baron 1999), the ACES equation of state, and the STOUT model atoms. The STOUT model atoms were constructed using the data available from P. A. M. van Hoof (2018). ACES (T. S. Barman et al. 2011) solves for the abundances assuming chemical equilibrium in a stellar atmosphere. The method is based upon that of W. R. Smith & R. W. Missen (1982), incorporating new experimental and theoretical thermodynamic data for 839 species (84 elements, 289 ions, 249 molecules, 217 condensates) with all available data updates applied. Chemical equilibrium concentrations for all atomic and molecular species (the species are selected at run time) are determined by the pressure, temperature, and density. This calculation is repeated at each layer in the atmosphere for each model iteration so that the final structure is self-consistent. PHOENIX/1D has been used on all types of supernovae (E. Baron et al. 1996, 2000, 2003a, 2003b, 2006, 2012, 2015, 2025a). The treatment of gamma-ray deposition and the resulting non-thermal electrons is described in E. Baron et al. (1994). PHOENIX/1D was used to analyze nebular spectra of SN 2011fe and transitional spectra of SNe 2001fe, 2002bo, 2003du, and 2014J (B. Friesen et al. 2014, 2017). The version and data sources of PHOENIX/1D are the same as those presented in P. H. Hauschildt et al. (2025).

In order to keep the compute time for the models within our means, we have not solved for the temperature structure, but rather chosen a few representative structures. Time-dependent effects may be important, and since our treatment of molecules is inherently time independent, this is another reason not to expend more computational resources than we have available to us. It is beyond the scope of the present work to fully model the dust continuum; therefore, we compare the models to the SN 2024vjm SED with the dust continuum subtracted out, that is, with the SED shown in Figure 6(c).

Figure 7(a) shows the synthetic spectrum of the W7-Iax model. The W7-Iax model is created from W7 by reducing the density of W7, such that the density profile is unchanged. The maximum velocity of W7 is reduced by a factor of 10, enforcing homology. The resulting W7-Iax model has a mass of $0.42 M_{\odot}$, a maximum velocity of 3000 km s^{-1} , and a kinetic energy of 3.5×10^{-3} foes. The composition structure of W7 is unchanged in W7-Iax. The model spectrum in Figure 7(a) has an isothermal $T = 2000 \text{ K}$ profile. The model reproduces the molecular features of CO with both the fundamental band ($\sim 4.3\text{--}5.1 \mu\text{m}$) and the first overtone ($\sim 2.2\text{--}2.5 \mu\text{m}$) matching the observed spectrum. There is no striking evidence for the SiO fundamental ($\sim 7.5\text{--}10 \mu\text{m}$), but the SiO first overtone ($\sim 4\text{--}4.3 \mu\text{m}$) is clearly evident (see Section 7). The forbidden lines in the model spectrum are much weaker than those in the observed SED, with most of the energy emitted by cobalt and iron transitions near $2 \mu\text{m}$. This could be due to how collisional rates are determined for the STOUT dataset, but may also be due to many other factors that are beyond the scope of this work. We have explored isothermal temperatures in the range of $1000\text{--}3000 \text{ K}$ as well as temperature profiles as obtained by T. Mera et al. (2026) without significant alteration

in the results, and therefore we take $T = 2000 \text{ K}$ as our fiducial model.

Figure 7(b) shows the synthetic spectrum of the N1def model with an isothermal $T = 2000 \text{ K}$ profile. Like the W7-Iax model, N1def reproduces the first overtone of CO, but the fundamental is not as well reproduced as it is in the W7-Iax model. Again, the forbidden lines are much too weak in the synthetic spectrum.

Table 5 shows the basic parameters of the two models, including the mass of CO and SiO produced.

