A radio-detected thermonuclear supernova from a single-degenerate progenitor with a helium star donor

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Type Ia supernovae (SNe Ia) are attributed to thermonuclear explosions of white dwarf (WD) stars destabilized by mass accretion from a companion star\footnote{arXiv:2210.07725v1 [astro-ph.HE] 14 Oct 2022}. Despite the important application of SNe Ia as standardizable candles for cosmology\footnote{arXiv:2210.07725v1 [astro-ph.HE] 14 Oct 2022}, there remains considerable uncertainty about the nature of their progenitors, in particular if the binary companions are themselves degenerate WD stars or non-degenerate main sequence or red giant stars. A way to discern between the “double-degenerate” channel (DD; the result of the merger of two WDs), and the “single-degenerate” channel (SD; the WD accretes matter from a non-degenerate companion star), is through characterizing the circumstellar environment. The environment around evolved WDs in the merger scenario is expected to be clean, whereas in the accretion scenario, material originating from the non-degenerate...
donor star is expected, produced through stellar winds or Roche-lobe overflow. Studies involving large samples of Type Ia supernovae typically disfavor the SD scenario, based on, for example, the lack of stripped hydrogen-rich (H-rich) material in nebular spectra or non-detections in X-ray. Also direct imaging of nearby Type Ia supernova sites and extensive observations of nearby SNe Ia at radio wavelengths, which should be sensitive to any shock interaction between the SN ejecta and the circumstellar material (CSM), have so far produced null results and have placed stringent limits on the CSM density around these SNe Ia. However, it has been argued that these radio limits do not rule out the low-density accretion winds of a non-degenerate helium (He) donor star, an evolved star which has lost its H envelope. The WD + He donor star SN Ia channel has been extensively investigated in the literature to explain SNe Ia with short delay times. The presence of He also plays a vital role in the double detonation model, a promising SN Ia explosion mechanism where a massive shell of accreted He accumulated on the surface of the WD ignites and triggers the detonation of the WD’s carbon-oxygen (CO) core.

Here we present the study of SN 2020eyj, first detected on 2020 March 7 UT (MJD = 58915.12) as part of the Zwicky Transient Facility (ZTF) survey, at \( \alpha = 11^h 11^m 47.19^s, \delta = +29^\circ 23' 06.5'' \) (J2000). The SN was classified as a SN Ia based on a low-resolution spectrum obtained on 2020 April 2, +25 days post-discovery, with the Palomar 60-inch telescope (P60) equipped with the Spectral Energy Distribution Machine (SEDM). Comparisons with Type Ia and Ibc spectra from the literature support the SN Ia classification (Sect. 2 and Fig. 1). Unusual evolution of the later light curve prompted us to obtain a second spectrum on 2020 July 20 with Keck/LRIS, +131 days past discovery. The LRIS spectrum was very similar to those of Type Ibn SNe (SNe Ibn), which are SNe that interact with helium-rich CSM and have spectra characterized by narrow (\( \sim \text{few} \times 10^3 \text{ km s}^{-1} \)) He emission lines while showing little to no H.

Based on the late time (tail phase) CSM-interaction dominated spectra (Fig. 2), SN 2020eyj falls in the category of the rare subclass of SNe Ia that show evidence of CSM interaction in their optical spectra (SNe Ia-CSM). The narrow emission lines in the spectra of such interacting SNe arise from shock interaction between the fast-moving SN ejecta and a slow-moving CSM. SNe Ia-CSM are strong contenders of the single degenerate SN Ia formation channel on account of the CSM, which is commonly assumed to originate from a non-degenerate donor star through stellar or accretion winds. Prior to SN 2020eyj, all the discovered SNe Ia-CSM exhibited prominent Balmer emission lines and only weak He emission features. SNe Ia-CSM are
further divided by the onset time of the CSM interaction. Typically, CSM interaction contributes significantly to or even dominates the spectral and light curve evolution of SNe Ia-CSM from the start, hindering unambiguous classification as SNe Ia. In contrast, a small subset of SNe Ia-CSM have shown delayed CSM interaction, like SN 2020eyj: SN 2002ic, PTF11kx (SN 2011km), and SN 2015cp. In these cases, the dense CSM is located far (> 10^{15} cm) from the binary system at the time of explosion. Notably, PTF11kx cemented SNe Ia-CSM as a bona fide SN Ia subclass by virtue of a delay of ~60 days, allowing for an indisputable SN Ia classification prior to CSM interaction. As in the other delayed interaction cases, SN 2020eyj initially shows a typical SN Ia bell-shaped light curve (Fig. 3) and a spectrum consistent with an SN Ia of the 91T subgroup without clear evidence for CSM interaction (Fig. 1). Then, at +50 days post discovery, the g-band light curve of SN 2020eyj diverges from a steady decline into a plateau that lasts ~200 days. Such an evolution is not expected for a normal SN Ia, as exemplified by the SN Ia template light curves (Fig. 3) fitted to the initial peak of SN 2020eyj (Sect. 3). Instead, the color change after +50 days is driven by the emergence of a “quasi”-continuum of blended Fe II lines blueward of 5700 Å, which are prominent in the late-time spectra of SN 2020eyj and typical for CSM-interaction dominated SNe such as SNe Ia-CSM. This quasi-continuum overlaps with the filter function of the photometric g band, so we interpret the start of the plateau at +50 days as the epoch when CSM interaction starts to contribute significantly or to even dominate the light curve of SN 2020eyj (Sect. 3). Assuming a SN ejecta velocity of 10^{4} km s^{-1}, the delay corresponds to an inner boundary to the CSM of ~ 4 \times 10^{15} cm. Save for the presence of He emission lines, the late-time spectra of SN 2020eyj are typical for the SN Ia-CSM class, with prominent broad Ca II emission from the near-infrared (near-IR) triplet and without any sign of O I λ7774 emission (Fig. 2). The compact and star-forming host galaxy of SN 2020eyj (Sect. 4), too, is consistent with those of other SNe Ia-CSM.

Despite the similarities between SN 2020eyj and other (delayed interaction) SNe Ia-CSM, the presence of He lines and absence of prominent H lines remains a striking difference with profound implications for the progenitor system. As H I is easier to ionize than He I, the absence of the lines indicates that the CSM around SN 2020eyj, and thus the companion star, is He-rich and H-poor. While the late-time spectra of SN 2020eyj are similar to SNe Ibn, which are presumed to be explosions of massive Wolf-Rayet (WR) stars (initial mass > 25 M_{\odot}, [33]) after periods of episodic mass loss, such short-lived stars are unlikely to be in a binary system with a WD as the WR star would undergo core collapse long before the WD formed. A merger involving
a degenerate He WD donor star is also disfavored, because in such merger models only a small amount of unburned He ($\sim 0.03 M_\odot$) is present close to ($\lesssim 10^{12}$ cm) the WD, whereas the CSM around SN 2020eyj resides at $> 10^{15}$ cm. Instead, a strong candidate for the donor star in the SN 2020eyj progenitor system is a non-degenerate He star (initial mass 1–2 $M_\odot$, e.g. $H_5$). WD + He star systems can be formed via binary evolution $^{14,49}$, are believed to originate from intermediate-mass binary systems, and are likely to be the dominant source of short delay time SNe Ia $^{50,51}$. This single-degenerate Type Ia SN channel has garnered recent interest because the very restrictive limits placed by radio non-detections and deep optical imaging $^{52}$ that exclude most H-rich donor star models, still allow for low CSM density WD + He star systems $^{13,52}$. The possible detection in pre-explosion HST imaging of the progenitor system of the Type Iax (SNe Ia similar to SN 2002cx $^{53}$) SN 2012Z, a blue compact source interpreted as a He-star donor $^{54}$, has further strengthened this hypothesis, although the thermonuclear nature of Type Iax SNe is debated.

The CSM interaction in SN 2020eyj is not only apparent from the spectra, but is also confirmed, for the first time in a Type Ia SN, through the detection of a radio counterpart, at a frequency of 5.1 GHz at +605 and +741 days after discovery (Sect. 1). The SN was not detected at X-ray wavelengths (Sect. 1). In modeling the synchrotron emission resulting from the shock interaction between the ejecta and the CSM, we consider two basic configurations resulting from mass loss from a non-degenerate donor star; a constant density shell and a wind-like density profile with density $\rho \propto r^{-2}$ (Fig. 4). A constant density shell could result from a mass ejection event such as a nova, whereas a wind-like CSM profile would be expected from an optically thick wind, where the mass-transfer rate from the donor star to the WD exceeds the maximum accretion rate of He-rich material that the WD can burn on its surface $^{13,17,55}$. In addition to a CSM arising from a SD scenario, we consider synchrotron emission resulting from the interaction of a SN Ia from a (DD) white dwarf merger interacting with the local interstellar medium (ISM) $^{55}$. For the SD shell model, the radio detections are best explained with a CSM mass of $M_{\text{csm}} = 0.36 M_\odot$ (Sect. 6), with the expectation that the radio light curve will start to drop off quite rapidly at $\sim 900$ days. For the SD optically thick wind model, assuming a pre-SN wind velocity of 1000 km s$^{-1}$, the bolometric light curve tail (Sect. 3) and radio detections of SN 2020eyj are well fitted with a mass-transfer rate of $10^{-3} - 10^{-2} M_\odot$ yr$^{-1}$, microphysics parameter $\epsilon_B = 10^{-5} - 10^{-3}$, and a CSM mass within $10^{17}$ cm of $M_{\text{csm}} = 0.3 - 1.0 M_\odot$, depending on the line of sight extinction affecting the tail phase of SN 2020eyj (Sect. 6). The DD ISM model (the striped lines in Fig. 4) requires unusually high ISM densities and does not recover the observed decline in flux, ruling out the DD formation channel.
for SN 2020eyj (Sect. 6). The best fit radio light curves of the shell and wind models (Fig. 4) differ in particular at early phases, with the wind model peaking much earlier than the shell model, but no radio data were obtained at these epochs. Instead, multi-frequency monitoring of the radio counterpart of SN 2020eyj until late phases (> 1000 days) will allow us to discriminate between the rapid drop off of the shell model, and a shallower decline expected in the case of a wind-like CSM.

