SN 2019hcc: A Type II Supernova Displaying Early O II Lines

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1 INTRODUCTION

Historically, supernovae (SNe) were initially classified according to specific observational characteristics, and then a physically mo-
Evolution pathways. SNe can be broadly classified into two main types - those which show Hydrogen lines (Type II) and those which do not (Type I). Core-collapse of a massive star with a retained Hydrogen envelope produces the Hydrogen-rich Type II SNe, whereas if such envelope has been stripped we observe stripped envelope supernovae (SESNe), which fall into the Hydrogen-poor Type I.

SNe II are considered a single population (Minkowski 1941) but a large spectral and photometric diversity is nowadays evident (e.g. Gutiérrez et al. 2017a). SNe II were historically split into two categories based on their photometric evolution, SNe IIL showing a linear decline in the light curve (Barbon et al. 1979) and SNe IIP showing a plateau for several weeks. Arcavi (2011) suggested that the difference in Type IIL, a typically brighter subclass of Type II supernovae, could be due to the presence of a magnetar. However, Anderson et al. (2014b) suggested that the diversity observed in SN II light-curves and their spectra is due to the mass and density profile of the retained Hydrogen envelopes. For years, it has been a matter of dispute whether IIL and IIP are a continuous population or have distinctly different physics and progenitors but, recently, increasing evidence has suggested that they are coming from a continuous populations (e.g. Anderson et al. 2014b; Sanders et al. 2015; Galbany et al. 2016; Valenti et al. 2016; de Jaeger et al. 2018). Anderson et al. (2014b) also noted that very few SNe II actually fit the classical description of SNe IIL as most show a plateau of some form. However, Davis et al. (2019) performed a spectroscopic analysis in the near-infrared (NIR) which found distinct populations corresponding to fast (SN IIL) and slow (SN IIP) decliners, though they suggested this could alternatively be accounted for by a gap in the data set.

Further splittings of SNe II are based on spectroscopic features. SNe Ib are transitional events between Hydrogen-rich SNe II and Hydrogen-poor SNe Ib (e.g. Filippenko et al. 1993). SNe IIn display narrow emission lines attributed to interaction with dense circumstellar material (e.g. Schlegel 1990). SN classification can be time dependent, as some objects have been observed to dramatically change their observables over time, ranging on timescales from weeks to years. In recent years, wide-field surveys have revealed a large diversity of unusual transients that include extreme transitional objects (Modjaz et al. 2019). One such example is SN 2017ens (Chen et al. 2018), a transition between a luminous broadline SN Ic and a SN IIn. SN 2017iiv is another, sharing properties with fast-declining SN II and SN Ib (Gutiérrez et al. 2020), or SN 2014C, which underwent a change from a SN Ib to SN IIn due to interaction with a Hydrogen-rich CSM (Milisavljevic et al. 2015). Objects such as these can support physical continuity between progenitors and explosion mechanisms of different types (Filippenko 1988).

Another finding of the wide-field survey has been the discovery of a population of ultra-bright ‘superluminous’ supernovae (Quimby et al. 2011). SLSNe are intrinsically rare with respect to discovery of a population of ultra-bright ‘superluminous’ supernovae (SLSNe I) and SLSNe II at maximum light of approximately -21 mag (Gal-Yam 2019a). However, recent measurements by Frohmaier et al. (Quimby et al. 2011; Inserra 2019). However, subsequent spectra identify SN 2019hcc as a moderately bright Type II supernova, similar to those discussed in Inserra et al. (2013a), due to the presence of Balmer lines. This is the first such object (to our knowledge) to be identified in the literature.

In this paper, we will show that SN 2019hcc, despite displaying a ‘w’ shape profile similar to those observed in SLSNe I, otherwise conforms with the typical properties of SNe I. We will then investigate possible mechanisms which could be responsible for producing such a ‘w’ shape profile in a SN II. This paper is organised as follows. In Section 2 we report the observations and how the data was obtained and reduced. In Section 3 the host galaxy and its properties are analysed. In Section 4 the rise time and explosion epoch are determined, and the photometry is presented. Section 5 contains a detailed analysis of the optical, NIR and bolometric light curves. Section 6 focuses on the spectra of SN 2019hcc, their properties are analysed. In Section 4, the rise time and explosion epoch are determined, and the photometry is presented. Section 5 contains a detailed analysis of the optical, NIR and bolometric light curves. Section 6 focuses on the spectra of SN 2019hcc, their properties are analysed. In Section 4, the rise time and explosion epoch are determined, and the photometry is presented. Section 5 contains a detailed analysis of the optical, NIR and bolometric light curves.
Figure 1. The finder chart for SN 2019hcc displaying the local environment, taken in r-band at MJD = 58660 by LCO. The host is a low luminosity galaxy. SN 2019hcc is marked by the white crosshairs, and in the blow-up image in the top-right corner.

negligible. Figure 1 shows the finder chart and the local environment of SN 2019hcc.

2.1 Data Reduction

Five optical spectra were taken over a range of 5 months with the NTT+EFOSC2 at the La Silla Observatory, Chile. This was under the advanced Public ESO Spectroscopic Survey of Transient Objects programme (ePESSTO+; Smartt et al. 2015). This was alongside a host galaxy spectrum taken over a year after explosion when SN 2019hcc was no longer visible. The spectra were reduced using the PESSTO NTT pipeline\(^1\). There was also one spectrum taken by the Goodman High Throughput Spectrograph at the Southern Astrophysical Research telescope (SOAR) (Clemens et al. 2004), reduced using the dedicated pipeline (Sánchez-Sáez et al. 2019).

Photometric data was obtained by the Las Cumbres Observatory (LCO; Brown et al. 2011) with the camera Sinistro built for the 1m-class LCO telescopes, and by the Liverpool Telescope (LT; Steele et al. 2004) on the Canary Islands. Images were combined using SNOoPY\(^2\) and the magnitudes were retrieved using PSF photometry, with the zero-point calibration completed using reference stars accessed from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Chambers et al. 2016) and the Vizier catalogues (Ochsenbein et al. 2000). This was performed using the code described in detail in Appendix A. Additional photometry was also taken by ATLAS, Swift + Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005) and the Gamma-Ray Burst Optical and Near-Infrared Detector (GROND; Greiner et al. 2008). GROND is an imaging instrument to investigate Gamma-Ray Burst Afterglows and other transients simultaneously in seven bands griJHK mounted at the 2.2 m MPG telescope at the ESO La Silla Observatory (Chile). The GROND images of SN 2019hcc were taken under the GREAT survey (Chen et al. 2018). GROND (Krühler et al. 2008), ATLAS and Swift data were reduced using their own pipelines. The photometry and spectroscopy logs, including dates, configurations, and magnitudes are reported in Appendix B. As Swift observes simultaneously with UVOT and the X-ray Telescope (XRT), we report that the corresponding upper limit on the unabsorbed 0.3-10 keV flux is 2.6x10\(^{-14}\) ergs (assuming a power law with photon index 2 and the Galactic column density of 4.9x10\(^{20}\) cm\(^{-2}\)) resulting in an upper limit on luminosity of ~10\(^{41}\) erg/s at SN 2019hcc distance. The closest non-detections were taken by ATLAS from 34 days to 22 days before discovery, with a confidence of 3\(\sigma\).

3 HOST GALAXY

The host galaxy spectrum for SN 2019hcc was taken with NTT+EFOSC2 (Buzzoni et al. 1984) at the La Silla Observatory, Chile, on MJD 59149, when the SN was no longer visible, as part of the ePESSTO+ programme (Smartt et al. 2015). The line fluxes were measured using the splot function in IRAF (Tody 1986) by taking a number of measurements and averaging to account for the uncertainty in the location of the continuum. The host galaxy spectrum was analysed using pyMCZ. This is an open-source Python code which determines the metallicity indicator, Oxygen abundance (12 + log(O/H)), through Monte Carlo sampling, and gives a statistical confidence region (Bianco et al. 2016). The input of this code is the line flux and associated uncertainties for lines such as [O ii] and H\(\alpha\) from the host galaxy spectrum. Kewley & Ellison (2008) found that the choice of metallicity calibration has a significant effect on the shape and y-intercept (12+log(O/H)) of the mass-metallicity relation, therefore multiple markers are used to measure the metallicity in an effort to give a representative range.

Figure 2 shows the input (upper panel) and output (lower panel) for pyMCZ (see Bianco et al. 2016). The metallicity estimators are those of Zaritsky et al. (1994) [Z94], McGaugh (1991) [M91], Maiolino et al. (2008) [M08], and Kewley & Ellison (2008) [KK04]. These metallicity markers are all based on \(R_{23}\), see Bianco et al. (2016) for a summary and further details:

\[
R_{23} = \frac{[O\,II]_{\lambda\lambda 3727 + [O\,III]_{\lambda 4959,5007}}}{H\beta} \tag{1}
\]

[N ii] \(\lambda 6584\) is not visible in this spectrum, and at this resolution it would be very difficult to resolve as it is so close to H\(\alpha\). A lack of [N ii] is an indicator of low metallicity, therefore the lower branches of the metallicity indicators were used in the code, apart from Z94, where only the upper branch is available in pyMCZ. The metallicity markers used are those available given the line fluxes which were input into pyMCZ, which are labelled in the top panel of Figure 2. Averaging them we obtain a host galaxy metallicity of 12 + log(O/H) = 8.08 ± 0.05, which is below solar abundance.

We also note that the H\(\alpha\)/H\(\beta\) flux ratio in the host spectrum is measured to be 2.2 ± 0.1, less than the intrinsic ratio 2.85 for case B recombination at T = 10\(^4\) K and n\(_e\) = 10\(^2\) - 10\(^4\) cm\(^{-3}\) (Osterbrock 1989). A ratio of less than 2.85 can result from an intrinsically low reddening combined with errors in the stellar absorption correction and/or errors in the line flux calibration and measurement (Kewley & Ellison 2008).

\(^1\) https://github.com/svalenti/pessto

\(^2\) SNOoPY is a package for SN photometry using PSF fitting and/or template subtraction development by E. Cappellaro. A package description can be found at http://sngroup.oapd.inaf.it/snoopy.html

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Models by Dessart et al. (2014) hint to a lack of SNe II below 0.4 Z⊙. However, this may be biased as higher luminosity hosts were used which tend to have higher metallicity. On the other hand, SLSNe I are predominantly found in dwarf galaxies, indicating that their progenitors have a low metallicity. A 0.5 Z⊙ threshold has been suggested for the formation of SLSNe I (Chen et al. 2017c). Lunnan et al. (2014) found a median metallicity of 8.35 ± 0.45 Z⊙ for a sample of 31 SLSNe I.

