SN 2022ann

a Type Icn supernova from a dwarf galaxy that reveals helium in its circumstellar environment

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SN 2022ann: a Type Icn supernova from a dwarf galaxy that reveals helium in its circumstellar environment

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Abstract

We present optical and near-infrared (NIR) observations of the Type Icn supernova (SN Icn) 2022ann, the fifth member of its newly identified class of SNe. Its early optical spectra are dominated by narrow carbon and oxygen P-Cygni features with absorption velocities of ~800 km s⁻¹; slower than other SNe Icn and indicative of interaction with a dense, H/He-poor circumstellar medium (CSM) that is outflowing slower than typical Wolf–Rayet wind velocities of ~1000 km s⁻¹. We identify helium in NIR spectra 2 weeks after maximum and in optical spectra at 3 weeks, demonstrating that the CSM is not fully devoid of helium. Unlike other SNe Icn, the spectra of SN 2022ann never develop broad features from SN ejecta, including in the nebular phase. Compared to other SNe Icn, SN 2022ann has a low luminosity (o-band absolute magnitude of ~-17.7), and evolves slowly. The bolometric light curve is well-modelled by 4.8 M⨀ of SN ejecta interacting with 1.3 M⨀ of CSM. We place an upper limit of 0.04 M⨀ of 56Ni synthesized in the explosion. The host galaxy is a dwarf galaxy with a stellar mass of 10^7.34 M⨀ (implied metallicity of log(Z/Z⊙) ≈ 0.10) and integrated star-formation rate of log (SFR) = -2.20 M⨀ yr⁻¹; both lower than 97 percent of galaxies observed to produce core-collapse supernovae, although consistent with star-forming galaxies on the galaxy Main Sequence. The low CSM velocity, nickel and ejecta masses, and likely low-metallicity environment disfavour a single Wolf–Rayet progenitor star. Instead, a binary companion is likely required to adequately strip the progenitor and produce a low-velocity outflow.

Key words: stars: massive – binaries: transients: supernovae.

1 Introduction

Massive stars M ≳ 8 M⨀ typically end their lives in terminal explosions known as core-collapse supernovae (CSCNe). Some massive stars, as a result of either strong stellar winds or interaction with a companion, are stripped of their hydrogen envelopes (Woosley, Langer & Weaver 1995; Eldridge, Izzard & Tout 2008; Tauris et al. 2013; Tauris, Langer & Podsiadlowski 2015), producing a stripped-envelope SN (SESN) of Type Ib. Further stripping can remove the helium envelope, exposing the remaining carbon/oxygen core. If such a star exploded, the resulting SN would lack signatures of hydrogen and helium, producing a Type Ic SN (SN Ic; for a review of spectroscopic classification; see Filippenko 1997). However, carbon burning lasts only ~100 yr for a star with a zero-age main sequence mass of ~25 M⨀. If we assume that the lack of observed helium is due to the absence of helium itself, this sets a stringent time-scale of no more than decades (or perhaps a few centuries) before the explosion for the entirety of the stripping to occur. Another possible way to produce SNe Ic may be to ‘hide’ the helium. The excitation of helium requires high-energy photons, such as gamma-rays produced

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by nearby radioactive iron-group elements (Filippenko et al. 1995; Clocchiatti et al. 1996; Dessart et al. 2012; Hachinger et al. 2012; Teffs et al. 2020; Williamson, Kerzendorf & Modjaz 2021). If the SN produces a small amount of iron-group elements, or if the helium and iron-group elements are physically separated from one another in the ejecta, it is possible for the helium to remain ‘hidden’.

A fraction of CCSNe display relatively narrow emission features in their optical spectra indicating that the SN is interacting with a dense, close-in circumstellar medium (CSM). While passing through the CSM, the SN shock will produce X-rays that travel in front of the shock, exciting the unshocked CSM. This material will emit through recombination lines and the spectral features will have a velocity width corresponding to the outflow velocity of the CSM, which is orders of magnitude lower than the velocity of the SN ejecta. Starting with the identification of SNe with narrow hydrogen lines, the classes of these objects are denoted with an ‘n’ (i.e. SN In for the hydrogen case; Filippenko 1989; Schlegel 1990). SNe with narrow He and weak or absent H lines were discovered over two decades ago (Matheson 2000); however, the discovery of SN 2006jc with its narrow He lines (e.g. Foley et al. 2007), luminous outburst 2 yr before explosion (e.g. Pastorello et al. 2007), and fast dust formation (Smith, Foley & Filippenko 2008) was the first ‘SN Inb’. The recently discovered Type Icn class (Fraser et al. 2021; Gal-Yam et al. 2022; Pellegrino et al. 2022; Perley et al. 2022), which have strong, narrow O and C lines but weak or absent H and He lines, presents additional complications to the stripping mechanism. Similarly to SNe Inb, SNe Icn have narrow emission features indicative of circumstellar interaction (CSI). However, their spectra show emission that is primarily (and in some cases, exclusively) from carbon and oxygen at early times, with little to no indication of hydrogen (unlike SNe Inb) or helium (unlike SNe Ibn). The lack of detected helium in the CSM surrounding an SN Icn is particularly confounding since it would require the removal of He from the surface of the star significantly before explosion such that it is no longer present in the CSM.

After the discovery of the first SN Icn, SN 2019hgp (Gal-Yam et al. 2022), the community has discovered one additional member of the subclass (SN 2021csp; Fraser et al. 2021; Perley et al. 2022) and reclassified two older SNe as SN Icn (SNe 2019ejc and 2021ckj; Pellegrino et al. 2022), giving a total of four confirmed SNe Icn. All SNe Icn with early-time spectroscopy show similar P-Cygni profiles from carbon and oxygen lines with absorption velocities (~1000–2000 km s^{-1}), consistent with that of SNe Ibn and Wolf–Rayet (WR) winds. The qualitative similarities between SNe Ibn and Icn are also analogous to the differences between WR subtypes, namely WN (He-rich/N-rich) and WO (C-rich/He-poor) stars, respectively. Because of this, WR stars are commonly invoked as progenitors for SESNe, including SNe Ibn and Icn. WR winds, in combination with a stage of enhanced mass-loss shortly before explosion, can explain the observed properties of SNe Ibn and Icn (e.g. Gal-Yam et al. 2022). However, several studies have suggested that WR stars cannot be the sole progenitor channel for SESNe (e.g. Eldridge et al. 2013). In particular, the local stellar environments of some SESNe appear to be older than one would expect for a WR star (Anderson et al. 2012; Sun, Maund & Crowther 2022). Within the SN Icn subclass, SN 2019jc exploded in the outskirts of its host galaxy in a region with low star-formation rate (SFR) density (Pellegrino et al. 2022). Moreover, the progenitor stars of several SNe IIn (SESNe with a low-mass H envelope; Filippenko 1988; Filippenko, Matheson & Ho 1993) show evidence of being in binary systems (e.g. Aldering, Humphreys & Richmond 1994; Crockett et al. 2008; Van Dyk et al. 2011; Bersten et al. 2012; Kilpatrick et al. 2017), with one having a confirmed binary companion (Maund et al. 2004; Fox et al. 2014). Both of the SNe Ib having pre-explosion detections of their progenitor systems (iPTF13bvn and SN 1991vr) are consistent with binary progenitor systems (Cao et al. 2013; Eldridge & Maund 2016; Folatelli et al. 2016; Kilpatrick et al. 2021, although see Groh, Georgy & Ekström 2013). SN 2017ein, the first SN Ic with a possible pre-explosion detection of its progenitor system, has a luminous progenitor system inconsistent with a single WR star, but consistent with a WR star in a binary with a luminous B-type star (Kilpatrick et al. 2018; Van Dyk et al. 2018). Additionally, there is a late-time event that was spatially consistent with SN 2006jc that could be a binary companion (Maund et al. 2016). Furthermore, detailed modelling of SESN light curves suggest they have low ejecta masses and 56Ni masses that are incompatible with single WR progenitors (e.g. Drout et al. 2011; Taddia et al. 2018, although see Afşariardchi et al. 2021). It remains unclear what fraction of SESNe arise from single WR stars or from binary systems.

In this work, we present observations and analysis of the fifth member of the SN Icn class, SN 2022ann. It was discovered in SDSS J101729.72–022535.6 by ATLAS (Tonry et al. 2022) on 2022 January 27.497 (UT dates are used throughout this paper) and classified by us as an SN Icn on 2022 February 6.283 (Davis et al. 2022). Detailed study of the well-observed SN 2022ann presents an opportunity to examine the progenitor of a rare but important CCSNe with extreme mass loss prior to explosion. This fifth example of an SN Icn also allows for a study of this small but growing and diverse SN class. Here, we present optical photometry and optical/near-infrared (NIR) spectroscopy of SN 2022ann, as well as a study of its host galaxy.

The paper is organized as follows. Section 2 presents the discovery of SN 2022ann, our observational follow-up campaign, and the resulting optical and NIR spectroscopy and optical imaging. In Section 3, we provide further insights on the data, model the light curve with CSI and 56Ni-decay models, and conduct a study of the host galaxy. In Section 4, we discuss the presence of helium in SNe Icn, the growing heterogeneity observed in the class of SNe Icn, and the progenitor system for SN 2022ann. We present our conclusions in Section 5.

2 OBSERVATIONS

SN 2022ann is offset from the nucleus of its host galaxy, SDSS J101729.72–022535.6, by 0.96′ (see Fig. 1). From host-galaxy Hα emission in our latest spectra of SN 2022ann, we measure a redshift z = 0.04938. We discuss the host galaxy in detail in Section 3.4.

