SN 2020cpg: an energetic link between type IIb and Ib supernovae

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ABSTRACT

Stripped-envelope supernovae (SE-SNe) show a wide variety of photometric and spectroscopic properties. This is due to the different potential formation channels and the stripping mechanism that allows for a large diversity within the progenitors outer envelope compositions. Here, the photometric and spectroscopic observations of SN 2020cpg covering ~ 130 days from the explosion date are presented. SN 2020cpg (z = 0.037) is a bright SE-SNe with the B-band peaking at $M_B = −17.75 \pm 0.39$ mag and a maximum pseudo-bolometric luminosity of $L_{\text{max}} = 6.03 \pm 0.01 \times 10^{42}$ erg s$^{-1}$. Spectroscopically, SN 2020cpg displays a weak high and low velocity H feature during the photospheric phase of its evolution, suggesting that it contained a detached hydrogen envelope prior to explosion. From comparisons with spectral models, the mass of hydrogen within the outer envelope was constrained to be $\sim 0.1$ M$_\odot$. From the pseudo-bolometric light curve of SN 2020cpg a $^{56}$Ni mass of $M_{\text{Ni}} \sim 0.27 \pm 0.08$ M$_\odot$ was determined using an Arnett-like model. The ejecta mass and kinetic energy of SN 2020cpg were determined using an alternative method that compares the light curve of SN 2020cpg and several modelled SE-SNe, resulting in an ejecta mass of $M_{\text{ej}} \sim 5.5 \pm 2.0$ M$_\odot$ and a kinetic energy of $E_K \sim 9.0 \pm 3.0 \times 10^{51}$ erg. The ejected mass indicates a progenitor mass of $18 \sim 25$ M$_\odot$. The use of the comparative light curve method provides an alternative process to the commonly used Arnett-like model to determine the physical properties of SE-SNe.

Key words: supernovae: general – supernovae: individual (SN 2020cpg)
1 INTRODUCTION

Core-Collapse Supernovae (CC-SNe) result from the death of stars with a Zero Age Main Sequence (ZAMS) mass of $M_{\text{ZAMS}} > 8 \, M_\odot$ (Woosley et al. 1995; Smartt 2009). These CC-SNe, separated into multiple categories based on their photometric and spectroscopic properties, are known as the H-rich Type II SNe (SNe II) and the H-poor stripped envelope SNe (SE-SNe). SNe II undergo little to no stripping of their outer hydrogen envelope prior to explosion and as such display strong hydrogen features throughout their spectral evolution. SE-SNe, however, lack the strong hydrogen features and display a variety of different spectroscopic properties depending on their elemental composition prior to core-collapse. The type of SE-SN can be determined by the presence and strength of both hydrogen and helium features within their spectra. These SNe include the H/He-rich Type Ib SNe (SNe Ib), the H-poor/He-rich Type Ib SNe (SNe Ibc) and the H/He-poor Type Ic SNe (SNe Ic).

SNe Ib(c) lack any prominent hydrogen (and helium) spectral lines (Filippenko 1997), as their progenitor stars are thought to have been fully stripped of their outer hydrogen and H/He envelopes prior to the core-collapse event. The stripping of the outer envelopes for these progenitor stars is expected to occur over the last stages of the stars life-cycle prior to core-collapse. The process required to strip the outer envelope from these massive stars is still under investigation. The predominant methods include binary interaction where mass is transferred to the companion star via Roche lobe overflow (e.g. Podsiedlowski et al. 1992; Stancliffe & Eldridge 2009; Soker 2017), and a single star formation channel where the outer envelope is stripped prior to collapse, during the Wolf-Rayet phase, by either stellar winds (e.g. Georgy et al. 2012; Gräfener & Vink 2015) or via rotational stripping (Groh et al. 2013). Despite the existence of multiple potential formation channels for SE-SNe, the binary star model seems to be favoured in recent years as the dominant source of SE-SNe progenitors. This is because the single star model is unable to produce the number of progenitors required to account for all the SE-SNe observed (Smith et al. 2011).

However, if the degree of stripping is not high enough to fully remove all of the hydrogen from the progenitor, a hydrogen envelope is present during the explosion resulting in a SNe Ib (see Woosley et al. 1994, for SN 1993J one of the best followed examples of SN Ib). SNe Ib are different to the other SE-SNe by the clear hydrogen features within their spectra that can persist for several months before slowly fading as the SN evolves into the nebular phase (see Filippenko 1997, 2000). Photometrically, SNe Ib are very similar to other SE-SNe displaying a main peak within the first two to three weeks from the explosion. Several SNe Ib also display a bright initial peak within a few days of the explosion prior to the main peak seen in all SE-SNe (see Bersten et al. 2012; Piro 2015). The initial luminous peak is thought to result from the shock cooling near the stellar surface (Waxman & Katz 2017), while the second main peak is a result of the radioactive decay of $^{56}\text{Ni}$ and $^{56}\text{Co}$ synthesised during the explosion. The dual peak light curve has been seen in several of the well observed SNe Ib, such as SN 1993J (Wheeler et al. 1993) and SN 2016gkg (Arcavi et al. 2017; Bersten et al. 2018), and also in some SNe Ib, such as SN 1999ex (Mazzali et al. 2002) and SN 2008D (Malesani et al. 2009). Although this feature is seen in both SNe Ib and Ib it is not observed in the majority of SNe, because the progenitor compactness causes the shock to cool more quickly than surveys can observe the shock breakout. However, thanks to the improving cadence of present surveys, the probability of covering and detecting this feature will increase.

Spectroscopically SNe Ib differentiate themselves from SNe Ibc-by the presence of the hydrogen features which fade over time as the spectra of SNe Ibc become more Ib-like, with the helium features becoming dominant. From detailed modelling of H-rich and H-poor SNe the mass of hydrogen within the outer envelope, $M_\text{H}$, required to form a SNe Ib has been found to be within the range of 0.01 – 1.0 $M_\odot$ (Srianan et al. 2019). Hachinger et al. (2012) constructed a detailed set of spectral models to determine the amount of hydrogen and helium that can be hidden within the outer envelope of SNe Ib/c respectively. From their synthetic spectra, Hachinger et al. (2012) concluded that as little as 0.025 – 0.033 $M_\odot$ is required to form a strong Hα absorption feature, suggesting that some Type Ib’s may display Hα features further blurring the distinction between Ib and Ib SE-SNe. More recently, Prentice & Mazzali (2017) showed that the distinction between the He-rich SE-SNe can be further blurred based on the strength of Hα emission within the spectra. Prentice & Mazzali (2017) created two further SE-SNe subcategories; the Type Ib(I), which display moderate H-rich spectra where the Hα P-Cygni profile is dominated by the absorption component relative to the emission profile, and the Ib(II), whose spectra only show some weak Hα with no obvious Balmer lines more energetic than Hα. The classification scheme of Prentice & Mazzali (2017) along with the findings of Hachinger et al. (2012) demonstrates that SNe Ib and Ib are likely more related than previously thought.

Here we present the photometric and spectroscopic evolution for SN 2020cpg, a Type Ib SN with a thin hydrogen layer, during the first ~ 130 days. SN 2020cpg was initially classified with the Supernova Identification code SNID (Blondin & Tonry 2007) as a Type Ib SN, from the spectrum obtained on 19/02/2020 with the Liverpool Telescope (LT; Steele et al. 2004). However, follow-up spectral observations suggests that SN 2020cpg displayed Hα features as seen in Type Ib SNe. In Section 2.2 we present the $BgVri$-band photometry for SN 2020cpg from the first 130 days after the explosion obtained through various Las Cumbres Observatory Global Telescope network telescopes (LCO; Brown et al. 2013), as part of the Global Supernova Project (GSP; Howell & Global Supernova Project 2017). The spectroscopic ob-
Observation of SN 2020cpg are presented in Subsection 2.3. In Section 3 we discuss the construction of the pseudo-bolometric light curve and the Arnett-like model used to obtain the physical parameters. In Section 4 we present the light curves for the $BgVri$-band photometry and the constructed pseudo-bolometric light curve, along with physical properties obtained by an Arnett-like model. In Section 4.3, we obtain the line velocity evolution, along with a comparison of SN 2020cpg spectra with other well followed Type Ib and IIb SNe. In Section 5 we discuss the potential presence of a hydrogen envelope and the spectral modelling done to determine its presence. We also discuss the use of hydrodynamical models to obtain more realistic explosion parameters and compare the results with those produced by the Arnett-like model. Finally, in Section 6 we summarise the finding on SN 2020cpg, giving final estimates for the physical parameters and a value of the progenitors initial mass.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Explosion date and Host Galaxy