The measured metallicity was compared to both Type II and SLSN I hosts. Table 1 contains the mean metallicity excluding Z94 (this is likely incorrect as it is the upper branch) from Figure 2, compared to averages for SLSNe I and SNe II. Schulze et al. (2020) performed a comprehensive analysis of SN hosts based on a sample of 888 SNe of 12 distinct classes, and found a median metallicity 12 + log(O/H) = 8.26 ± 0.26 for a sample of 37 SLSNe I. Galbany et al. (2018) presented a compilation of 232 SN host galaxies, of which 95 were Type II hosts with an average metallicity (12 + log(O/H)) of 8.54 ± 0.04. The mean metallicity for SN 2019hcc is within the range of the SLSN I host metallicity found by Schulze et al. (2020), and is low compared to the average metallicity of Type II hosts.

The host galaxy absolute magnitude was measured to be −15.8 ± 0.3 in r-band and −15.8 ± 0.2 in B-band. Gutiérrez et al. (2018) defined a faint host as having M_r ≥ −18.5 mag, and analysed the hosts of a sample of low-luminosity SNe II, finding a mean host luminosity of −16.42 ± 0.39 mag. Anderson et al. (2016) examined a sample of SNe II in a variety of host types and found a mean host luminosity M_r of −20.26 ± 0.14 mag. For SLSNe I, Lunnan et al. (2014) found a low average magnitude (M_B = −17.3 mag).

Table 1 also contains the average M_B magnitudes for both SLSNe I and SNe II from Schulze et al. (2020). SN 2019hcc has a lower luminosity and metallicity host with respect to the average value for SNe II and SLSNe I reported in the literature (see Table 1).

We retrieved further SN 2019hcc host galaxy properties by modelling the spectral energy distribution (SED) using the software package Prospector version 0.3 (Leja et al. 2017; Johnson et al. 2019). An underlying physical model is generated using the Flexible Stellar Population Synthesis (FSPS) code (Conroy et al. 2009). A Chabrier initial mass function (Chabrier 2003) is assumed and the star formation history (SFH) is approximated by a linearly increasing SFH at early times followed by an exponential decline at late times (functional form t⁻¹exp(−t/τ)).

The model was attenuated with the dust extinction. The mass of the host best matches the median SLSN I mass, whilst the SFR is low for both SLNSe I and SNe II. The age of the SN 2019hcc host has a large uncertainty that covers the range of both classes, and the magnitude is low for both classes. The SFR is significantly lower for SN 2019hcc. However, the mass of the host is lower than the median for both SLSNe I and SNe II, and therefore the sSFR falls between the two.

Figure 2. Top panel: NTT galaxy spectrum used as input for pyMCZ, with the relevant lines labelled. The Hα/Hβ ratio is 2.2 ± 0.1. The wavelength is in the rest frame. Bottom panel: Reproduced output of pyMCZ, the metallicity measured via several markers is displayed as box plots. The central value is the median (or 50th percentile). The inner box represents the inter-quartile range (IQR) - 50th to 16th percentile and 84th to 50th percentile (the 16% is an analogy to the Gaussian 1 σ interval), whilst the outer bars represent the minimum and maximum data values, excluding outliers. The outliers are those values further than 1.5×IQR from the edges of the IQR. The blue band is a range of solar metallicity values found in literature - from 8.69 in Asplund et al. (2009) to 8.76 in Caffau et al. (2011).

Figure 3 shows the best fit SED to the SN 2019hcc photometry for filters GALEX FUV (20.69 ± 0.14 mag) and NUV (20.48 ± 0.14 mag), PS1 G (19.86 ± 0.03 mag), V (19.76 ± 0.04 mag), I (19.74 ± 0.17 mag), andWISE W1 (20.58 ± 0.42 mag) and W2 (21.05 ± 0.40 mag). The magnitudes are in the AB system and corrected for Milky Way extinction. Table 1 shows the galaxies properties inferred from the best-fit SED to the host galaxy photometry. The E(B-V) inferred for SN 2019hcc matches well with the E(B-V) based on the Milky Way extinction. The mass of the host best matches the median SLSN I host mass, whilst the SFR is low for both SLSNe I and SNe II. The age of the SN 2019hcc host has a large uncertainty that covers the range of both classes, and the magnitude is low for both classes. The SFR is significantly lower for SN 2019hcc. However, the mass of the host is lower than the median for both SLSNe I and SNe II, and therefore the sSFR falls between the two.
The explosion epoch of MJD 58620, which is within the errors and consistent with the previous measurement.

For the epoch of maximum light, we used the phenomenological equation for light curves from Bazin et al. (2009). This form, as shown in Equation 3, has no physical motivation but rather is flexible enough to fit the shape of the majority of supernova light curves.

\[
f(t) = A\left(\frac{t - t_\text{rise}}{t_\text{rise} - t_\text{fall}}\right)^2 + B.
\]

Here \(t_\text{rise}\) and \(t_\text{fall}\) are free parameters. The derivative, as seen in Equation 4, was used to get the maximum epoch \(t_\text{max}\), and the uncertainties from the fit were propagated through the below equation (González-Gaitán et al. 2015):

\[
t_\text{max} = t_0 + t_\text{rise} \times \log\left(\frac{t_\text{rise}}{t_\text{rise} + t_\text{fall}}\right).
\]

The maximum epoch was found from the Bazin fit to be MJD 58636.2 ± 2.2 - this was done by fitting to the flux data, see the right panel on Figure 4. This will be the maximum hereafter referred to in the paper, and can be approximated as the peak in ATLAS \(o\)-band, as this is the band the majority of these points are in. Points with an error greater than 30 \(\mu\)Jy have been removed for clarity. Combining this result with the explosion epoch gives a rise time of 15.2 ± 7.5 days.

ATLAS \(o\)-band is close to \(R\)-band. The average \(R\)-band rise from the ‘gold’ samples (consisting of 48 and 38 SNe each from different surveys) of SNe II from Gonzalez-Gaitan et al. (2015) was 14.0 ± 1.3 days. Pessi et al. (2019) reported an average \(r\)-band rise time for a sample of 73 SNe II of 16.0 ± 3.6 days. Both results are consistent with our measured value - therefore it seems the rise of SN 2019hcc is typical for a SN II. In contrast, SLSNe I light-curves have longer timescales with an average rise of 28 and 52 days for SLSNe I Fast and Slow respectively (Nicholl et al. 2015; Incessa 2019). Despite the average longer rise of SLSNe I to SNe II, it should be noted that the fastest riser SLSNe I can have some overlap within the errors of the slowest SNe II values from Gonzalez-Gaitan et al. (2015).

4 PHOTOMETRY

4.1 Rise time and Explosion Epoch

We determined the rise time and explosion epoch following the methodology presented in Gonzalez-Gaitan et al. (2015). We applied this approach to the ATLAS data only, both orange and cyan, as it is the only photometry available which covers the pre-peak light curve albeit with many upper limits. It is not ideal to combine different bands however as there are few points it is an unavoidable uncertainty. We then measure the explosion epoch using a power law fit (Equation 2) from the earliest pre-peak upper limit to maximum luminosity:

\[
f(t) = a(t - t_{\text{exp}})^n \quad \text{if } t > t_{\text{exp}}
\]

\[
f(t) = 0 \quad \text{if } t < t_{\text{exp}}.
\]

Here \(a\) is a constant and \(n\) is the power index, both of which are free parameters, and \(t_{\text{exp}}\) is the explosion date in days. This fit was done using a least squares fit as implemented by scipy.curve_fit in Python to the pre-maximum light curve in flux, and the explosion epoch was measured to be MJD 58621.0 ± 7.2. An alternative method of measuring the explosion epoch is to take the midpoint between the first non-detection and the first detection - this would be between MJD 58609 and MJD 58631, giving an estimate of

4.2 Multi-band light curve

The majority of photometric data were taken by LCO in bands \(BVgriz\), and by LT in bands \(griz\). The light curve produced from this data was created using a code written using Python packages AstroPy and PhotUtils (see Appendix A for further detail). This was complemented by ATLAS data in the orange and cyan bands, UV data from Swift, optical (\(griz\)) and NIR (\(JHK\)) data from GROND. Figure 5 shows the photometric evolution of SN 2019hcc in all available bands. The UV data covers 21 days, and appears to follow a linear decline. The NIR data covers a similar period of 30 days, and are roughly constant in magnitude. There is a linear decline of \(\sim 50\) days from peak in all optical bands, with a magnitude change of \(\sim 1.5\) mag in \(r\)-band, followed by a steeper drop of \(\sim 2\) mag from 50 to 70 days. The decline rate is similar in the other bands with the exception of \(g\)-band which declines faster, at a rate of \(\sim 2\) mag in the first \(\sim 50\) days after maximum light, and subsequently \(\sim 3\) mag in the steeper decline. The \(BV\)-bands data for Swift were excluded as these were contaminated by host galaxy light. Such a contamination is far less in \(u,uvw1,uvw2\) and \(uvw2\). The Swift detections were at level of 3-4 \(\sigma\). GROND \(griz\) magnitudes were not template subtracted as there were no templates available. However,
the data were taken soon after maximum light, where the difference between the host galaxy magnitude and that of SN 2019hcc is at its maximum, and therefore should not add significant uncertainty. LT and LCO magnitudes were template subtracted as part of the photometry code described in Appendix A.

Figure 6 shows the evolution of the blackbody temperature fit to the photometric data together with the $B - V$ colour evolution, both for SN 2019hcc and a selection of SNe II. These are: SN 2013ej (Valenti et al. 2014), SN 2014G (Terreran et al. 2016), SN 2008Fq (Fassia et al. 2000, 2001), SN 2009dd and SN 2010aj (Inserra et al. 2013a) together with a sample of 34 SNe II from Faran et al. (2014). SNe 1998S and 2014G - a Type IIn and III, respectively - were chosen for their spectroscopic similarity to SN 2019hcc near peak. SN 2013ej,
As the ‘w’ shape profile of SN 2019hcc first spectrum is similar to that observed in SLSNe I, in Figure 7 we also compare the temperature evolution of SN 2019hcc with a sample of SLSNe I: iPTF16bad (Yan et al. 2017), SN 2010kd (Kumar et al. 2020), PTF12dam (Nicholl et al. 2013), and LSQ14mo (Chen et al. 2017b; Leloudas et al. 2015b). We selected this small subset of SLSNe I mainly due to the spectral similarity, see Section 7 for further information. We also compare to an average temperature evolution for SLSNe I (Inserra et al. 2017, and reference therein), similarly to what was previously done with SNe II. LSQ14mo is the only SLSNe I with a similar temperature evolution to SN 2019hcc.

5 LIGHT CURVE ANALYSIS

5.1 Bolometric light curve

We created a pseudo-bolometric light curve from an SED fit to the available photometry, which was interpolated according to the chosen reference band. We used the SDSS r−band and the ATLAS o−band as reference, as these bands should approximately cover a similar region of the electromagnetic spectrum, to cover as many epochs as possible. Each band was integrated using the trapezium rule. The redshift, distance, and reddening used were reported in Section 2.

The light curve evolution of SNe II was considered quantitatively by Anderson et al. (2014b) and Valenti et al. (2016). The decline of the initial steeper slope of a light curve and the second shallower slope can be described as S1 and S2 respectively - in SNe III, these are very similar or the same (Anderson et al. 2014b). S1 and S2 were originally described for V−band as reference, these bands should approximately cover a similar region of the electromagnetic spectrum, to cover as many epochs as possible. Each band was integrated using the trapezium rule. The redshift, distance, and reddening used were reported in Section 2.