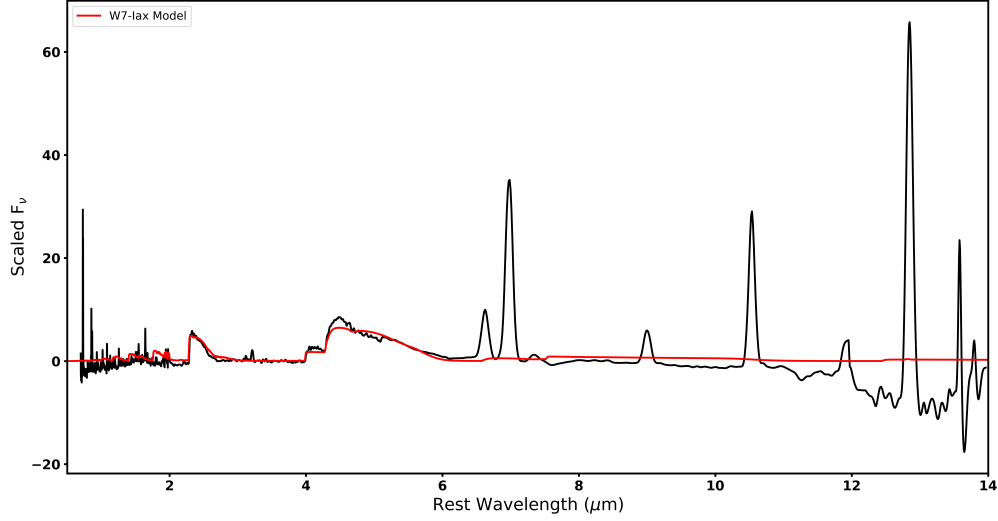
Both the W7-Iax model and the N1def model adequately reproduce the observed SN 2024vjm spectrum, bluishward of about $6 \mu\text{m}$. In order to examine how well they do reproducing the features, the spectra for the models were recalculated, but the opacity due to molecules was turned off. That is, the molecules were still present in the atmosphere, but their opacity was neglected. This is our standard method for obtaining unambiguous identifications in the synthetic spectra (S. Bongard et al. 2008; J. M. DerKacy et al. 2020). Figure 8 panels (a) and (b) show the resulting spectra for the W7-Iax model and the N1def model, respectively. The reason for the lack of strong forbidden lines appears to be that most of the energy is emitted by iron and cobalt lines in the wavelength range around $2 \mu\text{m}$. Figure 8(a) shows that while the W7-Iax model has many optical features, it is relatively devoid of atomic features in the NIR. The model produces a strong feature at $5.54 \mu\text{m}$ possibly due to C IV; however, there is no corresponding feature in the observed spectrum. The model does have a feature at $7.34 \mu\text{m}$ likely due to C II, as well as the [Co II] $10.52 \mu\text{m}$ line. Interestingly, the model shows a feature around $12.8 \mu\text{m}$ that appears to be made up of a blend of the [Ne II] 12.81 line and the [Fe III] 12.84 line, with the [Ne II] portion of the feature not matching the observation, lending credence to the identification of that feature as due to [Fe III] and not [Ne II].

Figure 8(b) shows that the N1def model also has most of the observed optical features, although the [Ca II] $0.73 \mu\text{m}$ line is very weak (it appears as a P Cygni line in the W7-Iax model). Again relatively devoid of features in the NIR, this model shows a weak feature at $5.54 \mu\text{m}$ possibly due to C IV, which is not in the observed spectrum. The model shows a P Cygni feature at $7.34 \mu\text{m}$ likely due to C II, as well as the [Co II] $10.52 \mu\text{m}$ line. The N1def model has a strong [Co III] $11.88 \mu\text{m}$ feature. Interestingly, the N1def model shows a feature around $12.8 \mu\text{m}$ that appears almost purely due to the [Ne II] 12.81 line with little evidence for blending from the [Fe III] 12.84 line. The model [Ne II] feature is clearly shifted to the blue compared to the observed feature, strengthening the case for the identification of that feature as due to [Fe III] and not [Ne II].