SN 2020cpg was first detected on 15/02/2020 (MJD = 58894.54) by Nordin et al. (2020) on behalf of the Zwicky Transient Facility (ZTF; Bellm et al. 2018). The last non-detection of SN 2020cpg, on 06/02/2020 (MJD = 58885.52), predates the ZTF discovery by 9 days. To place a better constraint on the explosion date of SN 2020cpg we modified the pseudo-bolometric light curve model to include the explosion date as a parameter, see Section 3.2. From this fit we obtain an explosion date of 08/02/20, MJD = 58887.7 ± 2.1 days, which we adopt throughout the rest of the paper. SN 2020cpg was associated with the galaxy SDSS J135219.64+133432.9 and was located 1.14" South and 24.07" West from the galaxy centre, just off the outer end of the host galaxy’s western spiral arm, as seen in Figure 1. Using the cosmological parameters of $H_0 = 73.0 \pm 5.0$ km/sec/Mpc, $\Omega_{\text{matter}} = 0.27$ and $\Omega_{\text{vacuum}} = 0.73$ gives a redshift distance of 158.6 ± 11.1 Mpc, with the distance calculation based on the local velocity field model from Mould et al. (2000). The host redshift of $z = 0.037$, implies a distance modulus of $m - M = 36.05 \pm 0.15$ mag.

2.2 Photometry

The initial $g$ and $r$-band photometry was obtained by ZTF using the ZTF-cam mounted on the Palomar 1.2m Samuel Oschin telescope several days ($t[MJD] = 58894.5$) before continuous follow-up occurred. This photometry was run through the automated ZTF pipeline (Masci et al. 2019) and is presented on Lasair transient broker (Smith et al. 2019). After the discovery, the $BgVri$-bands were followed by the Las Cumbres Observatory Global Telescope.

Figure 2. The absolute magnitude photometry of SN 2020cpg in the $BgVri$-bands along with the ATLAS $c$ and $o$-band covering ~ 130 days from the explosion date. The individual band light curves have been corrected for extinction, shifted by a constant magnitude and are shown in rest frame. The red dashed lines denote the epochs at which spectra were taken.
network (LCO; Brown et al. 2013) and reduced using the BAN-ZAI pipeline (McCully et al. 2018). Full $BgVri$-band photometry was obtained until 23/03/2020 from which point only $Vri$-band photometry could be obtained. Observation was obtained from a combination of 1 m telescopes from the Siding Spring Observatory (code: COJ), the South African Astronomical Observatory (code: CPT), the McDonald Observatory (code: ELP) and the Cerro Tololo Inter-American Observatory (code: LCO). Both $c$ and $d$-band photometry were also obtained by the Asteroid Terrestrial-impact Last Alert System (ATLAS; Smith et al. 2020) and reduced through the standard ATLAS pipeline (Tonry et al. 2018). The $BgVri+co$-band absolute light curve from the follow-up campaigns are shown in Figure 2. The photometry has been corrected for reddening using a Milky Way (MW) extinction of $E(B−V)_{MW} = 0.025 ± 0.001$ mag, obtained using the Galactic dust map calibration of Schlafly & Finkbeiner (2011) and extinction factor $R_V = 3.1$. The host galaxy extinction was taken to be negligible relative to MW extinction, as there was no noticeable Na D λ 5890, 5896 lines at the SN rest frame, (e.g. Poznanski et al. 2012). Also it should be noted that, as seen in Figure 1, SN 2020cpg was located far from the galactic centre where the effect of dust is likely reduced. All uncorrected LCO photometry and ATLAS photometry are given in Table A1 and Table A2 respectively.

2.3 Spectroscopy

Spectra from multiple telescopes were obtained over an 80 day post explosion and reduced through standard means available within each observatory pipeline. The classification spectrum of SN 2020cpg (Poidevin et al. 2020) was obtained with the LT, on 19/02/2020 using the Spectrograph for the Rapid Acquisition of Transients (SPRAT; Piascik et al. 2014) and was reduced by the LT automatic pipeline 3 (see Barnsley et al. 2012, for details on the pipeline). Several later spectra were also obtained using the LT. Additional spectra for SN 2020cpg were obtained by the advanced Public ESO Spectroscopic Survey for Transient Objects (ePESSTO)+ 3 (Smartt et al. 2015) using the ESO Faint Object Spectrograph and Camera mounted on the New Technology Telescope (NTT) (EFOSC2; Buzzoni et al. 1984). ePESSTO+ data were reduced as described in Smartt et al. (2015). The Alhambra Faint Object Spectrograph and Camera (ALFOSC) mounted on the Nordic Optical Telescope (NOT; Djupvik & Andersen 2010) provided several spectra of SN 2020cpg, which were reduced by the Fossgui pipeline 4. Multiple spectra were taken by the LCO 2 m Faulkes Telescope South (FTS) at COJ and Faulkes Telescope North (FTN) at the Haleakala Observatory (code: OGG). We attempted to obtain further spectra after two and a half months post explosion, however SN 2020cpg was too dim at this point for the available telescopes to obtain good quality spectra. All spectra have been binned to improve the S/N ratio, and de-reddened, assuming a standard $R_V = 3.1$ and the $E(B−V)$ given in Section 2.1. All spectra can be seen in Figure 3. The details on the phase from $B$-band max, observatory and instrument alongside the observed range are given in Table 1.

![Table 1. Details of the spectroscopic observations of SN 2020cpg. Phase from both the predicted explosion date (Phase$exp$) and the date of $B_{max}$ (Phase$B_{max}$) are given in rest-frame.](http://telescope.livjm.ac.uk/TellInst/Inst/SPRAT/)

3 METHOD

3.1 Pseudo-bolometric Light curve

From the $BgVri$-band photometry obtained for SN 2020cpg we constructed a pseudo-bolometric light curve, shown in Figure 4, using the pseudo-bolometric light curve code of Nicholl (2018). As we lack any UV or NIR data, we approximate the missing luminosity in these bands by extrapolating the blackbody spectral energy distributions that were fit to the $BgVri$-bands into the UV and NIR regions. The UV and NIR contributions to the pseudo-bolometric light curve are relatively small at peak time, contributing ~10–20% and ~15 – 25% respectively, compared to the optical contribution, which accounts for ~50 – 60% of total flux near bolometric peak (Lyman et al. 2014). We conclude that our extrapolation to UV and NIR bands does not introduce a significant error to the bolometric light curve.

Along with the pseudo-bolometric light curve of SN 2020cpg, we construct pseudo-bolometric light curves for SN 1993J (Richmond et al. 1994; Barbon et al. 1995; Richmond et al. 1996), SN 2003bg (Hamuy et al. 2009), SN 2008ax (Pastorello et al. 2008; Tsvetkov et al. 2009). SN 2009Jf (Sahu et al. 2011; Bianco et al. 2014). SN 2011dh (Tsvetkov et al. 2012; Sahu et al. 2013; Brown et al. 2014), iPTF13bvn (Brown et al. 2014; Fremling et al. 2016; Folatelli et al. 2016), SN 2013ge (Drout et al. 2016), 2015ap (Prentice et al. 2019) and SN 2016kg (Brown et al. 2014; Arcavi et al. 2017; Bersten et al. 2018). The comparison between these SE-SNe is shown in Figure 5. These SE-SNe were chosen as they all have comprehensive coverage over the first ~100 days post explosion, they all have well defined explosion dates and photospheric velocities both of which are required for the Arnett-like model used to obtain physical parameters. For these SE-SNe, we excluded any UV and NIR data available when constructing the pseudo-bolometric light curve ensuring the effects of the UV and NIR extrapolation did not greatly influence the comparison between the SE-SNe. Where SNe lacked Sloan Digital Sky Survey (SDSS) filters we used the corresponding Johnson-Cousins (J-C) filters to cover a similar wavelength range allowing for a more accurate comparison between the pseudo-bolometric light curves.