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Here the variables $A_0, w_0, n_0$ are free parameters describing the shape of the drop, $p_0$ describes the decline of the tail, and $t_{pt}$ describes the length of the plateau, measured from the explosion to the midpoint between the end of the plateau phase and start of the radioactive tail.

The top panel on Figure 8 shows the pseudo-bolometric light curve, however there is no distinguishable change in the slope leading to a clear distinction of S1 and S2, and after approximately 60 days past maximum the light curve transits into a ‘plateau-tail phase’ and then drops into a radioactive tail. As there are not multiple slopes in the initial decline, S1 and S2 will hereafter be collectively referred to as S2 for SN 2019hcc, leading to a Type IIL sub-classification for the supernova. The S2 decline was found to be $1.51 \pm 0.09$ mag per 50 days. The best-fit $t_{pt}$ was $66.0 \pm 1.1$ days, and $p_0$ was measured via a linear fit and found to be $1.38 \pm 0.49$ mag per 100 days. Valenti et al. (2016) found a mean length of the plateau in SNe II of $t_{pt} = 100$, which is up to the midway in the plateau-tail phase. Considering this average, SN 2019hcc has a relatively short plateau duration, which could suggest a lower ejecta mass, but could also be due to a smaller progenitor radius or a higher explosion energy (Popov 1993). This fitting was performed for the pseudo-bolometric light curve rather than $V$-band due to the sparsity of photometric data in this band, particularly for the tail of the light curve.

The middle panel of Figure 8 shows the full bolometric light curve - this was found by fitting a blackbody to the photometry and integrating between 200 Å and 25000 Å. The bolometric light curve required interpolation and extrapolation of additional points for epochs where some bands were not observed. This was done by taking a constant colour from the nearest points in the other bands - however this is an assumption which increases the uncertainty in the resultant curve. The tail luminosity $L_{tail}$ is marked, and a $^{56}$Co tail has been plotted using Equation 6, as from Jerkstrand et al. (2012), which gives the bolometric luminosity for the theoretical case of a fully-trapped $^{56}$Co decay.

If full trapping of gamma-ray photons from the decay of $^{56}$Co is assumed, the expected decline rate is $0.98$ mag per 100 days in $V$-band (Woosley et al. 1989; Anderson et al. 2014b). The tail of SN 2019hcc clearly declines faster than the $^{56}$Co tail as shown in the middle panel of Figure 8. If this is indeed the radioactive tail, it seems that SN 2019hcc displays incomplete trapping. This is not entirely unexpected as Gutiérrez et al. (2017b) suggested a few possibilities for incomplete trapping such as a lower ejecta mass, high kinetic energy or peculiar density profiles. However, dust formation could also result in a fast-declining tail, and additional effects such as a different radioactivity could affect the decline (Branch & Wheeler 2017), as well as CSM-ejecta interaction, which can contribute to the luminosity at late times (e.g. Andrews et al. 2019).

The lower panel of Figure 8 shows a comparison of the bolometric light curve of SN 2019hcc with Type II SNe 2013ej and 2014G, and with the Type IIn SN 1998S. These were chosen for comparison as they present a similar photometric evolution to SN 2019hcc (see Section 4). The bolometric light curves from the sample of SNe II from Faran et al. (2014) are also included, and two distinct branches can be seen which would correspond to the historic SN III and SN IIP sub-classifications. However, note the small sample size of this study compared with other sample analyses. All light curves have been normalised by the peak luminosity for comparison. This panel supports that the sample of SNe II discussed would all be considered SNe III, or fast decliners.

A SN III has been defined as where the $V$-band light curve declines by more than 0.5 mag from peak brightness during the first 50 days after explosion (e.g. Faran et al. 2014). The initial decline of SN 2019hcc was also measured in $V$-band and is displayed, along with other properties, in Table 2 together with the comparison SNe and the average values for SN IIP and SN III. Looking at Figure 8, the S2 slope of SN 2019hcc appears steeper, and the plateau shorter, than the comparison SNe II SN 2014G and SN 2013ej. However, SN 1998S has a faster initial decline, and appears to transition to the tail at a comparable epoch. SN 2013ej has the most distinct S1 and S2. The radioactive tail of SN 2019hcc shows a similar decline...
Table 2. Here $V_{50}$ is the $V$–band magnitude decline in the first 50 days (roughly equivalent to $S_2$), measured directly from the light curves with a linear fit. Rise times and peak absolute magnitude are in $R$–band for SN 2014G (Terreran et al. 2016) and SN 2013ej (Richmond 2014; Huang et al. 2015), or ATLAS $o$–band for SN 2019hcc. Rise time and peak values for SN 1998S is also in the $R$–band, however they are estimated from the light curve rather than taken from literature. Also shown are the average values for a sample of 10 SN III and 18 SN IIP from Paran et al. (2014). Though these populations have been previously discussed as continuous, the distinction is still useful to give context to the measured values. Anderson et al. (2014b) found a mean $S_2$ of 0.64 for a sample of 116 SNe II, roughly the average of the IIL and IIP sub-classes in the above. The rise time for SNe II is taken from Pessi et al. (2019). The average absolute peak magnitude in $R$–band for SNe II comes from Galbany et al. (2016).

| SN   | $V_{50}$  | Rise (days) | Peak (Absolute Mag) |
|------|----------|-------------|---------------------|
| SN 2019hcc | 1.52±0.03 | 15.3±7.4 | −17.7 |
| SN 2014G | 1.58±0.06 | 14.4±0.4 | −18.1 |
| SN 2013ej | 1.24±0.02 | 16.9±1 | −17.64 |
| SN 1998S | 1.87±0.07 | −18 | −18.1 |
| SNe II | 1.43±0.21 (IIL) | 0.31±0.11 (IIP) | 16.0±3.6 | −16.96±1.03 |

rate to all comparison SNe which also seem to display incomplete trapping, or at the very least a radioactive tail decay faster than $^{56}$Co decay. The SN 2019hcc light curve evolution drops out of the photospheric phase sooner than SN 2013ej and SN 2014G - implying a lower ejecta mass. It could therefore be suggested that the ejecta mass of SN 2019hcc is lower than the that of these other SNe, however other factors such as explosion energy could also play a role (Popov 1993).

5.2 $^{56}$Ni Production

Jerkstrand et al. (2012) presented a method to retrieve the $^{56}$Ni mass produced by comparing the estimated bolometric luminosity in the early tail-phase with the theoretical value of fully trapped $^{56}$Co deposition, which is given by:

$$L(t) = 9.92 \times 10^{41} \times \frac{M_{\text{Ni}}}{0.07M_\odot} \times \left(e^{-t/11.4d} - e^{-t/8.8d}\right)$$

Where $t$ is the time since explosion, $L(t)$ is the luminosity in ergs$^{-1}$ at that time, 8.8 days is the e-folding time of $^{56}$Ni and 11.14 days is the e-folding time of $^{56}$Co decay. It is also assumed that the deposited energy is instantaneously re-emitted and that no other energy source has any influence. To calculate the mass of $^{56}$Ni, the tail luminosity and the time at which the tail begins should be used in Equation 6.

A visible transition can be seen in Figure 8 into the tail of SN 2019hcc at 61 days past maximum, therefore we selected the tail luminosity as the magnitude at the point of transition. With this tail magnitude, according to the above approach, the mass of $^{56}$Ni is $0.035 \pm 0.008 M_\odot$. The uncertainty was calculated as 0.1 dex, as a measure of the distance to the adjacent points, as the exact location of the tail start is uncertain. This is only a lower limit due to likely incomplete trapping. Anderson et al. (2014b) performed this analysis on a large set of SNe II, and found a range of $^{56}$Ni masses from 0.007 to 0.079 $M_\odot$, with a mean value of 0.033 $M_\odot$ ($\sigma = 0.024$). A survey of literature values led to a mean mass $^{56}$Ni = 0.044 $M_\odot$ for a sample of 115 SNe II (Anderson 2019). Therefore we conclude that the value retrieved for SN 2019hcc is within the expected range for a SN II.

6 SPECTROSCOPY

Figure 9 shows the spectral evolution of SN 2019hcc, labelled with the phase with respect to maximum light (MJD 58636). The spectra have been flux-calibrated according to the broadband photometry. The last epoch was not calibrated according to the photometry as none was available. At +81 days, the SED no longer follows a blackbody assumption as the ejecta is now optically thin and the photospheric phase is over, however the blackbody fit to the the photosphere is a valid approximation for the earlier spectra. The light curve analysis from Section 5 suggests the end of the plateau/photospheric phase, $t_{\text{pt}}$, at approximately +66 days from explosion. Emission lines from the host galaxy can be seen, particularly from +53 days. The resolution of the spectra can be found in Appendix B, Table B.

The spectra were also corrected for redshift and de-reddened according to the Cardelli Extinction law using $A_V = 0.19$ mag and $R_V = 3.1$ (Cardelli et al. 1989). They have been offset for clarity on an arbitrary y-axis. The flux has been converted to log($F_\nu$) where $F_\nu = F_\lambda\lambda^2 /3 e 18$ to highlight the absorption features.

As can be seen, the first spectrum at +7 days after peak displays a ‘w’–shaped profile at the rest–wavelengths typical of O or II lines with absorption minima at approximately 4420 Å and 4220 Å, which originally motivated the classification as a SLSN I. However, these signatures disappear in subsequent spectra with the H$\alpha$ emission becoming the dominant spectral feature. Aside from the w–shape, the first spectrum is relatively featureless. A well developed H$\alpha$ profile can be seen from +19 days, as well as H$\beta$ and H$\gamma$, though less developed Balmer lines can also be seen at +7 days. Fe ii and He i lines can also be seen from the +7 days spectrum and become well-developed by +19 days. The typical core-collapse SN forbidden lines of [O i] at 6300, 6363 and [Ca ii] at 7291, 7323 are not seen despite SN 2019hcc appearing to reach the nebular phase, which roughly starts at 100–200 days (Fransson & Chevalier 1989). There could be a few possibilities for their absence. The first is that the nebular phase has not been reached. Alternatively, as the strength of [O i] increases with the ZAMS mass (e.g. Dessart & Hillier 2020), it would imply a ZAMS mass of the SN 2019hcc progenitor sufficiently low that the [O i] are not visible. Another possibility is that SN 2019hcc is too faint with respect to the host and the lines have not yet developed.

In SN 2014G, after ~80 days the emission feature of [Ca ii] at 7291, 7323 starts to become visible, approximately coincident with the sudden drop in the light curve (Terreran et al. 2016). SN 2013ej also shows [Ca ii] and [O i] forbidden lines from 109 days, when the SN entered the nebular phase (Bose et al. 2015), suggesting SN 2019hcc is unusual in this respect. However, Branch & Wheeler (2017) noted the spectra of some SN IIL (e.g. SN 1986E, SN 1990K) do not contain the standard emission lines of core-collapse supernovae, and the forbidden lines arising in the ejecta may be suppressed by high densities or obscured by the circumstellar medium (CSM) that produces the extended HydrogenÎ­Î° emission.