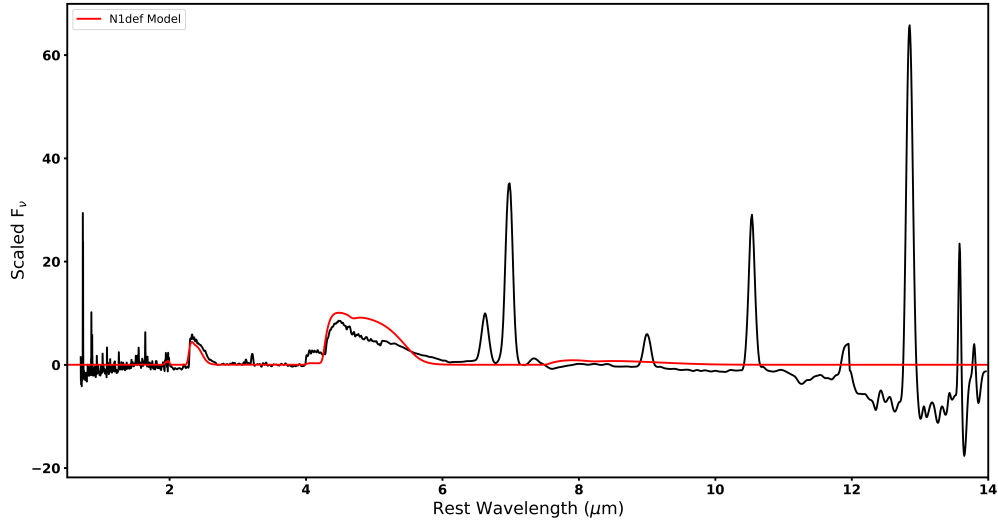
7. Discussion

7.1. Atomic Lines

L. A. Kwok et al. (2025b) identified permitted lines of iron group elements Fe II/III, Co II/III, Ni II, Ti II, permitted lines of O I, Si II/III, Ca II, as well as forbidden [Fe II], [Co II], [Ni II/III], [Mg II], [Ne II], [Ar II], [Ca IV]. We find similar IDs, except we don't find neon or magnesium. Primarily, we find lines due to [Ar II/III], [Ca II], [Fe II/III], [Co II/III], [Ni II], and permitted lines from the same ions. Note that in Figure 3 the line near $12.8 \mu\text{m}$ is identified as due to [Fe III]



(a)



(b)

Figure 7. (a) A simple model, W7-Iax, using W7 abundances with an ejecta mass of $0.42 M_{\odot}$ and the velocities reduced by a factor of 10 (the W7-Iax model). This model has isothermal ejecta with $T = 2000$ K, and γ -ray deposition from the (reduced) radioactive nickel is included. (b) The N1def model. This model has isothermal ejecta with $T = 2000$ K and includes γ -ray deposition.

Table 5
Model Parameters

Model	Ejecta Mass ($M_{\odot}$)	$v_{\max}$ (km s^{-1})	E_{KE} (foe)	E/M (foe/ $M_{\odot}$)	CO Mass ($M_{\odot}$)	SiO Mass ($M_{\odot}$)
W7-Iax	0.42	3000	3.5×10^{-3}	0.008	0.025	0.016
N1def	0.075	8800	1.4×10^{-2}	0.018	0.023	0.0015

$12.84 \mu\text{m}$ and not the [Ne II] resonance line, since the observed feature is significantly redward of the [Ne II] $12.81 \mu\text{m}$ wavelength. Figure 9(a) shows the observed spectrum in velocity space. The velocity extent of the [Co II] $10.52 \mu\text{m}$ resonance line, the [Ne II] $12.81 \mu\text{m}$ resonance line (assuming the $12.8 \mu\text{m}$ feature is due to [Ne II]), and the [Fe III] $12.84 \mu\text{m}$

resonance line (assuming the $12.8 \mu\text{m}$ feature is due to [Fe III]). The velocity extent of the [Co II] line is similar to that of the putative [Fe III] line, while if the $12.8 \mu\text{m}$ feature is due to [Ne II], it would have to be significantly more redshifted from its rest wavelength. L. A. Kwok et al. (2025b) identified a feature near $12.8 \mu\text{m}$ as due to the [Ne II] $12.81 \mu\text{m}$ line, which

