How much hydrogen is in Type Ib and IIb supernova progenitors?

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ABSTRACT

Core-collapse supernovae showing little or no hydrogen (denoted by Type IIb and Ib, respectively) are the explosions of massive stars that have lost some or most of their outer envelopes. How they lose their mass is unclear, but it likely involves binary interaction. So far, seven progenitors of such supernovae have been identified in pre-explosion imaging (five for Type IIb events and two for Type Ib events). Here, we evolve detailed binary stellar evolution models in order to better understand the nature of these progenitors. We find that the amount of hydrogen left in the envelope at the time of explosion greatly depends on the post-interaction mass-loss rate. The leftover hydrogen, in turn, strongly affects progenitor properties, such as temperature and photospheric radius, in non-trivial ways. Together with extinction and distance uncertainties in progenitor data, it is difficult to deduce an accurate progenitor hydrogen mass from pre-explosion imaging. We quantify this uncertainty and find that available data are consistent with a proposed Type Ib–IIb hydrogen mass threshold of $\approx 0.033 \, M_\odot$, implying that even Type Ib progenitors are not pure helium stars. These results alleviate the proposed tension between the Type Ib classification of SN 2019yvr and its candidate progenitor properties. We also estimate the brightness of a surviving 2019yvr progenitor companion, which might be detected in future observations.

Key words: stars: evolution – stars: massive – supernovae: general – supernovae: individual (SN 1993J, SN 2008ax, SN 2011dh, SN 2013df, iPTF13bvn, SN 2016gkg, SN 2019yvr)

1 INTRODUCTION

Type IIb supernovae (SNe) are explosive transients in which broad hydrogen lines are initially detected but then disappear, leading to a Type Ib SN appearance, for which no hydrogen is detected at all (Filippenko 1988; Nomoto et al. 1993). The explanation for this observed phenomenon is that a hydrogen envelope of a very low mass is present in Type Ib progenitors, while for Type Ib progenitors the envelope contains even less hydrogen, or none at all (Dessart et al. 2011).

A likely mechanism for removing the hydrogen envelope, or part of it, is the interaction between a massive star in a binary system and its companion (Podsiadlowski, Joss & Hsu 1992; Yoon, Woosley & Langer 2010; Claey et al. 2011; Yoon, Dessart & Clocchiatti 2017; Lohe et al. 2019, Saravan, Marchant & Kalogiera 2019, Naim et al. 2020). The minimal hydrogen mass which would give rise to a Type IIb appearance (vs. a Type Ib) is uncertain, with estimates varying between even a hydrogen mass of $0.001 \, M_\odot$ giving rise to a Type IIb appearance (Dessart et al. 2011) to a Ib–IIb threshold mass of $M_{\text{H,min}} \approx 0.033 \, M_\odot$ (Hachinger et al. 2012).

The nature of the progenitors of Type Ib and Type IIb SNe can be constrained by using pre-explosion photometry, when available. A total of five Type IIb SN progenitors have been identified, from SN 1993J (Podsiadlowski et al. 1993; Aldering, Humphreys & Rich-
and all Type Ib and Type IIn SN progenitors in a unified framework. We used detailed binary stellar-evolution simulations combined with synthetic photometry to find the best-fitting models for all progenitors in a uniform way, and we compare their properties.

In Section 2 we describe the main aspects of the stellar evolution simulations and the generation of synthetic photometry from the evolutionary endpoints. In Section 3 we describe the observational data that we fit our computed models to. In Section 4 we present our main findings, and discuss them in comparison to earlier works in Section 5. We summarize in Section 6.

2 NUMERICAL METHOD

2.1 Stellar evolution

We use the Modules for Experiments in Stellar Astrophysics code (mesa, version 10398, Paxton et al. 2011, 2013, 2015, 2018) to evolve stellar models. The methodology is the same as that of Gilkis et al. (2019), where more details can be found. In this work we expand the parameter space of the initial conditions, and describe the main aspects of the evolution.