Assuming a standard ΛCDM cosmology (H_0 = 70 km s^{-1} Mpc^{-1}, Ω_M = 0.3, Ω_Λ = 0.7), the host-galaxy redshift corresponds to a distance of 218 Mpc, which we adopt as the distance to SN 2022ann throughout this paper. We also adopt a foreground reddening of E(B − V)_{MW} = 0.034 mag (Schlafly & Finkbeiner 2011). Because of the narrow lack of absorption lines from the interstellar medium in spectra of SN 2022ann, we assume the host galaxy extinction to be negligible. While we lack the necessary data to support this claim further (i.e. by measuring a Balmer decrement), the similar colours to other SNe Icn (see Section 3.1) suggest that SN 2022ann is not significantly extinguished. Basic parameters for SN 2022ann and its host galaxy are shown in Table 1. Next, we describe our observations and data reduction.

2.1 Photometry

We present our photometric observations of SN 2022ann in Fig. 2, where our data continue for 90 d after discovery. A portion of the photometric data are provided in Table A1, while the full table will...
Figure 1. Funder charts of SN 2022ann (right-hand panel) and its host galaxy, SDSS J101729.72−022535.6 (centre and left). North is up and east is to the left. The left-hand panel is an 8′ × 8′ finder chart centred on the position of SN 2022ann from archival griz DECam images. To the east are members of the V1CG 662 galaxy group at z = 0.0495 (Lee et al. 2017). The DECam images were processed by the Dark Energy Spectroscopic Instrument Legacy Imaging Surveys (Dey et al. 2019). The centre panel is a 3′ × 3′ close-up view with the location of SN 2022ann marked. SN 2022ann is offset slightly to the northwest of SDSS J101729.72−022535.6. The right-hand panel is created from 3′ × 3′ Pan-STARRS gri images from 3 February, 30 January, and 3 February that are mapped to the blue, red, and green channels of the image, respectively.

### Table 1. Basic observational parameters of SN 2022ann.

| Parameter                        | Value         |
|----------------------------------|---------------|
| Time of first detection (MJD)    | 59604.5       |
| Estimated time of explosion (MJD)| 59600.5       |
| Estimated time of maximum (MJD)  | 59613.5       |
| RA (12000)                       | 10h17m29.66s  |
| Dec (12000)                      | −22°25′35″45″ |
| Redshift                         | 0.04938 ± 0.0004 |
| E(B−V) − V_{MW}                  | 0.034 ± 0.001 mag |
| E(B−V) − V_{host}                | 0             |
| m_{B}^{discovery}                | 19.22 ± 0.11 mag |
| m_{B}^{peak}                     | −17.47 mag    |
| m_{B}^{peak}                     | 19.00 ± 0.069 mag |
| M_{B}^{peak}                     | −17.69 mag    |

SN 2022ann was observed in the c and o bands by ATLAS between −8 and 21 d. We use the ATLAS forced photometry server (Tonry et al. 2018; Smith et al. 2020; Shingles et al. 2021) to recover the difference-image photometry for SN 2022ann. To remove erroneous measurements and have significant SN flux detection at the location of SN 2022ann, we apply several cuts on the total number of individual data points and nightly averaged data. Our first cut uses the χ² and uncertainty values of the point-spread-function (PSF) fitting to remove discrepant data. We then obtain forced photometry of eight control light curves located in a circular pattern around the location of the SN with a radius of 17′. The flux of these control light curves is expected to be consistent with zero within the uncertainties, and any deviation from zero would indicate that there are either unaccounted systematic biases or underestimated uncertainties. We search for such deviations by calculating the weighted mean of the set of control light-curve measurements for a given epoch after removing any >3σ outliers (for a more detailed discussion, see Rest et al., in preparation). If the weighted mean of these photometric measurements is inconsistent with zero, we flag and remove those epochs from the SN light curve. This method allows us to identify potentially incorrect measurements without using the SN light curve itself. We then bin the SN 2022ann light curve by calculating a 3σ-cut weighted mean for each night (ATLAS typically has four epochs per night), excluding the flagged measurements from the previous step.

We also observed SN 2022ann with the Lulin Compact Imager on the 1-m telescope at Lulin Observatory from 2022 February 11 to 2022 March 8 in the griz bands. The images were calibrated using bias and flat-field frames following standard procedures. To account for background emission due to its host galaxy, we subtracted Pan-STARRS 3σ cutout images (Magnier et al. 2020) using the image convolution and subtraction software, HOTPANTS (Becker 2015). We then performed forced photometry in each frame using DoPhot (Schechter, Mateo & Saha 1993) within photpipe (Rest et al. 2005). The photometry was calibrated using Pan-STARRS griz local standard stars (Flewelling et al. 2020).

We also obtained uBgVri-band images of SN 2022ann using Sinistro cameras on Las Cumbres Observatory (LCO) 1.0 m telescopes.

1 https://github.com/rest2021/atlaslc

be made available in electronic format online. We define the time of explosion, $t_o$, as the mid-point between the last pre-explosion non-detection and the first detection. For SN 2022ann, there are two relevant ATLAS non-detections with which we can estimate the time of explosion: a deeper, but earlier non-detection on 2022 January 13.5 (MJD 59592.5) and a shallower, but later non-detection on 2022 January 17.5 (MJD 59596.5) with corresponding limiting magnitudes of $\sigma = 20.37$ mag and 19.47 mag, respectively. In our analysis, we use the later non-detection to estimate the time of explosion as 2022 January 21.5 (MJD 59600.5). Doing so results in a rise time in the $o$-band of ~10 d, which is similar to that of other SNe Ibc/Icn, but we note that the non-detections are not particularly constraining. As we do not perform any detailed modelling that relies on a precise measurement of $t_o$, the current constraint is sufficient for our analysis presented here. We estimate the time of maximum brightness using the $o$-band light curve owing to its coverage at early times. The light curve is very flat around peak (see Section 3). We estimate the time of peak brightness to be the mid-point of this flat region, which yields a $t_{peak}$ of 2022 February 03.5 (MJD 59613.5). Phases for SN 2022ann in this paper are given relative to the $o$-band time of maximum unless stated otherwise.
from 2022 February 11 to 2022 March 8. The photometry was collected as part of the Global Supernova Project (GSP) and from separate programs (Pis R. Foley and C. Kilpatrick). GSP data were reduced using the lcogtSnpipe pipeline (Valenti et al. 2016), which extracts PSF magnitudes after calculating zero-points and colour terms (Stetson 1987). \textit{UBV} photometry was calibrated to Vega magnitudes using Landolt (1992) standard fields, and \textit{gri} photometry was calibrated to AB magnitudes (Smith et al. 2002) using Sloan Digital Sky Survey (SDSS) catalogues. Background subtraction was performed using HOTPANTS with template images obtained after the SN had faded. Data from separate programs were reduced using the same procedures described above for the Lulin telescope, but with SkyMapper images as templates and SkyMapper local standard stars (Wolf et al. 2018) in the \textit{u} band. Both reduction methods produce results consistent with one another when comparing epochs with overlapping coverage.

Imaging was also obtained on 2022 February 13 in the \textit{BVri} bands with the 1-m Nickel telescope at Lick Observatory. The images were calibrated using bias and sky flat-field frames following standard procedures and were subtracted with a reference image obtained on 2022 March 12. PSF photometry was performed, and photometry was calibrated relative to Pan-STARRS photometric standards (Flewelling et al. 2020).

We also observed SN 2022ann with the T80 telescope via the Southern Photometric Local Universe Survey (S-PLUS; Mendes de Oliveira et al. 2019) Transient Extension Program (STEP; Kilpatrick et al. 2022). We used the standard S-PLUS observation strategy described by Mendes de Oliveira et al. (2019) to observe SN 2022ann in \textit{griz} from 2022 April 16 to 2022 May 5. These data were initially processed for pixel-level corrections using the JYPE pipeline (Cristóbal-Hornillos et al. 2014). We then reduced all STEP data using photpipe (Rest et al. 2005), including masking, regridding each image to a common image centre in Swarp (Bertin 2010), PSF photometry with DoPhot (Schechter et al. 1993), and photometric calibration using Pan-STARRS DR2 standard stars observed in the same field as SN 2022ann (Flewelling et al. 2020). Next, we subtracted \textit{griz} template images obtained from the same telescope and reduced in the same way from 2022 June 15 using HOTPANTS. Finally, we performed forced photometry in the subtracted images at the site of SN 2022ann using a custom version of DoPhot.

Additional \textit{gri}-band imaging was obtained through the Young Supernova Experiment (YSE) (Jones et al. 2021) with the Pan-StARRS telescope (PS1; Kaiser et al. 2002) between 2022 January 30 and 2022 February 21. The YSE photometric pipeline is based on photpipe (Rest et al. 2005). Each image template was taken from stacked PS1 exposures, with most of the input data from the PS1 3π
survey. All images and templates are resampled and astrometrically aligned to match a sky cell in the PS1 sky tessellation. An image zero-point is determined by comparing PSF photometry of the stars to updated stellar catalogues of PS1 observations (Chambers et al. 2017). The PS1 templates are convolved with a three-Gaussian kernel to match the PSF of the nightly images, and the convolved templates are subtracted from the nightly images with HOTPAINTS (Becker 2015). Finally, a flux-weighted centroid is found for each SN position and PSF photometry is performed using forced photometry. The nightly zero-point is applied to the photometry to determine the brightness of the SN for that epoch.

SN 2022ann was also observed with the Ultraviolet Optical Telescope (UVOT; Roming et al. 2005) onboard the Neil Gehrels Swift Observatory (Gehrels et al. 2004) on 2022 July 08.95 (MJD 59768.95, 155.5 d after o-band maximum). We performed aperture photometry with a $5''$ region with uvotsource within HEASoft v6.26,$^2$ following the standard guidelines from Brown et al. (2014). We detect no UV emission from the SN in this image and obtain a $3\sigma$ limiting magnitude of 23.016 in the $u$-band. This non-detection is not shown in Fig. 2, but is made available in Table A1.