3.2 Physical parameters

The bolometric luminosity of a SN is intrinsically linked to several physical parameters, those being the mass of nickel synthesised...
Figure 3. Spectroscopic evolution of SN 2020cpg with details of the observations given in Table 1. The epochs on the right side are relative to $B_{\text{max}}$ in rest frame. The $H_{\alpha}$, He I, Fe II, Ca II and O I features have been noted along with the main telluric feature at 7600, ⊗. The spectra have been binned to reduce the noise.

during the explosion, the amount of material ejected from the outer layers of the progenitor and the kinetic energy of the ejected mass. This relation was first formulated for Type Ia SNe by Arnett (1982) who assumed that all the energy that powers the bolometric light curve originated from the decay of $^{56}\text{Ni} \rightarrow ^{56}\text{Co}$ and the decay of $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$. While the model was initially formulated for SNe that do not undergo a hydrogen recombination phase, such as those seen in SE-SNe Ib/c and SNe Ib, it has been used regularly for multiple types of SNe. This is done by ignoring the recombination phase and restricting the fitting to the rise and fall of the peak of
the bolometric light curve that is powered by radioactive activity, as done in Lyman et al. (2016). The Arnett-like model also assumes that all $^{56}\text{Ni}$ is located in a point at the centre of the ejecta, that the optical depth of the ejecta is constant throughout the evolution of the light curve, the initial radius prior to explosion is very small and that the diffusion approximation used for the model is that of photons. While these assumptions are acceptable, the approximation of constant opacity has a severe effect on diffusion timescale which is dependent on the estimated ejecta mass and kinetic energy of the SN. The effect of neglecting the time-dependent diffusion on the $^{56}\text{Ni}$ mass was discussed by Khatami & Kasen (2019), who concluded that this results in an over estimation of the $^{56}\text{Ni}$ mass. Through alternative modelling methods it was seen that the $^{56}\text{Ni}$ mass was overestimated by the Arnett-like model by ~ 30 – 40% (see, Dessart et al. 2016; Woosley et al. 2021).

We initially used the Arnett-like model to determine the physical parameters of SN 2020cpg and compare the results to several other SE-SNe. In the Arnett-like model the kinetic energy and ejecta mass have a strong dependence on the diffusion timescale, $\tau_m$, of the bolometric light curve, which is given as:

$$\tau_m = \frac{\kappa_{\text{opt}}}{\beta c} \left( \frac{6 M_{\text{ej}}^3}{5 E_k} \right)^{1/4}. \quad (1)$$

Where $M_{\text{ej}}$ is the mass of ejected material and $E_k$ is the kinetic energy of the supernovae. Also $c$ is the speed of light, $\beta$ is the constant of integration derived by Arnett (1982) that takes the value of $\beta \approx 13.8$ and $\kappa_{\text{opt}}$ is the optical opacity of the material ejected by the SN. For the Arnett-like model a constant value of $\kappa_{\text{opt}} = 0.06 \pm 0.01 \text{cm}^2 \text{g}^{-1}$ was used. The degeneracy between the ejecta mass and kinetic energy was broken using the photospheric velocity event obtained from the velocity of the Fe ii $\lambda 5169$A line measured at maximum bolometric luminosity. This is the epoch when the outer ejecta has the largest contribution to the luminosity under the assumption of homogeneous density. The model was also adjusted to include the SN explosion date to allow for an improved fit and to place a constraint on the rise time of the SN. For SE-SNe with well observed pre-maximum and well defined explosion dates we use the dates provided. The explosion date of SN 2020cpg was obtained by constraining the fitting to limit the potential explosion date to after the date of last non-detection and prior to the initial observation.

Due to the known problems with the Arnett-like model, in Section 5.3 we discuss an alternative method for determining the ejecta mass and kinetic energy of SN 2020cpg by comparing the light curve properties and physical properties determined by hydro-dynamical modelling of other SE-SNe, as done for SN 2010ah in Mazzali et al. (2013, here after PM13). This method re-scales the physical parameters of other SE-SNe using equation 1 under the assumption that the optical opacity of the two SNe are equivalent. This is physically a more robust assumption than a fixed opacity for all SE-SNe as adopted by the Arnett-like model. A comparison between the results obtained from the Arnett-like model and the PM13 model is presented later in Section 5.3.

4 RESULTS

4.1 Multi-colour light curves

The early time rise of both the $B$ and $V$-bands were missed in the follow-up campaign, however the peaks in both bands were observed, shown in Figure 2. The bluer bands peaked several days before the red bands, $t_{\text{rise}}^{\text{blue}} \approx 15$ days post explosion and $t_{\text{rise}}^{\text{red}} \approx 19$ days. Both the $B$ and $g$-bands were followed for ~ 30 days by LCO before the photometry bands dropped below the brightness threshold required for follow-up. The brightness for the $B$ and $g$-bands fell by ~ 2 magnitudes in the 30 days from the photometric peak as a result of the SN rapidly cooling. The remaining bands fell at a slower rate, dropping by roughly 1 magnitude in the same time period, before their decline slowed down as the light curve transitioned to the exponential tail produced by the radioactive decay $^{56}\text{Co}$ synthesised in the explosion. The ATLAS $c$-band was followed for approximately 100 days from the expected explosion date with the $o$-band being followed for a further 30 days. The peaks in both bands were not well observed, especially in the $c$-band. As with the other bands the redder $o$-band declines at a slower rate just after maximum light when compared to the $c$-band. The ATLAS bands have a greater error associated with them compared to the $BgVri$-bands, and as the ATLAS bands cover a similar wavelength range as the $BgVri$ they were not used when constructing the pseudo-bolometric light curve.

The light curves for He-rich CC-SNe display a variation within the evolution of their light curves due to the range of progenitor properties. As such the $BgVri$-band photometry for SN 2020cpg was compared with those of SN 1993J, SN 2003bg, SN 2009jf, SN 2011dh, iPTF13bvn, SN 2013ge, SN 2015ap and SN 2016gkg. The absolute magnitude photometry for these SNe relative to SN 1993J, SN 2003bg, SN 2009jf, SN 2011dh, iPTF13bvn, SN 2013ge, SN 2015ap and SN 2016gkg. The absolute magnitude photometry for these SNe relative to SN 2020cpg is brighter than the majority of the other SNe that we compare to, with only SN 2009jf and SN 2015ap being of similar brightness. The $B$ and $g$-bands evolve in a similar way to that of SN 2015ap while the other bands evolve more similar to SN 2009jf. Due to the lack of pre-maximum light observations it is not possible to determine if SN 2020cpg had a shock breakout cooling peak similar to that seen in several other SE-SNe, such as SN 1993J and SN 2016gkg.

4.2 Pseudo-bolometric Light Curves

The pseudo-bolometric rise time for SN 2020cpg is $t_{\text{rise}}^{\text{bol}} \approx 16.0 \pm 2.5$ days. Once peak luminosity had been reached the light curve rapidly declines for the next ~ 34 days before settling on the exponential tail. Due to lack of much pre-peak photometry the rise of the pseudo-bolometric light curve is not as well constrained as the post-peak light curve. SN 2020cpg reaches a peak luminosity of log($L_{\text{max}}$) = 42.78 ± 0.08 [erg s$^{-1}$], which is higher than the average luminosity of Type IIb + IIb(I), which has a value of log($L_{\text{max}}$) = 42.2 ± 0.1 [erg s$^{-1}$], and the average maximum luminosity of Type IIb + IIb(I), log($L_{\text{max}}$) = 42.09 ± 0.17 [erg s$^{-1}$], as given in Prentice et al. (2019), showing that SN 2020cpg lies at the brighter end of the SE-SNe regime.

We fit the pseudo-bolometric light curve of SN 2020cpg

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**Table 2.** Epoch of light curve maximum, rise time in rest-frame and peak absolute magnitude for the $BgVri$ photometry bands for SN 2020cpg

| Band | $MJD_{\text{max}}$ | Rise time (days) | $t_{\text{rise}}^{\text{max}}$ | $M_{\text{max}}$ |
|------|-------------------|------------------|-----------------|----------------|
| $B$  | 58902.1           | 14.7 ± 2.5       | 18.38 ± 0.02    | −17.75 ± 0.39 |
| $g'$ | 58903.1           | 16.0 ± 2.1       | 18.05 ± 0.02    | −18.04 ± 0.40 |
| $V$  | 58904.7           | 17.0 ± 2.1       | 18.16 ± 0.02    | −17.91 ± 0.38 |
| $c$  | 58906.0           | 18.8 ± 2.3       | 18.10 ± 0.05    | −17.97 ± 0.38 |
| $r'$ | 58906.2           | 18.6 ± 2.1       | 18.06 ± 0.02    | −18.00 ± 0.38 |
| $o'$ | 58908.3           | 21.1 ± 2.4       | 18.05 ± 0.05    | −18.01 ± 0.39 |
| $i'$ | 58909.2           | 22.0 ± 2.1       | 18.05 ± 0.02    | −18.00 ± 0.38 |

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and the derived physical parameters are given in Table 4. As expected the Arnett-like model deviates from the pseudo-bolometric light curves at later times ($t \geq 40$ days) when the SNe start to transition into the nebular phase. Relative to the other SNe, SN 2020cpg has a high nickel mass similar to both SN 2009jf and SN 2015ap, shown in Table 4. The similar $M_{\text{Ni}}$ between SN 2020cpg and both SN 2009jf and SN 2015ap is expected from their comparable peak luminosities. The ejecta mass and kinetic energy of SN 2020cpg is also higher than the majority of the SE-SNe we have looked at, suggesting that the progenitor of SN 2020cpg was a high mass star prior to the stripping of the outer envelope. However, due to the problems associated with the Arnett-like approach, we discuss an alternative approach to obtain the values for $M_{\text{ejc}}$ and $E_k$ in Section 5.3, where we then use the values for $M_{\text{ejc}}$ and $E_k$ derived using the PM13 method to estimate the progenitor mass.