We evolved stellar models with initial primary masses of \( M_1/M_\odot \in \{11, 12, 13, 14, 16, 19, 22, 25\} \), initial orbital periods of \( P/d \in \{5, 10, 18, 33, 60, 110, 201, 367, 669, 1219, 2223\} \), and four mass ratio ranges resulting in companion masses as listed in Table 1. The metallicity in our models is \( Z \), and all Type Ib and Type IIn SN progenitors in a unified framework. We used detailed binary stellar-evolution simulations combined with synthetic photometry to find the best-fitting models for all progenitors in a uniform way, and we compare their properties.

In Section 2 we describe the main aspects of the stellar evolution simulations and the generation of synthetic photometry from the evolutionary endpoints. In Section 3 we describe the observational data that we fit our computed models to. In Section 4 we present our main findings, and discuss them in comparison to earlier works in Section 5. We summarize in Section 6.

### Table 1. Initial masses for stellar evolution calculations.

| \( M_1/M_\odot \) | \( M_2/M_\odot \) | \( M_3/M_\odot \) | \( M_4/M_\odot \) | \( M_5/M_\odot \) |
|------------------|-----------------|-----------------|-----------------|-----------------|
| 11               | 10              | 9               | 7               | 4               |
| 12               | 11              | 10              | 8               | 5               |
| 13               | 12              | 11              | 8               | 5               |
| 14               | 13              | 12              | 9               | 5               |
| 16               | 15              | 14              | 10              | 6               |
| 19               | 18              | 16              | 12              | 7               |
| 22               | 21              | 19              | 14              | 8               |
| 25               | 24              | 22              | 16              | 9               |

Note. The second column lists the companion masses for simulations with a mass ratio within \( 0.9 < Q < 1 \), the third column lists the companion masses for simulations with \( 0.8 < Q < 0.9 \), the fourth column lists the companion masses for \( 0.6 < Q < 0.7 \) and the fifth column lists the companion masses for simulations with \( 0.35 < Q < 0.45 \).

2.1.2 Wind mass loss

For hot (effective surface temperatures of \( T_{\text{eff}} \geq 11000 \) K) phases of the evolution, wind mass loss follows the theoretical prescription of Vink, de Koter & Lamers (2001, hereafter V01) if the surface hydrogen mass fraction \( X_\text{e} \), \( X_\text{eff} \leq 0.4 \). For hydrogen-deficient envelopes with \( X_\text{eff} < 0.4 \) we use either the empirical mass-loss rate relation of Nugis & Lamers (2000, hereafter NL00) or the theoretical recipe provided by Vink (2017, hereafter V17), so that each evolution track which reaches \( X_\text{eff} < 0.4 \) is simulated twice, once with each of the prescriptions.

For cool \( (T_{\text{eff}} \leq 10000 \) K) phases of the evolution, the empirical relation given by de Jager, Nieuwenhuizen & van der Hucht (1988, hereafter dJ88) is employed. For \( 10000 \) K \( < T_{\text{eff}} < 11000 \) K the wind mass-loss rate is interpolated between the hot and cool prescriptions.

2.1.3 Mass transfer efficiency

Rather than assume an arbitrary constant mass transfer efficiency, we employ a physically motivated prescription which continuously updates the mass transfer efficiency during the stellar evolution computation, according to the ability of the companion star to accrete mass. More details are given by Gilkis et al. (2019).

2.1.4 Mixing

The Ledoux stability criterion is used to define convective regions, where mixing is treated according to mixing-length theory (MLT; Böhm-Vitense 1958; Henyey, Vardy & Bodenheimer 1965) with a mixing-length parameter of \( \alpha_{\text{MLT}} = 1.5 \). Overshooting above convective regions follows the exponentially decaying prescription of Herwig (2000), with a decay scale of \( f_{\text{ov}} H_F \), where \( f_{\text{ov}} = 0.016 \) and \( H_F \) is the pressure scale height. We employ the MLT++ treatment of MESA for superadiabatic convection (Paxton et al. 2013).