### 2.2 Spectroscopy

We spectroscopically followed SN 2022ann starting at 2.8 d and continuing through 80.8 d after maximum light. The optical spectra were obtained with the Kast dual-beam spectrograph (Miller & Stone 1993) on the Lick Shane 3-m telescope, the Goodman spectrograph (Clemens, Crain & Anderson 2004) on the NOIRLab 4.1-m Southern Astrophysical Research (SOAR) telescope at Cerro Pachón, the Alhambra Faint Object Spectrograph (ALFOSC) on the Nordic Optical Telescope (NOT), second-generation Low Resolution Spectrograph (LRS2; Chonis et al. 2016) on the Hobby–Eberly Telescope (HET), Binospec on the MMT, the Gemini Multi-Object Spectrograph (GMOS; Davies et al. 1997) on the 8.1-m Gemini-South telescope, and the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on the 10-m Keck I telescope. A log of all observations is presented in Table A2. Observations were taken at low airmass (2) with the slit at the parallactic angle (Filippenko 1982) (unless the instrument was equipped with an Atmospheric-Dispersion Corrector, in which case the slit was aligned through SN 2022ann and the nucleus of its host galaxy). Spectroscopic data are available on ziggy,$^3$ or upon request to the corresponding author.

To reduce the Kast, Goodman, GMOS, and LRIS spectral data, we used the UCSC Spectral Pipeline$^4$ (Siebert et al. 2019), a custom data-reduction pipeline based on procedures outlined by Foley et al. (2003), Silverman et al. (2012), and references therein. The two-dimensional (2D) spectra were bias-corrected, flat-field corrected, adjusted for varying gains across different chips and amplifiers, and trimmed. Cosmic ray rejection was applied using the ppaappec algorithm to individual frames. Multiple frames were then combined with appropriate masking. One-dimensional (1D) spectra were extracted using the optimal algorithm (Horne 1986). The spectra were wavelength-calibrated using internal comparison-lamp spectra with linear shifts applied by cross-correlating the observed night-sky lines in each spectrum to a master night-sky spectrum. Flux calibration was performed using standard stars at a similar airmass to that of the science exposures, with ‘blue’ (hot subdwarfs; i.e. sdO) and ‘red’ (low-metallicity G/F) standard stars. We correct for atmospheric extinction. By fitting the continuum of the flux-calibrated standard stars, we determine the telluric absorption in those stars and apply a correction, adopting the relative airmass between the standard star and the science image to determine the relative strength of the absorption. We allow for slight shifts in the telluric A and B bands, which we determine through cross-correlation. For dual-beam spectrographs, we combine the sides by scaling one spectrum to match the flux of the other in the overlap region and use their error spectra to correctly weight the spectra when combining. More details of this process are discussed elsewhere (Foley et al. 2003; Silverman et al. 2012; Siebert et al. 2019).

Data obtained with ALFOSC and Binospec were reduced using standard techniques, which included correction for bias, overscan, and flat-field. Spectra of comparison lamps and standard stars acquired during the same night and with the same instrumental setting have been used for the wavelength and flux calibrations, respectively. When possible, we further removed the telluric bands using standard stars. Given the various instruments employed, the data-reduction steps described above have been applied using several instrument-specific routines. We employed standard IRAF commands to extract all spectra.

The LRS2 data were processed with Panacea,$^5$ the HET automated reduction pipeline for LRS2. The initial processing includes bias-correction, wavelength calibration, fiber-trace evaluation, fiber normalization, and fiber extraction; moreover, there is an initial flux calibration from default response curves, an estimation of the mirror illumination, as well as the exposure throughput from guider images. After the initial reduction, we used an advanced code designed for crowded IFU fields to perform a careful sky subtraction and host-galaxy subtraction. Finally, we modelled the target SN e with a Moffat (1969) PSF model and performed a weighted spectral extraction.

We present our full optical spectral time series of SN 2022ann, consisting of 11 spectra obtained between +2.8 and +80.8 d, in Fig. 3.

We obtained NIR (0.94–2.45 µm) spectra of SN 2022ann using the Near-Infrared Echellelette Spectrometer (NIRES; Wilson et al. 2004) on the 10-m Keck II telescope as part of the Keck Infrared Transient Survey (KITS), a NASA Keck Key Mission Strategy Mission Support program (PI R. Foley). A log of observations is given in Table A2. We observed the SN at two positions along the slit (AB pairs) to perform background subtraction. An A0V star was observed immediately before or after the science observation. We reduced the NIRES data using spectool v.5.0.2 (Cushing, Vacca & Rayner 2004); the pipeline performs flat-field corrections using observations of a standard lamp and wavelength calibration based on night-sky lines in the science data. We performed telluric correction using xtellcor (Vacca, Cushing & Rayner 2003). The NIR spectra are shown in Fig. 4.

Observations were primarily coordinated using YSE–P2 (Coulter et al. 2022, 2023); an open-source, general-purpose Target and Observation Management (TOM) platform.

### 3 ANALYSIS

Below we examine the spectra and light curves of SN 2022ann, detailing its unique characteristics and comparing to other SESNe. We also construct and model its bolometric light curve, as well as provide an analysis of the host galaxy.

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2We used the calibration data base (CALDB) version 20201008.
3https://ziggy.ucolick.org/sn2022ann
4https://github.com/msiebert1/UCSC_spectral_pipeline
5https://github.com/grzeimann/Panacea
3.1 Photometric analysis

Although the explosion date and rise time are not strongly constrained (see discussion in Section 2), SN 2022ann appears to have a rise time of $\sim 10$ d, making it a relatively fast-rising SN, comparable to other SNe Icn and SNe Ibn (e.g. Hosseinzadeh et al. 2017). The light curves of SN 2022ann are not well-sampled in all observed bands right after discovery, so we rely on the $\sigma$-band photometry to characterize the time of maximum brightness and the overall shape of the light curves near peak. We report the luminosity at discovery and maximum brightness in Table 1.

SN 2022ann has a similar shape in all $roi$ bands for epochs with overlapping data, and we use the combination of the $\sigma$ and $r$ light curves, which have complementary temporal coverage, to better assess the evolution of SN 2022ann. In these bands, SN 2022ann is slowly evolving for about 25 d after discovery; it rises by 0.03 mag from discovery to peak (in 2 d) and declines by 0.25 mag in 18 d after peak. SN 2022ann varies by only 0.5 mag over a period of $> 24$ d. After the relatively consistent brightness (in these bands), the SN begins to decline much faster (0.9 mag d$^{-1}$) starting around 25 d after maximum. Both bluer and redder bands seem to have a more pronounced rise and decline around maximum light, but the lack of data in those bands makes it difficult to have strong conclusions about their morphology.

In Fig. 5, we compare the $\sigma$-band and $c/g$-band light curves of SN 2022ann with those of the other known SNe Icn, two SNe Ibn (SNe 2006jc, Foley et al. 2007; Pastorello et al. 2007; and 2011hw, Smith et al. 2012), and the $R$-band SN Ibn template provided by Hosseinzadeh et al. (2017). Compared to these SNe, SN 2022ann has a unique evolution in $r$ with its relatively flat and long-lived peak. SN 2022ann declines roughly 0.035 mag d$^{-1}$ for the first 10 d after peak, while SNe 2019jc and 2019hgp decline at roughly twice that rate. Between 30 and 50 d after peak, SN 2022ann declines faster (0.090 d$^{-1}$) than SN 2019hgp (0.055 d$^{-1}$).

SN 2022ann has relatively low peak $r$-band luminosity ($M_r = -17.8$ mag), but falls within the bounds of the SN Icn sample. Despite showing a high degree of uniformity in their early-time spectra (see Section 3.3), SNe 2022ann, 2019hgp, and 2019jc vary in peak absolute brightness by $\sim 1.5$ mag. SN 2022ann has significantly lower luminosity at peak than SNe 2021ckj, 2021csp, and the SN
Figure 4. NIR spectra of SN 2022ann taken at +10.1 and + 19.1 d relative to o-band maximum. Spectra have been binned by a factor of four. Rest wavelengths of several He lines are marked in the top panel by red triangles. The bottom left-hand panel shows a close-up view of the spectra near prominent features; He\textsc{i}, C\textsc{i}, and O\textsc{i} lines are marked. Note that the He\textsc{i} 1.083 μm line is well-isolated owing to the small velocity of SN 2022ann. The bottom right-hand panel shows a zoom-in on the region of He\textsc{i} 1.86 and 2.06 μm; however, we cannot identify any emission because of the relatively low S/N at these wavelengths.

Ibn template (which Hosseinzadeh et al. (2017) notes is biased towards bright and slowly evolving objects). SN 2022ann evolves more slowly near its maximum brightness, and declines faster at later times relative to other SNe Ibn and the Ibn Ibn template; however, SN Ibn 201 lh\textsc{w} has a similar plateau near peak (Smith et al. 2012).

In contrast, the g-band evolution of SN 2022ann is similar to that of SN 2019hgy. They reach comparable peak luminosity (∼18.3 mag and −18.7 mag, respectively), and decline rapidly at 0.09 mag d⁻¹ afterward. Unlike SN 201 lh\textsc{w}, which has a plateau in both r and g, SN 2022ann declines rapidly in the g/\textit{r} band and has an evolution similar to that of other SNe Ibn at this blue wavelength.

We show the g−r colour evolution of SN 2022ann in Fig. 6, along with the colour curves of the other SNe Ibn presented by Pellegrino et al. (2022). SN 2022ann begins very blue at maximum light and grows redder over the next 30 d. After this, it quickly becomes blue again. SNe 2019hgy, 2019jc, and 201ckj also seem to follow this trend; however, the large uncertainties make commenting on the colour-curve morphology difficult.