4.3 Spectral Evolution and Comparison

At early times, the spectra of SN 2020cpg (Figure 3) shows a large blue excess. The spectra rapidly cool until around $+15$ days from $B_{\text{max}}$. Prominent He i lines are present throughout the spectral evolution with the He i 5876 Å line being the most prominent and the 6678 Å line becoming stronger at around +23 days. Around +1 days post $B_{\text{max}}$ the spectrum develops an absorption feature located in the Hz region which persists for $\sim 30$ days. At earlier times during the spectral evolution, the Hz feature is split into a high velocity and low velocity component which merge into a single Hz feature at later times. The presence of the Hz line provides strong evidence that SN 2020cpg is not a standard Type Ib SN and may be an intermediate SN between the H-rich and H-poor SE-SNe. While the feature around 6300 Å may be interpreted as the presence of silicon, this is not likely, because it would imply that absorption from other silicon transitions, around 4100 and 5900 Å should be detected in this and later spectra which is not observed. Moreover, when identified as silicon, the line shift would indicate a velocity of 3000 km s$^{-1}$ which is far too slow for this epoch. These pieces of evidence along side the lack of silicon in the spectra of other well observed Type Ib/c SNe gives strong evidence that the feature is the result of the presence of hydrogen within the outer envelope. Later, the spectral evolution shows the development of Fe ii $\lambda\lambda$4924, 5018, 5169 lines, although it should be noted that the Fe ii lines are located close to He i lines making the separation of these lines difficult, especially given the high noise in this region of the spectra.

The evolution of the line velocities for Hz, He i $\lambda\lambda$5876, 6678, 7065 and Fe ii $\lambda\lambda$4924, 5018, 5169 were determined by the fitting of a Gaussian to each feature to locate the minima. The line evolution of each elemental feature is shown in Figure 7. The line velocities derived from the Gaussian fits are given in Figure 8. The main source of error for these elemental line velocities comes from the low S/N of the spectra, especially on the fringes where the Fe ii line is located, which makes the fitting of the Gaussian more difficult. This results in an error derived from the Gaussian fitting of approximately 15%, with a negligible error associated with the redshift. For the Hz feature, we separate the minimum into two distinct high and low velocity components. The high velocity feature is visible from the second spectrum, $\sim 4$ days, until approximately +15 days post $B_{\text{max}}$, as shown by the solid red line in Figure 7. At this point the high velocity and low velocity components blend together in the later spectra to form a single Hz feature. There is a clear separation between the high and low velocity Hz components, with the low velocity remaining relatively constant in velocity with a decline of $\sim 2000$ km s$^{-1}$ from $\sim 14500$ km s$^{-1}$

with the Arnett-like model using a photospheric velocity of $v_{\text{ph}} \approx 12500 \pm 1500$ km s$^{-1}$ to break the degeneracy between the kinetic energy and ejecta mass. The value of $v_{\text{ph}}$ was obtained from the average Fe ii line velocities at peak light. The average value of the Fe ii triplet was used instead of the commonly employed Fe ii $\lambda$5169 line due to the low signal to noise ratio within the Fe ii region of the spectrum taken around peak luminosity. From the Arnett-like model fit to SN 2020cpg's pseudo-bolometric light curve we derive a nickel mass of $M_{\text{Ni}} = 0.27 \pm 0.08$ M$_{\odot}$. The ejecta mass and kinetic energy given by the fit had a value of $M_{\text{ejc}} = 3.4 \pm 1.0$ M$_{\odot}$ and $E_k = 2.9 \pm 0.9 \times 10^{51}$ erg respectively. This process was then repeated for the bolometric light curves of the other SE-SNe shown in Figure
km s$^{-1}$ to $\sim 12500$ km s$^{-1}$ while the high velocity component drops by $\sim 5000$ km s$^{-1}$ from $\sim 21000$ km s$^{-1}$ to $\sim 16500$ km s$^{-1}$ before the lines seem to merge into one constant H$\alpha$ feature. The He I $\lambda 5876$ feature remains strong throughout the spectral evolution while the He I $\lambda 6678$ feature, while not always visible due to high noise, follows the velocity evolution of He I $\lambda 5876$. The signal to noise ratio in the Fe II region made finding the velocity evolution harder than for the other lines. The velocity of the He I and Fe II lines all follow a similar trend declining from $\sim 13000$ km s$^{-1}$ to $\sim 10000$ km s$^{-1}$. From the velocity evolution we determine that the photospheric velocity of SN 2020cpg at peak luminosity has an average value of $12500 \pm 1200$ km s$^{-1}$, taken from the velocity of the He I and average Fe II features.

We compare the spectra of SN 2020cpg, a H-rich (SN 2011dh), and a H-poor (SN 2015ap) SN, within the range 4000 – 9000 Å presenting the evolution of the hydrogen features and the line strength relative to standard SNe Ib and IIb, see Figure 9. Both SN 2011dh and SN 2015ap were close, well observed, SE-SNe allowing for clear comparisons to SN 2020cpg. This is especially true of SN 2015ap, which photometrically appears similar to SN 2020cpg in both shape and luminosity. The epochs chosen were relative to the peak of the pseudo-bolometric light curve so
Table 4. Physical properties of several SE-SNe derived from the fitting of the Arnett-like model described in Section 3 and shown in Figure 5. The photometric velocity used for each SN was taken from their discovery paper.

| SN   | v_ph [km s^{-1}] | M_{Ni} [M_\odot] | M_{He} [M_\odot] | E_{k} [10^{33} erg] |
|------|------------------|-----------------|-----------------|---------------------|
| 1993J | 8000 ± 1000 | 0.11 ± 0.03 | 2.0 ± 0.8 | 8.8 ± 0.3 |
| 2003bg | 10000 ± 500 | 0.13 ± 0.04 | 2.8 ± 0.9 | 1.7 ± 0.5 |
| 2008ax | 7500 ± 500 | 0.14 ± 0.04 | 2.6 ± 1.0 | 0.9 ± 0.3 |
| 2009j | 11000 ± 500 | 0.27 ± 0.09 | 4.0 ± 1.4 | 2.9 ± 1.0 |
| 2011dh | 7000 ± 1000 | 0.09 ± 0.02 | 1.8 ± 0.8 | 0.5 ± 0.1 |
| iPTF13bvn | 8000 ± 1000 | 0.07 ± 0.02 | 1.7 ± 0.6 | 0.6 ± 0.2 |
| 2013ge | 10500 ± 500 | 0.12 ± 0.03 | 2.7 ± 0.8 | 1.8 ± 0.5 |
| 2015ap | 16000 ± 1000 | 0.22 ± 0.05 | 1.4 ± 0.4 | 2.2 ± 0.6 |
| 2016egb | 8000 ± 1000 | 0.10 ± 0.02 | 1.9 ± 0.4 | 0.7 ± 0.2 |
| 2020cpg | 12500 ± 1200 | 0.27 ± 0.08 | 3.4 ± 1.0 | 2.9 ± 0.9 |

Table 3. Details for several historical Type Ib and Ibb SNe which have been compared to SN 2020cpg. Sources: 1: Richmond et al. (1994), 2: Barbon et al. (1995), 3: Richmond et al. (1996), 4: Pastorello et al. (2008), 5: Hamuy et al. (2009), 6: Tsvetkov et al. (2009), 7: Sahu et al. (2011), 8: Tsvetkov et al. (2012), 9: Sahu et al. (2013), 10: Bianco et al. (2014), 11: Brown et al. (2014), 12: Fremming et al. (2016), 13: Folatelli et al. (2016), 14: Drout et al. (2016), 15: Arcavi et al. (2017), 16: Bersten et al. (2018) and 17: Prentice et al. (2019).