2.2 Synthetic photometry generation

In order to compare the endpoints of our stars to pre-SN observations, we generate synthetic photometry for the combined flux contribution of both components at each endpoint. We do not assume that the star is a blackbody at the end of its life, but instead we associate a spectrum to each stellar endpoint. For endpoints with associated spectra, we determine the synthetic photometry using synphot (STScI Development Team 2018). To associate a spectrum to each
For hot-star regime (15000 K ≤ $T_{\text{eff}}$ ≤ 55000 K) we use the synthetic spectra computed with the 

\texttt{tlusty} code (Lanz & Hubeny 2003, 2007). This regime uses two \texttt{tlusty} grids. For 15000 K ≤ $T_{\text{eff}}$ ≤ 30000 K the BSTAR2006 Galactic metallicity grid with a microturbulent velocity of $V_t = 2$ km s$^{-1}$ is used (Lanz & Hubeny 2007). For 30000 K < $T_{\text{eff}}$ ≤ 55000 K the OSTAR2002 Galactic metallicity grid with a microturbulent velocity of $V_t = 10$ km s$^{-1}$ is used (Lanz & Hubeny 2003). Each grid contains computed spectra for several different effective temperatures and surface gravity values, $g$. Synthetic photometry for stellar evolution endpoints with no corresponding spectrum in the grid are calculated using a two-dimensional interpolation between the nearest four spectra with pairs of $T_{\text{eff}}$ and $g$ values in the grid. Some of the endpoints in our simulations have a surface gravity slightly lower than the lowest value for which a \texttt{tlusty} synthetic spectrum is available. For these cases we perform a one-dimensional interpolation between nearby available points in the grid (see Appendix A).

For the WR regime (55000 K < $T_{\text{eff}}$) we use synthetic spectra computed with the \texttt{rowx} code (Gräfener, Koesterke & Hamann 2002; Hamann & Gräfener 2003; Sander et al. 2015). We use the MW WNE and MW WN-L20 grids presented by Todt et al. (2015). The former are used for models with $X_e < 0.05$, and the latter for $X_e \geq 0.05$. Each grid contains synthetic spectra for several effective temperatures and transformed radii (Schmutz, Hamann & Wesolowski 1989) defined as

\[
R_e = R_\odot \left( \frac{v_{\infty}/2500 \text{ km s}^{-1}}{\sqrt{DM/10^{-4} M_\odot \text{ yr}^{-1}}} \right)^{2/3},
\]

where $R_e$ is the stellar radius, $v_{\infty}$ the terminal wind velocity, $M$ the wind mass-loss rate and $D$ the so-called clumping factor which allows for an inhomogeneous wind density. Models with $X_e < 0.05$ (MW WNE grid) have $v_{\infty} = 1600$ km s$^{-1}$, while models with $X_e \geq 0.05$ (MW WN-L20 grid) have $v_{\infty} = 1000$ km s$^{-1}$. All models use $D = 4$. The stellar evolution endpoints are assigned magnitudes by a two-dimensional interpolation between the nearest four pairs of $T_{\text{eff}}$ and $R_e$.

Each spectrum is subjected to extinction according to the reddening model given by Cardelli, Clayton & Mathis (1989). We vary the extinction parameter $A_V$ from 0.035 to 3.5 in steps of 0.035, and the reddening-law parameter $R_V$ from 2 to 6 in steps of 0.1. In total, each stellar evolution endpoint is assigned synthetic magnitudes for 4100 combinations of $A_V$ and $R_V$ in every relevant filter (later, when comparing to observations, we choose only the subset of extinction values consistent with the $E(B-V)$ ranges presented in the literature for each progenitor, see below). We apply this extinction to account for the combined contributions of the Milky Way and the supernova host.

3 OBSERVATIONAL DATA

Here we list the sources of observational data for pre- and post-explosion photometry (when available) which we fit our models to. We summarise the observed pre-explosion magnitudes, the dust reddening parameter $E(B-V)$ and host galaxy distance of the SN progenitors in Table 2. We do not attempt to fit post-explosion photometry to a surviving companion model because of the various possible contributions to the post-explosion flux, such as from the SN itself, its remnant, or a light echo (see, for example Fox et al. 2014 regarding SN 1993J). We do require that the companion star in our models not violate any upper limits derived from post-explosion observations. In Table 3 we summarise the post-explosion upper limits which we adopt for five SNe.