3.2 Bolometric analysis and modelling

In order to understand what is powering SN 2022ann, we construct its bolometric light curve using extrabol (Thornton & Villar 2022). extrabol interpolates the light curve using a Gaussian process with a 2D kernel, accounting for correlation in both time and wavelength. Each observed epoch is then fit to a blackbody spectral energy distribution (SED), inferring bolometric luminosities, blackbody radii, and blackbody temperatures with time. Our spectra are well-described by a blackbody until + 34 d, indicating that this approximation should be appropriate until at least that epoch.

In Fig. 7, we display the resulting bolometric light curve, as well as the derived blackbody radius and temperature evolution for SN 2022ann. We restrict our bolometric light curve to epochs with photometric coverage over at least four filters (−0.35 d after maximum brightness). Soon after explosion, SN 2022ann is very hot ($T > 25 000$ K), but cools over the next 15 d until it reaches ∼7000 K, where it plateaus. The temperature derived from the photometric SED fitting is consistent with that of fitting the continua of our optical spectra (Section 3.3), indicating that spectral features are not significantly affecting this analysis. The photosphere initially expands at a rate of 4900 km s⁻¹ until +15 d, when it reaches its maximum extent. Our +34-d spectrum has a blackbody continuum and P-Cygni features while our +66-d spectrum has prominent forbidden-line emission indicating that the SN has become nebular by that time; therefore, SN 2022ann likely entered its nebular phase between +34 and +66 d, beyond the range of our analysis of the bolometric light curve.

The blackbody properties of SN 2022ann are broadly similar to those of other SNe Ibn and Ibn. The temperature evolution of SN 2022ann is similar to that of other SNe Ibn and Ibn (Pellegrino et al. 2022). For the first ∼2 weeks after peak luminosity, the blackbody radius of SN 2022ann expands at a constant velocity of 4900 km s⁻¹, which should correspond to the photosphere. This value is significantly different from the absorption velocity (800 km s⁻¹), further indicating that the spectral features originate from the CSM. However, we note that we never detect any spectral features with $v > 1000$ km s⁻¹, which is puzzling considering that our last epochs appear to be in the nebular phase.

The photometric properties of SN 2022ann at maximum light are inconsistent with radioactive decay of 56Ni. If SN 2022ann is powered by 56Ni, its peak bolometric luminosity of ∼10⁴⁴ erg s⁻¹ is directly related to the 56Ni mass (Arnett 1982). Using this relation, we determine that SN 2022ann would require 2.8 M⊙ of 56Ni to match its peak luminosity. However, given the rapid decline after maximum and the spectral signatures of CSI present at this epoch (see Section 3.3), it is unlikely that SN 2022ann is powered chiefly by radioactive decay at peak light. In particular, assuming that the SN is optically thin at late times with instantaneous γ-ray trapping and full efficiency, the late-time luminosity limits the 56Ni mass to <0.04 M⊙, smaller than the low end of the SESN population (Lyman et al. 2016). We therefore rule out radioactive decay as the primary power source for SN 2022ann near peak.

The narrow spectral features and blue colours at early times suggest that SN 2022ann is primarily powered by CSI. To estimate the SN and CSM properties with the goal of gaining insight into the progenitor system, we use MOSFiT (Guillochon et al. 2017) to numerically model the photometry with a CSI model (as described by Chevalier 1982; Chatzopoulos, Wheeler & Vinko 2012; Villar et al. 2017; Jiang, Jiang & Villar 2020). The inner and outer SN ejecta density distributions are modelled as two power laws ($ρ_{\text{inner}} \propto r^{-α}$ and $ρ_{\text{outer}} \propto r^{-α}$, respectively). In our modelling, we assume fixed power laws with $δ = 1$ and $n = 10$. We assume an optical opacity, $κ$, of 0.04 cm² g⁻¹ (Rabinak & Waxman 2011), and a temperature floor of 6800 K. We fix $R_0 = 10^{12}$ cm, which is similar to the progenitor radius determined for SN 2019hgy (4 × 10¹¹ cm; Gal-Yam et al. 2022), and consistent with the modelled inner CSM radii for the Pellegrino et al. (2022) sample. We also assume $ε$, the kinetic-to-thermal energy conversion efficiency, to be fixed at 0.5 (Dessart, Audit & Hillier 2015). We experimented with letting $R_0$ and $ε$ vary as done in Pellegrino et al. (2022), but found they were too degenerate with other parameters to fit meaningfully in our case. We allow for the following parameters to vary freely:

(i) $M_0$, the ejecta mass;
(ii) $M_{\text{CSM}}$, the CSM mass;
(iii) $v_0$, the ejecta velocity;
(iv) $ρ$, the density at $R_0$.
(v) $n_{H, \text{host}}$, the hydrogen column density of the host galaxy;
(vi) $s$, the power-law index in the CSM distribution $\rho_{CSM} \propto r^{-s}$;
(vii) $t_{\text{exp}}$, time of explosion relative to maximum light; and
(viii) $\sigma$, the noise term.

We show the band-by-band light-curve fit from MOSFIRE in Fig. 8 and the best-fitting CSM model parameters in Table 2. SN 2022ann is consistent with 4.79 M$_\odot$ of ejecta interacting with 1.32 M$_\odot$ of CSM. This ejecta mass is higher than what was found via modelling of other SNe Icn [although, close to the high end of the ejecta mass distribution of SN 2021csp in Pellegrino et al. (2022)]. We measure a CSM mass of 1.32 M$_\odot$; also higher than the previously reported values for SNe Icn. The total mass measured in our system is in disagreement with a single massive WR progenitor (pre-SN mass $\gtrsim 10$ M$_\odot$). We measure an inner CSM density of $\log \rho = -9.01$ g cm$^{-3}$, which matches well with the models presented in Pellegrino et al. (2022). We note that $\rho$ is highly sensitive to changes in $s$, which we let vary while Pellegrino et al. (2022) fixed $s = 0$, 2. Never the less, we take this as an indication that our measurement for CSM density is reasonable.

![Figure 5](https://example.com/image5.png)

Figure 5. Light-curve comparisons in $r$ (left-hand panel) and $g$ (right-hand panel) to similar astronomical transients: $o$-band and $r$-band photometry for SN 2022ann is included in the respective comparisons to increase coverage. When $r$ and $g$ photometry for comparison objects was not available in literature, the most similar available filters were selected and noted. In the left-hand panel, we also display in hatched-blue the Hosseinzadeh et al. (2017) SN Ibn template light curve. As the explosion time for SN 2006jc is not well-constrained, we match the estimated maximum-light epoch presented by Pastorello et al. (2007) to the maximum of the SN Ibn template. SN 2022ann is slow-evolving and somewhat faint relative to the other objects around peak.

![Figure 6](https://example.com/image6.png)

Figure 6. Colour evolution ($g-r$) of SN 2022ann and the SN Icn sample from Pellegrino et al. (2022). All SNe Icn have similar colours.

![Figure 7](https://example.com/image7.png)

Figure 7. Bolometric light curve (top panel), blackbody radius evolution (middle panel), and blackbody temperature evolution (bottom panel) for SN 2022ann as derived from Extrapol. Measurements are shown as black curves with the 1σ uncertainty as a grey band. The temperatures derived from spectra and photometry largely agree, although are discrepant at the earliest spectral epoch. The $g-i$ colour at peak is consistent with the lower spectral temperature, but the uncertainty is likely larger than the formal errors shown in the plot. Radioactive-decay models matched to the peak and tail of the light curve (2.8 M$_\odot$ and 0.04 M$_\odot$, respectively) are shown in the top panel in blue. A curve indicating a constant expansion of 4900 km s$^{-1}$ since the time of explosion, is shown in the middle panel as a dotted red line.
a resulting \( t_{\text{exp}} \) that is inconsistent with our photometric constraints. Never the less, modelling of the light curve indicates an intermediate mass progenitor for SN 2022ann that is inconsistent with a single WR star. Constraining SNe Icn progenitors through light-curve modelling clearly requires more rigor, and multiwavelength observations (particularly UV and X-ray) of future SNe Icn will be critical.

### 3.3 Spectroscopic analysis

The earliest spectrum in our data set is also the spectrum with which we classified SN 2022ann (Davis et al. 2022). As noted in that report, the early-time spectrum has a blue continuum with prominent narrow C II and C III P-Cygni features. There is also a weak O I \( \lambda 7774 \) P-Cygni line. The minimum of the absorption for the C II \( \lambda 6583 \) line has a velocity of \( -870 \text{ km s}^{-1} \). This spectrum is similar to that of other SNe Icn soon after explosion (Pellegrino et al., 2022), with SN 2022ann being especially similar to SN 2019hgp (Gal-Yam et al. 2022) at a comparable phase.

Our spectral series, shown in Fig. 3, exhibits a unique evolution, even among SNe Icn. The continuum for each spectrum is smooth and can be described by a blackbody. Until \( +3.6 \text{ d} \), the spectra have narrow P-Cygni features from C II, O I, and later C II and He I. The earliest spectra \((\leq 4.8 \text{ d})\) also show a forest of highly ionized lines of C, O, and Ne blueward of \( \sim 5200\AA \). The later spectra continue to have narrow carbon and oxygen emission, although as forbidden [C I] and [O I]. This transition from permitted P-Cygni profiles to pure-emission forbidden lines between \( +3.16 \) and \( +6.36 \text{ d} \) marks the time when the CSN becomes optically thin. This period also corresponds to when the light curve begins to fade quickly (see Fig. 2).