The flux of H$\alpha$ in the +178 days spectrum (excluding the narrow host contribution component) is ~5 times that of H$\beta$. For case B recombination in the temperature regime 2500 $\leq T(K) \leq 10000$ and electron density $10^6 \leq n_e \leq 10^8$, the H$\alpha$ line should be 3 times stronger than H$\beta$ (Osterbrock & Ferland 2006). However, the case B recombination is not observed in SNe II before a couple of years.
Kozma & Fransson (1998) suggested at 200 days past explosion in SN 1987A this ratio should have been around 5, based on the total calculated line flux and using a full Hydrogen atom with all \( n \)-states up to \( n = 20 \) included. The ratio of SN 2019hcc appears similar to SN 1987A and other SNe II at the onset of the nebular phase. Despite the \( \text{H} \alpha / \text{H} \beta \) ratio being higher than the case B recombination, it is still sufficiently low that we can conclude that any additional flux to \( \text{H} \alpha \) should be insignificant. Excess flux in \( \text{H} \alpha \) could be a clue that \( \text{H} \alpha \) is also collisionally excited, suggesting interaction (Branch et al. 1981). As the \( \text{H} \alpha \) profile evolves it appears to become asymmetrical, suggesting a multi-component fit in the late spectra. The simplest explanation for this is that a mostly spherical ejecta is interacting with a highly asymmetric, Hydrogen-rich CSM (Benetti et al. 2016). This is in contrast with the quick decay of the tail, suggesting that such asymmetry might be intrinsic of the ejecta or the result of other lines that are not resolved, for example 

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**Figure 9.** The spectra for SN 2019hcc and their phase with respect to maximum light (MJD 58636). The wavelength is in the rest frame. The spectra have been corrected according to the photometry (excluding the last epoch which had no photometry available), de-reddened and redshift-corrected. They have also been smoothed using a moving average - this recalculates each point as the average of those one either side, in this case for five iterations - (black) with the original overlaid (red). The flux has been converted to \( \log(\text{F}_\nu) \) to emphasize absorption features. The most prominent elements have been labelled - here ‘Metals’ refers to a combination of Ba \( \ni \), Sc \( \ni \) and Fe \( \ni \).

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**Figure 10.** SN 2019hcc at +29 days post peak is compared to moderately luminous Type II SN 2014G and SN 2013ej, and SLSN I iPTF16bad which displays \( \text{H} \alpha \) at late time (at +100 days post peak) in its spectra. SN 2019hcc at +53 days past peak is also compared to SN 1998S. The wavelength is in the rest frame. Text in red refers to Type II, while in blue to the only SLSN I.

6.1 Spectral Comparison

Comparison of SN 2019hcc with the moderately luminous SNe II (Inserra et al. 2013a) reported in Section 5 and Figure 6, together with SLSN I iPTF16bad, is shown in Figure 10. iPTF16bad at late times displays \( \text{H} \alpha \) emission due to the collision with a H-shell ejected approximately 30 years prior, thought to be due to pair instability pulsations (Yan et al. 2015, 2017), and merits comparison as it is a SLSN I displaying a \( \text{H} \) shaped profile at early times and \( \text{H} \alpha \) at late times. SN 2019hcc has a good match with some features, e.g. Balmer lines, however there are some discrepancies in the comparison, such as the lack of a P-Cygni profile for \( \text{H} \alpha \) in iPTF16bad. The Fe \( \ni \) lines at approximately 5000 Å are also not observable in the spectrum of the SLSN I. If the \( \text{H} \alpha \) in SN 2019hcc was a consequence of interaction similar to iPTF16bad, we would expect other signs of interaction. These could be undulations or...
a second peak in the light curve (e.g. Nicholl et al. 2016; Inserra et al. 2017), but the SN 2019hcc light curve appears to be that of a typical SN II (see Section 5). Additionally, the relatively earlier appearance of the Hα emission in SN 2019hcc would require a much closer H-shell than for iPTF16bad.

Figure 10 also displays a comparison to moderately luminous SNe II SN 2013ej, SN 2014G, and SN 1998S. SN 1998S did not have a spectrum available at the +29 days epoch, so is shown at the nearest later epoch, with SN 2019hcc at +53 days for comparison. The spectra do not significantly evolve in this time frame. There are strong similarities between spectral features at the epoch of comparison, with good matches of Hα and Fe II features. The comparison would strengthen that SN 2019hcc is a Type II.

Figure 11 shows a closer look at the Hα profiles for the previous spectra, and additionally SN 2018bsz, a SLSN I. In SLSNe I, carbon lines produced in the Hα region could be mistaken for Hydrogen, such as in the case of SN 2018bsz, which displays C II i.6580 line in the Hα region (Anderson et al. 2018a). SN 2018bsz does also show Hydrogen but it is not observed at the phase being considered here. However, if C II is present in a spectrum, we should observe it at &5723 and &5890 (Anderson et al. 2018a), lines which are not seen in SN 2019hcc, while Hβ can be seen at &4861. This strengthens the idea that is indeed Hα observed in SN 2019hcc as opposed to C II.

SN 2019hcc spectra show an emission redward of Hα at approximately 6720 Å visible at +29 days. Figure 11 shows that SN 2018bsz also contains the redward emission at approximately 6720 Å. Singh et al. (2019) identifies this as [S II] lines at 6717 Å and 6731 Å from the parent H II region.

### 6.2 Investigating Signs of Interaction in the Photospheric Spectra

A multi-component Hα profile which does not completely hide the absorption component hints to a degree of interaction. Here the narrow component would belong to the unshocked wind, whilst the medium component to the shocked wind/ejecta. Another sign of interaction between the ejecta and the CSM could be a high velocity (HV) component in the Balmer lines (e.g. Inserra et al. 2013a; Gutiérrez et al. 2017a). The normal velocity originates from the receding photosphere, whilst the high velocity is generated further out where the CSM interaction may excite the Hydrogen to cause a second, high-velocity absorption feature (e.g. Arcavi 2017). The size and shape of this feature could be related to the progenitor wind density (Chugai et al. 2007). A small absorption blueer than the Hα P-Cygni has been observed in several SNe II but its nature is not always linked to Hα (Gutiérrez et al. 2017a). Such a feature, named ‘Cachito’, has previously been attributed to HV features of Hydrogen, or Si II i.6533. These features were identified in Inserra et al. (2013a) for some moderately luminous SNe II. Gutiérrez et al. (2017a) also found the ‘Cachito’ feature is consistent with Si II at early phases, and with Hydrogen at later phases.

#### 6.2.1 High Velocity features

In the top panel of Figure 12, an absorption blue-ward of Hα can be seen in SN 2019hcc at +19 days and +29 days at around 6250 Å, however after this epoch it becomes less clear. An absorption feature can also be seen in SN 2013ej, and arguably SN 2014G, as seen in Figure 11. The presence of a potential HV Hβ additional to the Hα at a similar velocity would strengthen the latter’s status as a HV feature of Hydrogen (e.g. Chugai et al. 2007; Gutiérrez et al. 2017a; Singh et al. 2019). The lower panel on Figure 12 shows the Hβ profile for SN 2019hcc at the epochs where it is visible, and an absorption blueward of the P-Cygni could be identified. Gutiérrez et al. (2017a) found that 63% of their sample of SNe II with HV Hα in the plateau phase showed a HV Hβ at the same velocity. Gutiérrez et al. (2017a) also reported that if the absorption is produced by Si II its velocity should be similar to those presented by other metal lines, such as Fe II i.5169, a good estimator for the photospheric velocity (Hamuy et al. 2001).

The velocity of this possible Hα HV absorption feature in SN 2019hcc was measured at +19 days and +29 days, with respect to Hα and Si II at 6355 Å. The Fe II lines were also measured for comparison. Figure 13 displays the measured velocities in SN 2019hcc for various lines at different epochs in its evolution. The velocity was found by fitting a Gaussian to the absorption features and finding the minimum - after +29 days, this fitting was not successful, therefore there are only two points available. With reference to Figure 13 it can be seen that the measured Si II velocity is close to the Fe II velocity at both epochs, suggesting that it is near the photospheric velocity. This would lend support to the feature being more likely associated with Si II. For the HV component, it would be expected the velocity of the HV Hβ to match that of the HV Hα, and this is not what is found by our velocity analysis. Considering this infor-

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**Figure 11.** A comparison of the Hα profiles for a variety of moderately luminous SNe II and SLSNe I. The wavelength is in the rest frame. Text in red refers to Type II, while in blue to SLSNe I. The velocity is with respect to Hα.

**Figure 12.** The measured velocities in SN 2019hcc for various lines at different epochs in its evolution.
2.5 \log(F) + constant
+19 days
+29 days
+53 days
+81 days

Figure 12. Top panel: the H\(\alpha\) profile evolution of SN 2019hcc, the spectra have been smoothed using a moving average. The velocity is with respect to H\(\alpha\). All spectra show a small feature blue-ward of H\(\alpha\) after smoothing, which could be a HV component indicating early CSM-ejecta interaction. The red dashed line tracks the H\(\alpha\) absorption, and the blue dashed line the possible HV component. Bottom panel: the same as the above panel but with respect to H\(\beta\). The velocity is with respect to H\(\beta\).

Figure 13. The velocity comparisonsof different lines for SN 2019hcc, over three different epochs, alongside the velocities of SN 2014G for Fe II, H\(\alpha\) and H\(\beta\). Velocities of SN 1998S from Anupama et al. (2001) and Terreran et al. (2016), SN 2014G from Terreran et al. (2016). The average velocities are found from 122 Type II SNe (Gutiérrez et al. 2017a), the figure reproduced from Dastidar et al. (2021) and reference therein, shown with a 1-sigma error.

6.2.2 Photospheric H\(\alpha\) profile

Another sign of interaction in the spectra would be a multi-component H\(\alpha\) profile with additional components to a simple P-Cygni profile. To investigate the possible presence of multi-components, the profile of SN 2019hcc taken from its highest resolution spectrum at +19 days was decomposed by means of Gaussian profiles. In a non-perturbed SN ejecta, the expected components would be both an absorption and an emission from the P-Cygni, as well as emission from the host galaxy. Any additional component could therefore suggest an ongoing ejecta-CSM interaction.

In Figure 14 we display a composite Gaussian function. The velocities of 122 SNe II are included in the plot, and show the velocities measured for SN 2014G, SN 2019hcc and SN 1998S are roughly as expected for SNe II.
One of the most interesting features displayed by SN 2019hcc is its early ‘w’ shaped feature resembling that of SLSNe. Understanding its nature, composition and the possibility that it is not a trademark of SLSNe I will have important consequences during the Vera C. Rubin and the Legacy Survey for Space and Time (LSST) era. LSST will deliver hundreds of SLSNe (Inserra et al. 2021) and thousands of CC-SNe for which we might not have the luxury of multiple epoch spectroscopy.