SN 1993J (IIb)

We use the pre-explosion photometry of SN 1993J from Aldering et al. (1994). We follow Maund et al. (2004) and take the distance to the host galaxy of SN 1993J, M81, to be $d = 3.63 \pm 0.14$ Mpc from the Cepheid distance modulus (Ferrarese et al. 2000). We set the range of the dust reddening parameter $E(B-V)$ to 0.2 mag ≤ $A_V$ ≤ 1 mag (Matheson et al. 2000) and $R_V = 3.1$.

Post-explosion observations of SN 1993J (Maund et al. 2004; Fox et al. 2014) can supply additional information on the surviving companion. Fox et al. (2014) discuss the various contributions to the flux at the SN site 20 years after the explosion, and suggest that the companion might be observed in the far UV, while the flux in longer wavelengths results from the fading SN. As mentioned above, we do not try to fit the post-explosion UV data, but we rather take the brighter bounds from the magnitudes reported by Fox et al. (2014) as upper limits on the flux contribution of the surviving companion (Table 3).

SN 2008ax (IIb)

The progenitor of SN 2008ax has been studied by Crockett et al. (2008) and Folatelli et al. (2015). We take the pre-explosion magnitudes from Folatelli et al. (2015), who revised the analysis of Crockett et al. (2008) by using high-resolution post-explosion images to subtract nearby contaminating stellar sources. We adopt the distance of $d = 7.77 \pm 1.54$ Mpc to the host galaxy of SN 2008ax, NGC 4490, following Folatelli et al. (2015). We take a host galaxy reddening of $E(B-V)_{\text{host}} = 0.3 \pm 0.1$ mag (Crockett et al. 2008; Folatelli et al. 2015) and neglect the small Milky Way contribution of $E(B-V)_{\text{MW}} = 0.019$ mag (Schlafly & Finkbeiner 2011). Folatelli et al. (2015) provide post-explosion upper limits on the remaining companion (listed in Table 3), which we include in our analysis.

SN 2011dh (IIb)

The pre-explosion photometry for SN 2011dh is taken from Maund et al. (2011). We follow Ergon et al. (2014) in adopting a distance of $d = 7.88^{+1.13}_{-0.99}$ Mpc to the host galaxy of SN 2011dh, the Whirlpool Galaxy, and in taking a total dust reddening of $E(B-V)_{\text{MAX}} = 0.07^{+0.07}_{-0.04}$ mag. Maund (2019) used a light echo to isolate the flux contribution of a surviving companion. We take the upper limit in
Table 2. Pre-explosion magnitudes, dust extinction and host galaxy distance.

| SN    | $U$    | $B$    | $V$    | $R$    | $I$    | $E(B-V)/$mag | $d$/Mpc |
|-------|--------|--------|--------|--------|--------|--------------|---------|
| 1993J | $21.45 \pm 0.2$ | $21.73 \pm 0.07$ | $20.6 \pm 0.16$ | $19.87 \pm 0.11$ | $19.43 \pm 0.17$ | $0.193^{+0.129}_{-0.129}$ | $3.63 \pm 0.14$ |
| 2008ax| $> 22.9$  | $24.14 \pm 0.22$ | $23.85 \pm 0.42$ | $23.61 \pm 0.22$ | $0.3^{+0.1}_{-0.1}$ | $7.77 \pm 1.54$  |
| 2011dh| $23.39 \pm 0.25$ | $22.36 \pm 0.02$ | $21.83 \pm 0.04$ | $21.28 \pm 0.04$ | $21.2 \pm 0.03$ | $0.07^{+0.07}_{-0.04}$ | $7.9 \pm 1.0$  |
| 2013df| $> 25.65$  | $24.535 \pm 0.071$ | $23.144 \pm 0.055$ | $0.0968^{+0.0061}_{-0.0061}$ | $16.6 \pm 0.4$ |
| iPTF13bnvE | $25.8 \pm 0.12$ | $25.8 \pm 0.11$ | $25.88 \pm 0.24$ | $12.37 \pm 0.04$ | $26.7 \pm 2.5$ |
| iPTF13bnvF | $25.99 \pm 0.14$ | $26.06 \pm 0.13$ | $25.82 \pm 0.12$ | $12.37 \pm 0.04$ | $26.7 \pm 2.5$ |
| 2016gkg| $24.46 \pm 0.22$ | $24.31 \pm 0.18$ | $24.02 \pm 0.2$ | $10.071^{+0.008}_{-0.003}$ | $26.4 \pm 5.3$ |
| 2019yvr| $26.2882 \pm 0.1622$ | $25.3812 \pm 0.0319$ | $24.7471 \pm 0.0221$ | $23.8333 \pm 0.0319$ | $0.53^{+0.27}_{-0.16}$ | $14.4 \pm 1.3$ |