The spectral sequence displays a gradual weakening of high-ionization lines with a contemporaneous strengthening of low-ionization lines (both relative to the continuum). Between \( +2.8 \text{ d} \) and \( +16.7 \text{ d} \), we identify several narrow P-Cygni lines from C II \( \lambda 5890, 6583, 7231, 7236, \) C III \( \lambda 4650, \) and O I \( \lambda 7774 \). We identify several transitions from C II, C III, O II, Ne I, and Ne II in the forest of lines between 3400 and 5200 Å in our earliest spectra. At these epochs, He I features are not detected in this wavelength range. There is faint emission near the expected location of He II \( \lambda 4686 \), but the peak is blueshifted by \( \sim 600 \text{ km s}^{-1} \); the offset may be the result of blending with other lines. Regardless, we do unambiguously detect any He features in these early-time optical spectra.

In the \(+10.1\text{-d} \) NIR spectrum, we detect the 1.083 \( \mu \text{m} \) He I line with a P-Cygni profile and an absorption velocity of \(-720 \text{ km s}^{-1} \). We do not detect any He lines in a contemporaneous \((+10.5\text{-d}) \) optical spectrum. The NIR He feature becomes stronger in the \(+19.1\text{-d} \) spectrum, while we still do not detect any He lines in a contemporaneous \((+20.5\text{-d}) \) optical spectrum. We finally detect He I \( \lambda 4922 \) in the \(+28.6\text{-d} \) optical spectrum.

Fig. 9 highlights prominent C, O, He, and H lines. The velocity of maximum absorption, corresponding to the \( \tau = 2/3 \) surface, for each line is about \(-800 \text{ km s}^{-1} \), with maximum wind velocities ranging from roughly \(-1500 \text{ to } -2000 \text{ km s}^{-1} \). The C II \( \lambda 5890 \) line shows a notably faster velocity of maximum absorption at \(-1300 \text{ km s}^{-1} \), but this line is likely blended with He I \( \lambda 5876 \), changing the line profile. As the spectrum evolves, the C II emission is still prominent, and the absorption velocity decreases to \(-800 \text{ km s}^{-1} \).

Pellegrino et al. (2022) examined optical spectra of four SNe Icn and did not detect He I in any of them. They detected weak He II \( \lambda 4686 \) in a single spectrum of one SN (SN 2019jc); however, the spectrum has many absorption lines near that wavelength and the claimed feature is weaker than several other unidentified absorption features. Their data set only contained optical spectra and the latest

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**Figure 8.** Band-by-band light-curve fits with CSM model from M0SFiT. Photometry is plotted with scatter points, while modelled light curves from 250 walkers are plotted with solid lines. We evolved the walkers through 50,000 iterations. A corner plot of our posterior distributions is provided in Fig. A1.

**Table 2.** CSM model parameters for SN 2022ann from 5000 iterations in M0SFiT.

| Parameter | Value |
|-----------|-------|
| \( M_\text{ej} (M_\odot) \) | 4.79 \( \pm 0.33 \) |
| \( M_\text{CSM} (M_\odot) \) | 1.32 \( \pm 0.12 \) |
| \( v_\text{ej} (\text{km s}^{-1}) \) | 2680 \( \pm 120 \) |
| \( \log \rho (\text{g cm}^{-3}) \) | \(-9.01 \pm 0.79 \) |
| \( \log \rho_{\text{host}} (\text{cm}^{-2}) \) | 17.13 \( \pm 1.48 \) |
| \( s \) | 0.86 \( \pm 0.33 \) |
| \( t_{\text{exp}}(\text{d}) \) | \(-14.50 \pm 2.00 \) |
| \( \log \sigma \) | \(-0.83 \pm 0.04 \) |

Our fit gives an ejecta velocity of \( \sim 2700 \text{ km s}^{-1} \), which similarly to the velocity measured from the bolometric light curve (4900 km s\(^{-1}\)), indicates a higher velocity than any observed features in the spectra. This velocity is substantially lower than the ejecta velocities measured for the other SNe Icn; 2700 km s\(^{-1}\) is less than half that of the next-lowest velocity (SN 2019jc) and \( \sim 10 \) per cent of the highest-velocity SN Icn (SN 2019hgp). This again raises the question of why spectral features with \( v > 1000 \text{ km s}^{-1} \) are never seen.

While our light-curve modelling indicates an intermediate mass progenitor with higher mass compared to the other SNe Icn, we note that the masses are very sensitive to the underlying model assumptions, which have not been explored rigorously in the context of SNe Icn. For example, increasing the opacity or \( \epsilon \) can easily lower the total mass to <2 \( M_\odot \). Furthermore, we fix \( R_0 = 10^{12} \) cm in the assumption that SN 2022amn and other SN Icn share a similar CSM configuration (Gal-Yam et al. 2022; Pellegrino et al. 2022). However, modelling of SNe IIn indicates a much larger initial radius (e.g. Dessart et al. 2015). We experimented with fixing \( R_0 = 10^{12} \) cm and recovered ejecta mass closer to \( \sim 10 M_\odot \), albeit with

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spectrum was obtained 22 d after peak light. If SN 2022ann had a similar data set, it also would not have shown a clear He detection. Perley et al. (2022) detected a weak He I $\lambda$5876 line in their spectra of SN 2021csp (this SN was included in the Pellegrino et al. 2022 sample), but the detection required high-S/N data. Furthermore, it is possible that any He I $\lambda$5876 line in other SNe Icn is obscured by the absorption component of the adjacent, strong C II $\lambda$5890 P-Cygni line. It is possible that all SNe Icn have helium, but either high-S/N optical spectra, NIR spectra, or optical spectra taken $\sim$25 d after peak light are necessary to robustly detect the lines.

As noted from its photometry, SN 2022ann is very blue near peak brightness and quickly becomes redder (see Section 3.1). Our first spectrum ($t = +2.8$ d) exhibits a blue continuum with relatively weak spectral features; fitting to the continuum of the spectrum, we find that it is well-described by a blackbody with $T \approx 12$ 000 K. Over time, the continuum becomes redder, but is still well-described by a blackbody through our +31.6-d spectrum when the temperature has decreased to $\sim$9000 K. This evolution is consistent with the temperatures derived from the photometry.

Starting around 30 d after peak, SN 2022ann starts to fade quickly. The +63.6-d and +80.8-d spectra do not have any detected P-Cygni absorption features and we detect forbidden emission lines. Therefore, we consider SN 2022ann to have entered the nebular phase between +31.6 and +63.6 d. At +80.8 d, the strongest features are from [O I] and [C II] (shown in detail in Fig. 10). Each of these lines is both narrow (e.g. [O I] $\lambda$6300 has a full width at half-maximum intensity, FWHM, of $\sim$1000 km s$^{-1}$) and double peaked, where the two peaks are offset by 650 km s$^{-1}$ for each line. The FWHM is consistent with the P-Cygni absorption velocity from earlier epochs and significantly smaller than the photospheric velocity derived from modelling the light curve. Given the ejecta mass of 4.79 M$_\odot$ and CSM mass of 1.32 M$_\odot$ (see Section 3.2), the CSM is unlikely to be sufficiently substantive to significantly decelerate the ejecta, and in that case the line emission should originate from the CSM. The double-peaked profiles imply that the source of these lines is asymmetric, which combined with their low velocity cannot be explained by the SN ejecta without fine tuning. We conclude that the forbidden lines originate from CSM and not the SN.
Figure 10. Double-peaked nebular lines of forbidden C and O seen in the LRIS spectrum at +80.8 d plotted in velocity space relative to their rest-frame wavelengths. Unbinned spectra are shown in faded blue lines, while solid blue lines show spectra binned by a factor of 3. Vertical lines show −650 and 0 km s⁻¹.

Figure 11. Early-time (<10 d after peak light) spectral comparison of SN 2022ann and other SNe Icn, SN Ibn 2006jc, SN Ibn 2011hw, and SN Ic 2007gr. Labelled phases are with respect to r- or o-band maximum light. Notable features are marked with vertical lines. The bottom panel displays a subset of the spectra (SNe 2019hgp, 2019jc, and 2022ann) in the region <5200 Å. We mark several potential features from highly ionized lines of C, O, and Ne. We mark He II in magenta, but it does not match the nearby features in SN 2022ann particularly well. Spectra for SNe 2006jc, 2007gr, and 2019hgp were obtained from WISEREP (Yaron & Gal-Yam 2012).

 ejecta. However, at the same late-time epochs, we do not see broad (>1000 km s⁻¹) spectral features in any late-time spectrum, and so we do not clearly detect any nebular spectral features from the SN ejecta.

In Fig. 11, we compare the +2.8 and +4.8-d spectra of SN 2022ann to those of other SNe at similar epochs (~+1 week). We include other SNe Icn, two SNe Ibn (SNe 2006jc and 2011hw; Foley et al. 2007; Pastorello et al. 2007; Smith et al. 2012), and the normal SN Ic 2007gr (Valenti et al. 2008). At early times (~+2.8 d relative to maximum light), SN 2022ann is similar to other SNe Icn, which together show a high degree of homogeneity despite the scatter in their luminosities. Particularly, we find excellent matches to SNe 2019hgp and 2019jc, all of which have blue continua, prominent C II and O I P-Cygni features, and a similar forest of lines blueward of ~5200 Å. Notably, SNe 2019hgp, 2019jc, and 2022ann all contain Ne II. This species is not commonly seen in CCSNe, yet three of the five SNe Icn (SNe 2019jc, 2019hgp, and now 2022ann; Gal-Yam et al. 2022; Pellegrino et al. 2022) have Ne II in their early-time spectra. Ne should be produced in the progenitor during carbon burning. While this scenario would suggest the presence of Mg in the ejecta, we do not clearly identify any Mg lines in the spectra of SN 2022ann.
However, we note that this may be because many of the stronger Mg lines fall either in the range of the blue forest or atop strong C and O lines. While SN 2021csp has C II lines similar to these SNe Icn, O I is much weaker. The forest of highly ionized lines C, O, and Ne observed in the other SNe Icn is not present in its spectra, though this may be due to a high density of Fe lines saturating the continuum in that region.