that all SNe were at similar stages in their evolution. The epochs compared are ~5, 0, +5 and + 30 days relative to peak luminosity. The red region in Figure 9 highlights the Ho region. It is clear that early on the spectra of SN 2020cpg are more similar to those of SN 2015ap, especially in the Ho region, and in the spectra evolution of SN 2020cpg to the mean of SN 2015ap. As seen for the spectroscopic evolution of SN 2020cpg when compared to the mean of SN 2015ap, we have considered here, only SN 2009j and SN 2015ap have similar luminosities to SN 2020cpg. This suggests that SN 2020cpg is brighter than the average SE-SNe. As we also compare the maximum luminosity for SN 2020cpg to the median peak luminosity of SNe Ib + Ib(II) and SNeIb + Ibb(I) in Prentice et al. (2019) showing that SN 2020cpg is located at the brighter end of the luminosity range displayed by H-rich SNe. The rise time of SN 2020cpg is similar to most other SNe we have looked at, although the pseudo-bolometric light curve of SN 2020cpg is broader than many of the SN shown in Figure 5. The high pseudo-bolometric luminosity indicates a large amount of 56Ni. An Arnett-like model fit yielded a total 56Ni mass of M_{Ni} = 0.27 ± 0.08 M_\odot. From the analysis of several SE-SNe performed by Prentice et al. (2019), the Arnett-like model derived mean nickel masses of <M_{Ni}>= 0.07 ± 0.03 M_\odot for SNeIb + Ibb(I) and <M_{Ni}>= 0.09 ± 0.06 M_\odot for SNeIb + Ibb(II). Therefore, SN 2020cpg produced roughly triple the mean nickel mass, placing it on the extreme end of the SNe.

Despite the similarity in mean 56Ni between SNeIb + Ibb(I) and SNeIb + Ibb(II), Prentice et al. (2019) showed that SNeIb + Ibb(II) 56Ni masses display a bimodal distribution with a high mass region, where the 56Ni mass of SN 2020cpg resides. From the distribution of 56Ni mass given by Prentice et al. (2019), SN 2020cpg behaves like H-poor SE-SNe. It should be noted that most neutrino-driven explosion models cannot produce M_{Ni} greater than ~ 0.23 M_\odot (Suwa et al. 2018), although a study of literature M_{Ni} values done by Anderson (2019) found that ~ 30% of hydrogen-poor SE-SNe and ~ 7% of hydrogen-rich SE-SNe have 56Ni masses that are greater 0.23 M_\odot. This discrepancy arises from the assumptions of the Arnett-like model, see Section 3.2, which result in an overestimation of the M_{Ni}. Taking into account this overestimation the M_{Ni} of SN 2020cpg is reduced to ~ 0.16 – 0.19 M_\odot, placing SN 2020cpg’s M_{Ni} within, although close to, the upper limits of neutrino-driven explosion models. However, as we have compared the M_{Ni} of SN 2020cpg with other 56Ni masses derived by the Arnett-like model and there is uncertainty in the overestimation of the model, we use the value of mass of 56Ni derived from the Arnett-like model as the upper limit of M_{Ni} for SN 2020cpg.

5 DISCUSSION

With a maximum luminosity of 6.03 ± 0.01 × 10^{42} erg s^{-1}, SN 2020cpg is brighter than the average SE-SNe. Among the SNe

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5.1 Hydrogen Envelope

As seen for the spectroscopic evolution of SN 2020cpg when compared to well observed Type Ib and Ibb SNe, there is strong evidence for the presence of a hydrogen envelope surrounding the progenitor of SN 2020cpg. The separation of the H feature into a high velocity and a low velocity component suggests that the hydrogen
Figure 7. Evolution of SN 2020cpg spectra. The spectra have been plotted between 4000 – 8000 Å to highlight the regions where prominent Hα, He i and Fe ii features are visible. The different elements are shown by the different lines, with Hα = red, He i = blue and Fe ii = green, and different element lines given by different styles. Lines are only shown when line features are clearly visible within the spectra.
is located in two distinct regions within the outer envelope of the progenitor star. A thin outer envelope and an inner region where the hydrogen and helium are thoroughly mixed together corresponding to the high and low velocity component respectively. While the two component Hα features are not common among H-rich SE-SNe, it has been observed in other SNe, with SN 1993J displaying a clear double Hα feature throughout the photospheric phase. The velocity of the high velocity component for SN 1993J does not seem as large as that for SN 2020cpg relative to the low velocity component. This suggests that the amount of hydrogen stripped from the progenitor of SN 2020cpg is greater than that of SN 1993J prior to the explosion, which is further supported by the weak Hα feature seen in the spectral evolution of SN 2020cpg. The presence of a weak Hα absorption feature provides evidence that SN 2020cpg is not a standard Type Ib SNe but rather a Type Ib(II).

5.2 Model Comparisons

By comparing the spectra of SN 2020cpg with model spectra, we can gain insight on the potential elemental composition of the outer layers prior to explosion. Teffs et al. (2020) calculated a set of synthetic SE-SNe models based on a single mass progenitor, with varying degrees of H/He stripping that produces several Type Ic/Ib/IIb analogue SNe. Teffs et al. (2020) estimated the energy of a set of well observed Type Ib SNe by comparing synthetic and observed spectra at pre-, near- and post-peak luminosities.

A similar method is applied in this work to SN 2020cpg. The pre- and near-peak spectra of SN 2020cpg are very blue and with few strong features. The early synthetic Type Ib-like spectra in Teffs et al. (2020) are typically redder due to a stronger amount of Fe-group elements mixing, producing strong line blocking in the near UV. As such, the conditions in which the early spectra of SN 2020cpg are produced are beyond the scope of this comparison and can be explored in future work.

We first compare two spectra at approximately +15 and +30 days after B-band maximum to the Type Ib model from Teffs et al. (2020) in Figure 10a, where the red spectra include the non–thermal effects on hydrogen and the black do not. These non–thermal effects arise from the interactions with energetic electrons that are created by the scattering of gamma-rays released from the decay chain of $^{56}$Ni and $^{56}$Co, (Lucy 1991). This Type Ib model has an ejecta mass of $\sim 5.7 \times 10^{-3} M_{\odot}$, with 1.3 $M_{\odot}$ of helium and 0.1 $M_{\odot}$ of hydrogen. For the earlier spectrum at the top of Figure 10a and when focusing on the Hα and He i features, we find the best fit to be that of a 5 foe model that does not include the non–thermal effects on H, where 1 foe is $1 \times 10^{51}$ erg. The inclusion of non–thermal hydrogen produces a deep and broader Hα line that is not reflected in the spectrum of SN 2020cpg. In the second spectrum considered, we instead find that the 3 foe explosion model matches the spectrum of SN 2020cpg at this late phase. At this lower energy and later phase, the Hα line is more narrow and when the non–thermal effects of hydrogen are not included, the 6000–6500 Å region is well reproduced.

As SN 2020cpg has been designated both as a Type Ib and a Type Ibb, we also compare our helium rich, but hydrogen free, Type Ib models at the same epochs in Figure 10b. For this, we also include the “best fit” models from Figure 10a that do not consider the non–thermal effects of hydrogen as black lines. For the earlier spectrum, we find that the 3 foe Ib model does a reasonable job of reproducing the 6000–6500 Å region without requiring H, but the $\lambda 6678$ He i line is stronger than in the observed spectrum. For the later spectrum, the energy is reduced from the Ib model again to 1 foe and also reproduces this 6000–6500 Å region.

From this, we can infer several properties of the SN 2020cpg regarding its elemental composition. The assumption that helium has non–thermal effects while H does not is unlikely to be physically viable. However, the mass of hydrogen in the Ib model clearly produces too strong of an Hα line. Not including any hydrogen in the model while maintaining a He–rich outer atmosphere results in strong $\lambda 6678$ and $\lambda 7065$ He i lines. The re-emission from the Hα feature reduces the strength of the $\lambda 6678$ He i line while affecting the $\lambda 7065$ He i line less. The best fit Ib models having low energy also suggests the He rich material is confined to lower velocities, such as those below a hydrogen rich shell as seen in the Ib models. We suggest that a lower mass of hydrogen ($M_{H} < 0.1 M_{\odot}$) could result in a weaker Hα feature but still produce enough re-emission to reproduce the 6000–6500 Å region in these late phases. A more detailed model would need to be calculated to derive a stronger estimate on the mass and distribution of H in SN 2020cpg.