Figure 15 shows the O ii features in the early spectrum for SN 2019hcc, together with the Type II SNe used for previous comparison, and the previous sample of SLSNe I. The approximate location of peaks and troughs of the SN 2019hcc O ii lines are marked by dashed vertical lines for comparison. iPTF16bad (Yan et al. 2017) was chosen due to the late Hα emission, and SN 2010kd (Kumar et al. 2020) for the carbon emission which resembles Hα. PTF12dam (Nicholl et al. 2013) was chosen for being a well-sampled SLSN I, and LSQ14mo (Chen et al. 2017b) for its similarity to SN 2019hcc with respect to the O ii feature at a similar epoch. SN 2014G, amongst the SNe II, appears to have the strongest resemblance to SN 2019hcc, showing a similar pattern in the wavelength region around 4000 Å. A point to note is that SN 2019hcc does not entirely match the O ii feature in the SLSN I - the redder absorption is blue-shifted in comparison.

The features usually associated with O ii are formed by many tens of overlapping lines (Anderson et al. 2018b; Gal-Yam 2019b), and can be contaminated by carbon and metal lines, and also by the presence of well-developed Balmer lines, all of which mean the features cannot be uniquely identified as O ii. Therefore, whilst SN 2019hcc, SN 2014G, and SN 1998S could be valid candidates to show O ii features as the Balmer lines are less prominent, SN 2013ej is less likely as it shows a strong Hα profile suggesting the spectrum is dominated by Hβ at λ4861 and Hγ at λ4340.

Gal-Yam (2019a) tackled the challenge of line identification with comparison of absorption lines to lists of transitions drawn from the National Institute of Standards and Technology (NIST) database. He found that O ii emission lines appear in the gaps between O ii absorption, which corresponds to the two peaks - see Figure 15 2nd and 4th dashed lines from the left. Anderson et al. (2018b) suggested that a change in the morphology of the spectrum in this wavelength region (between SNe) may be produced through differences in ejecta density profiles or caused by overlapping lines such as Fe ii.

Oxygen lines appear when Oxygen is ionised by sufficiently high temperatures, 12000-15000 K (e.g. Inserra 2019). However, the presence of O ii lines around 4000-4400 Å might be a consequence of non-thermal excitation (Mazzali et al. 2016). This requires a power source in the CO core of massive stars (Mazzali et al. 2016). A lack of O ii lines would be the product of rapid cooling or lack of non-thermal sources of excitation (Quimby et al. 2018).

A non-thermal excitation could be in the form of strong X-ray flux from a magnetar, such as the injection of X-rays from an interaction between the SN ejecta and a magnetar wind (Maeda et al. 2007). Vurm & Metzger (2021) modelled SLSNe powered by a relativistic wind from a central engine, such as a millisecond pulsar or magnetar, which injects a nebula of relativistic electron/positron pairs and radiation behind the expanding supernova ejecta shell. These quickly radiate their energy via synchrotron and inverse Compton (IC) processes in a broad spectrum spanning the X-ray/gamma-ray band, a portion of which heats the ejecta and powers the supernova emission. This process will be most efficient at early times after the explosion, when the column density through the ejecta is at its highest. Non-thermal excitation could also be due to high energy electrons produced by γ-rays from the radioactive decay of 56Ni (Li et al. 2012), however such a process would more likely be relevant.
at later times. It could also be produced by ejecta-CSM interaction (Nynmark et al. 2006), with a CSM rich in Oxygen producing the associated spectral features (Chatzopoulos & Wheeler 2012). No SLSN I to date has shown narrow lines in its spectra (Nicholl et al. 2014; Inserra 2019), and interaction models are yet to reproduce the light curve evolution of some SLSNe I (e.g. Chatzopoulos et al. 2013). Though supposed to be typical to SLSNe I (Branch & Wheeler 2017), O ii lines have already been seen in other SNe, such as SN Ibn OGLE-2012-SN-006 (Pastorello et al. 2015) and SN Ib SN 2008D (Soderberg et al. 2008). SN 2008D was a normal core-collapse SN with an associated X-Ray flash (e.g. Li 2008), whereas OGLE-2012-SN-006 was interpreted as a core-collapse event powered by ejecta-CSM interaction (Pastorello et al. 2015). The presence of O ii spectroscopic features here support the argument that ejecta-CSM interaction may be an important factor in maintaining the high levels of energy required to ionize Oxygen (Pastorello et al. 2015).

7.1 Spectral Modelling

Reproducing the ‘w’ shape of the first spectrum with spectral modelling could cast light on the conditions required to produce it. If the feature is reproduced by modelling Oxygen at a higher temperature than the spectra which display this feature, it would suggest non-thermal excitation is necessary to produce this feature.

We used TARDIS (Kerzendorf & Sim 2014), an open-source radiative transfer code for spectra modelling of SNe, to model SN 2019hcc’s first spectrum. The code uses Monte-Carlo methods to obtain a self-consistent description of the plasma state and compute a synthetic spectrum. TARDIS was originally designed for Type Ia SNe and recently improved to be used for Type II spectra (Vogl et al. 2019), although the time varying profile of H α remains difficult to reproduce. TARDIS assumes that the ejecta is in a symmetric and homologous expansion, and as such there is a direct correlation between time since explosion and the temperature at this time.

SN 2019hcc was modelled as having a uniform ejecta composition and the results are presented in Figure 16. Model spectra were created with various abundances and temperatures and then normalised for comparison with SN 2019hcc. The temperatures were chosen to be around 8100 K (near the measured temperature of SN 2019hcc) or around 14000 K (closer to the SLSNe I used for comparison, see Figure 7). Higher temperatures up to around 20000 K were also considered in order to investigate the effect of the temperature on the resulting spectra. The velocity was kept constant for all spectra, at 8000 km/s (start 6000 km/s, stop 8000 km/s), similar to the photospheric velocity measured by Fe ii (see Figure 13). Elements were investigated individually - with abundances of up to 100% for one element. Starting from the approximate epoch and luminosity of SN 2019hcc, the spectra at approximately 8100 K were modelled by adjusting the input parameters until matching the temperature to that measured from the +7 days spectrum for SN 2019hcc after Cardelli correction, as marked in the figure. The high temperature spectra around 15000 K were found by increasing the luminosity and decreasing the time since explosion in the model.

Modelling revealed that at the lower temperature of 8100 K, Carbon, Oxygen, and Helium are not sufficiently excited to show any lines, therefore they have been omitted from the figure. However, metal (Fe, Mg, Ti) and Balmer lines do show line profiles in this region which could have the potential to reproduce the absorption lines seen for SN 2019hcc. Hydrogen does not have largely

| SN name       | Type  | EW (blue/red) | FWHM (blue/red) |
|---------------|-------|---------------|-----------------|
| SN 2019hcc    | SN IIL | 1.11±0.05    | 1.06±0.03       |
| SN 2014G      | SN IIL | 0.77±0.03    | 1.03±0.05       |
| SN 1998S      | SN Ibn | 0.94±0.06    | 0.77±0.04       |
| SN 2010kd     | SLSN I | 1.39±0.07    | 1.24±0.02       |
| LSQ14mo       | SLSN I | 1.61±0.06    | 1.29±0.04       |

Table 3. Equivalent widths (EW) and full width at half maximum (FWHM) of the absorption of the blue line profile over the red of the ‘w’ feature.

Figure 15. SN 2019hcc +7 days post peak is compared to moderately luminous SNe II and SLSNe I. These spectra are displayed in terms of F(ν) to emphasise the absorption features, and the wavelength is in the rest frame. SN 2014G also appears to show a ‘w’ shaped profile at 4000-4400 Å. The dashed lines correspond to the peaks and troughs of the O ii line region in SN 2019hcc. Text in red represents Type II, text in blue SLSN.
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**Figure 16.** The output of the Tardis modelling - spectra with various abundances and temperature. The vertical dashed lines mark the absorption lines for the SN 2019hcc ‘w’ feature.

significant absorption in this region compared to these metals. Also shown in Figure 16 are elements at a higher temperature which is typical of SLSNe I at a similar phase to SN 2019hcc’s first spectrum (see Figure 7). These do not match well the overall spectrum of SN 2019hcc but it can be noted that Carbon, Oxygen and Nitrogen produce lines in the region of interest. The bottom model spectrum of Figure 16 shows that at approximately 19000 K a ‘w’ feature can be produced with a CNO composition (with an even split of abundances). Note that Nitrogen has a relatively small effect in comparison to Carbon and Oxygen in producing this shape. The ‘w’ feature for SN 2019hcc is slightly shifted compared to the SLSNe I used for previous comparison - such a shift is evident in the red absorption but not the blue. A possible explanation for SN 2019hcc ‘w’ profile could be a combination of metals at a lower temperature (8100 K) and a non-thermally excited CNO layer. Considering that the temperatures of LSQ14mo and SN 2010kd are around 13000 K (at this temperature CNO does not show a ‘w’ feature), this could confirm that these SLSNe I require non-thermal excitation to produce this feature.

The feature of SN 1998S looks different to SN 2019hcc - both lines of the ‘w’ feature have a different shape. The ‘w’ feature in SN 1998S is likely caused by Titanium and a combination of other metals like Barium (Faran et al. 2014), which is also seen at redder wavelengths in SN 1998S but not in SN 2019hcc. Titanium does not look responsible for SN 2014G or SN 2019hcc as the ratios and shapes of the two profiles are different. The contribution from the combination of metals including Iron can be seen clearly in SN 2019hcc at 5169 Å, however Iron lines cannot account for the strong absorption in the ‘w’ feature region. Reproducing the strength of lines would appear to require CNO abundances at higher temperatures - for example Oxygen and Carbon at approximately 14000 K could account for the broader red wing of SN 2019hcc. A combination of CNO at higher temperatures than SN 2019hcc spectrum (i.e. 8100K) and metals at 8100K could be causing the final feature. However, with the tested models it seems impossible to completely reproduce the ‘w’ feature. Nevertheless, it appears models at T > 14000 K are required to reproduce the strength of the absorption, suggesting a non-thermal excitation responsible for the CNO elements SN 2019hcc at +7 days.

Equivalent width (EW) ratios are measured in order to provide a more quantitative analysis of the feature. These are reported in Table 3 in the form of the EW of the blue line over the red one, as well as the same ratio for full width at half maximum (FWHM). Of the SNe II, only SN 2019hcc has an EW over 1. The SLSNe I in this table also have a ratio over 1 and are larger with respect to that of SN 2019hcc. In both cases the SLSNe I have a slightly higher FWHM than the SNe II although this is not statistically conclusive due to the small size of the sample. These ratios cannot offer anything conclusive as it suggests all these ‘w’ features are of a slightly different nature, and could possibly be affected by temperatures, abundances, non-thermal excitation, or the presence of other lines such as metal lines. Possibly SN 2014G could also be non-thermally excited, or have different metal contributions, though its nature looks different to the other SNe as it is the only spectrum with a significantly stronger red line than blue.