A viable progenitor scenario for SN 2020eyj needs to explain not only the presence and properties of a He CSM, but also its detached configuration, as inferred from the ~ 50 days delay in the CSM interaction in SN 2020eyj. The delayed Type Ia-CSM SN 2002ic, for which a inner CSM boundary of $1.7 \times 10^{15}$ cm was inferred, the CSM free cavity was attributed to a possible drop in mass-transfer rate in the final stage of evolution of the system, or the emergence of a low density fast wind evacuating the CSM. In the case of PTF11kx, the delayed CSM interaction was explained by a scenario involving a symbiotic nova progenitor, where recurrent novae on the surface of the WD sweep up the wind-deposited CSM into shells. The most recent nova event then evacuated the nearby CSM, resulting in a CSM-free cavity and a detached CSM. SN 2020eyj shows strong similarities to PTF11kx, which may hint at a common progenitor scenario. Both SNe have $g$- and $r$-band light curves that are virtually identical up until day +50 (Fig. 7) when accounting for host galaxy extinction (Sect. 3), and, except for the nature of the narrow emission lines, both SNe have similar spectra throughout their evolution (Figs. 1 and 2). For SN 2020eyj, a nova progenitor could look like V445 Puppis (V445 Pup, Sect. 6), the only known nova system that showed He-rich, but H-free, nova ejecta. Notably, the V445 Pup system is considered a prime candidate progenitor system for the He star + WD SN Ia channel, as it is claimed to be host to a WD with a mass close to the Chandrasekhar limit. Additionally, V445 Pup is host to a prominent carbon rich equatorial dusty disc which could explain the luminous IR counterpart of SN 2020eyj. In the mid-IR SN 2020eyj rivals some of the most IR-bright SNe observed to date (Fig. 5) in brightness, which we attribute to an IR echo from radiatively heated pre-existing dust with a dust mass of order $10^{-2} M_\odot$ (Sect. 5). The initial models invoking recurrent novae for the origin of PTF11kx were challenged by the CSM masses involved, which were too large by orders of magnitude for symbiotic nova mass build-up models. Similarly, the mass resulting from a V445 Pup-like nova outburst (not more than $10^{-3} M_\odot$; Sect. 3) is insufficient to explain the CSM mass observed in SN 2020eyj. However, a recent study of the long-lived radio evolution of V445 Pup suggests that the equatorial disk could have pre-dated (and survived) the nova outburst.
which would allow for mass build-up in the disc between nova eruptions. This scenario would require the SN to occur soon after the nova outburst, and before the resumption of mass-transfer between the donor and WD reforms the disc at small radii. We note a nova similar to the year 2000 event of V445 Pup would not have been detectable at the distance of SN 2020eyj (Sect. 6).

From the optical spectra and light curve, its infrared emission, and the detection and evolution of its unique radio counterpart, it is clear SN 2020eyj is a SN Ia interacting with a dense CSM. The presence of the CSM rules out a DD merger scenario, and instead offers strong evidence for the SD scenario for SN 2020eyj, in particular for the, so far hypothesized, He star + WD formation channel. This channel is likely to be the dominant source of short-delay SNe Ia, and understanding the timescale of SN Ia supernova activity is important towards understanding the chemical evolution of galaxies, in which nucleosynthesis in Type Ia supernovae plays a significant role. However, it is unclear how representative SN 2020eyj is, as monitoring usually stops after a seemingly normal SN Ia has been classified. The unusual properties of SN 2020eyj were only noted by virtue of its relatively near distance, which allowed for the detection of the unusual light curve tail, and the efforts of ZTF to classify every transient brighter than 19th magnitude. Systematic spectroscopic follow up of SNe Ia with long-lived light curves will be needed to constrain the rate of SNe Ia similar to SN 2020eyj, which represents the first observational example of the previously speculated class of SN Ia-He CSM, and the first SN Ia where a SD origin is confirmed through a radio detection.
Figure 1: The first spectrum of SN 2020eyj is consistent with a Type Ia(-CSM). The SEDM classification spectrum of SN 2020eyj, obtained \( \sim 12 \) days after peak and shown in black, is compared with Type Ia-91T SN 2001V [68], Type Ia-CSM PTF11kx [64], Type Ia SN 2004eo [69] and Type Ic SN 1994I [70]. Phases are relative to peak, which in the case of SN 2020eyj has an uncertainty of a couple of days. A number of important absorption features are indicated at the expected wavelengths. Notably, the spectrum of SN 2020eyj lacks any sign of O I 7774 Å absorption.
Figure 2: The spectra of SN 2020eyj in the tail phase are dominated by CSM interaction. The spectra of SN 2020eyj at late phases (in black) are compared with the prototypical Type Ibn SN 2006jc and the Type Ia-CSM SN PTF11kx. The spectra show features common to SNe Ia-CSM, such as the quasi-continuum blueward of 5700Å and broad Ca II emission. The main SN emission features are identified in the top spectrum. The bottom spectrum is of the host of SN 2020eyj, obtained at +678 days, some 300 days after the SN had faded below the detection limit of ZTF. Some unresolved galaxy lines are marked. Phases are relative to discovery, which in the case of SN 2006jc was at or after the peak.
Figure 3: **The multi-band light curve of SN 2020eyj can be divided into a diffusion peak phase and a long-lived interaction-powered tail phase.** The light curves of SN 2020eyj are shown with over-plotted SN Ia template fits to the initial peak (Sect. 3). The most recent mid-IR epoch (W1 and W2) is outside the date range plotted here, and is shown in Fig. 5 instead. Open circles indicate synthetic photometry derived from the spectra. Phase is in rest-frame days since discovery (MJD = 58915.2). Apparent magnitudes on the left y-axis, absolute magnitudes on the right y-axis, where $\mu$ is the distance modulus. Non-detections with $5\sigma$ upper limits are indicated by triangles. The photometry has been binned into one-night bins. The diamond markers on top indicate the epochs of spectroscopy. The bottom panel shows the $g - r$ color for the nights in which both $g$ and $r$ photometry was obtained, with overplotted the color evolution of a typical SN Ia. The error bars represent $1\sigma$ uncertainties.
Figure 4: **The radio detections of SN 2020eyj at 5.1 GHz can be reconciled with CSM interaction.** For the wind model, where the CSM follows a density profile of \( \rho \propto r^{-2} \), we assume a pre-SN wind velocity of 1000 km s\(^{-1}\) and adopt a mass-transfer rate as inferred from fitting the bolometric light curve of SN 2020eyj. Depending on the level of line of sight extinction affecting the bolometric light curve (Sect. 6), the wind model fits the observations well for the microphysics parameter \( \epsilon_B = 1.7 \times 10^{-3} \) (1.5 \( \times 10^{-5} \)), and a CSM mass of \( M_{\text{csm}} = 0.3 M_\odot \) (1 \( M_\odot \)) within 10\(^{17}\) cm (Sect. 6) when E(B-V) = 0 mag (0.5 mag). For the shell model\(^ {71, 72}\), where the CSM is concentrated in a constant density CSM shell, we assume \( \epsilon_B = 0.1 \), and obtain a best estimate for the CSM mass of \( M_{\text{csm}} = 0.36 M_\odot \) and a CSM interaction end time of \( t_{\text{end}} = 665 \) days (a width of 8.6 \( \times 10^{16} \) cm; Sect. 6). In both the wind and shell model fits, \( \epsilon_c = 0.1 \) is assumed. We also show radio light curves from a model involving a DD Type Ia SN interacting with the ISM (Sect. 6). In order to fit the individual radio detections, this model requires unusually high ISM densities, and neither fit reproduces the observed decline in flux, ruling out the DD scenario.
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**Competing Interests** The authors declare no competing interests.

**Contributions** ECK led the follow-up observations and is the primary author of the manuscript. JJ conducted the spectral analysis and SN Ia light curve modeling, and contributed to the source and infrared analysis. JS contributed significantly to the writing of the manuscript and the source analysis, and conducted follow-up observations with the NOT. JM and MPT led the radio observations and data analysis. TJM, LC, CH and PL conducted the radio light curve modeling. SS conducted the host galaxy analysis. MG conducted follow-up observations with Keck. SM contributed to the writing, and the infrared interpretation. SY contributed to the data analysis. DAP conducted follow-up observations with the Liverpool Telescope. NLS conducted the precursor search. CF, KD and YS conducted follow-up observations. AGY contributed to the writing and source analysis. JL and MS conducted the SEDM spectrum analysis. KM, CO, TMR and

[1] http://gsaweb.ast.cam.ac.uk/alerts
SDR contributed to the writing and source analysis. IA, ECB, JSB, SLG, MMK, FJM, MSM, SP, JP, RR, DS are ZTF builders. All authors contributed to edits to the manuscript.