The SN Ibn spectra are qualitatively similar to those of SNe Icn, with analogous narrow lines of He and blue continua. The SNe Ibn in our comparison have a combination of narrow emission lines with and without P-Cygni absorption components, which arise from different regions in the system, or from viewing-angle dependencies on the CSM. Meanwhile, the SNe Icn have exclusively P-Cygni line profiles. At this epoch, none of the SNe Icn show broad features as seen in SN 2007gr.

We compare these SNe after peak and at late times (if data are available) in Fig. 12. After their similar spectral behaviour at peak light, the SNe Icn diverge from one another around 1 month after peak. As discussed by Pellegrino et al. (2022) at these times, the luminous SNe 2021csp and 2021ckj have developed broad features with high velocities ($\sim 10,000$ km s$^{-1}$) indicative of SN ejecta. The spectra also show a ‘break’ in their continua blueward of 6000 Å, which Perley et al. (2022) attributed to Fe II fluorescence caused by C SII in the post-shock CSM, a phenomenon originally observed in SNe Ibn (Foley et al. 2007). SN 2019hgp retains narrow lines for longer, but also develops broad P-Cygni features and resembles a spectroscopically normal SN Ic (Gal-Yam et al. 2022). SN 2019hgp also develops a similar, albeit weaker, blue continuum break. Uniquely, the spectrum of SN 2022ann does not show any broad features 1 month after peak, and remains dominated by narrow P-Cygni lines originating from the CSM. SN 2022ann does not develop the blue pseudo-continuum seen in the other SNe Ibn/Icn.

In the nebular phase, SN 2022ann has a unique spectrum with a relatively flat (in f$_{cont}$) continuum and narrow [C I] and [O I] emission lines. In contrast, the other SNe Icn have blue spectra with an Fe-fluorescence bump, broad undulations, and weak or no narrow emission lines. The emission lines in SN 2022ann are similar in strength and width to the He emission seen in SN 2006jc, indicating that they are from CSM and not SN ejecta. On the other hand, SN 2006jc has a Fe-fluorescence bump and continuum shape similar to the SNe Icn besides SN 2022ann. SN 2006jc also has an additional thermal component rising in the red end of the optical, attributed to hot dust (Smith et al. 2008).
3.4 Host-galaxy analysis

SN 2022ann was discovered in a faint host galaxy (SDSS J101729.72–022535) with no published redshift or distance information (Davis et al. 2022). The redshift measured from the CSM lines in the SN spectrum was \( z = 0.049 \). However, the absorption components of these P-Cygni lines can inconsistently shift the wavelength of the maxima. Therefore, we look for emission lines from the host galaxy in the last SN spectrum (when the SN emission is faintest) to obtain a better redshift estimate. We identify an H\(_e\) emission line (\( \sim 1.7\sigma \)) at \( z = 0.04938 \pm 0.0004 \), which makes SN 2022ann the second-closest known SN Icn after SN 2019jc (Pellegrino et al. 2022). At this redshift, the galaxy has an absolute magnitude of \( M_B = -14.4 \pm 0.2 \) mag,\(^6\) making it a dwarf galaxy with a luminosity intermediate between the Sagittarius Dwarf and the Small Magellanic Cloud, and among the lowest-luminosity SN host galaxies yet discovered (Gutiérrez et al. 2018; Schulze et al. 2021; Taggart & Perley 2021). We also note that SN 2022ann appears to be in a galaxy group, since several other galaxies such as V1CG 662 (Lee et al. 2017) are at a redshift similar to that of SN 2022ann (Fig. 1).

To characterize the properties of the host galaxy in more detail, we performed elliptical aperture photometry on the host using images from wide-field public surveys. The host was only detected in optical public imaging (it was not detected by GALEX, 2MASS, or WISE). Host-galaxy photometry (AB mag, not corrected for Galactic extinction) is presented in Table A3.

We modelled the broad-band SED using the LE PHARE package (Arnouts et al. 1999; Ilbert et al. 2006), correcting the photometry for Milky Way foreground extinction prior to fitting. We omitted the \( \alpha \)- and \( \gamma \)-band limits since they do not usefully constrain the SED models. The code utilizes the population-synthesis templates of Bruzual & Charlot (2003), summed according to an exponentially declining burst of star formation and with stellar metallicities between \( 0.2Z_{\odot} < Z < Z_{\odot}\) and assuming a Chabrier initial-mass function (IMF; Chabrier 2003). Dust attenuation in the galaxy is applied to the SED models by adopting the Calzetti et al. (2000) attenuation law.

We derived a stellar mass of \( \log(M/M_{\odot}) = 7.34^{+0.11}_{-0.30} \) and an integrated SFR of \( \log(\text{sSFR}) = -2.20^{+0.09}_{-0.07} \text{ M}_{\odot} \text{ yr}^{-1} \), both of which are consistent with known local (<11 Mpc) dwarf galaxies (Davis et al. 2009) – see the local Volume Legacy galaxies (LVL) plotted in Fig. 13. Using the mass and SFR estimates from the SED modelling, we estimate the host-galaxy metallicity, employing the mass-metallicity relation of Mannucci et al. (2010), which is roughly continuous even in this low stellar mass regime (Kirby et al. 2013). We derive a metallicity of \( \log(Z/Z_{\odot}) = 0.10^{+0.09}_{-0.07} \), assuming a solar relative oxygen abundance of \( 12 + \log(O/H) = 8.69 \) (Asplund et al. 2009).

Fig. 13 shows the integrated SFR plotted against stellar mass for various types of CCSNe from PTF (Schulze et al. 2021) and ASAS-SN (Taggart & Perley 2021). We see that SN 2022ann has the lowest mass and SFR of any SN Icn yet discovered (although there are only 5 SN Icn host galaxies) and is lower in stellar mass and SFR than the vast majority of galaxies that produce CCSNe (both at 3rd percentile for CCSNe).

However, similarly to other SN Icn host galaxies, SN 2022ann closely follows the star-forming main sequence, with a specific SFR of \( \log(\text{sSFR}) = -9.54^{+0.05}_{-0.06} \), 0.2 dex above the median for CCSN hosts. However, when considering only dwarf galaxies (\( M < 10^8 \text{ M}_{\odot} \)), SN 2022ann has a comparatively low sSFR (5th percentile).\(^7\)

4 DISCUSSION

SN 2022ann is part of the small but quickly growing class of SNe Icn. Its unique photometric and spectroscopic behaviour among the known members demonstrates that this class is relatively heterogeneous. The detection of He in the spectra of SN 2022ann, and the way in which it was detected, suggests that perhaps all SN Icn have He in their systems. Finally, the extreme host-galaxy properties of SN 2022ann combined with its rare observables constrain its progenitor system. We discuss these areas in detail below.

4.1 Helium in SNe Icn

Optical spectra of SNe Icn, by definition, lack He emission. If He lines are present at all, they are weak. This is in contrast to SNe Ibn,

\( ^6\)Throughout the host analysis, as in the rest of the paper, we assumed \( \Lambda \text{CDM} \) cosmology (\( H_0 = 70 \text{ km} \text{ s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3, \Omega_{\Lambda} = 0.7 \)).

\( ^7\)We caution that since we lack UV data, the uncertainties in the derived SFR are large (Childress et al. 2013). A more detailed spectroscopic comparison of SN 2022ann with other SN Icn host galaxies will be discussed in future work (Taggart et al., in preparation).
where He emission lines dominate their spectra. While this difference may be the result of different abundances, it is possible that SNe Ibn are able to excite He in their circumstellar environments from non-thermal photons while SNe Icn are not. Detailed modelling of SNe Ibn and SNe Icn is beyond the scope of this paper, but considering the detection of He in SN 2022ann, we remark on its ubiquity in SNe Icn below.

Because of its high ionization and excitation energies, it is generally difficult to detect He in SNe Ic (Hachinger et al. 2012; Dessart et al. 2020; Teffs et al. 2020; Williamson et al. 2021; Shahbandeh et al. 2022), especially at optical wavelengths. A number of obstacles could complicate identification of He in SNe Icn and SN 2022ann in particular. The strongest He I line in the optical, He I $\lambda$5876, is coincident with the absorption minimum of the P-Cygni profile of the strong C II $\lambda$5889 line, making it challenging to disentangle (see Section 3.3). The density of high-ionization C, O, and Ne lines at $\lambda < 5200$ Å in the early-time spectra similarly makes unambiguously identifying He II $\lambda\lambda$4686 and He I $\lambda$4922 difficult. The emission component of the He II $\lambda$4922 line that emerged at later times was weak at early times.

It is therefore challenging to determine the presence of He in SNe Icn with only low-S/N optical spectra obtained near peak light, which may be why Pellegrino et al. (2022) did not clearly detect He in their sample. Our detections of He in SN 2022ann were either in NIR spectra (using the strongest He line, which is in the NIR at $\lambda 1.083 \mu$m) or at later times in optical spectra. Fraser et al. (2021) and Perley et al. (2022) both detected He in SN 2021csp in NIR spectra and high-S/N early optical spectra, respectively. Robust detection of He in SNe Icn may require high-S/N optical spectra near peak, NIR spectra, or late-time optical spectra.

Clear He detections in SNe 2021csp and 2022ann, as well as a potential detection in SN 2019jc, directly indicate that He is present in their circumstellar environments. Modelling of late-time spectra of SN 2019hpN did not support the presence of He; however, Gal-Yam et al. (2022) were unable to rule out a contribution from He II in earlier spectra. SN 2021ckj lacks the data necessary for a clean detection. With this small sample, we conclude that a large fraction of, and perhaps all, SNe Icn contain He in their circumstellar environments. Early-time, high-S/N, and NIR observations of future SNe Icn will be critical for determining the ubiquity of He in this class.