Table 5. Spectral details for the spectra used in Figure 9, including the date the spectra were obtained and the instrument used to obtain them. All spectra shown in this table and Figure 9 are from the sources below: 1: Arcavi et al. (2011), 2: Ergon et al. (2014), 3: Shiuvers et al. (2019), 4: Prentice et al. (2019).

| SN     | Plot Date | Instrument       | Source |
|--------|-----------|------------------|--------|
| 2011dh | a 12/06/2011 | FOS, 1          | 1      |
|        | b 17/06/2011 | ALFOSC          | 2      |
|        | c 25/06/2011 | ALFOSC          | 2      |
|        | d 14/07/2011 | ALFOSC          | 2      |
|        | a 15/09/2015 | KAST            | 3      |
| 2015ap | b 20/09/2015 | FLOYDS_S        | 4      |
|        | c 23/09/2015 | FLOYDS_N        | 4      |
|        | d 20/10/2015 | KAST            | 3      |
| 2020cpg| a 17/02/2020 | COJ eni2        | -      |
|        | b 20/02/2020 | EFOSC2          | -      |
|        | c 23/02/2020 | EFOSC2          | -      |
|        | d 23/03/2020 | EFOSC2          | -      |
Figure 9. Comparison of SN 2020cpg (blue) with a characteristic SN Ib (SN 2015ap, red) and a characteristic SN IIb (SN 2011dh, green) at several epochs relative to pseudo-bolometric peak. The epochs shown are around a: ~5 days, b: +0 days, c: +5 days, d: +30 days. The grey shaded area denote the region where the Hα feature should be located if hydrogen is present within the outer envelope of the progenitor. The spectrum used for each of the plots along with the instrument used to obtain them are detailed in Table 5 and can all be found on WiseRep (Yaron & Gal-Yam 2012).

At these two epochs, the photosphere has receded deep into the CO rich region of the ejecta as shown by the presence of the Ca τ NIR triplet and the O I λ 7771. Early spectra of Type IIb do not show these features as the abundances of these elements are lower in the H/He-rich shells. Both models are shown with (red line) and without (black line) the non thermal effects of hydrogen, but both include these effects on the helium. For the Type IIb-like models at these epochs, the spectra that do not treat the non thermal effects of hydrogen, are better able to reproduce the observed spectral structure between 6000–6500 Å that would typically contain a strong Hα feature. Due to the depth of the photosphere and the lack of a strong Hα feature, this suggests that the total Hα mass is less that 0.1 M⊙, and that the distribution of the hydrogen is further out in the ejecta with respect to the photospheric velocity of the two epochs chosen.

The model shown at the top in Figure 10a is a 5 foe explosion, with the majority of the 0.1 M⊙ of hydrogen at velocities greater than ≈15000 km s⁻¹, while the 3 foe explosion in the lower model contains hydrogen at velocities greater than ≈12000 km s⁻¹. Both models favour both the estimated explosion energy from the Arnett fits in Section 4.2 and the suggestion that some hydrogen is at high velocities. The He I λ 6678 line is relatively too strong for either epoch to match when we do not include non–thermal excitation of the hydrogen. This suggests that a lower mass of hydrogen can still be responsible for some fraction of the 6000-6500 Å feature, likely coincident with Si II causing a re-emission of flux further redward, reducing the strength of the He I λ 6678 without affecting the He I λ 5876, 7065 and 7281 lines. However, for a full picture of how the hydrogen and helium are distributed and how much is present, a detailed stratified model would need to be produced, which is beyond the scope of this work.

5.3 Re-scaled Light curves

As mentioned in Section 3.2, the Arnett-like model is limited in its viability to obtain realistic ejecta mass and kinetic energy due to the assumption that the optical opacity is constant throughout the bolometric light curve and that the ejecta are optically thick. The
Figure 10. Top (a): Comparison of SN 2020cpg spectra with two different energy (3 and 5 foe) Type IIb models. Where $t_p$ indicates the epoch of bolometric peak. The red model spectra include the non thermal effects of hydrogen while the black model spectra omit the non thermal effects. Both models include the non thermal effects on He. Several important contributing elements, in particular those near the Hα line, are shown above their feature within the spectra.

Bottom (b): SN 2020cpg spectra at +15 and +30 days from $B$-band maximum fit with a IIb-like model and with a Ib model with 3 foe of energy at a time of +12 days from $t_p$ and 1 foe of energy at a time of +21 days respectively. The IIb model has an ejecta mass of $\approx 5.7 \, M_\odot$, with $1.3 \, M_\odot$ of helium and $0.1 \, M_\odot$ of hydrogen.
problem with these assumptions is that helium is optically transparent at the temperatures reached surrounding the peak light phase of the light curve. In order to account for the effects of the helium layer on the ejecta mass and kinetic energy a detailed hydrodynamical model is required. However, this would not have been easily done with SN 2020cpg due to the lack of early time photometry and the low signal to noise ratio for the spectra. In order to estimate the physical parameters for SN 2020cpg we transform equation 1 to obtain a ratio for the ejecta mass and kinetic energy between SN 2020cpg and other SE-SNe that have detailed hydrodynamical models:

\[ \frac{E_{k1}}{E_{k2}} = \frac{\frac{2}{\tau_m} \times \frac{v_{\text{ph1}}}{} \times \frac{\kappa_1^{-1}}{}}{\frac{2}{\tau_m} \times \frac{v_{\text{ph2}}}{} \times \frac{\kappa_2^{-1}}{}} \]  

\[ \frac{M_{\text{ejc1}}}{M_{\text{ejc2}}} = \frac{\frac{2}{\tau_m} \times \frac{v_{\text{ph1}}}{} \times \frac{\kappa_1^{-2}}{}}{\frac{2}{\tau_m} \times \frac{v_{\text{ph2}}}{} \times \frac{\kappa_2^{-2}}{}} \]  

Where \( \tau_m \) is the diffusion time of the light curve, \( v_{\text{ph}} \) is the photospheric velocity at maximum light and \( \kappa \) is the optical opacity of the SN ejecta. Due to the difficulty in determining \( \kappa \) we have assumed that it is the same for both SNe. This assumption holds strong for SNe of the same classification type due to the similar elemental structure between the two SNe and becomes weaker as different types of SN are compared to one another. However, as we will be using only SE-SNe to obtain the ejecta mass and kinetic energy of SN 2020cpg the problem that arises from the use of SNe with different opacities should be minimised.

We compare SN 2020cpg with SN 1993J (Nomoto et al. 1993), SN 1994I (Sauer et al. 2006), SN 2002ap (Mazzali et al. 2002), SN 2003bg (Mazzali et al. 2009), SN 2004aw (Mazzali et al. 2017) and SN 2008D (Mazzali et al. 2008; Tanaka et al. 2009), all SE-SNe that have undergone hydrodynamical modelling. Since several of the above SNe, including SN 2020cpg, lack early time photometric data, it was not always possible to determine \( \tau_m \). Instead we used the width of the pseudo-bolometric light curve taken from 0.5 mag below peak light as an alternative to \( \tau_m \). Due to the width of the light curve being influenced by both the ejecta mass and kinetic energy, as shown in equation 1, this allowed for a direct comparison between the widths of the light curves and physical properties of SN 2020cpg and the modelled SE-SNe. The details on photospheric velocity and light curve widths for each SN along with the \( M_{\text{ejc}} \) and \( E_k \) of SN 2020cpg given by equation 2 and equation 3 are shown in Table 6.

We obtain physical parameters for SN 2020cpg using both the photospheric velocity at pseudo-bolometric peak, \( v_{\text{ph}}(t = \text{max}) \), for the individual SNe and the photospheric velocity at \( t = 16 \) days from the reported explosion date, \( v_{\text{ph}}(t = 16) \). We use \( v_{\text{ph}}(t = \text{max}) \) to break the degeneracy between the ejecta mass and kinetic energy as it would be the velocity of the photosphere when all of the light has diffused through the ejecta. \( v_{\text{ph}}(t = 16) \) was also used to compare different SNe at the point when SN 2020cpg had reached maximum pseudo-bolometric light, allowing a direct comparison between SNe to be made. The values for the physical parameters obtained from comparisons with hydrodynamical models are higher than those derived from using the Arnett-like model, as expected when comparing the Arnett-like model with hydrodynamical models. The main outlier in Table 6 is the properties predicted from the SN 2003bg, a hypernova, which despite having a relatively high kinetic energy possessed a low photospheric velocity at pseudo-bolometric peak, resulting in a low ejecta mass and large kinetic energy.