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**Data Availability**  The optical spectra and photometry of SN 2020eyj will be made available via the WISeREP archive. Data from the NEOWISE-R mission and the Asteroid Terrestrial-impact Last Alert System were obtained from a public source. Radio data from the electronic Multi-Element Radio Linked Interferometre Network (e-MERLIN) will be made available on request.

**Code Availability**  Upon request, the corresponding author will provide code used to produce the figures.
Methods

1 Observations

**Optical spectroscopy** The first optical spectrum of SN 2020eyj was obtained with the Spectral Energy Distribution Machine (SEDM)\(^{24}\) mounted on the Palomar 60-inch telescope (P60)\(^{23}\), +25 days after discovery. All SEDM spectra are automatically reduced and calibrated with pysedm\(^{24}\), and the quality of the SEDM spectrum of SN 2020eyj was further improved using hypergal (Lezmy et al., in prep). Follow-up spectroscopy was obtained from +131 days onward with the Low-Resolution Imaging Spectrometer (LRIS)\(^{75}\) on the Keck I telescope, and the Alhambra Faint Object Spectrograph and Camera (ALFOSC) on the Nordic Optical Telescope (NOT)\(^{76}\). A host spectrum was obtained at +678 days, after the SN had fully faded from view. The spectra were reduced in a standard manner, using LPIPE\(^{77}\) and TYPEIT\(^{78,79}\) for Keck/LRIS and NOT/ALFOSC, respectively.

A log of the obtained spectra is provided in Table 1 and the epochs of spectroscopy are indicated by the diamond markers on top of the light curves in Fig. 3. The spectra were absolute flux-calibrated against the $r$-band magnitudes using the Gaussian Process interpolated magnitudes and then corrected for Milky Way (MW) extinction. All spectral data and corresponding information will be made available via WISeREP\(^{80}\). We present the peak SEDM spectrum in Fig. 1 and the later sequence of spectra in Fig. 2.

The initial spectrum obtained with SEDM is characterized by broad absorption features (Sect. 2). The later spectra are shaped by broad Fe lines, in particular the quasi-continuum blueward of 5700 Å, and a prominent Ca II near-IR triplet. Superimposed on the continuum are narrow He emission lines, as well as Hα. We measure FWHM velocities of the He emission lines and Hα in the spectra obtained with Keck at +131 and +251 days, by fitting a Lorentzian profile to the complete lines, as well as to just the blue wings. The receding red wings in the He and Hα lines are significantly attenuated (Fig. 9 and Sect. 5), so the intrinsic FWHM velocities are better represented by (double) the blue wing FWHM. We report these FWHM velocities in Table 2. The asymmetric line profile we associate with the SN also applies to the Hα emission line, suggesting the presence of H in the CSM. In the spectrum obtained at +131 days, Hα has an equivalent width (EW) of 14 Å, not corrected for contribution by the host. By comparison, the He I emission lines at

https://wiserep.weizmann.ac.il

28
5876, 6678 and 7065 Å in the same spectrum have EWs of 47 Å, 43 Å and 61 Å, respectively. As H is easier to ionize than He, the more prominent He lines means that the CSM must predominantly consist of He. By epoch +329 days, the Hα luminosity has dropped to the luminosity of the Hα narrow emission line in the host spectrum obtained at +678 days (Sect. 4).

**Optical photometry**  Follow-up photometry was obtained as part of public and partnership ZTF survey observations with the ZTF camera on the P48 telescope in the g and r bands, and later phases were also covered in the i band. The P48 data were reduced and host subtracted using the ZTF reduction and image subtraction pipeline, which makes use of the ZOGY algorithm for reference image subtraction. Following the rationale illustrated in, we apply the difference image zero point magnitude to convert fluxes from units in detector data number (DN) to μJy, and translate fluxes to AB magnitudes. We apply a detection threshold of S/N ≳ 3, and for non-detections we compute 5 sigma upper limits. Table 3 lists the ZTF magnitudes and upper limits.

Additional photometric epochs were obtained with the Liverpool Telescope (LT), the SEDM on the P60, the LCO telescopes (program id. NOAO2020B-012), and ALFOSC on the NOT, with data reduced and host subtracted using the pipelines described in or standard methods. In this work we also make use of the forced photometry service from the ATLAS survey, which contained valuable photometry in the o and c bands. One i-band epoch was obtained from the Pan-STARRS1 data archive.

ZTF and ATLAS also obtained observations of the location of SN 2020eyj in the nights immediately preceding the first detection, with limiting magnitudes in the ZTF g band on 2020 March 5 and 6 UT of 20.8 and 19.7, respectively, and the (binned) observations in o band from ATLAS on March 5 UT correspond to a limiting magnitude of 20.2. Phases in this study are relative to the first ZTF detection (MJD = 58915.212, 2020 March 7 UT) in rest-frame days, unless stated otherwise. Given the excellent constraints on the nights before, this epoch is also close to the time of first light.

All magnitudes are reported in the AB system. The reddening corrections are applied using the extinction law with $R_V = 3.1$. The extinction in the MW was obtained from as $E(B−V) = 0.024$ mag. The photometric magnitudes of SN 2020eyj are listed in Table 3. The ATLAS and P48 light curves are shown in Fig. 3 binned into 1-night bins to enhance the signal to noise ratio (S/N).
Infrared photometry  Following a report\(^9\) of a mid-IR detection of SN 2020eyj in the 2021 data release of the NEOWISE Reactivation (NEOWISE-R)\(^9\) survey, we queried the IPAC Infrared Science Archive\(^7\) for any NEOWISE-R detections at the position of SN 2020eyj. After filtering out poor quality data and binning individual exposures following the method described in\(^9\), the SN was recovered in both \(W1\) and \(W2\) filters (3.4 and 4.6 \(\mu\)m, respectively) in all four 2020 and 2021 epochs, with the earliest detection at +59 days after explosion (Fig. 3 and Table 5). The host is not detected in (stacked) WISE data prior to the SN explosion (Fig. 5, top panels), so we assume the contribution from the host is negligible and all observed flux is due to the SN.

Radio  We observed SN 2020eyj with the electronic Multi-Element Radio Linked Interferometre Network (e-MERLIN) in two epochs. The first epoch, with a duration on target and phase calibrator of \(\sim 16\) hours, was conducted on 2021 November 19 (centred on MJD 59538.29), +605 days after discovery and included six e-MERLIN telescopes (Mk2, Kn, De, Cm, Da and Pi). The second epoch was conducted during 6 consecutive days between 2022 April 6 and 12 (mean MJD 59678.59, +741 days after discovery). Between 5 and 6 telescopes (including the Lovell) participated, with some antennae missing part of the runs due to technical problems. Due to the significantly smaller field of view of the Lovell telescope, the pointing centre of the second epoch was shifted by 1 arcmin to include an inbeam calibrator in the primary beam of this telescope. 3C 286 and OQ 208 were used as amplitude and bandpass calibrators, respectively. The phase calibrator, J1106+2812, was correlated at position \(\alpha_{\text{J2000}} = 11^h06^m07.2617^s\) and \(\delta_{\text{J2000}} = 28^\circ12'47.065''\), at a separation of 1.7\(^\circ\) from the target and was detected with a flux density of 150 mJy. We centered our observations at a frequency of 5.1 GHz, using a bandwidth of 512 MHz. The data were correlated with the e-MERLIN correlator at Jodrell Bank Observatory (JBO), using 4 spectral windows, each of 512 channels, with 1 sec integrations and 4 polarizations.

We calibrated and processed the data using the e-MERLIN CASA pipeline\(^9\) version v1.1.19 running on CASA version 5.6.2. We used the 10 mJy inbeam source to self-calibrate the residual phases and amplitudes of the target source. Cleaning was done with the software package \texttt{wsclean} \(^1\). Final images of the target were produced with a synthesized beam of 80 mas \(\times\) 35 mas at a P.A. of 28\(^\circ\), and 94 mas \(\times\) 71 mas at a P.A. of \(-71^\circ\), in the first and second epoch, respectively. The 1-\(\sigma\) rms of the images is 17 and 8 \(\mu\)Jy beam\(^{-1}\), respectively. The target is detected in both epochs as an unresolved source as characterized with task IMFIT. We estimate the uncertainty of the peak flux density to be a quadratic sum of the image rms and a conservative 10\% amplitude
Figure 5: SN 2020eyj was accompanied by a bright mid-IR counterpart. Top left panel: a coadded image of the last NEOWISE-R epoch before the SN explosion, without any sign of the SN host. Top right panel: the coadded image in the $W1$ filter of the 2020 November NEOWISE-R epoch, +261d after explosion, with SN 2020eyj clearly visible. Bottom panel: a mid-IR light curve comparison of SN 2020eyj in the $W2$ filter (4.6 $\mu$m) to a sample of SNe observed with Spitzer at 4.5$\mu$m, adapted from [97], including Type IIn SNe (in black), Type Ia-CSM SNe (in red), Type Ibc SNe (in blue), and Type Ibn SN 2006jc (in lilac). Additionally, the light curves of a sample of SNe Ia from [98] is plotted in green. SN 2020eyj (in pink large circles) is among the brightest SNe observed in the mid-IR, at the level of the Type IIn SN 2010jl and SNe Ia-CSM 2005gj and PTF11kx. The error bars represent 1$\sigma$ uncertainties.
Figure 6: The position of the radio detection is consistent with the position of SN 2020eyj in the optical. Left panel: A $3' \times 3'$ color composite image, obtained with NOT/ALFOSC, of the compact star-forming host galaxy of SN 2020eyj and its environment. Right panel: The average position of the e-MERLIN detections (black circle, 0.01'' uncertainty), the position reported in GaiaAlerts ($G$ band, green circle, 0.06'' uncertainty), and the position of SN 2020eyj in the ALFOSC epoch at +382 days ($r$ band, red circle, 0.1'' uncertainty), overlaid on a $4'' \times 4''$ Pan-STARRS1 $i$-band data of the host.

scale calibration error. The final flux density of the source is $80 \pm 20$ and $60 \pm 10$ $\mu$Jy beam$^{-1}$ in the first and second epoch, respectively. The radio source is located at an average position of $\alpha_{\text{J2000}}.0 = 11^h11^m47.1763^s$ and $\delta_{\text{J2000}}.0 = 29°23'06.45''$, with an estimated uncertainty of 10 mas.