4.2 Heterogeneity in SNe Icn

Although the sample is still small, SNe Icn already appear to be highly diverse in several of their properties. For instance, the current sample of five SNe Icn have a range of luminosities at peak that is nearly the same as that for the much larger SN Ibn sample (Hosseinzadeh et al. 2017). The luminosity differences persist at late times ($t > 30$ d). The early photometric evolution also appears to be quite heterogeneous with SN 2019hpN having a smooth rise and fall, SN 2021csp having a fast rise and linear decline, and SN 2022ann having nearly a plateau. However, at late times, SN Icn decline rates are more similar.

Despite the photometric diversity, the SN Icn spectra are remarkably similar at maximum brightness; all SNe Icn have blue continua, narrow P-Cygni features from C and O, and a lack of H and strong He lines or other features. SN 2021csp displays higher-ionization lines than the other SNe Icn, but the generic features persist. All SNe Icn with maximum-light spectra exhibit strong, narrow P-Cygni lines regardless of photometric properties. In contrast to SN Ibn, no SN Icn has yet been discovered that has only emission features (lacking a P-Cygni absorption component). These similarities suggest similar compositions and dynamics in SNe Icn circumstellar environments.

On the other hand, the spectral behaviour of SNe Icn diverges after peak light. All SNe Icn with late-time spectra, apart from SN 2022ann, eventually developed broad features as some, if not all, of the narrow interaction lines disappeared. Meanwhile, we never see broad lines from SN 2022ann, indicating either a very low explosion velocity that is similar to that of the pre-explosion wind ($\sim 800$ km s$^{-1}$) or that the SN ejecta are veiled throughout our observations. In all of our spectra of SN 2022ann, there are signs of continued CSI with a C/O-rich CSM. SNe Icn also show differing amounts of Fe fluorescence.

A possible explanation for the diverse late-time behaviour is a shared but asymmetric configuration of CSM causing a viewing-angle dependence on the optical-depth evolution. This scenario is able to explain observed spectroscopic diversity, while maintaining similar global CSM properties across SNe Icn. For example, a toroidal configuration of CSM is commonly invoked to explain spectroscopic diversity observed in SNe Ibn, and could explain the differing times at which the SN Icn ejecta become visible. However, a torus of C- and O-rich CSM observed face-on would produce broad emission features in early-time spectra, a phenomenon not observed in SNe Icn so far.

Another possibility is that the circumstellar environments around SNe Icn, and potentially the mechanisms by which they are created, are themselves heterogeneous. The amount of Fe fluorescence could be tied to the host-galaxy metallicity, and therefore the abundance of Fe in the CSM. Assuming a mass–metallicity relationship for the host galaxies, the SNe Icn shown in Fig. 13 exhibit increasing levels of Fe fluorescence with higher-metallicity hosts. However, Fe fluorescence can be affected by a number of other factors besides abundance, such as CSM density and geometry. While simple modelling of SN Icn bolometric light curves has yielded relatively similar explosion properties throughout the subclass (Pellegrino et al. 2022), more rigorous theoretical modelling of these systems could reveal global differences in their circumstellar environments or point to different progenitor scenarios entirely. More late-time observations and a larger sample of SNe Icn could also help better constrain the relative contributions of radioactive decay and CSI to the light curves.

4.3 Progenitor system

The observables of SN 2022ann provide constraints on its progenitor system. The low absorption velocities, total mass of the system, and host-galaxy environment all independently indicate that a massive WR star cannot be the progenitor of SN 2022ann. Therefore, we favour a binary progenitor scenario. The strong, narrow C and O lines and lack of H and strong He lines in the spectra of SN 2022ann indicate that it is the result of an explosion in a star in a C/O-rich and H/He-poor circumstellar environment, consistent with what others have concluded for SNe Icn (Fraser et al. 2021; Gal-Yam et al. 2022; Pellegrino et al. 2022; Perley et al. 2022). Although we do not detect broad lines consistent with being SN ejecta, it is probable that the ejecta are also H/He poor, similar to other SNe Icn. These two properties shape our basic view of the progenitor system: a highly stripped star exploding within a dense, H/He-poor CSM.

SN 2022ann has two systemic velocities, $\sim 800$ km s$^{-1}$ from the P-Cygni absorption and $\sim 4900$ km s$^{-1}$ from the expansion of the photospheric radius derived from the bolometric light curve.

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8Pellegrino et al. (2022) claimed a He II detection for SN 2019jc, but the feature is similar in strength to several nearby unidentified lines.
Although these could be different measurements of a highly asymmetric system, it is more likely that the photospheric velocity comes from a physically different component than the absorption velocity. This scenario is possible if low-density CSM is ejected at the lower velocity well before the SN and the high-velocity SN ejecta is beneath the CSM outflow.

In the case of a constant stellar wind, we can place a limit on the extent of the CSM. P-Cygni features are present until at least 34 d after explosion. Assuming an SN velocity of 4900 km s$^{-1}$, the CSM must extend to at least $r \approx 10^{15}$ cm. If the CSM was a single ejection event and represents a thin shell with an expansion velocity of 800 km s$^{-1}$, the ejection must have occurred $>200$ d before explosion. If we assume a shock velocity of 30000 km s$^{-1}$, the shock would catch up to a CSM at $10^{15}$ cm in 5 d, exactly coincident with our first spectrum. Therefore, it is unfortunately impossible to distinguish between a wind and an outburst scenario.

Assuming the measured absorption velocity ($\sim 800$ km s$^{-1}$) is the escape velocity of a radiatively driven wind, we measure

$$\frac{M}{R} = 1.67 \frac{M_\odot}{R_\odot}.$$

(1)

The velocity and the resulting mass-to-radius ratio is much smaller than that of a WR star (Sander et al. 2019). Additionally, the two Galactic WO2 stars, WR 102 and WR 142, have $M/R > 30$, but the WR3 WR 93b has $M/R \approx 18$ (with all having terminal velocities of $v_\infty \approx 5000$ km s$^{-1}$). Low-mass (1 M\odot) WO model stars have $M/R \approx 5$ (Langer 1989). In contrast, the CSM for SN 2022ann has a wind velocity an order of magnitude lower, resulting in the low mass-to-radius ratio. Such a low wind velocity requires either (1) an extended photosphere out of hydrostatic equilibrium, (2) an outflow that is not driven by radiation pressure, (3) a very asymmetric outflow where the line-of-sight velocity is a small fraction of the true velocity, or (4) the wind originating from a single, but non-WR star. The last two options seem highly unlikely or completely unphysical.

At the end of their lives, core-collapse progenitor stars are particularly active (e.g. Kilpatrick et al. 2021; Jacobson-Galán et al. 2022). SNe Ib are expected to be extremely active, with the progenitor stars of SN 2006jc and SN 2019uo having luminous outbursts only 1–2 yr before explosion (Foley et al. 2007; Pastorello et al. 2007; Strotyjanohn et al. 2021). Such an outburst would certainly cause a departure from hydrostatic equilibrium for at least some time, but then we would expect the velocity to be even higher than the escape velocity. This scenario would require there to be additional high-velocity material at even larger radii that could be detected with late-time monitoring (Tianyanont et al. 2016; Margutti et al. 2017; Mauermann et al. 2018).

If we assume that the wind is radiatively driven at the Eddington luminosity, then we find

$$T = 50, 400 \, \text{K} \left(\frac{k}{0.2 \, \text{cm}^2 \, \text{g}^{-1}}\right)^{-1/4} \left(\frac{v}{800 \, \text{km} \, \text{s}^{-1}}\right)^{-1/4} \left(\frac{M}{10 \, M_\odot}\right)^{-1/4}.$$

(2)

While the opacity may be significantly higher than that of electron scattering, this places a reasonable limit on the effective temperature of the progenitor in this scenario. Although the star is more extended than a normal WR star, it is still very hot with the peak of its emission in the UV. Never the less, ‘cool‘ WO stars may be the progenitors of some SNe Ic.

Alternatively, the velocity seen may not be the escape velocity from the progenitor star, but the escape velocity from a binary system (e.g. see Tauris, Langer & Podsiadlowski 2015). Studies have shown that binary interaction can strip stars of their H/He-envelopes and drive runaway mass loss (Podsiadlowski, Joss & Hsu 1992; Yoon, Woosley & Langer 2010). Modelling of ultrastripped SNe (USNe) yield small ejecta and $^{56}$Ni masses comparable to those of SNe Icn, which is inconsistent with WR progenitors (Drout et al. 2013; De et al. 2018; Yao et al. 2020). Detailed analysis of these objects suggests binary progenitor systems. Binary systems have several evolutionary pathways along which mass transfer can happen. Therefore, heterogeneity in the resulting CSM and ultimately SNe Icn would be expected.

Recent studies have also proposed that the merger of a WR star and a compact object can reproduce the observed properties of several fast, multwavlength transients, including SNe Icn (Metzger 2022). In this scenario, an extended delay (>100 yr) between the common envelope event and the merger may explain asymmetric, He-poor CSM at the observed velocities in SNe Icn. Spectral modelling of this progenitor scenario will help confirm this as a channel for creating at least a subset of fast optical transients, including SNe Icn and SN 2022ann.

CCSNe progenitors typically have short lifetimes (up to a few tens of million years), where the SNe often occur during the star-formation event that formed the SN progenitor (where the SN can quench local star formation). Among dwarf galaxies (<10$^9$ M\odot), the host galaxy of SN 2022ann has a low sSFR, which suggests that SN 2022ann outlived its epoch of star formation or exploded before other high-mass stars formed. The latter is statistically unlikely and a larger sample of SNe Icn with low-mass host galaxies will be able to test this possibility. The former is intriguing since the lifetime of a typical starburst in a dwarf galaxy is ~100 Myr (Lee et al. 2009), which would disfavour OB-type progenitors and favour a lower-mass progenitor star that might require a companion to fully strip its H/He envelope.