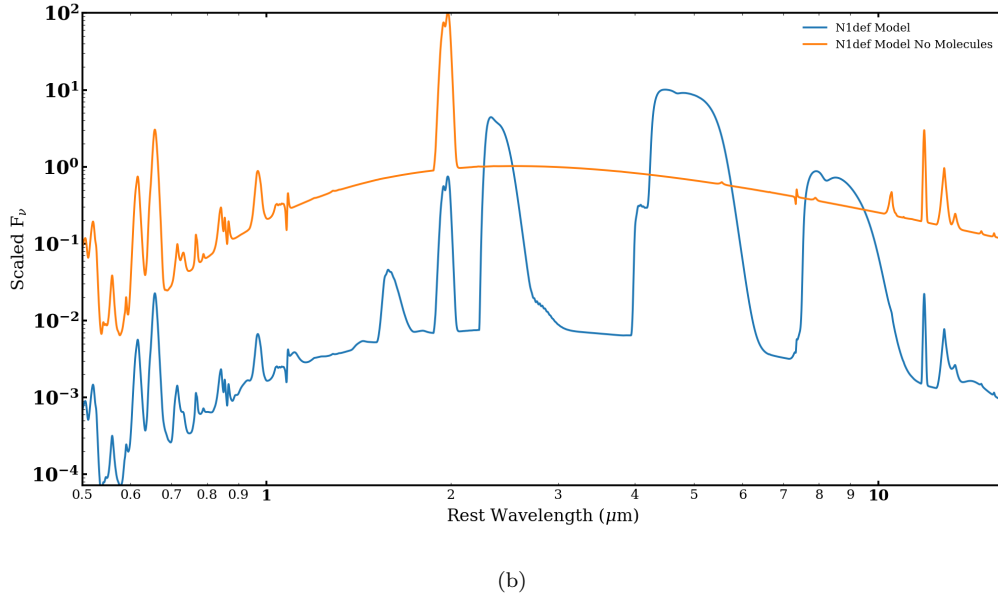
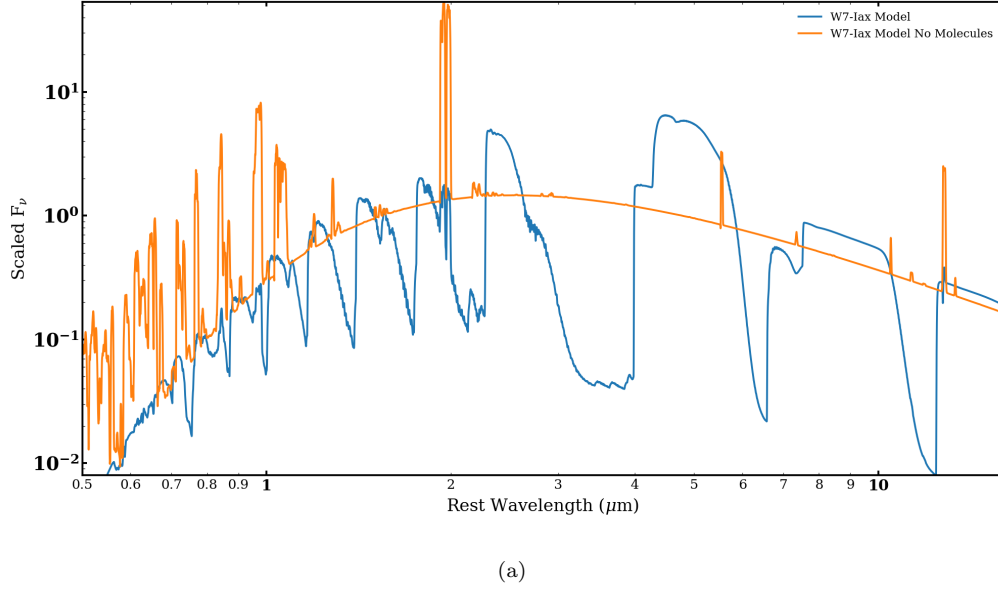


Figure 8. (a) The W7-Iax model shown in Figure 7(a) is compared to the same model but where the molecule opacity has been ignored. Most of the energy comes out in lines due to iron and cobalt near $2 \mu\text{m}$. (b) The N1def model shown in Figure 7(b) is compared to the same model but where the molecule opacity has been ignored. Most of the energy comes out in lines due to iron and cobalt near $2 \mu\text{m}$.

is narrow and centrally peaked, concluding that since neon is produced in low-density regions, the neon must be thoroughly mixed; therefore, the explosion must be due to a pure deflagration and not a violent merger.

7.1.1. Stable Nickel

Importantly, we also identify the [Ni II] 6.636 resonance line and Ni II lines near $1.09 \mu\text{m}$ at this epoch, indicating the presence of stable nickel. This is a strong test for models, since stable nickel implies burning at high densities where the electron capture rates are large enough to neutronize the material.

7.1.2. The $1.94 \mu\text{m}$ Feature

In Figure 3, we identify a feature at $1.98 \mu\text{m}$ with Ni II. A similar feature was identified in SNe Ia by B. Friesen et al. (2014) as due to the [Ni II] $1.94 \mu\text{m}$ doublet, even though the feature is significantly redward of the rest wavelength of the doublet. Recent analysis of a set of NIR spectra of SNe Ia found evidence for the [Ni II] $1.94 \mu\text{m}$ doublet (S. Kumar et al. 2026). In their sample, the observed feature tended to be redshifted, but not by the $0.04 \mu\text{m}$ found by B. Friesen et al. (2014). Figure 9(b) presents a zoomed-in view of the SN 2024vjm spectrum, focusing on the region around $1.94 \mu\text{m}$. It shows that the [Ni II] $1.94 \mu\text{m}$ doublet does not well match any of the observed features seen in the spectrum.