The average position of the e-MERLIN detections relative to the optical positions of SN 2020eyj is shown in Fig. 6. The radio detection is consistent with the position of the SN in the ALFOSC epoch at +382 days ($r$ band), and the position reported in GaiaAlerts of the detection of SN 2020eyj in $G$ band at +42 days.

X-ray On 27 April 2022, we observed SN 2020eyj for 3.8 ks with the X-ray telescope XRT between 0.3 and 10 keV aboard the Neil Gehrels Swift Observatory. We analyzed the
data with the online-tools of the UK *Swift* team\(^\text{\footnotesize 1}\) that use the methods described in \(^\text{\footnotesize 103, 104}\) and the software package *HEASoft* version 6.26.1. SN 2020eyj evaded detection down to a count-rate of 0.003 count s\(^{-1}\) (3\(\sigma\) limit). To convert the count-rate limit into a flux limit, we assumed a power-law spectrum with a photon index \(\Gamma\) of 2 and a Galactic neutral hydrogen column density of \(1.9 \times 10^{20} \text{ cm}^{-2}\) \(^\text{\footnotesize 105}\). Between 0.3–10 keV the count-rate limit corresponds to an unabsorbed flux of \(1.1 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\) and a luminosity of \(< 2.4 \times 10^{41} \text{ erg s}^{-1}\).

### 2 SN Ia classification

During the peak phase of SN 2020eyj, an optical spectrum was obtained with the low-resolution (R\(\sim\)100) SEDM on the P60, +25 days (rest-frame) after discovery. This high S/N spectrum was characterized by broad absorption features (Fig. \[^\text{\footnotesize 1}\]), based on which SN 2020eyj was classified as a Type Ia SN at redshift \(z = 0.03\) \[^\text{\footnotesize 22}\]. Using *SNIascore*, a deep-learning-based classifier of SNe Ia based on low-resolution spectra, \(^\text{\footnotesize 106}\) noted that the SN could be a Type Ibc SN erroneously classified as SN Ia due to the degeneracy between peak spectra of SNe Ibc with those of SNe Ia at post-peak phases, but their classifier anyway favored a SN Ia classification. In general, based on the comparison study by \[^\text{\footnotesize 31}\], Type Ibc SNe erroneously classified as Type Ia(-CSM/91T) are a lot less common than the inverse. Here we scrutinize the SEDM spectrum using comparisons with SNe from the literature, based on spectral matching with the *SuperNova IDentification (SNID)* \(^\text{\footnotesize 107}\) and *Superfit* \(^\text{\footnotesize 108}\) classification tools, where the SNID template library has been supplemented with the Type Ibc templates from \[^\text{\footnotesize 109}\]. We adopt a \(g\)-band peak epoch of MJD = 58929 ± 2, based on the light curve fitting described in Sect. \[^\text{\footnotesize 3}\] with the uncertainty driven by the poor sampling of our photometry around peak.

The top 10 SNID (rlap > 10) and Superfit matches are all of Type Ia, and include normal SNe Ia such as SN 2004eo \[^\text{\footnotesize 69}\] and 91T-like SNe such as SN 2001V \[^\text{\footnotesize 85}\]. The best matching SN of Type Ibc (rlap = 8) is the Type Ic SN 1994I \[^\text{\footnotesize 70, 110–112}\]. The phases corresponding to the matched SNe Ia are all post-peak, ranging from +12 days to +\(~\)50 days, whereas the matching SN Ibc spectra are all within a few days from peak. The phase of the SEDM spectrum of SN 2020eyj is +12 days post peak, which corroborates the SN Ia classification.

In terms of spectral features, the SEDM spectrum shows broad absorption lines that based

\(\text{https://www.swift.ac.uk/user_objects/}\)

The photon index \(\Gamma\) is defined as the power-law index of the photon density \((N(E) \propto E^{-\Gamma})\).
on the spectral comparisons can be unambiguously identified as Si II, Fe II and Ca II (Fig. 1). Compared to normal SNe Ia as exemplified by SN 2004eo, the Si II features in SN 2020eyj are quite shallow. Diluted Si II absorption is common for 91T-like SNe Ia, as in the spectrum of SN 2001V. Type Ia-CSM are known to show 91T-like spectra around peak 31. As a SN strongly interacting with a CSM, the presence of diluted Si II in the SEDM spectrum of SN 2020eyj is consistent with a Type Ia(-CSM) classification. In terms of expansion velocity, the velocity of the Si II λ6355 absorption feature in the SEDM spectrum is $8900 \pm 600 \text{ km s}^{-1}$. This velocity is on the slow side for the SN Ia sample described in 113, but consistent with the 114 SN Ia sample and comparable to, for example, SN 2004eo (Fig. 1).

Another notable feature in the SEDM spectrum is the complete lack of O I 7774 Å absorption (Fig. 1). Even though O I absorption in SNe Ia is quite common, in particular 91T-like SNe Ia can have shallow or non-existent O I 115. This is clearly visible in the matched spectrum of SN 2001V. In contrast, SNe Ibc that lack O I absorption are extremely uncommon, especially at $\sim 12$ days post peak 116, 117.

An absence of oxygen lines is typical for Type Ia-CSM spectra, both as an absorption feature around peak and as emission in later epochs 28, 118, as seen in the early and late spectra of PTF11kx in Figs. 1 and 2 respectively. Similarly, the late spectra of SN 2020eyj lack any sign of O I λ7774 emission (Fig. 2). Other features in the late-time spectra of SN 2020eyj that are typical for Type Ia-CSM include prominent broad Ca II emission and a high Hα/Hβ Balmer ratio, which indicates that the emission lines are likely produced through collisional excitation rather than recombination 28. The high S/N spectrum at +251 days shows both Hα and Hβ emission, but after correcting for contribution by the host, only Hα shows some residual flux related to the transient.

In conclusion, based on its spectral features we classify SN 2020eyj as a Type Ia(-CSM) SN. Furthermore, as we discuss in Sect. 3, the light curves of SN 2020eyj show strong similarities to those of PTF11kx, the SN that cemented SNe Ia-CSM as a subclass.

3 Light curve analysis

Light curve fits The light curve of SN 2020eyj (Fig. 3) can be divided into two phases, similar to its spectral evolution. In the first phase, lasting $\sim 50$ days, the light curve follows a fairly typical bell-like shape, peaking at $m \sim 17.2$ in both the $r$ band and the ATLAS bands, which at a luminosity distance of 131.4 Mpc (Sect. 4) corresponds to $M \sim -18.4$, not accounting for host extinction.
During the first phase the light curve has a red $g - r$ color, consistent with the classification spectrum. The second phase, the tail phase from +50 days onward, is characterized by a slowly evolving light curve with spectra that are dominated by CSM interaction. While the $r$-band light curve continues to fade, albeit at a slower rate of $\sim 0.6$ mag per 100 days between day +50 and +251, the $g$-band light curve plateaus. This results in a $g - r$ color change to blue (see bottom panel of Fig. 3), which based on the spectra is driven by the pseudo-continuum blueward of 5700 Å. This Fe II feature, typical for CSM-powered spectra, is well traced by the ZTF $g$ band (4100 – 5500 Å). From +251 days onward, the light curve fades in all bands at a rate of $\sim 1$ mag per 100 days.

The transition between the two phases is well captured by the photometry at +50 days, when the decline in $g$ band is abruptly halted and changes to a plateau lasting $\sim 200$ days. This divergence of the $g$-band light curve from a smooth decline is likely the epoch where CSM interaction starts contributing (significantly) to the light curve, and where the spectra start to look like those of SNe Ibn. But even though the late spectra may be similar to SNe Ibn, the light curve is unlike those of documented SNe Ibn. SNe Ibn are characterized by uniform rapidly evolving blue light curves \cite{2020ApJ...895..120T}, peaking at $M_r \sim -19.5$. There are a handful of long-lived, slowly evolving SNe Ibn reported in the literature, but they are either much brighter than SN 2020eyj \cite{2020ApJ...895..119T,2020ApJ...895..170C} or have a much longer risetime \cite{2020ApJ...895..130R}. None of the literature SNe Ibn show a long-duration ($> 300$ days) slowly evolving light-curve tail like the one observed in SN 2020eyj. It is worth noting there have been suggestions in the literature that some SNe Ibn may come from thermonuclear explosions, hidden by a dense CSM \cite{2020ApJ...895..122L}. The discovery of SN 2020eyj seemingly supports that notion.