In summary, at temperatures of approximately 19000 K CNO could reproduce the ‘w’ feature. Some absorption in this region at a temperature of 8100 K could be caused by metal lines e.g. Titanium, however this cannot entirely account for the ‘w’ feature in SN 2019hcc spectrum. Metals would also produce stronger lines at bluer wavelengths (3500-4000 Å) which are not seen in SN 2019hcc, though these could be obscured by yet more lines in this region. For thermally exciting CNO much higher temperatures are needed than that observed for SN 2019hcc, therefore non-thermal excitation may be required to produce such features in SN 2019hcc. This appears to also be the case for LSQ14mo and SN2010kd, which show the feature despite LSQ14mo being almost 6000 K short of the required excitation temperature.

He i can also be non-thermally excited, however this excitation usually comes from CSM interaction at the outer boundary of the ejecta (e.g. Chevalier & Fransson 1994), whereas for the non-thermal excitation of O ii in this scenario the exciting X-ray photons would originate from the central engine. The ejecta Helium region would be further away than the Oxygen region for these central high-energy photons which, in our proposed scenario, would explain the absence of He i in the first spectrum of SN 2019hcc. Additionally, though the abundance of Oxygen in the progenitor is relatively low compared to other elements such as Hydrogen, the first spectrum is relatively featureless so O ii is not competing with other lines in this region.

Hence, the next question to address is what could cause the non-thermal excitation of such CNO lines.
7.2 Ejecta-CSM interaction scenario
The presence of O η lines could be the consequence of ejecta-CSM interaction (e.g. Pastorello et al. 2015). Mazzali et al. (2016) suggested that X-rays would be required for the non-thermal excitation of O η lines, and these X-rays could originate from interaction (Nymark et al. 2006). However, Chevalier & Fransson (1994) suggested that in ejecta-CSM interaction with a SN density profile consistent with that of an RSG progenitor, as with the majority of Type II, the photons produced would be primarily in the UV-range, thus not providing sufficient non-thermal excitation to ionise the Oxygen.

There are no distinctive narrow emission lines in the spectrum of SN 2019hcc, nor is there any unusual behaviour in the light curve such as multiple peaks or undulations which would suggest collision with a shell (e.g. Nicholl et al. 2016; Inserra et al. 2017). A possible HV component of Hα blue-ward of the main emission could be indicative of early weak/moderate CSM-ejecta interaction - as this interaction may excite the Hydrogen to cause a second, high-velocity absorption feature (e.g. Arcavi 2017, []). However, our results on the HV Hα analysis reported in Section 6.2.1 suggest that the presence of a HV Hα is unlikely with the absorption blue-ward than Hα plausibly associated with Si η. The overall Hα profile was also analysed and decomposed in multiple components investigating the nature of the profile. However, it was found that no additional components are required to reproduce the shape aside from the expected ejecta P-Cygni and the narrow Hα line from the host galaxy. Therefore, CSM-ejecta interaction is not a viable source for generating high-energy photons capable of non-thermally excited the O η lines in SN 2019hcc.

7.3 Magnetar scenario
A magnetar could produce the non-thermal excitation required to ionize Oxygen and produce the O η features (e.g. Mazzali et al. 2016). Dessart et al. (2012) suggested the magnetar’s extra energy heats material and thermally excites the gas. Alternatively, Gilkis et al. (2016) and Soker & Gilkis (2017) suggested that magnetar-driven SLSNe are powered not by the neutrino-driven mechanism but a jet feedback mechanism from jets launched at magnetar birth. These high energy jets could potentially provide the energy to drive O η excitation at early times, and have been used to link magnetars to Gamma Rays Bursts (GRBs) (Wheeler et al. 2000). The generation of a non-relativistic jet during the early supernova phase is a consequence in both the core-collapse and magnetar models of GRBs (Burrows et al. 2007).

Kasen & Bildsten (2010) suggested that a magnetar birth is likely to happen in a few percent of all core-collapse supernovae, and may naturally explain some of the brightest events seen. Orellana et al. (2018) found that magnetar-powered models can actually generate a diversity of Hydrogen-rich SNe, both ordinary and brighter ones. Through their modelling, it was found that the observational appearance of SNe II powered by magnetars can be extremely varied and can also mimic those of normal SNe IIP. Magnetars are thought to form by fast rotation in the collapsing Iron core (Duncan & Thompson 1992). It is suggested that magnetars are preferentially formed in the most massive stars collapsing to a neutron star - with a progenitor mass in excess of 40M⊙ (Davies et al. 2009). However, it has also been suggested that magnetars do not require massive progenitors to form - alternatives could be a ‘fossil-field’ model, where a seed B-field is inherited from the natal molecular cloud (Davies et al. 2009) or an interacting binary system which causes spin-up in the collapsing CO-core (Cantiello et al. 2007).

Chen et al. (2017a) found an apparent correlation between magnetar spin-down period and host metallicity from a sample of 19 SLSNe I, indicating that faster-rotating magnetars reside in more metal-poor environments. Such a correlation could be a consequence of several factors - Martayan et al. (2007) found that massive stars rotate more rapidly at lower metallicity (0.2 Z⊙) than solar, whilst Mokiem et al. (2007) found in low metallicity environments mass loss of rotating stars is reduced. However, the spin periods of low metallicity stars and neutron stars would also very likely be affected by other parameters. Generally, the greater the spin period, the greater the peak luminosity (Kasen & Bildsten 2010; Inserra et al. 2013b), therefore a high metallicity host environment could be correlated with low luminosity explosions powered or affected by a magnetar.

From the equations in Kasen & Bildsten (2010), a grid of B14 (B/10^{14} G) and Pms (the spin period in ms) of a magnetar as a function of the peak luminosity and rise time was produced, using the code presented in Inserra et al. (2013b). Multiple grids were created by varying the ejecta mass in the model, in order to investigate its effect. Figure 17 shows an ejecta mass of 2 M⊙ vs. 5 M⊙. These ejecta masses were chosen based on the bolometric light curve fitting of SN 2019hcc (using the code of Inserra et al. 2013b) and that of SN 2014G which is one of the other potential Type II showing the ‘w’-shaped feature. We retrieved an ejecta mass of approx. 2.3 M⊙ and 5.0 M⊙, respectively. The fitting was focused on matching the rise time and peak magnitude rather than attempting to accurately reproduce the entire shape of the light curve including the tail, as this is also affected by other factors such as 56Ni or CSM interaction. The range of values in the grid are based on the fact that the neutron stars cannot spin faster than 1 ms without breaking up and that spin periods <30 ms can substantially modify the thermal evolution of the supernova (Kasen & Bildsten 2010), while B values are those retrieved from galactic magnetars ≈ 10^{14} - 10^{15} G (Woods & Thompson 2006). This figure shows that increasing the ejecta mass, but preserving B14 and Pms, would result in a longer rise time with the luminosity not as significantly affected. SN 2019hcc’s location in this parameter space (see Figure 17) shows that a lower luminosity supernova (i.e. not a SLSN) could be produced by a high magnetic field and a relatively lower spin. The blue dashed line represents the core-collapse limit for peak luminosity vs. rise time (Inserra 2019). Sukhbold & Thompson (2017) also presented a proof-of-concept model of a magnetar mechanism producing Type IIP light curve properties for a range of initial spin periods and equivalent dipole magnetic field strengths, and found for a SNe of peak bolometric luminosity of ~24.5, approximately that of SN 2019hcc, one would expect a Pms of 2m and a B14 of 100 - this agrees very well with the 5 M⊙ model in Figure 17.

This modelling suggests it is possible to have a magnetar formed as a remnant without injecting further substantial energy to the supernova event leading to superluminous brightness. This could provide sufficient non-thermal contribution to excite the O η lines which appear in the early spectra. The sub-solar metallicity found in Section 2 would not provide support for the tentative hypothesis of a correlation between host environment metallicity and magnetar luminosity, as the metallicity is similar to that of the typical low metallicity environments of SLSNe I, whilst the luminosity is typically lower than that of SLSNe I.
8 CONCLUSIONS

The first spectrum of SN 2019hcc appears relatively featureless aside from a ‘w’ feature around 4000 Å, characteristic of O n lines typical of SLSNe I. The redder absorption appears to be relatively blue-shifted with respect to SLSNe I. The spectra show a clear Hα profile from +19 days, as well as spectral similarity to various literature SNe II, and the bolometric light curve evolution is that of a SNe II. The host metallicity was sub-solar, a value lower than the typical Type II SNe (Gutiérrez et al. 2018). The temperature and colour evolution were typical of a Type II.

Such a ‘w’-shaped feature (usually and historically) attributed to O n has never been identified and analysed in SNe II as such and only recognised in SN 2014G thanks to the analysis reported in this paper. Modelling of this ‘w’ feature using TARDIS (Kerzendorf & Sim 2014) suggested it could be produced by the excitation of CNO at a temperature of 19000 K, which is more than twice that measured from the spectrum, suggesting these lines would therefore be non-thermally excited. Another result of the modelling was that absorptions at these wavelengths could also be the result of metal lines at 8100 K, a temperature in agreement with that measured. In SLSNe I these lines have been suggested as excited by X-rays produced by a magnetar, or alternatively CSM-ejecta interaction. As there is no sign of any interaction both in the light curve and spectra, aside from a tentative HV component, and potential interaction at late epochs, the CSM-ejecta interaction at early time is disfavoured. We built a model grid, following the work of Kasen & Bildsten (2010) and using the code by Inserra et al. (2013b), and found that a magnetar could be formed as a remnant in a Type II. This would require that the magnetar does not provide enough additional energy to the supernova event to power up the light curve to superluminous luminosities. The magnetar remnant could therefore non-thermally excite the Oxygen whilst not having a significant contribution to the light curve evolution. Therefore, combining such results with those of the spectral modelling, we conclude that the ‘w’ feature seen in SN 2019hcc’s first spectrum could be due to a combination of non-thermally excited CNO and thermally excited metal lines.

The object here presented could then bridge the gap between SLSNe I and normal luminosity core collapse supernovae, as well as reveal more about magnetar formation requirements and mechanisms. Our analysis also shows that a magnetar is a viable remnant of a Type II supernova explosion, the effects on which could be observed in the form of an early ‘w’-shaped profile around 4000–4400 Å. This would suggest that such lines are not exclusive to SLSNe I and cannot be used as a sole feature to classify those extreme transients.

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This research made use of Photutils, an Astropy package for detection and photometry of astronomical sources (Bradley et al. 2020). Based on data products from observations made with ESO Telescopes at the La Silla or Paranal Observatories under ESO programme ID 179.A-2010.

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DATA AVAILABILITY

The data underlying this article are available in the article and in its online supplementary material. The photometry code is available at the following GitHub account https://github.com/eparrag1/Photometry.