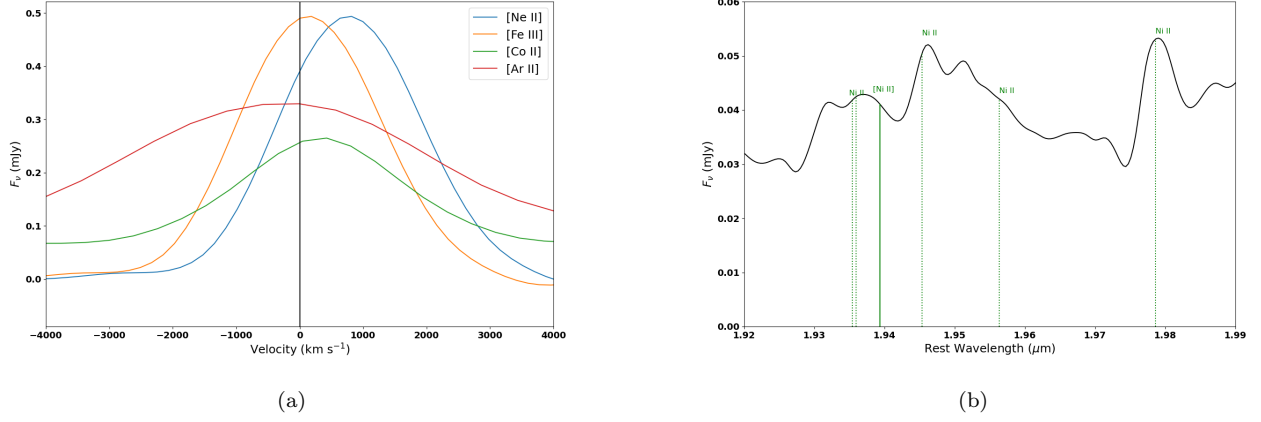


Figure 9. (a) The velocity space extent of the observed [Co II] 10.52, [Ne II] 12.81, and [Fe III] 12.84 μm lines. The 12.8 feature is the same observed feature, simply shifted to be identified with [Ne II] in one case and with [Fe III] in the other case. (b) A zoomed-in view of the 1.9 μm region of the SN 2024vjm spectrum. The [Ni II] 1.94 μm line does not match the observed features. The strong permitted ($\log(gf) > 0$) lines shown match some features, in particular, the observed 1.98 μm feature.

Also shown in Figure 9(b) are strong ($\log(gf) \geq 0$), high-excitation Ni II permitted lines. One of the lines is reasonably well identified with the observed P Cygni feature near 1.98 μm , and a Ni II 1.9454 μm line is also plausibly associated with an observed P Cygni feature; however, the Ni II 1.9563 μm line is not associated with a strong observed feature, and the Ni II 1.9353 and 1.9359 μm lines together with the [Ni II] 1.94 μm doublet could be producing another observed emission feature. These features, along with the [Ni II] 6.64 μm resonance line, make a case for the presence of stable nickel in the SN 2024vjm ejecta. However, the specific formation of the lines in the 1.94 μm region is likely due to blends of nickel and cobalt lines. For the 1.98 μm feature, there is a Co II line, but it is much weaker, with $\log(gf) \sim -2$, thus it is likely that the feature is predominantly due to Ni II with a small contribution from Co II.

7.2. Model Comparison

Comparison of the models shown in Figure 8, which include molecular opacity for both the W7-Iax and N1def models with their counterparts neglecting molecular opacity, makes it clear that molecular opacity plays an important role in producing the model spectra. While the contributions from the fundamental and first overtone of CO are obvious in both models, both models also produce SiO. For the N1def model, the contributions from CO and SiO seem to account for most of the molecular emission, while for the W7-Iax model, the entire SED is dominated by molecular features not limited to just the fundamental and first overtones of CO and SiO. The W7-Iax model produces a significant amount of SiS, whose fundamental is at about 14.2 μm , but clearly other molecular opacity is important in the synthetic spectrum.