The low host-galaxy mass and metallicity ($Z \approx 0.1 \, Z_\odot$) also suggests a low progenitor metallicity. Given its likely low metallicity and extreme stripping, the progenitor of SN 2022ann is less likely to have significant line-driven mass loss. The alternatives are either mass loss to a companion or episodic, perhaps explosive mass loss. The former is responsible for the mass loss of the majority of SN Ib and Ib progenitor stars (e.g. Smith et al. 2011; Yoon, Dessart & Clocchiatti 2017), but has trouble explaining the degree of mass stripping necessary for SN 2022ann. The latter has been seen in two SNe Ib (Foley et al. 2007; Pastorello et al. 2007; Strotyjanohn et al. 2021) and several SNe IIn (Smith et al. 2010; Foley et al. 2011; Mauerhan et al. 2013; Ofek et al. 2014; Strotyjanohn et al. 2021), and inferred for several other SNe with dense CSM (see Smith 2014, for a review). It is natural to expect a similar mass-loss mechanism for SN 2022ann; however, the absorption velocities are lower than expected for this case. A combination of non-conservative mass transfer to a binary star, which could create the low-velocity outflow, and episodic mass loss, which could cause the extreme stripping, may be necessary for SN 2022ann.

5 CONCLUSIONS

We have presented optical photometry and optical/NIR spectroscopy of SN 2022ann, the fifth reported SN Icn, and its host galaxy, SDSS J101729.72–022535.6. SN 2022ann has several unique and extreme properties relative to the other members of this small subclass. Our observations of SN 2022ann provide unique insight into the origins
of the rarest SN explosions, and undiscovered endpoints of stellar evolution.

The denotative characteristics of SNe Icn, including SN 2022ann, are early-time optical spectra with blue continua that show narrow P-Cygni lines of C and O while lacking (strong) H and He features. The absorption minimum velocities of these features measure at ~1000 km s$^{-1}$ across the SNe Icn.

SN 2022ann has a uniquely constant brightness at early times and a relatively rapid late-time decline in redder bands after this plateau. At peak it is also has relatively low luminosity compared to other known SNe Icn, which have diverse peak luminosities as a whole. We model the bolometric light curve of SN 2022ann, finding that it is well-described by 4.79 M$_\odot$ of ejecta interacting with 1.32 M$_\odot$ of CSM. We place a conservative upper limit on the $^{56}$Ni mass at 0.04 M$_\odot$.

Through its photospheric phase, the spectra of SN 2022ann are well-described by a blackbody continuum with narrow P-Cygni lines primarily from C and O. Unlike other SNe Ibn and Icn, SN 2022ann never shows broad lines that could be associated with SN ejecta, nor a high blue continuum flux from Fe fluorescence. The lack of any broad lines despite a high velocity for the photosphere is perplexing.

The lack of Fe fluorescence suggests either (1) the Fe abundance is low, or (2) there is an insufficient flux of high-energy photons necessary to pump the electrons.

While we do not clearly detect any He emission in our early-time optical spectra of SN 2022ann, we detect He lines in both of our NIR spectra (first epoch at +10.1 d) and our later optical spectra (starting at 28.6 d). Other SNe Icn have weak He lines in their early spectra (Fraser et al. 2021; Pellegrino et al. 2022; Perley et al. 2022). While some SNe Icn have no clear detection of He, those cases lack high-SN early spectra NIR spectra, and late-time optical spectra. We posit that He may be ubiquitous in SNe Icn but specific observations are necessary to detect it. A focus on obtaining these observations for future SNe Icn will be necessary to measure the amount of He in these systems.

Whereas other SNe Icn have CSM velocities consistent with WR winds (~1000–2000 km s$^{-1}$) (Fraser et al. 2021; Gal-Yam et al. 2022; Pellegrino et al. 2022; Perley et al. 2022), the CSM of SN 2022ann has a velocity of only ~800 km s$^{-1}$, inconsistent with known WO stars and below the escape velocity for a compact massive star that is necessary to avoid strong H emission. The progenitor star of SN 2022ann may have been ‘puffed up’ by an outburst and out of hydrostatic equilibrium before explosion. Alternatively, the wind velocity may be indicative of the escape velocity from a binary system rather than from the progenitor star itself.

The host galaxy of SN 2022ann is a low-mass dwarf galaxy with log(M/M$_\odot$) = 7.34$^{+0.11}_{-0.10}$ and a low SFR of log(SFR) = −2.20$^{+0.30}_{-0.30}$ M$_\odot$ yr$^{-1}$. The dwarf-galaxy nature of SN 2022ann is likely linked to this extreme environment. In particular, the galaxy-averaged metallicity of ~0.1 Z$_\odot$ suggests that the progenitor of SN 2022ann likely had low metallicity, making line-driven mass loss inefficient and unlikely to fully strip the H/He envelope from the progenitor star. A binary companion could provide a mechanism for the necessary enhanced mass loss.

Given the low CSM velocity, low $^{56}$Ni and ejecta masses, and SFR-poor host-galaxy environment, we favour a binary-stripping progenitor scenario for SN 2022ann over a single massive WR progenitor. The rarity of SNe Icn may indicate that they are created during a brief or uncommon stage in binary evolution. Observations of future SNe Icn, particularly at late times and in the NIR, will be critical for constraining the nature of this path of stellar evolution.

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DATA AVAILABILITY
Photometric data presented in Fig. 2 and Table A1 are available in an electronically readable table provided in the supplementary material of this article. Spectra presented in Figs 3 and 4 are available at https://ziggy.ucolick.org/sn2022ann, or upon reasonable request to the corresponding author.

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Figure A1. Corner plot of 1D and 2D posteriors from the light-curve modelling of SN 2022ann with MOSFiT. We used an ensemble-based Markov chain Monte Carlo with 250 walkers to sample our parameter space through 50 000 iterations. All priors were flat either in logarithmic or linear space as denoted in the corner plot. 2D histograms have been smoothed using a Gaussian kernel with a standard deviation of 1.

Table A1. Log of photometric observations of SN 2022ann. UBV filters reported in Vega-based magnitudes, while all other filters are reported in AB magnitudes. Data provided in table are not extinction-corrected. Magnitude uncertainties are presented in parentheses following the magnitudes. A portion of the data is shown here; the full data will be provided via an electronically readable table online.

| MJD   | Instrument | Filter | Apparent magnitude |
|-------|------------|--------|--------------------|
| 59604.5 | ATLAS-ACAM1 | o      | 19.22 (0.11)       |
| 59605.6 | ATLAS-ACAM1 | o      | 19.14 (0.11)       |
| ... | ... | ... | ... |
Table A2. Log of spectroscopic observations for SN 2022ann.

| UT date     | Phase (d) | Telescope | Instrument | Range (Å) | Exp. time (s) |
|-------------|-----------|-----------|------------|-----------|---------------|
| 2022 Feb. 06.3 | +2.8      | Shane     | Kast       | 3250–10,380 | 2400          |
| 2022 Feb. 08.3 | +4.8      | SOAR      | Goodman    | 3810–6690  | 1800          |
| 2022 Feb. 13.6 | +10.1     | Keck-II   | NRES       | 9200–23,500 | 1200          |
| 2022 Feb. 14.0 | +10.5     | NOT       | ALFOSC     | 3620–8575  | 3600          |
| 2022 Feb. 20.2 | +16.7     | SOAR      | Goodman    | 4815–8600  | 2400          |
| 2022 Feb. 22.6 | +19.1     | Keck-II   | NRES       | 9200–23,500 | 2400          |
| 2022 Feb. 24.0 | +20.5     | SOAR      | Goodman    | 3705–8565  | 1800          |
| 2022 Feb. 26.0 | +22.5     | HET       | LRS2       | 3480–6610  | 1200          |
| 2022 Mar. 01.3 | +25.8     | Shane     | Kast       | 3130–9615  | 4800          |
| 2022 Mar. 04.1 | +28.6     | Keck-I    | LRS1       | 2990–9790  | 1500          |
| 2022 Mar. 07.1 | +31.6     | MMT       | Binospec   | 3670–8760  | 2000          |
| 2022 Apr. 08.1 | +63.6     | Gemini-S  | GMOS       | 5270–8950  | 3000          |
| 2022 Apr. 25.3 | +80.8     | Keck-I    | LRS1       | 3600–9670  | 3200          |

Table A3. Host-galaxy photometry measured from pre-imaging all-sky public imaging surveys. Photometry is not corrected for Galactic foreground extinction. Upper limits are 2σ.

| Filter | AB mag | Uncertainty | Survey         | Reference |
|--------|--------|-------------|----------------|-----------|
| u'     | >22.37 | –           | SDSS DR16      | [1]       |
| g'     | 22.77  | 0.12        | DESI Legacy Imaging | [2]     |
| r'     | 22.72  | 0.27        | SDSS DR16      | [1]       |
| i'     | 22.72  | 0.39        | Pan-STARRS     | [3]       |
| z'     | 22.38  | 0.16        | Pan-STARRS     | [2]       |
| r'     | 22.21  | 0.25        | SDSS DR16      | [1]       |
| i'     | 22.40  | 0.37        | Pan-STARRS     | [3]       |
| z'     | 22.10  | 0.27        | SDSS DR16      | [1]       |
| y'     | 22.25  | 0.36        | Pan-STARRS 3PI | [3]       |
| <19.92 | –      | SDSS DR16   |                | [1]       |
| <19.22 | 0.31   | Pan-STARRS  |                | [3]       |
| >15.81 | –      | Pan-STARRS  |                | [3]       |

Note. [1] York et al. (2000), [2] Dey et al. (2019), and [3] Flewelling et al. (2020).

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