Notes. HST $U$ filters: F300W (2008ax), F336W (2011dh), HST $B$ filters: F435W (2011dh, iPTF13bnv), F438W (2019yvr), F439W (2013df), F450W (2008ax, 2016gkg); HST $V$ filter: F555W (2011dh, 2013df, iPTF13bnv, 2019yvr); HST $R$ filters: F606W (2008ax, 2016gkg), F625W (2019yvr), F658N (2011dh); HST $I$ filter: F814W (2008ax, 2011dh, 2013df, iPTF13bnv, 2016gkg, 2019yvr).

Table 3. Upper limits we consider from post-explosion data.

| SN    | $F218W$ | $F225W$ | $F275W$ | $F336W$ | $F438W$ | $F439W$ | $F450W$ | $F555W$ | $F606W$ | $F814W$ | $F850LP$ | $F105W$ | $F125W$ | $F160W$ |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1993J | $> 21.62$ | $> 21.599$ | $> 22.234$ | $> 22.563$ | $> 21.493$ | $> 21.366$ | $> 20.876$ | $> 21.371$ | $> 18.686$ | $> 19.519$ | $> 19.374$ |
| 2008ax| $> 25.6$  | $> 25.7$  | $> 26.6$  | $> 26.9$  | $> 26.3$  | $> 26.4$  | $> 26.2$  | $> 25.8$  | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ |
| iPTF13bnvE | $> 26.4$  | $> 26.48$ | $> 26.64$ | $> 25.88$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ |
| iPTF13bnvF | $> 26.4$  | $> 26.64$ | $> 25.88$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ |
| 2016gkg| $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ | $> 24.49$ |

Note. All values are given in Vega magnitudes.

the F435W filter, and treat the brighter bounds reported by Maund (2019) in the F225W and F336W filters as upper limits (Table 3).

SN 2013df (IIb)

The pre-explosion photometry for SN 2013df is taken from Van Dyk et al. (2014). The Cepheid-based distance, $d = 16.6 \pm 0.4$ Mpc, to the host galaxy of SN 2013df, NGC 4414, is taken from Freedman et al. (2001). We follow Van Dyk et al. (2014) and take a total dust extinction of $A_V = 0.3 \pm 0.05$ mag, which translates to $E(B-V) = 0.0968 \pm 0.0161$ mag for $R_V = 3.1$.

iPTF13bnv (Ib)

We consider two sets of photometry estimates for iPTF13bnv, one from Eldridge et al. (2015) and one from Folatelli et al. (2016). Eldridge & Maund (2016) report post-explosion observations of iPTF13bnv, from which we take the brighter bounds as upper limits on the flux contribution of the companion star that we include in our analysis (Table 3). Folatelli et al. (2016) also report post-SN observations of iPTF13bnv, from which we take the upper limit in the F225W filter and treat the brighter bounds in the F438W, F555W and F814W filters as upper limits (Table 3). Our analysis of iPTF13bnv is performed once with the combination of the pre-SN photometry form Eldridge et al. (2015) and the post-SN photometry of Eldridge & Maund (2016) (denoted iPTF13bnvE) and a second time with the pre-SN and post-SN photometry reported by Folatelli et al. (2016) (denoted iPTF13bnvF).