7.2.1. SiO and SiS

Figure 10(a) shows a comparison of the synthetic spectrum for the W7-Iax model, the same spectrum with SiO opacity turned off, and the same spectrum with both SiO and SiS opacity turned off. Interestingly, the flat band seen in the SN 2024vjm spectrum from ~ 4 to 4.25 μm is produced by the SiO first overtone, so we can confidently identify the presence of SiO as well as CO in SN 2024vjm. A feature in the same wavelength range has been attributed to [Ca V] by L. A. Kwok

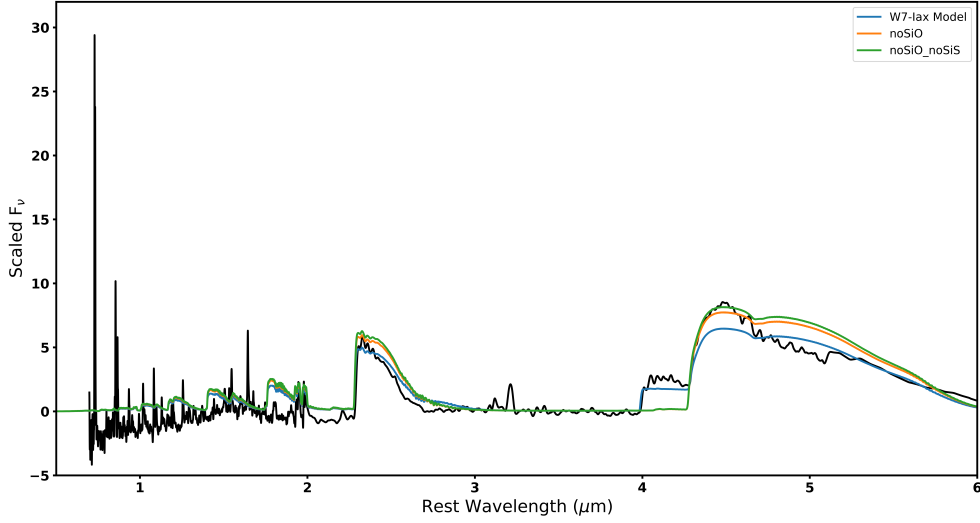
et al. (2025a) in the normal SNe Ia 2022gy and 2022aaiq, but here we are sure that it is due to the SiO first overtone. Since the first overtone of SiO is present, the fundamental band of SiO also plays a role, but it is more difficult to match the features produced in the synthetic spectrum with those of the observed. The SiS creates a strong feature in the ~ 6.5 – 7.5 μm range (from the first overtone), but since the model does not produce the strong forbidden lines in this region, it is hard to definitively identify or rule out the presence of SiS. Figure 10(b) shows the N1def model spectrum with the opacity of SiO turned off. The stronger SiO first overtone in the W7-Iax model compared to that of N1def, more closely fits the observed SN 2024vjm spectral feature, but since the strong forbidden lines are missing for both models, it is premature for definitive statements about which model is favored. Nevertheless, it seems reasonable to conclude that the mass of CO and SiO produced by the W7-Iax model approximately corresponds to the mass produced in the SN 2024vjm ejecta, in particular that the SiO mass should be closer to $10^{-3} M_\odot$ than to $10^{-4} M_\odot$.

7.3. Previous CO Identifications in Thermonuclear SNe

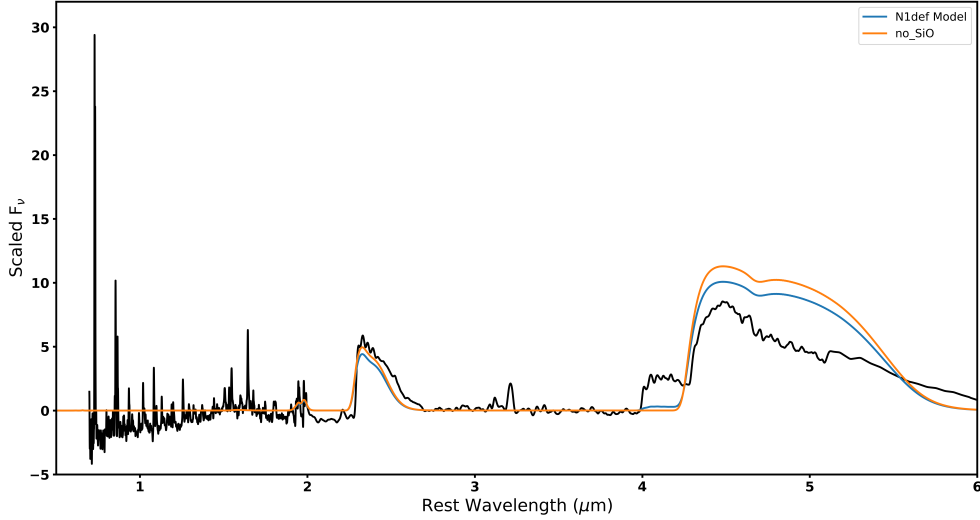
E. Y. Hsiao et al. (2020) saw a steep drop in the light curve of the 2003fg-like LSQ2014fmg around a month postmaximum light that they attributed to the formation of CO. At the same epoch, there is no evidence for a steep drop in the light curve of SN 2024vjm. However, SN 2024vjm went behind the Sun about 2 months postmaximum, so that drop likely occurred later, with the onset of CO formation.