REFERENCES

Anderson J. P. 2019, A&A, 628, A7
Anderson J. P., et al., 2014a, MNRAS, 441, 671
Anderson J. P., et al., 2014b, ApJ, 786, 67
Anderson J. P., et al., 2016, A&A, 589, A110
Anderson J. P., et al., 2018b, A&A, 620, A67
Anderson J. P., et al., 2018a, A&A, 620, A67
Andrews J. E., et al., 2019, ApJ, 885, 43
Angus C. R., et al., 2019, MNRAS, 487, 2215
Anupama G. C., Sivarani T., Pandey G., 2001, A&A, 367, 506
Arcavi I., 2017, Hydrogen-Rich Core-Collapse Supernovae. p. 239, doi:10.1098/rspt-3-319-21846-5.39
Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, ARA&A, 47, 481
Astropy Collaboration et al., 2013, A&A, 558, A33
Astropy Collaboration et al., 2018, MNRAS, 483, 350
Barbon R., Ciatti F., Rosino L., 1979, A&A, 72, 287
Bazin G., et al., 2009, A&A, 499, 653

Benetti S., et al., 2016, MNRAS, 456, 3296
Bianco F. B., Modjaz M., Oh S. M., Fierroz D., Liu Y. Q., Kewley L., Graur O., 2016, Astronomy and Computing, 16, 54
Bose S., et al., 2015, ApJ, 806, 160
Bradley L., et al., 2020, astrophyphotutils: 1.0.0, doi:10.5281/zenodo.4044744, https://doi.org/10.5281/zenodo.4044744
Branch D., Wheeler J. C., 2017, Supernova Explosions, doi:10.1007/978-3-662-55054-0.
Branch D., Falk S. W., McCall M. L., Rybski P., Uomoto A. K., Wills B. J., 1981, ApJ, 244, 780
Brown T. M., et al., 2011, in American Astronomical Society Meeting Abstracts #218, p. 132.02
Burrows A., Dessart L., Livne E., Ott C. D., Murphy J., 2007, ApJ, 664, 416
Buzzoni B., et al., 1984, The Messenger, 38, 9
Caffau E., Ludwig H. G., Steffen M., Freytag B., Bonifacio P., 2011, Sol. Phys., 268, 255
Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682
Cantiello M., Yoon S. C., Langer N., Livio M., 2007, A&A, 465, L29
Cardelli J. A., Clayton G. C., Mathis J. S., 1989, ApJ, 345, 245
Chabrier G., 2003, PASP, 115, 763
Chambers K. C., et al., 2016, arXiv e-prints, p. arXiv:1612.05560
Chatzopoulos E., Wheeler J. C., 2012, ApJ, 760, 154
Chatzopoulos E., et al., 2011, ApJ, 729, 143
Chatzopoulos E., Wheeler J. C., Vinko J., Horvath Z. L., Nagy A., 2013, ApJ, 773, 76
Chen T.-W., Smartt S. J., Yates R. M., Nicholl M., Krühler T., Schady P., Dennefeld M., Inserra C., 2017a, MNRAS, 470, 3566
Chen T. W., et al., 2017b, A&A, 602, A9
Chen T.-W., et al., 2017c, ApJ, 849, L4
Chen T. W., et al., 2018, ApJ, 867, L31
Chevalier R. A., Fransson C., 1994, ApJ, 420, 268
Chugai N. N., Chevalier R. A., Urotbin V. P., 2007, ApJ, 662, 1136
Clemens J. C., Crain J. A., Anderson R., 2004, in Moorwood A. F. M., Iye M., et al., Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 5492, Ground-based Instrumentation for Astronomy. pp 331-340, doi:10.1117/12.550069
Conroy C., Gunn J. E., White M., 2009, ApJ, 699, 486
Cutri R. M., et al., 2013, Explanatory Supplement to the AllWISE Data Release Products, Explanatory Supplement to the AllWISE Data Release Products
Dastidar R., et al., 2021, arXiv e-prints, p. arXiv:2103.09166
Davies B., Figer D. F., Kudritzki R.-P., Trombely C., Kouveliotou C., Wachter S., 2009, ApJ, 707, 844
Davis S., et al., 2019, ApJ, 887, 4
Delgado A., Harrison D., Hodgkin S. L., Leeuwen M. V., Rixon G., Yoldas A., 2019, Transient Name Server Discovery Report, 2019-957, 1
Dessart L., Hillier D. J., 2020, A&A, 642, A33
Dessart L., Hillier D. J., Waldman R., Livne E., Blondin S., 2012, MNRAS, 426, L76
Dessart L., et al., 2014, MNRAS, 440, 1856
Duncan R. C., Thompson C., 1992, ApJ, 392, L9
Faran T., et al., 2014, MNRAS, 445, 554
Fassia A., et al., 2000, MNRAS, 318, 1093
Fassia A., et al., 2001, MNRAS, 325, 907
Filippenko A. V., 1988, AJ, 96, 1941
Filippenko A. V., Matheson T., Ho L. C., 1993, ApJ, 415, L103
Foreman-Mackey D., Sick J., Johnson B., 2014, Python-Fsps: Python Bindings To Fsps (V0.1.1), doi:10.5281/zenodo.12157
Fransson C., Chevalier R. A., 1989, ApJ, 343, 323
Frohmaier C., et al., 2021, MNRAS, 500, 5142
Gaia Collaboration et al., 2016, A&A, 595, A1
Gal-Yam A., 2012, Science, 337, 927
Gal-Yam A., 2019a, ApJ, 882, 102
Gal-Yam A., 2019b, ApJ, 882, 102
Galbany L., et al., 2016, AJ, 151, 33

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APPENDIX A: PHOTOMETRY CODE

The pipeline of the photometry code which was used to produce the light curve from the LCO and LT photometry is here described. The total flux is calculated from the pre-reduced data (bias, flat) by the Iteratively Subtracted PSF Photometry from PhotUtils (Bradley et al. 2020) - the Point Spread Function (PSF) is taken to be a Gaussian as this is found to produce a good fit and is an acceptable approximation. The PSF fitting is confined to a 50-pixel-width square around the central SN coordinates. With an average FWHM below 10 pixels, this size is assumed to safely include all the associated flux. Alternatives to the Gaussian PSF were also considered - such as an ePSF (effective PSF) constructed from reference stars, as well as aperture photometry. The Gaussian PSF was found to be the method where the scatter between adjacent points was minimised. The magnitude is calculated as below (where \( Z_P \) is the zero-point):

\[
\text{Mag} = Z_P - 2.5 \log(\text{Counts}/\text{Exposure}) \quad (A1)
\]

Valid PSF fits are filtered by setting a threshold of 3\( \sigma \) and requiring no close stars which would suggest an unreliable fit. These constraints are optimised through variation and inspection of residuals. The uncertainty is obtained by combining in quadrature the uncertainty in the fit given by the PSF and the uncertainty in the image. The uncertainty in the image is given by:

\[
\text{Error} = \sqrt{\frac{\text{Counts} + \text{Sky}}{\text{Gain}}} + N_{\text{pix}} \times (\text{Readnoise} + \text{Sky}) \quad (A2)
\]

Where Sky is the sky counts over an area the size of the SN, calculated by finding the sigma-clipped mean in the environment surrounding the SN and multiplying by the number of pixels, \( N_{\text{pix}} \) in the above. Gain and Readnoise come from the header of each fits file. The equation below shows how this uncertainty in counts is converted to magnitude.

\[
\text{Error} = 2.5 \frac{\ln(10)}{\ln(1)} \sqrt{\frac{\text{Error(Count)}}{\text{Count(Total)}}} \quad (A3)
\]

This uncertainty is then combined in quadrature with the extinction and the colour uncertainties, which are taken as 0.03 and 0.011 respectively. These values are taken from Valentini et al. (2016) for one telescope and is carried over as an approximation for the others. Such an assumption might appear unreasonable, but it is indeed acceptable as these terms are a small contribution to the uncertainty budget, and these values are roughly representative (ranges are 0.02-0.09 for extinction, and 0.011-0.036 for the colour). Cosmic ray artifacts are removed using lacosmic (van Dokkum et al. 2012).

The \( Z_P \) are found by fitting the PSF to reference stars and reversing the magnitude calculation. This is achieved in the code by accessing the Pan-STARRS (Chambers et al. 2016) catalogue using Vizier (Ochsenbein et al. 2000) and selecting all available stars in a 5 arcmin radius around the SN coordinates (see Figure 1). To improve the quality of the PSF fit, multiple images taken on the same night (when available) were (and can be in a general workflow) aligned and stacked using the SNooPy (SuperNova PhotometrY) package \(^6\). Template subtraction for this code is as follows: host images (which could be combined using SNooPy, excluding poorer images) and the flux of both the host image and each SN image are found using the PSF fitting method described above. Equation A1 is used to convert the host flux to what it would be if it had the same \( Z_P \) and exposure of the SN image, then the fluxes are subtracted, and the uncertainties propagated.

Figure A1 displays the PSF fitting for a few example images. The first column displays the image data, whilst the second and third show the residual and PSF fit, respectively. As can be seen, the Gaussian PSF fit can produce relatively clean residual images, and the code recognises multiple sources.

APPENDIX B: DATA

This paper has been typeset from a \TeX/L\LaTeX file prepared by the author.

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\(^6\) SNooPy is a package for SN photometry using PSF fitting and/or template subtraction developed by E. Cappellaro. A package description can be found at http://sngroup.oapd.inaf.it/ecsnoopy.html.
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Table B1. Spectroscopy Data as displayed in Figure 9. The resolutions of the spectra are found from measuring the skylines using IRAF, excluding the SOAR spectrum resolution which was taken from http://www.ctio.noao.edu/soar/content/goodman-spectrograph-gratings.

| Epoch | Phase from maximum (days) | Instrument | Grisms | Range (Å) | Resolution (Å) |
|-------|--------------------------|------------|--------|-----------|----------------|
| 58643 | 7                        | EFOSC2     | Gr 11  | 3380-7520 | 13.7           |
| 58655 | 19                       | SOAR       | 400mm  | 3200-8500 | 6.0            |
| 58665 | 29                       | EFOSC2     | Gr 13  | 3685-9315 | 25.7           |
| 58689 | 53                       | EFOSC2     | Gr 13  | 3685-9315 | 17.4           |
| 58717 | 81                       | EFOSC2     | Gr 13  | 3685-9315 | 17.1           |
| 58814 | 178                      | EFOSC2     | Gr 13  | 3685-9315 | 17.3           |
| 59149 | Host Spectrum            | EFOSC2     | Gr 13  | 3685-9315 | 16.0           |

Table B2. The measured apparent magnitudes of the host galaxy for SN 2019hcc from LT and LCO images.

| Filter | Apparent Magnitude         |
|--------|----------------------------|
| B      | 20.70 (0.18)               |
| V      | 20.05 (0.23)               |
| g      | 20.68 (0.24)               |
| r      | 20.67 (0.28)               |
| i      | 20.37 (0.29)               |
| z      | 20.56 (0.18)               |

Table B3. NIR GROND magnitudes as seen in Figure 5

| MJD | Phase from maximum (days) | J     | H     | K     |
|-----|----------------------------|-------|-------|-------|
| 58644 | 8                         | 18.08 (0.17) | 17.87 (0.25) | 17.64 (0.50) |
| 58648 | 12                        | 18.08 (0.17) | 17.90 (0.25) | 17.80 (0.03) |
| 58661 | 25                        | 18.23 (0.18) | 17.64 (0.23) | 17.12 (0.28) |
| 58667 | 31                        | 18.26 (0.18) | 17.91 (0.23) | 17.56 (0.32) |
| 58674 | 38                        | 18.33 (0.17) | 18.00 (0.23) | -        |
## Table B4. Photometry data shown in Figure 5.