The post-peak decline rates and peak magnitudes of SNe Ia are strongly correlated (the Phillips relation \cite{1993ApJ...413..527P}), with brighter (fainter) SNe Ia evolving slower (faster). We fit the first phase of the multi-band light curves with SNooPy\footnote{https://users.obs.carnegiescience.edu/cburns/SNooPyDocs/html/} to determine if the width (stretch) of SN 2020eyj is consistent with the expected peak luminosity. The light curve of SN 2020eyj up to +50 days is well described by a SN Ia light curve with an adopted stretch of $s_{BV} = 1.2 \pm 0.1$ and an extinction of $E(B - V) = 0.5 \pm 0.1$ mag (adopting a total-to-selective extinction ratio $R_V = 2.0$), resulting in a peak magnitude $\sim 0.06$ mag fainter than expected from the Phillips relation. The required line-of-sight extinction is considerable, but is consistent with the host extinction of $E(B - V) = 0.54^{+0.14}_{-0.12}$ mag derived from host galaxy Balmer lines (Sect. 4). We apply the same fitting method to the light curve of PTF11kx, consisting of published and previously unpublished photometry. For PTF11kx we adopt the same stretch factor of 1.2, and obtain an extinction of $E(B - V) = 0.27$
The light curves of SN 2020eyj are consistent with a SN Ia and its H-rich analog SN Ia-CSM PTF11kx. We simultaneously fit the $g$, $r$, and $i$ light curves of the initial peak phases of both SN 2020eyj and PTF11kx with the SN Ia light curve fitter SNooPy. SN 2020eyj is well fit with stretch factor 1.2 and $E(B-V) = 0.5 \pm 0.1$ mag. Similarly, PTF11kx is well fit with stretch factor 1.2 and $E(B-V) = 0.25 \pm 0.02$ mag. Panels show the absolute magnitude light curves of SN 2020eyj and PTF11kx, after correcting for the host extinction derived from the fit. From left to right: $g$ band; $r$ band for SN 2020eyj and $r/R$ band for PTF11kx; $i$ band. Open circles indicate synthetic photometry derived from the spectra. The error bars represent 1$\sigma$ uncertainties.

After correcting for the fitted host extinction, the resulting absolute magnitude light curves of SN 2020eyj and PTF11kx are practically identical in $g$ and $r$ band for the first $\sim 45$ days, even though the fits are independent (Fig. 7). The $r$-band light curves peak at $M_r \sim -19.3$ for both SNe, consistent with both SNe Ia and SNe Ia-CSM, although both SNe are on the fainter end of the sample of SNe Ia-CSM described by 28. From the light-curve fits we obtain for SN 2020eyj rise times in $g$ and $r$ band of $14 \pm 2$ and $16 \pm 2$ days since discovery, respectively. This is fast for a SN Ia 124, but similar to PTF11kx (Fig. 7).

An important caveat about the light curve fit is that the intrinsic decline rate of SN 2020eyj could appear slower because of the contribution by CSM interaction. Based on the color evolution of the light curve, we know from day +50 onward that the CSM contribution is significant, but it
is reasonable to assume that some CSM interaction already contributes to the light curve at earlier epochs. This means that the stretch parameter we measure should be regarded as an upper limit, and as a result so is the peak luminosity of the fit. The main purpose of the light curve fit was to demonstrate that the light curve evolution of SN 2020eyj can indeed be reconciled with that of a SN Ia.

**Bolometric light curve** The light curve of SN 2020eyj around peak has limited photometric coverage, both in wavelength and cadence, which hinders the construction of a precise, full bolometric light curve. Instead, we compute the bolometric light curve based on the SN Ia light curve template fit obtained in Sect. 3 for epochs when the photometry (notably g band) still matches well with the fitted light curve (up to +38 days after discovery, Fig. 7). From the fitted optical light curves, we flux calibrate, correct for host extinction and integrate the spectral time-series from 1250 Å from the UV to the near-IR (1000-25000 Å). For the tail phase, we integrate the Keck spectra at +131 and +251 days from 3000 to 10000 Å, and apply a linear extrapolation in the UV to zero flux at 2000 Å. There is little spectroscopic (Fig. 2) and color (Fig. 3) evolution between the Keck spectrum at +251 days and the NOT spectrum at +328 days, so we extend the pseudo-bolometric light curve to the final photometric epoch at +383 days obtained with ALFOSC on the NOT assuming a constant bolometric correction applied to the g-band magnitude. Fig. 8 shows the bolometric luminosity inferred from the template fit, the Keck spectra, and the final photometric epoch. The template fit to the initial peak included considerable line of sight extinction of E(B−V) = 0.5 mag (Sect. 3), but for the CSM-interaction driven tail phase the extinction is poorly constrained. If the line of sight extinction to the SN is primarily due to the host, as the host extinction derived from the Balmer decrement seems to indicate (Sect. 4), the full SN light curve would be similarly affected. However, if the dust extinction is local to the SN, geometrical effects and/or dust destruction could result in variable extinction between the SN Ia peak and the tail phase. As such, for the tail phase we show in Fig. 8 two extreme cases of E(B−V) = 0.5, as applied to the peak phase, and E(B−V) = 0 mag. Depending on the tail phase dust extinction, the total integrated energy radiated across the bolometric light curve amounts to 0.6−1.2 × 10^{50} erg.

4 **Host galaxy**

The host of SN 2020eyj is a faint and compact galaxy with designation SDSS J111147.15+292305.9 (Fig. 6). We retrieved science-ready co-added images from the *Galaxy Evolution Explorer (GALEX)* general release 6/7, the Sloan Digital Sky Survey data release 9 (SDSS DR 9), and the
Figure 8: The bolometric light curve of SN 2020eyj can be described with a radioactive decay model for the peak phase, and an optically thick wind for the tail phase. For the initial SN Ia peak of SN 2020eyj we adopt the bolometric light curve (solid blue line) accompanying the SN Ia template fit to the gri photometry (Sect. 3). Overplotted are the associated bolometrically corrected luminosities up until +40 days. From epoch +46 days onward the SN Ia template fit does not accurately describe the observed (g band) photometry any longer (Fig. 7). The blue dotted line shows the continuation of the bolometric light curve of the underlying SN Ia. The three measurements in the tail phase are based on the integration of the two Keck spectra, extrapolated to the UV, and a bolometrically corrected photometric ALFOSC epoch. We show both the measurements assuming no line of sight extinction (in green) and an extinction of E(B-V) = 0.5 mag (in orange). The dotted lines represent the fits to the tail phase measurements using the analytical model from[13], following the same color scheme for the level of extinction. In the transition region from the diffusion peak to the CSM interaction-powered tail, between +50 and +100 days, the sum of the models would overestimate the luminosity, suggesting the CSM configuration is more complicated than a simple wind-like density profile.
Panoramic Survey Telescope and Rapid Response System (Pan-STARRS, PS1) DR1 and measured the brightness of the host using LAMBDAR (Lambda Adaptive Multi-Band Deblending Algorithm in R) and the methods described in [129]. We augment this data set with an optical $r$-band image obtained with ALFOSC on the NOT on 2022 May 2 and UV observations from Swift/UVOT from 2022 April 27. The photometry on the UVOT images was done with uvotsource in HEASoft and an aperture encircling the entire galaxy (aperture radius 8″). Table 4 lists all measurements. We fit the host galaxy SED with the software package Prospector to determine the host galaxy properties. We assumed a Chabrier initial mass function and approximated the star formation history (SFH) by a linearly increasing SFH at early times followed by an exponential decline at late times (functional form $t \times \exp (-t/\tau)$, where $t$ is the age of the SFH episode and $\tau$ is the $e$-folding timescale). The model was attenuated with the $E(B-V)$ model. The priors were set identical to [129]. The fit resulted in a low host-galaxy mass of $\log(M/M_\odot) = 7.79^{+0.15}_{-0.34}$.

We obtained a host galaxy spectrum with LRIS/Keck after SN 2020eyj had faded from view, at +678 days past discovery. We identify unresolved ($\lesssim 150$ km s$^{-1}$) host galaxy lines in the spectrum, such as numerous Balmer lines in emission and absorption, [N II] $\lambda\lambda$6548,6583, [O II] $\lambda\lambda$3726,3729, [O III] $\lambda\lambda$4959,5007 and [S II] $\lambda\lambda$6716,6731, based on which we measure a redshift of $z = 0.0297 \pm 0.0001$. Adopting a flat cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_M = 0.3$, this redshift corresponds to a luminosity distance to SN 2020eyj of 131.4 Mpc, which we use throughout this paper. Correcting for MW extinction the adopted distance results in a host galaxy absolute magnitude of $M_r = -15.8$.