SN 2016gkg (IIb)

We take the pre-explosion photometry for SN 2016gkg from Kilpatrick et al. (2021a), transformed from their AB magnitudes to Vega magnitudes. Similarly to Kilpatrick et al. (2017), we take from Nasonova, de Freitas Pacheco & Karachentsev (2011) the distance $d = 26.4 \pm 5.3$ Mpc to the host galaxy of SN 2016gkg, NGC 613. We follow Arcavi et al. (2017) and adopt a host galaxy reddening of $E(B-V)_{\text{host}} = 0.09^{+0.08}_{-0.06}$ mag, which together with a Milky Way extinction of $A_{V,\text{MW}} = 0.053$ mag (Schlafly & Finkbeiner 2011) and $R_V = 3.1$ gives $E(B-V) = 0.1071^{+0.066}_{-0.039}$ mag. Kilpatrick et al. (2021a) report late-time observations of SN 2016gkg from which we take the upper limit in the F275W filter, and treat the brighter bounds in the F438W and F606W filters as upper limits (Table 3), transformed from their AB magnitudes to Vega magnitudes.

MNRA 000, 1–17 (2022)
SN 2019yvr (Ib)

We take the pre-explosion photometry from Kilpatrick et al. (2021b), transformed from their AB magnitudes to Vega magnitudes. We follow Kilpatrick et al. (2021b) and adopt a distance of \( d = 14.4 \pm 1.3 \) Mpc to the host galaxy of SN 2019yvr, NGC 4666, derived from the light curve of the Type Ia SN ASASSN-14lp which occurred in the same galaxy (Shappee et al. 2016). Kilpatrick et al. (2021b) find from the colour curves of SN 2019yvr a host reddening of \( E(B - V)_{\text{host}} = 0.51^{+0.27}_{-0.16} \) mag. Together with the Milky Way contribution of \( E(B - V)_{\text{MW}} = 0.02 \) mag (Schlafly & Finkbeiner 2011) we have \( E(B - V) = 0.53^{+0.27}_{-0.16} \) mag.

4 RESULTS

4.1 Endpoints of stellar evolution simulations

Of the 352 combinations of initial conditions (detailed in Section 4), 191 reached a point where \( T_{\text{eff}} > 10000 \) K and \( X_H < 0.4 \) along their evolution, and were therefore simulated twice, for the two hot hydrogen-deficient wind schemes. Of the 543 simulations that we ran, 49 encountered numerical problems or entered common envelope evolution (CEE; where the orbital separation becomes smaller than the sum of the two stellar radii) before the end of the simulation and were discounted. In total, we have 494 useful binary evolution tracks, which reached the end of core carbon burning. The endpoints of the stellar evolution are shown in Figure 1. Models are classified according to their effective surface temperature and surface hydrogen mass fraction, as follows:

- Red supergiant (RSG): \( T_{\text{eff}} \leq 4.8 \) kK, \( 0.01 \leq X_H \);
- Yellow supergiant (YSG): \( 4.8 \) kK < \( T_{\text{eff}} \) < \( 7.5 \) kK, \( 0.01 \leq X_H \);
- Blue supergiant (BSG): \( 7.5 \) kK < \( T_{\text{eff}} \) < \( 55 \) kK, \( 0.01 \leq X_H \);
- Hot helium giant (HeG): \( 15 \) kK < \( T_{\text{eff}} \) < \( 55 \) kK, \( X_H < 0.01 \);
- Cool helium giant: \( T_{\text{eff}} < 15 \) kK, \( X_H < 0.01 \);
- Early nitrogen-sequence WR (WNE): \( 55 \) kK < \( T_{\text{eff}} \), \( X_H < 0.05 \);
- Late nitrogen-sequence WR (WNL): \( 55 \) kK < \( T_{\text{eff}} \), \( 0.05 \leq X_H \).