| MJD   | Phase from maximum (days) | B   | V   | g   | r   | i   | z   | Telescope |
|-------|---------------------------|-----|-----|-----|-----|-----|-----|-----------|
| 58644 | 8                      | -   | -   | 18.84 (0.11) | 18.73 (0.09) | 18.78 (0.11) | 18.69 (0.12) | GROND     |
| 58647 | 11                     | -   | -   | 19.19 (0.31) | 19.01 (0.22) | 19.51 (0.26) | 19.22 (0.26) | LT        |
| 58647 | 11                     | -   | -   | -   | 19.37 (0.29) | -   | -   | LCO       |
| 58648 | 12                     | -   | -   | 19.15 (0.03) | 18.87 (0.10) | 18.90 (0.12) | 18.75 (0.12) | GROND     |
| 58651 | 15                     | -   | -   | -   | -   | 19.67 (0.44) | -   | LCO       |
| 58653 | 17                     | -   | -   | -   | -   | 19.48 (0.40) | 19.23 (0.38) | LCO       |
| 58653 | 17                     | -   | -   | -   | -   | 19.06 (0.42) | -   | LT        |
| 58656 | 20                     | -   | -   | 19.50 (0.40) | 19.23 (0.38) | 19.46 (0.32) | 19.59 (0.45) | LT        |
| 58657 | 21                     | 20.30 (0.30) | 19.46 (0.36) | 19.65 (0.36) | 19.44 (0.35) | 19.78 (0.36) | -   | LCO       |
| 58659 | 23                     | 19.48 (0.29) | 19.58 (0.37) | 19.75 (0.37) | 19.43 (0.29) | 19.80 (0.36) | -   | LCO       |
| 58660 | 24                     | 20.60 (0.31) | 19.49 (0.34) | 19.96 (0.39) | 19.47 (0.27) | 19.77 (0.33) | -   | LCO       |
| 58661 | 25                     | -   | -   | 19.72 (0.03) | 19.16 (0.17) | 19.22 (0.17) | 19.14 (0.17) | GROND     |
| 58662 | 26                     | 20.52 (0.25) | 19.62 (0.36) | 19.86 (0.37) | 19.47 (0.29) | -   | -   | LCO       |
| 58662 | 26                     | -   | -   | 20.04 (0.42) | 19.46 (0.25) | 19.84 (0.26) | 19.63 (0.29) | LT        |
| 58664 | 28                     | 20.86 (0.34) | 19.69 (0.38) | 20.17 (0.43) | 19.72 (0.31) | -   | -   | LCO       |
| 58665 | 29                     | 20.70 (0.29) | 19.74 (0.39) | 20.03 (0.40) | 19.51 (0.29) | 19.88 (0.36) | -   | LCO       |
| 58667 | 31                     | -   | -   | 19.83 (0.03) | 19.34 (0.03) | 19.28 (0.14) | 19.23 (0.14) | GROND     |
| 58670 | 34                     | -   | -   | 20.46 (0.51) | 19.63 (0.27) | 19.79 (0.26) | 19.67 (0.32) | LT        |
| 58673 | 37                     | 21.15 (0.38) | 19.94 (0.42) | 20.37 (0.47) | 19.68 (0.31) | -   | -   | LCO       |
| 58674 | 38                     | -   | -   | 20.08 (0.03) | 19.44 (0.03) | 19.42 (0.14) | 19.35 (0.14) | GROND     |
| 58675 | 39                     | -   | -   | -   | 19.67 (0.31) | 19.86 (0.30) | 19.89 (0.37) | LT        |
| 58680 | 44                     | 21.48 (0.73) | 20.43 (0.66) | 20.95 (0.71) | 19.90 (0.45) | 19.97 (0.46) | -   | LCO       |
| 58684 | 48                     | -   | 20.56 (0.62) | 21.38 (0.81) | 20.05 (0.41) | 20.46 (0.50) | -   | LCO       |
| 58685 | 49                     | -   | -   | -   | 20.10 (0.46) | 20.62 (0.45) | 20.42 (0.51) | LT        |
| 58690 | 54                     | 22.31 (0.59) | 20.93 (0.66) | 22.13 (1.06) | -   | -   | -   | LCO       |
| 58694 | 58                     | -   | -   | 21.94 (1.00) | 20.95 (0.49) | 22.04 (0.71) | 21.29 (0.65) | LT        |
| 58697 | 61                     | 22.51 (0.60) | -   | 22.91 (1.50) | 21.37 (0.63) | 21.55 (0.73) | -   | LCO       |
| 58704 | 68                     | -   | -   | -   | 21.57 (0.68) | -   | 22.41 (1.09) | LT        |
| 58713 | 77                     | -   | -   | -   | 21.28 (0.69) | 21.40 (0.71) | -   | LT        |
| 58716 | 80                     | -   | -   | -   | 20.91 (0.55) | -   | -   | LCO       |
| 58725 | 89                     | 23.86 (1.15) | 22.07 (1.09) | -   | 21.52 (0.67) | 22.59 (1.16) | -   | LCO       |
| 58732 | 96                     | -   | -   | -   | -   | 22.71 (1.28) | -   | LCO       |
| 58767 | 131                    | -   | -   | -   | -   | 21.76 (0.80) | -   | LT        |
| 58772 | 136                    | -   | -   | 23.03 (1.74) | -   | -   | 22.61 (1.17) | LT        |

## Table B5. Swift AB magnitudes as seen in Figure 5.

| MJD   | Phase from maximum (days) | UVM2 | UVW1 | UVW2 | u   |
|-------|---------------------------|------|------|------|-----|
| 58645 | 9                         | 20.72 (0.14) | 20.21 (0.24) | 20.71 (0.20) | 19.68 (0.21) |
| 58651 | 15                        | 20.78 (0.31) | >20.39 | 20.72 (0.31) | >19.72 |
| 58658 | 22                        | 20.80 (0.15) | 20.50 (0.20) | 21.17 (0.21) | 20.54 (0.32) |
| 58660 | 24                        | 21.30 (0.23) | 20.67 (0.24) | 21.72 (0.32) | >20.58 |
| 58663 | 27                        | 20.76 (0.16) | 20.79 (0.24) | 20.95 (0.19) | >20.70 |
| 58666 | 30                        | 21.32 (0.21) | 20.67 (0.22) | 21.14 (0.21) | >20.71 |
Table B6. ATLAS AB magnitudes as reported in Figure 5.

| MJD  | Phase from maximum (days) | cyan | orange |
|------|---------------------------|------|--------|
| 58609| -27                       | >20.61 | - |
| 58609| -27                       | >20.69 | - |
| 58609| -27                       | >20.43 | - |
| 58609| -27                       | >19.91 | - |
| 58611| -25                       | -     | >20.15 |
| 58611| -25                       | -     | >20.16 |
| 58611| -25                       | -     | >19.81 |
| 58617| -19                       | -     | >20.06 |
| 58617| -19                       | -     | >20.12 |
| 58617| -19                       | -     | >20.20 |
| 58617| -19                       | -     | >20.44 |
| 58619| -17                       | -     | >19.71 |
| 58619| -17                       | -     | >19.65 |
| 58619| -17                       | -     | >19.74 |
| 58620| -16                       | -     | >19.01 |
| 58620| -16                       | -     | >19.00 |
| 58620| -16                       | -     | >19.13 |
| 58620| -16                       | -     | >19.22 |
| 58620| -16                       | -     | >19.40 |
| 58621| -15                       | -     | >19.41 |
| 58621| -15                       | -     | >19.51 |
| 58621| -15                       | -     | >19.56 |
| 58621| -15                       | -     | >19.60 |
| 58623| -13                       | -     | >17.86 |
| 58623| -13                       | -     | >19.14 |
| 58623| -13                       | -     | >18.98 |
| 58623| -13                       | -     | >19.20 |
| 58631| -5                        | -     | 19.25 (0.22) |
| 58631| -5                        | -     | 18.97 (0.24) |
| 58631| -5                        | -     | 18.55 (0.21) |
| 58633| -3                        | 18.73 (0.11) | - |
| 58633| -3                        | 18.83 (0.11) | - |
| 58633| -3                        | 18.73 (0.11) | - |
| 58633| -3                        | 18.70 (0.16) | - |
| 58637| 1                         | 18.57 (0.09) | - |
| 58637| 1                         | 18.84 (0.10) | - |
| 58637| 1                         | 18.55 (0.08) | - |
| 58637| 1                         | 18.54 (0.09) | - |
| 58643| 7                         | 18.90 (0.15) |
| 58643| 7                         | 18.87 (0.15) |
| 58643| 7                         | 19.11 (0.20) |
| 58643| 7                         | 18.96 (0.17) |
| 58645| 9                         | 18.80 (0.13) |
| 58645| 9                         | 18.69 (0.11) |
| 58645| 9                         | 19.14 (0.18) |
| 58645| 9                         | 18.79 (0.17) |
| 58647| 11                        | 19.16 (0.21) |
| 58647| 11                        | 19.16 (0.21) |
| 58649| 13                        | 18.90 (0.31) |
| 58649| 13                        | 18.81 (0.26) |
| 58659| 23                        | 19.01 (0.21) |
| 58659| 23                        | 19.54 (0.33) |
| 58659| 23                        | 18.96 (0.19) |
| 58659| 23                        | 19.33 (0.30) |
| 58659| 23                        | 19.05 (0.23) |
| 58659| 23                        | 19.53 (0.35) |
| 58665| 29                        | 20.07 (0.29) |
| 58665| 29                        | 19.91 (0.26) |
| 58665| 29                        | 19.57 (0.21) |
| MID  | Phase from maximum (days) | cyan   | orange          |
|------|--------------------------|--------|-----------------|
| 58667| 31                       | -      | 19.62 (0.27)    |
| 58667| 31                       | -      | 19.70 (0.27)    |
| 58667| 31                       | -      | 19.17 (0.16)    |
| 58667| 31                       | -      | 19.31 (0.21)    |
| 58669| 33                       | 19.89 (0.31) | -            |
| 58669| 33                       | 19.55 (0.24) | -            |
| 58669| 33                       | 19.17 (0.17) | -            |
| 58670| 34                       | 19.99 (0.31) | -            |
| 58670| 34                       | 20.16 (0.34) | -            |
| 58671| 35                       | 19.92 (0.30) | -            |
| 58671| 35                       | 20.01 (0.30) | -            |
| 58671| 35                       | 19.51 (0.24) | -            |
| 58674| 38                       | -      | 19.49 (0.23)    |
| 58674| 38                       | -      | 19.62 (0.23)    |
| 58674| 38                       | -      | 19.69 (0.29)    |
| 58685| 49                       | -      | 18.97 (0.30)    |
| 58723| 87                       | -      | 20.23 (0.33)    |