Based on the Balmer decrement measured in the host spectrum, we estimate a host extinction with $E(B-V) = 0.54^{+0.14}_{-0.12}$ mag, in agreement with the extinction obtained by fitting the light curves of SN 2020eyj with a SN Ia template (Sect. 3). The line ratios of $\log_{10}([\text{O III}] \lambda5007 / H\beta) = 0.39$ and $\log_{10}([\text{N II}] \lambda6583 / H\alpha) = -1.26$ put the host galaxy well into the regime of star forming galaxies on the BPT diagram [133]. Adopting the parameterisation of the empirical oxygen calibration O3N2 by [134], we obtain an oxygen abundance of $12 + \log(O/H) = 8.14 \pm 0.03$. Such a low oxygen abundance is expected for a low mass galaxy [135].

The host properties of 16 SNe Ia-CSM were reported in [28, 42]. These authors concluded that all objects in their samples exploded in star-forming late-type galaxies (spiral and dwarf galaxies).

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[1] https://github.com/AngusWright/LAMBDAR
[2] https://github.com/bd-j/prospector
with absolute magnitudes between $M_r = -20.6$ and $-18.1$ mag. The hosts of 3 SNe in this sample evaded detection in archival SDSS images, implying an absolute magnitude of $M_r > -18$ mag. SN 2020eyj exploded in a markedly low-luminosity star-forming dwarf galaxy with an absolute $r$-band magnitude of only $M_r = -15.8$ mag (not corrected for host attenuation). However, the modeling of the host galaxy SED and the Balmer decrement reveal non-negligible attenuation of $0 < E(B-V) < 0.55$ mag ($3\sigma$ confidence interval from host SED modeling) or $0.2 < E(B-V) < 1$ mag ($3\sigma$ confidence interval from the Balmer decrement), which would alleviate the apparent extremeness of the host galaxy.

5 Dust properties

IR emission is commonly observed in interacting SNe, and can be attributed to the condensation of dust in the SN ejecta or in the shocked CSM, or to pre-existing dust in the CSM that is heated radiatively by the SN emission or by the ejecta/CSM shock interaction (e.g.,\textsuperscript{136–139}). The mid-IR luminosity of SN 2020eyj is at a similar level as for the most IR-luminous interacting SNe, such as Type IIn and SNe Ia-CSM, and is $2-4$ magnitudes brighter than the mid-IR luminosities of Type Ia, Ib/c and Ibn SNe (Fig. 5 bottom panel).

Assuming optically thin dust, the flux $F_\nu$ can be written as\textsuperscript{140}:

$$F_\nu = \frac{M_d B_\nu(T_d) \kappa_\nu(a)}{d^2},$$

where $M_d$ is the mass of the dust, $B_\nu$ the Planck blackbody function, $T_d$ the temperature of the dust, $\kappa_\nu(a)$ the dust absorption coefficient as function of dust particle radius $a$, and $d$ the distance to the observer. For simplicity, we assume a simple dust population of a single size composed entirely of amorphous carbon with grain size of $0.1$ $\mu$m with the corresponding absorption coefficient $\kappa$ as in\textsuperscript{141,142}, and fit the WISE data to obtain an estimate of the dust temperature and mass. Over the first three epochs, up to $+412$ days, we derive a constant dust temperature of $\sim 800$ K (Table 6), consistent with a lack of color evolution in the WISE photometry (Fig. 3). Only at the fourth WISE epoch ($+614$ days) do we see a significant drop in the dust temperature, to $608 \pm 23$ K. These dust temperatures are well below the expected evaporation temperature of dust ($1500$ K for silicates and $1900$ K for graphite grains, e.g.\textsuperscript{139}). In addition to the dust temperatures, we obtain dust mass estimates of $(1.8 \pm 0.3) \times 10^{-3}$ $M_\odot$ to $(9.9 \pm 2.1) \times 10^{-3}$ $M_\odot$ for the first and the final WISE epochs, respectively (Table 6). The dust mass estimated for the final epoch corresponds to a CSM
mass of $1 \times (0.01/r_{dg}) \, M_\odot$, where $r_{dg}$ is the dust-to-gas ratio.

In the case of optically thin dust that we consider here, the blackbody radius can be interpreted as a lower limit to the radius at which the dust resides. In the case of SN 2020eyj, the blackbody radius is $(2.5 \pm 0.2) \times 10^{16}$ cm in the first epoch, and increases thereafter to $(6.4 \pm 0.6) \times 10^{16}$ cm at +614 days (Table 6). Assuming a SN ejecta velocity of $10^4$ km s$^{-1}$, by +59 days the ejecta would only have traveled $\sim 20\%$ of the distance inferred from the blackbody fit at that epoch. Combined with the constant dust temperature, this suggests that the IR emission of SN 2020eyj is dominated by pre-existing dust getting radiatively heated by CSM interaction emission, as was the case in Type Ia-CSM SN 2005gj\(^{142}\). Furthermore, because the dust reached a temperature of 800 K as early as +59 days and showed no significant evolution afterwards, it is unlikely that any surrounding dust was evaporated due to the SN, because such hot dust would have dominated the IR flux. For a peak SN luminosity of $\sim 10^{43}$ erg s$^{-1}$ (Fig. 8), the dust evaporation radius is $R_{\text{evap}} = (0.34–2.6) \times 10^{17}$ cm, depending on dust grain size and composition\(^{139}\). The lack of dust at the sublimation temperature implies that the immediate region surrounding the SN was devoid of dust, much like the CSM-free cavity inferred from the SN light curve.

The He I and H$\alpha$ emission line profiles show the red wing being attenuated with time (Fig. 9). Such an evolution in the line profiles has been interpreted to result from condensation of dust in the ejecta or the shocked CSM, obscuring the receding red wing of the emission line\(^{138,143,144}\). Similar line profiles have been observed in many SNe Ia-CSM\(^{28}\) and in the prototypical Type Ibn SN 2006jc, where the evolution of the line profiles was attributed to dust condensing in a cool dense shell produced by the interaction of the ejecta with CSM also producing a substantial IR excess\(^{137}\). Interestingly, such line profile evolution has also been observed in the He nova V445 Pup, where it was attributed to dust obscuration within the shell\(^{61}\). In particular, for Type Ia-CSM SN 2005gj dust formation was inferred from line profiles\(^{28}\), while the bulk of the IR emission was also attributed to pre-existing dust\(^{142}\). Finally, the prototypical Type Ia-CSM SN 2002ic was also accompanied by a bright IR counterpart, which was attributed to an IR echo arising from the pre-existing dusty CSM\(^{136}\).

6 CSM origin

**Optically thick wind** Using progenitor models for the He star donor SN Ia channel from\(^{14,13}\) investigated the CSM properties resulting from this channel, where accretion from a non-degenerate
He star allows the accompanying WD to reach the Chandresekhar limit. The study by [13] focused on the low circumstellar density regime, where the CSM properties in the WD + He star systems still adhere to the stringent CSM constraints imposed by radio non-detections of SNe Ia [9–12]. Here we explore if the models with sufficiently dense CSM, with a wind-like density profile ($\rho \propto r^{-2}$), can explain the interaction powered light-curve tail of SN 2020eyj and the detections at radio wavelengths. In order to quantify the properties of the CSM, we fit the CSM interaction-powered tail of the bolometric light curve using the analytical model from [13], and use the resulting mass-transfer rates to fit the radio detections.

Fig. 8 shows the bolometric light curve of SN 2020eyj, with the initial peak described by the SN Ia template fit (solid line), and for the tail phase the luminosities inferred from the Keck spectra at +131 and +251 days and the ALFOSC epoch at +383 days (Sect. 3). From the light curve described by the SN Ia component alone (solid and dotted line), it is also clear that the late-time light curve of SN 2020eyj cannot be powered by $^{56}$Ni decay, since the flux integrated across the Keck spectrum at +131 days is already at least ten times larger than what the radioactive decay delivers. Also plotted are the CSM-interaction model fits to the light curve tail, both for an E(B-V) = 0 mag and E(B-V) = 0.5 mag as discussed in Sect. 3. Assuming a pre-SN wind velocity of 1000 km s$^{-1}$, the CSM-powered tail of SN 2020eyj is consistent with mass-transfer rates between $10^{-3}$ $M_\odot$ yr$^{-1}$ (E(B-V) = 0 mag) and $3 \times 10^{-2}$ $M_\odot$ yr$^{-1}$ (E(B-V) = 0.5 mag), which is 1-2 orders of magnitude larger than considered in the original study [13]. At these very high mass-transfer rates, the critical mass accretion rate by the WD is exceeded, and the excess is ejected as an optically thick wind resulting in an extended He envelope [13]. In the model the forward shock reaches to $\sim 10^{17}$ cm in 800 days. If we assume a wind velocity of 1000 km s$^{-1}$, the CSM mass within $10^{17}$ cm in the models range from 0.3 $M_\odot$ to 1 $M_\odot$, for E(B-V) = 0 and 0.5 mag, respectively.