8. Conclusions

We obtained a spectrum of the dim SN Iax SN 2024vjm with JWST on day +196.1, which, combined with JWST imaging from day 196.9, allows the construction of an SED with coverage from 0.7 to 21 μm . The observed spectrum shows strong permitted and forbidden lines of intermediate-mass (Ca and Ar) and iron group elements (Ni, Co, Fe). While the [Ne II] 12.81 μm resonance line may be present, there are no other obvious neon lines, and [Fe III] fits the feature just as well, in addition to fitting other observed features, strengthening the 12.84 [Fe III] identification. This makes the absence of neon an important model discriminator. The observed SED



(a)



(b)

Figure 10. (a) The W7-Iax model shown in Figure 7(a), compared to the same model with the SiO opacity turned off and with both the SiO and SiS opacities turned off. (b) The N1def model shown in Figure 7(b) is compared to the same model with the SiO opacity turned off.

shows strong emission from both the CO fundamental and first overtone as well as a pronounced feature that is well fit by the first overtone of SiO, indicating that SN 2024vjm has formed both CO and SiO by this epoch. The presence of [Ni II] as well as permitted Ni II lines at this late epoch implies that densities are high enough that electron capture is effective, a strong constraint on explosion scenarios, in that the high densities must occur either in the progenitor or material must be ejected from the bound remnant (and likely efficiently mixed into the ejecta).

The line widths of the iron group elements are narrower and therefore are present at lower velocities than, in particular, the [Ar II] and [Ar III] lines, indicating radial stratification. On the other hand, the [Ar II] and [Ar III] lines are not flat topped, indicating that they are not confined to a shell. Furthermore,

the [Ca II] doublet is resolved, with each component symmetric around about zero velocity with a velocity width of $\sim 500 \text{ km s}^{-1}$, significantly smaller than the $\sim 3000 \text{ km s}^{-1}$ width of the argon features. This could possibly be due to the formation of the calcium features in a circumstellar wind.

The simple dust model constructed argues for a small amount of carbonate dust. While a single epoch cannot determine whether the dust is newly formed or preexisting, we have made a case that the dust is preexisting.

We calculated synthetic spectra of two characteristic explosion models: a modified version of W7, W7-Iax, where the ejecta mass and velocities have been artificially reduced, but the compositions are unaltered, and N1def, a pure deflagration model that leaves behind a bound remnant. In both cases, our synthetic model spectra produced forbidden

line features that are much weaker than seen in the observed spectrum, but molecular features that agree reasonably well with those observed. Both models produced significant emission from CO and SiO, while the W7-Iax model also produced SiS. The lack of fidelity of the model to the observations makes it hard to rule out the presence of SiS, but it does not seem to be needed. If SiS could be definitively ruled out, the molecular features would seem to favor a fully mixed model like N1def over a radially stratified model like the W7-Iax model, since in N1def SiO forms at the highest density, inhibiting the formation of SiS, whereas in the W7-Iax model SiS and SiO form just below the C+O shell. However, the W7-Iax model reproduces the SiO first overtone significantly better than does N1def, suggesting that the amount of SiO produced by the W7-Iax model is approximately the amount in the ejecta of SN 2024vjm. W7-Iax also produces significant molecular absorption features blueward of $2\ \mu\text{m}$ that are absent in both N1def and the observed spectrum. Thus, definitive conclusions about whether the ejecta of SN 2024vjm are more uniform like that of N1def or more radially stratified like that of the W7-Iax model are premature.

Future work will focus on obtaining stronger forbidden lines, defining a criterion to determine the presence or absence of a bound remnant, the formation of in situ dust, and the presence or absence of neon.

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