There is a clear trend in the ejecta mass and kinetic energy obtained using the PM13 method which arises from the type of SN that SN 2020cpg is compared to, with the He-rich SE-SNe resulting in a generally larger values while the values obtained from He-poor SNe are noticeably lower. As SN 2020cpg is a He-rich SN, we use the physical parameters obtained from the Type Ib and Ibc SNe to determine the values of the ejected mass, \( M_{\text{ejc}} \), and kinetic energy, \( E_k \), for SN 2020cpg. The value obtained using \( v_{\text{ph}}(t = 16) \) for the ejecta mass was \( 4.0 \pm 1.5 \, M_\odot \) and a kinetic energy of \( 5.0 \pm 2.0 \times 10^{51} \) erg. It should be noted that the PM13 model is limited in scope and should not be expected to predict values of both \( M_{\text{ejc}} \) and \( E_k \) to a precision greater than 0.5 \( M_\odot \) and 1.0 \( \times 10^{51} \) erg respectively. The values produced using \( v_{\text{ph}}(t = \text{max}) \) converge on the physical parameters with an average standard deviation of 1.85 while the \( v_{\text{ph}}(t = 16) \) has an average standard deviation of 1.89. This suggests that using the photospheric velocity at pseudo-bolometric peak for each SN converge on a value better than the photospheric velocity at SN 2020cpg pseudo-bolometric peak. The values for the ejecta mass and kinetic energy produced by the PM13 method are much higher than those predicted by the Arnett-like model, as expected due to the contribution of the helium envelope and the effect of having similar optical opacities. However, the ejecta mass derived from the PM13 method matches the value obtained by comparing the spectra of SN 2020cpg with the spectral models of Tefs et al. (2020), although the kinetic energy given by the modelling is lower than that predicted using the method from PM13.

The ejecta mass given by the spectral modelling and compar-
isolation with modelled SE-SNe has a value roughly double that given for Ib + Ib(I) and Ib + Ib(I) by Prentice et al. (2019) which take a mean value of $2.2 \pm 0.9 \, M_\odot$ and $2.7 \pm 1.0 \, M_\odot$ respectively. This places SN 2020cpg in the higher mass range of SE-SNe with only one H-rich and two H-poor SE-SNe having similar ejecta mass. The ejecta mass predicted by the Arnett-like model is closer to the mean values given by Prentice & Mazzali (2017) although still greater than the median, showing that by all standards SN 2020cpg was a more massive event than the typical SE-SNe. The lower ejecta mass estimated by the Arnett-like model is expected, as this has been seen in several SNe such as SN 2008D which was estimated to have an ejecta mass of $2.9^{+1.0}_{-0.6} \, M_\odot$ from an Arnett-like approach (Lyman et al. 2016) and $\sim 5 - 7 \, M_\odot$ from hydrodynamical modelling (Mazzali et al. 2008; Tanaka et al. 2009). When compared to the ejecta masses of the H-rich SE-SNe, SN 2020cpg lies in the region that has been associated with an extended progenitor. As the ejecta mass obtained using the comparative method of PM13 and the spectral modelling of Telfs et al. (2020) are in close agreement, we take the PM13 method as a valid replacement for the Arnett-like model to obtain the ejecta mass when dealing with SE-SNe. The PM13 method will also improve in the future as more SE-SNe undergo hydrodynamical modelling.

From the PM13 method the derived kinetic energy takes a value of $\sim 9.0 \times 10^{51} \, \text{erg}$ which is greater than both the spectral modelling and the Arnett-like model. This kinetic energy place SN 2020cpg on the border of the Hypernovae, which are thought to have kinetic energies on the order of $10^{52} \, \text{erg}$. The kinetic energy derived from spectral modelling tends towards a lower kinetic energy than the PM13 method, however, larger than the kinetic energy estimated by the Arnett-like model. The Arnett-like model derived a kinetic energy of $\sim 2.9 \times 10^{51} \, \text{erg}$ which is similar to the kinetic energy suggested by the spectral modelling. However, given the high $^{56}\text{Ni}$ mass the kinetic energy derived from the Arnett-like model is unlikely to be enough to synthesis the required amount of nickel.

From the derived ejecta mass, under the assumption that the progenitor did not collapse into a black hole but holds a $1.4 \, M_\odot$ neutron star, the progenitors core mass can be assumed to be $M_{\text{core}} + M_{\text{ejecta}} = M_{\text{total}} \approx 6.0 \pm 2.0 \, M_\odot$. Here we assumed that the mass of the outer envelope was $\sim 1.5 \, M_\odot$. This core mass is just higher than the majority of SE-SNe investigated in Prentice & Mazzali (2017) which takes a mean value $< 5 \, M_\odot$. A core mass of $6.0 \pm 2.0 \, M_\odot$ is thought to originate from a progenitor with an initial mass of $18 - 25 \, M_\odot$. (Sukhbold et al. 2016) suggests that the progenitor of SN 2020cpg would have had a high mass prior to explosion, within the range of $18 - 25 \, M_\odot$.

As mentioned earlier with the Arnett-like model, the opacity for both SN 2020cpg and the comparison SN is neither constant nor the same. To this end we used equation 1 to obtain an opacity for SN 2020cpg, which had a value of $\kappa_{\text{opt}} = 0.10 \pm 0.04 \, \text{cm}^2 \, \text{g}^{-1}$. Using the opacity for SN 2020cpg we then obtained the opacities of all the SE-SNe we compared with SN 2020cpg, which are shown in Table 7. As expected the He-rich SNe tend to have a lower opacity than the He-poor SNe, due to the fact that the helium present within the ejecta is virtually transparent to the optical photons. The opacity for SN 2008D has two values due to the different ejecta masses that we used. By looking at the opacities determined using the above method it is clear that a single time-independent value of the opacity should not be used for all types of SE-SNe, as done with the Arnett-like model discussed in Section 3.2.

### Table 7. Opacities derived from the SN 2020cpg opacity. There seems to be a trend with the He-rich SNe having a lower opacity than the He-poor SNe.

| SN       | Type      | Opacity [cm$^2$ g$^{-1}$] |
|----------|-----------|--------------------------|
| 03bg     | Ib-Hyper  | 0.27 ± 0.19              |
| 09J      | Ib        | 0.06 ± 0.04              |
| 08D      | Ib        | 0.08 ± 0.06              |
| 04aw     | Ic        | 0.13 ± 0.10              |
| 94l      | Ic        | 0.10 ± 0.08              |
| 02ap     | Ic-BL     | 0.19 ± 0.16              |

6 SUMMARY AND CONCLUSIONS

The study of SN 2020cpg and the discovery of the weak hydrogen features within the otherwise SN Ib-like spectra shows formation channels between SNe Ib and Ib are not as rigid as previously thought. From the coverage of SN 2020cpg we were able to compare the evolution of SN 2020cpg with several other SE-SNe. Photometrically, SN 2020cpg looks very similar to the Type Ib SN 2009jf in peak luminosity, although the light curve of SN 2020cpg is slightly broader compared to SN 2009jf. Spectroscopically SN 2020cpg initially looked similar to the Type Ib SN, such as SN 2015ap, with the main difference being the presence of the weak Hα feature within the spectra of SN 2020cpg. As the spectra evolve, the Hα feature becomes more dominant until it rivals the Hα 1.5876 feature in strength, making SN 2020cpg resemble more that of a Type Ib SN, such as SN 2011dh. Due to the weak Hα feature that is shown within the spectra of SN 2020cpg we believe that it was a Type Ib(I) SN. As the Hα feature grows in strength from the initial spectrum, we suggest that the hydrogen may have existed in a thin envelope as well as mixed into the outer layers of the helium shell prior to the explosion, which became more dominant as the photosphere receded through the mixed hydrogen/helium layer.