Fig. 8 shows the wind model radio light curves fitted to the radio detections at 5.1 GHz, adopting $\epsilon_c = 0.1$ and mass-transfer rates of $10^{-3}$ $M_\odot$ yr$^{-1}$ and $3 \times 10^{-2}$ $M_\odot$ yr$^{-1}$, for E(B-V) = 0 and 0.5 mag, respectively. We consider both synchrotron emission with synchrotron self-absorption (SSA) and free-free absorption (FFA), but note that at the late phase of the radio detection, FFA only has a minor impact. The radio light curve with an adopted mass-transfer rate of $10^{-3}$ $M_\odot$ yr$^{-1}$ is consistent with the radio detections of SN 2020eyj at 5.1 GHz, with microphysics parameter $\epsilon_B = 1.7 \times 10^{-3}$. For the high extinction scenario, with a mass-transfer rate of $3 \times 10^{-2}$ $M_\odot$ yr$^{-1}$, the model fits when $\epsilon_B = 1.5 \times 10^{-5}$. In either case, the late time evolution follows the observed power law decline rate of the observed radio luminosity of $\beta = -1.6$, which is comparable to that
for hydrogen-free SNe Ibc\textsuperscript{135}.

It is worth noting that the bolometric light curve only extends to +400 days, whereas the first detection of SN 2020eyj at 5 GHz took place at +605 days. Furthermore, it has been argued that the mass-transfer rates associated with the optically thick wind phase (\( \geq 10^{-7} \, M_\odot \, \text{yr}^{-1} \)) do not lead to SNe Ia, but rather to accretion induced collapse of the WD\textsuperscript{146}.

CSM shells The CSM surrounding the H-rich analog of SN 2020eyj, PTF11kx, was argued to be concentrated in shells\textsuperscript{144}. Models for the radio emission of SNe Ia colliding with a constant-density shell of CSM have been previously presented in the literature, along with approximate functional forms to describe the evolution of the optically thick synchrotron light curve\textsuperscript{72}. Since those models assume hydrogen-rich material, for our calculations we modify \( n_e = \rho/m_p \) to \( n_e = \rho/(2m_p) \); otherwise we use the default parameters, notably \( \epsilon_B = 0.1 \). We explore shell models with a range of CSM masses \( M_{\text{csm}} = (0.01 - 1) \, M_\odot \) and interaction end times from \( t_{\text{end}} = 328 \) days (the spectrum that does not show prominent He I lines) to \( t_{\text{end}} = 763 \) days (the second radio detection) – in this model, interaction must have ended before the second radio detection for the radio emission to have declined between the two observations. We assume a shell inner radius of \( R_{\text{in}} = (30,000 \, \text{km s}^{-1})(50 \, \text{days}) = 1.3 \times 10^{16} \, \text{cm} \) to close the system of equations in the model; then, the ranges of \( M_{\text{csm}} \) and \( t_{\text{end}} \) correspond to a range of shell widths \( \Delta R/R_{\text{in}} = 3.4 - 7.5 \). For each model we calculate the representative model error as \( \sigma_{\text{mod}} = \max(|L_{\nu,\text{obs}}(t_i) - L_{\nu,\text{mod}}(t_i)|/\Delta L_{\nu,\text{obs}}(t_i)) \), where subscripts “obs” and “mod” refer to observed and modeled values, \( L_{\nu} \) is spectral luminosity, and \( \Delta L_{\nu} \) is the error on the luminosity (flux error only; error in distance is not included). The best-fit model by this metric has \( M_{\text{csm}} = 0.36 \, M_\odot \) and \( t_{\text{end}} = 665 \) days, which is a very similar mass to what is found for PTF11kx based on analysis of its optical spectra\textsuperscript{147}. We find models with \( \sigma_{\text{mod}} \leq 3 \) have \( t_{\text{end}} \approx (500 - 763) \) days and \( M_{\text{csm}} \approx (0.2 - 0.5) \, M_\odot \), while those with \( \sigma_{\text{mod}} \leq 1 \) (i.e., a better fit) have \( t_{\text{end}} \gtrsim 580 \) days and \( M_{\text{csm}} \approx (0.3 - 0.4) \, M_\odot \). The best fit shell model is shown in Fig. 4.

V445 Puppis The nova outburst of V445 Pup in the year 2000 lacked any Balmer emission in the spectra of its ejecta, but instead was characterized by He and carbon emission lines\textsuperscript{58,59}, making it the first and so far only known He nova system. Based on light curve modeling, a mass (\( \geq 1.35 \, M_\odot \)) close to the Chandrasekhar limit was inferred for the WD in V445 Pup\textsuperscript{62}, consistent with the observed high ejecta velocities up to 8450 km s\(^{-1}\)\textsuperscript{61}. Combined with a high mass-transfer rate > \( 10^{-7} \, M_\odot \, \text{yr}^{-1} \), where half of the accreted matter remains on the WD\textsuperscript{62}, V445 Pup is
considered to be a prime candidate progenitor for the single degenerate He + WD SN Ia progenitor channel.

Based on infrared spectra showing prominent carbon lines\textsuperscript{58,60} and a rapid decline in the light curve of V445 Pup, it was shown that a carbon-rich thick dust shell must have formed in the nova ejecta\textsuperscript{58,59}. High resolution near-IR images resolved the nova event into an expanding narrow bipolar shell with bulk velocities of $\sim 6700 \, \text{km s}^{-1}$, and a perpendicular central dust disc that strongly attenuates the optical He I emission lines arising from the receding shell\textsuperscript{61}. Seven years after the outburst, the bipolar shell of V445 Pup, as imaged in the near-IR, extended to $\sim 10^{17}$ cm, and the central dust torus had an outer radius (perpendicular to the lobes) of $\gtrsim 10^{16}$ cm\textsuperscript{61}. A recent study of the long-lived radio evolution of V445 Pup showed the system was continuously synchrotron luminous for years after the outburst\textsuperscript{65}. The synchrotron emission originated from the inner edge of the equatorial disc, and was interpreted as interaction between a wind coming off the WD from nuclear burning, and the surviving disc. The persistence of the disc through the nova outburst suggests the disc is at least comparable in mass with the mass of the nova ejecta, which was estimated to be $\sim 10^{-4} \, M_\odot$\textsuperscript{62}. In turn, the mass of the WD in V445 Pup, close to the Chandrasekhar limit, limits the ejecta mass in the system to not more than $\sim 10^{-3} \, M_\odot$ (their Fig. 7).

**ISM** Radio emission can potentially arise from a Type Ia SN in the double-degenerate scenario as a result of interaction with the ISM. We have modeled the radio light curve from such a merger scenario in the same way as in\textsuperscript{12,56} i.e., we assume that the supernova is the result of two merging white dwarfs with masses 0.9 and 1.1 $M_\odot$ as described by\textsuperscript{148}. The outermost ejecta has a density slope $\propto \rho^{-n}$ with $n = 13$ (see\textsuperscript{56} for a discussion on $n$). The microphysics parameters are the standard values $\epsilon_e = 0.1$ and $\epsilon_B = 0.01$. The modeled radio emission increases with time (Fig. 4), and to agree with the observed 5.1 GHz fluxes at +605 and +741 days, the ISM electron density has to be $660 \, \text{cm}^{-3}$ and $450 \, \text{cm}^{-3}$, respectively, assuming fully ionized hydrogen and helium with He/H = 0.1. For $n = 13$ and fixed $\epsilon_e$, the electron density scales roughly as $\epsilon_B^{-0.74}$, so other ISM densities are possible accordingly. For a likely upper limit on $\epsilon_B$ of 0.1, the ISM density would be $n_e = 85 \, \text{cm}^{-3}$ to fit the flux at the second epoch, and for $\epsilon_B$ of 0.001, $n_e = 2570 \, \text{cm}^{-3}$. The increase in radio flux with time is opposite to what is observed, and is a property for all our ISM models with $n > 7.1$. Lower $n$-values are not expected\textsuperscript{56} and the densities required in our ISM models are much higher than normal ISM densities. Moreover, for the $n = 13$, $\epsilon_B = 0.01$ model, where $n_e = 450 \, \text{cm}^{-3}$, the modeled flux for the first epoch undershoots by 2 sigma (Fig. 4). In summary, our
radio observations and their modeling argue strongly against an ISM scenario, which arises from a double degenerate progenitor system. Furthermore, the observed strong helium lines are also at odds with an ISM scenario. We therefore conclude that SN 2020eyj did not result from the thermonuclear runaway of a WD in a DD progenitor system, leaving the SD scenario as the only viable alternative.