SN 2020cpg exploded producing an estimated Nickel mass of $\sim 0.3 \pm 0.1 \, M_\odot$ and from comparisons with hydrodynamic models of well studied He-rich SE-SNe an ejecta mass of $\sim 5.5 \pm 2.0 \, M_\odot$ and a kinetic energy of $\sim 9.0 \pm 3.0 \times 10^{51} \, \text{erg}$. From spectral modelling the amount of helium expected within the ejecta is $1.3 \, M_\odot$ with a further $0.1 \, M_\odot$ of hydrogen contained within the outer envelope with a large majority of it existing above a velocity of $\sim 15000 \, \text{km s}^{-1}$. From this modelling and the assumption that a neutron star remnant was formed, SN 2020cpg would have had a core mass of $M_{\text{core}} = 6.0 \pm 2.0 \, M_\odot$ which corresponds to a progenitor star with an initial mass of $M_{\text{ZAMS}} \approx 18 - 25 \, M_\odot$. Due to the distance to the host galaxy and the position of SN 2020cpg within the host galaxy, it is unlikely that there are any pre-explosion images of high enough quality to allow for the progenitor of SN 2020cpg to be determined. Further modelling of SN 2020cpg may give evidence for the progenitor however that is beyond the scope of this paper.

The use of the PM13 model provides an alternative approach to the Arnett-like model in determining the ejecta mass and kinetic energy of new SE-SNe. The PM13 method accounts for the effects of the heliump layer and the time dependency of the optical opacity, both of which are ignored in the Arnett-like approach. The PM13 model produces eject mass and kinetic energies that resemble those derived from comparison of optical spectra with spectral models, where as the Arnett-like approach seems to underestimate these values. Unlike the Arnett-like model, when used on SE-SNe the PM13 model requires several SNe of the same classification to constrain the ejecta mass and kinetic energy. This can lead to some outliers, like hypernovae, distorting the results. However as more
SE-SNe undergo hydrodynamical modelling the constraining power of the PM13 model increase and the effect the outliers have is reduced.

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**DATA AVAILABILITY**

Data will be made available on the Weizmann Interactive Supernova Data Repository (WISEREP) at https://wiserep.weizmann.ac.il/.

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Table A1. Apparent $BgVri$ LCO Photometry of SN 2020cpg, no k-correction or extinction correction applied.

| MJD$_B$ | B(err) | MJD$_g'$ | g'(err) | MJD$_V$ | V(err) | MJD$_r'$ | r'(err) | MJD$_i'$ | i'(err) |
|---------|--------|----------|--------|---------|--------|----------|--------|---------|--------|
| 58900.362 | 18.39(0.02) | 58901.544 | 18.55(0.09) | 58900.367 | 18.25(0.02) | 58904.501 | 18.49(0.08) | 58900.380 | 18.41(0.02) |
| 58900.364 | 18.37(0.02) | 58900.371 | 18.05(0.01) | 58900.369 | 18.28(0.02) | 58900.376 | 18.35(0.02) | 58900.382 | 18.40(0.02) |
| 58902.316 | 18.35(0.02) | 58900.374 | 18.20(0.01) | 58902.322 | 18.20(0.02) | 58900.378 | 18.24(0.02) | 58902.335 | 18.24(0.02) |
| 58902.319 | 18.36(0.02) | 58900.376 | 18.08(0.01) | 58902.324 | 18.18(0.02) | 58902.331 | 18.16(0.02) | 58902.336 | 18.22(0.02) |
| 58903.337 | 18.49(0.02) | 58902.328 | 18.06(0.01) | 58903.343 | 18.10(0.02) | 58903.333 | 18.14(0.02) | 58903.355 | 18.20(0.02) |
| 58903.340 | 18.45(0.02) | 58900.36 | 18.06(0.01) | 58903.345 | 18.08(0.02) | 58903.352 | 18.16(0.02) | 58903.357 | 18.17(0.02) |
| 58905.101 | 18.35(0.02) | 58903.349 | 18.07(0.01) | 58905.238 | 18.10(0.02) | 58903.354 | 18.13(0.02) | 58905.251 | 18.17(0.02) |
| 58905.233 | 18.39(0.02) | 58905.242 | 18.05(0.01) | 58905.240 | 18.11(0.02) | 58905.247 | 18.07(0.02) | 58905.253 | 18.18(0.02) |
| 58905.236 | 18.41(0.02) | 58905.245 | 18.06(0.01) | 58906.256 | 18.24(0.02) | 58905.249 | 18.09(0.02) | 58906.269 | 18.06(0.02) |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

This paper has been typeset from a TeX/LaTeX file prepared by the author.
Table A2. Apparent c+o band ATLAS photometry for SN 2020cpg. Photometry has not been corrected for either extinction or k-correction.

| MJD_c | c(err) [mag] | MJD_o | o(err) [mag] | MJD_o | o(err) [mag] |
|-------|--------------|-------|--------------|-------|--------------|
| 58903.464 | 18.10(0.06) | 58901.489 | 18.33(0.08) | 58953.488 | 19.32(0.17) |
| 58903.499 | 18.10(0.05) | 58901.493 | 18.23(0.07) | 58957.400 | 19.80(0.30) |
| 58903.503 | 18.19(0.06) | 58901.500 | 18.24(0.06) | 58957.412 | 19.59(0.20) |
| 58903.512 | 18.18(0.05) | 58901.511 | 18.22(0.06) | 58957.415 | 19.87(0.27) |
| 58911.503 | 18.13(0.05) | 58905.562 | 18.07(0.05) | 58961.441 | 19.38(0.16) |
| 58931.502 | 19.27(0.13) | 58905.565 | 18.09(0.05) | 58961.444 | 19.78(0.22) |
| 58931.522 | 19.59(0.17) | 58905.573 | 18.06(0.05) | 58961.465 | 19.67(0.21) |
| 58931.530 | 19.45(0.15) | 58905.583 | 18.10(0.05) | 58965.446 | 19.26(0.20) |
| 58931.539 | 19.46(0.16) | 58913.454 | 18.20(0.07) | 58965.457 | 19.73(0.29) |
| 58935.583 | 19.78(0.25) | 58913.458 | 18.10(0.06) | 58965.491 | 19.55(0.21) |
| 58935.586 | 19.55(0.21) | 58913.463 | 18.24(0.07) | 58969.404 | 20.12(0.30) |
| 58959.426 | 20.14(0.30) | 58913.477 | 18.19(0.07) | 58969.417 | 19.83(0.23) |
| 58959.430 | 19.66(0.19) | 58917.449 | 18.25(0.18) | 58969.421 | 20.02(0.27) |
| 58959.438 | 20.18(0.28) | 58917.457 | 18.32(0.19) | 58969.428 | 19.75(0.22) |
| 58959.455 | 20.05(0.27) | 58917.467 | 18.78(0.27) | 58971.423 | 19.68(0.26) |
| 58967.415 | 19.96(0.23) | 58925.533 | 18.70(0.21) | 58971.439 | 19.54(0.25) |
| 58967.425 | 20.10(0.26) | 58925.538 | 18.65(0.17) | 58977.446 | 19.21(0.28) |
| 58967.460 | 20.10(0.28) | 58933.537 | 19.36(0.18) | 58981.387 | 19.63(0.20) |
| 58982.391 | 20.06(0.25) | 58933.543 | 19.02(0.13) | 58981.404 | 20.07(0.30) |
| 58987.397 | 20.12(0.27) | 58933.547 | 19.14(0.15) | 58981.415 | 19.76(0.26) |
| 58933.559 | - - 58895.366 | 19.94(0.23) |
| 58937.496 | - - 58895.380 | 20.12(0.28) |
| 58937.498 | - - 58899.354 | 19.76(0.18) |
| 58937.508 | - - 58899.358 | 20.08(0.25) |
| 58937.522 | - - 58899.393 | 20.06(0.24) |
| 58941.433 | - - 58997.324 | 20.07(0.28) |
| 58941.445 | - - 58997.331 | 20.13(0.28) |
| 58941.448 | - - 58997.335 | 20.06(0.30) |
| 58941.463 | - - 58999.352 | 19.83(0.28) |
| 58943.479 | - - 58999.355 | 19.77(0.29) |
| 58943.484 | - - 59006.346 | 19.44(0.30) |
| 58949.477 | - - 59013.351 | 20.26(0.30) |
| 58949.482 | - - 59013.357 | 20.25(0.29) |
| 58951.461 | - - 59013.367 | 20.23(0.28) |
| 58951.469 | - - 59021.328 | 20.08(0.27) |
| 58951.482 | - - 59021.346 | 20.04(0.27) |
| 58953.467 | - - 59025.321 | 20.26(0.30) |
| 58953.474 | - - 59029.318 | 19.44(0.30) |
| 58953.478 | - - 59037.297 | 19.95(0.29) |