**Precursor search** The CSM surrounding SN 2020eyj could have originated from one or more novae such as observed in V445 Pup. We investigate if a similar outburst at the location of SN 2020eyj can be found in ZTF data going back > 2 years. The position of SN 2020eyj was observed 772 times (after quality cuts) in the $g$, $r$, and $i$ bands across 202 different nights in the final 2.29 years before the SN explosion. There are no significant pre-explosion detections in unbinned or binned light curves (1-day to 90-day long bins) following the search method described by [150]. When combining observations in week-long bins we reach a median limiting absolute magnitude of $-14.28$ in the $r$ band ($-14.26$ in the $g$ band). We can hence rule out precursors that are brighter than $-14$ magnitude $21\%$ of the time in the $r$ band ($16\%$ of the time in $g$ band). Precursors brighter than magnitude $-15$ can be ruled out $49\%$ of the time in $r$ band ($39\%$ for $g$ band) in the final 2.29 years before the SN. The nova outburst of V445 Pup peaked at $m_V = 8.6$ [151], which at a distance of 8.2 kpc [68] equates to an absolute magnitude of $M_V = -1$, far below the detection threshold of ZTF.
Figure 9: The He and Hα emission line profiles in the late spectra of SN 2020eyj show evidence for dust formation. The He I emission lines at 5876 Å, 6678 Å and 7065 Å all show strong attenuation in the receding red wings, and an apparent blue shift over time between the +131 and +251 days epochs. Such line asymmetry is commonly observed in SNe Ia-CSM [28], and is interpreted as due to the condensation of dust in the ejecta or shocked CSM, obscuring the red wing (Sect. 5). The Hα emission line at +131 days also shows asymmetry and there is a (minor) decline in flux between the two epochs shown here. By +329 days, the Hα luminosity has dropped to the level of the line emission in the host spectrum (Sect. 1).
Table 1: Log of spectroscopic observations of SN 2020eyj and its host. Phase is relative to discovery epoch, in rest-frame.

| MJD  | Observation Date (UT) | Phase past discovery (rest-frame days) | Telescope + Instrument |
|------|-----------------------|----------------------------------------|------------------------|
| 58941.2 | 2020 Apr 02            | 25                                     | P60+SEDM               |
| 59050.3 | 2020 Jul 20             | 131                                    | Keck1+LRIS             |
| 59150.5 | 2020 Oct 28             | 228                                    | P60+SEDM               |
| 59162.2 | 2020 Nov 09             | 240                                    | NOT+ALFOSC             |
| 59173.6 | 2020 Nov 30             | 251                                    | Keck1+LRIS             |
| 59253.9 | 2021 Feb 08             | 329                                    | NOT+ALFOSC             |
| 59615.4 | 2022 Feb 05             | 678                                    | Keck1+LRIS             |
Table 2: FWHM velocity measurements of prominent emission lines in the +131 and +251 days Keck spectra. Listed are both the FWHM velocities measured from fitting the full line with a Lorentzian line profile, as well as twice the half width at half maximum of the blue wing. The latter measurements better represents the true FWHM velocity, because the receding red wings in the emission lines are strongly attenuated (Fig. 9).

| Phase | He I λ5876 | He I λ6678 | He I λ7065 | Hα |
|-------|------------|------------|------------|-----|
|       | Full (km s<sup>-1</sup>) | Blue wing (km s<sup>-1</sup>) | Full (km s<sup>-1</sup>) | Blue wing (km s<sup>-1</sup>) | Full (km s<sup>-1</sup>) | Blue wing (km s<sup>-1</sup>) |
| +131  | 1080       | 1540       | 960        | 1270 | 780     | 1080 |
| +251  | 1500       | 2680       | 1150       | 1750 | 1140    | 2000 |

48
Table 3: Optical ZTF photometry of SN 2020eyj, in observed magnitudes. Phase is relative to discovery epoch, in rest-frame.

| MJD     | Phase | Filter | magnitude | error | Limiting magnitude | Telescope+Instrument |
|---------|-------|--------|-----------|-------|--------------------|----------------------|
| 58909.28 | -5.8  | g      | -         | -     | 21.02              | P48+ZTF              |
| 58909.32 | -5.7  | r      | -         | -     | 21.38              | P48+ZTF              |
| 58911.22 | -3.9  | r      | -         | -     | 20.32              | P48+ZTF              |
| 58911.40 | -3.7  | g      | -         | -     | 21.32              | P48+ZTF              |
| 58912.29 | -2.8  | g      | -         | -     | 20.94              | P48+ZTF              |
| 58912.40 | -2.7  | r      | -         | -     | 21.14              | P48+ZTF              |
| 58913.24 | -1.9  | r      | -         | -     | 20.68              | P48+ZTF              |
| 58913.28 | -1.9  | g      | -         | -     | 20.82              | P48+ZTF              |
| 58914.23 | -1.0  | g      | -         | -     | 19.71              | P48+ZTF              |
| 58915.21 | 0.0   | g      | 19.66     | 0.20  | 20.30              | P48+ZTF              |
| 58915.37 | 0.2   | r      | 19.11     | 0.09  | 20.57              | P48+ZTF              |
| 58939.21 | 23.3  | r      | 17.24     | 0.01  | 20.90              | P48+ZTF              |
| 58939.21 | 23.3  | r      | 17.30     | 0.01  | 21.00              | P48+ZTF              |
| 58939.22 | 23.3  | r      | 17.23     | 0.02  | 20.62              | P48+ZTF              |
| 58939.32 | 23.4  | g      | 17.86     | 0.03  | 20.63              | P48+ZTF              |
| 58941.18 | 25.2  | r      | 17.27     | 0.05  | -                  | P60+SEDM             |
| 58941.25 | 25.3  | g      | 17.96     | 0.03  | 20.73              | P48+ZTF              |
| 58954.23 | 37.9  | r      | 17.65     | 0.02  | 21.08              | P48+ZTF              |
| 58954.28 | 37.9  | g      | 18.77     | 0.04  | 21.29              | P48+ZTF              |
| 58962.25 | 45.7  | g      | 18.95     | 0.04  | 21.43              | P48+ZTF              |
| 58962.27 | 45.7  | r      | 18.11     | 0.02  | 21.13              | P48+ZTF              |
| 58964.21 | 47.6  | g      | 19.00     | 0.04  | 21.51              | P48+ZTF              |
| 58964.21 | 47.6  | g      | 19.10     | 0.04  | 21.46              | P48+ZTF              |
| 58964.21 | 47.6  | g      | 19.04     | 0.04  | 21.53              | P48+ZTF              |
| 58965.24 | 48.6  | g      | 19.03     | 0.04  | 21.56              | P48+ZTF              |
| 58967.24 | 50.5  | g      | 19.19     | 0.05  | 21.39              | P48+ZTF              |
| 58967.24 | 50.5  | g      | 19.15     | 0.05  | 21.38              | P48+ZTF              |
| 58967.24 | 50.5  | g      | 19.14     | 0.05  | 21.29              | P48+ZTF              |

(This table is available online in its entirety.)
Table 4: Host galaxy photometry. Magnitudes are not corrected for reddening.

| Survey/Telescope | Instrument | Filter | Magnitude     |
|------------------|------------|--------|---------------|
| GALEX            | $FUV$      |        | 21.37 ± 0.38  |
| GALEX            | $NUV$      |        | 20.99 ± 0.14  |
| Swift            | UVOT       | $w2$   | 21.45 ± 0.16  |
| Swift            | UVOT       | $m2$   | 21.66 ± 0.27  |
| Swift            | UVOT       | $w1$   | 21.31 ± 0.24  |
| SDSS             | $u$        |        | 21.16 ± 0.23  |
| SDSS             | $g$        |        | 20.26 ± 0.06  |
| SDSS             | $r$        |        | 19.86 ± 0.05  |
| SDSS             | $i$        |        | 19.74 ± 0.13  |
| PanSTARRS        | $g$        |        | 20.46 ± 0.10  |
| PanSTARRS        | $i$        |        | 19.94 ± 0.08  |
| PanSTARRS        | $z$        |        | 19.71 ± 0.16  |
| PanSTARRS        | $y$        |        | 20.21 ± 0.57  |
| NOT ALFOSC       | ALFOSC     | $r$    | 19.99 ± 0.03  |
Table 5: Mid-IR photometry of SN 2020eyj from the WISE telescope, in observed magnitudes (AB) and binned per each 1-2 day epoch. Phase is rest-frame days since the discovery epoch.

| MJD      | Phase | W1   | W2   |
|----------|-------|------|------|
|          | (rest-frame days) | (magnitude) | (error) | (magnitude) | (error) |
| 58975.45 | 58.5  | 17.29| 0.03 | 17.26 | 0.03 |
| 59181.42 | 258.5 | 16.72| 0.02 | 16.70 | 0.04 |
| 59339.60 | 412.0 | 16.40| 0.02 | 16.31 | 0.02 |
| 59548.01 | 614.4 | 17.30| 0.04 | 16.76 | 0.03 |
Table 6: Infrared and dust properties. Dust mass and temperature (columns 3 and 4, assuming 0.1\(\mu\)m amorphous carbon grains), blackbody temperature, radius and luminosity (columns 5 - 7), and the cumulative radiated energy (column 8).

| MJD    | Phase | \(M_{\text{dust}}\) (10\(^{-3}\) \(M_\odot\)) | \(T_{\text{dust}}\) (K) | \(T_{\text{BB}}\) (K) | \(r_{\text{BB}}\) (10\(^{16}\) cm) | \(L_{\text{BB}}\) (10\(^{42}\) erg s\(^{-1}\)) | Cumulative (10\(^{49}\) erg) |
|--------|-------|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 58975.5| 58.5  | 1.8 ± 0.3                       | 801 ± 23        | 1268 ± 63       | 2.5 ± 0.2       | 1.2 ± 0.3       | -               |
| 59181.4| 258.5 | 2.8 ± 0.5                       | 809 ± 27        | 1291 ± 27       | 3.2 ± 0.3       | 2.0 ± 0.4       | 2.7 ± 0.4       |
| 59339.6| 412.0 | 4.8 ± 0.5                       | 778 ± 16        | 1201 ± 38       | 4.2 ± 0.2       | 2.6 ± 0.4       | 5.8 ± 0.7       |
| 59548.0| 614.4 | 9.9 ± 2.1                       | 608 ± 23        | 826 ± 35        | 6.4 ± 0.6       | 1.4 ± 0.3       | 9.3 ± 1.0       |