Wolf-Rayet (WR) stars can appear also in carbon- or oxygen-sequences if their surface nitrogen mass fractions are low enough, though this does not occur in our models. Although the WR phenomenon is not defined by temperature, but rather by the wind mass loss and corresponding transformed radius (Eq. 1), for the evolution endpoints our definition by temperature suffices. We consider models with a metallicity close to (or slightly above) Galactic Galactic WR stars have a minimum luminosity of \( L_{\text{WR}}^{\text{min}} \approx 10^{4.9} L_\odot \) (Shenar et al. 2020). We do not have models with \( L < L_{\text{WR}}^{\text{min}} \) and \( T_{\text{eff}} > 55 \) kK. The reason that our simple temperature threshold for WR stars works is that we are looking at the final evolutionary stage, after the end of core carbon burning, and a significant expansion and cooling of the outer layers. During earlier phases, such as core helium burning, the models ultimately classified as helium giants were more compact and hotter (\( T_{\text{eff}} > 55 \) kK) but should probably not have been given a WR classification.

The models classified as WNE stars or as helium giants all result from evolutionary tracks which employed the NL00 wind scheme. The vast majority of models classified as WNL stars result from evolutionary tracks which employed the V17 wind scheme. The minimal leftover hydrogen mass among the V17 models is \( M_H \approx 10^{-4} M_\odot \) (with a corresponding surface hydrogen mass fraction of \( X_H = 0.01 \)), while most of the NL00 models have \( M_H < 10^{-4} M_\odot \).

The leftover hydrogen mass in the envelope strongly affects the stellar radius, as we show in Figure 2. For \( M_H \geq 0.1 M_\odot \), there is a tight relation between \( M_H \) and \( R \), while for lower \( M_H \), the general trend is similar though there is a large spread corresponding to differences in luminosity, with higher luminosity corresponding to smaller radii at a given \( M_H \). The high sensitivity of the stellar radius to the leftover hydrogen mass shown in Figure 2 indicates the importance of covering a large number of models in the relevant parameter space of initial conditions.

As explained by Gilkis et al. (2019), the mass transfer efficiency during Roche-lobe overflow (RLOF) is computed continuously during the evolution according to the thermal timescale of the accreting star and its size relative to its own Roche lobe. While the efficiency of mass transfer does not impact much the mass lost from the donor star and its subsequent evolution and final characteristics, the companion star is greatly affected. This is of interest if the companion star contributes a non-negligible fraction of the flux in pre-explosion images, or if we have post-explosion photometry (Appendix B). The mean effective mass transfer efficiency that results from the custom mass transfer efficiency prescription of Gilkis et al. (2019) is presented in Figure 3. The main parameter which lowers the mass transfer efficiency is the mass of the companion star, with lower companion masses resulting in low efficiencies because of the limited ability of the relatively low-mass stars to accrete material at the rate it is lost from the primary star during RLOF. Overall, the resulting effective mass transfer efficiency strongly depends on the mass ratio, with the efficiency increasing as the initial mass of the companion approaches that of the primary.

4.2 Best-fitting progenitor models

For each SN progenitor, we find the best-fitting progenitor model by finding the minimal \( \chi^2 \), computed as

\[
\chi^2 = \sum_{\lambda} \left( \frac{m_{\lambda}^{\text{obs}} - m_{\lambda}^{\text{calc}}}{\Delta m_{\lambda}^{\text{obs}}} \right)^2, \tag{2}
\]

where \( m_{\lambda}^{\text{obs}} \) and \( \Delta m_{\lambda}^{\text{obs}} \) are the magnitudes and their errors from Table 2, \( m_{\lambda}^{\text{calc}} \) are the computed magnitudes, and \( \lambda \) denotes the various filters. We compute \( m_{\lambda}^{\text{calc}} \) in four different approaches to dust extinction: (i) setting the reddening law parameter fixed at \( R_V = 3.1 \) and \( E(B - V) \) fixed at the nominal value from Table 2 for each SN; (ii) setting \( R_V = 3.1 \) and allowing \( E(B - V) \) to vary within the range defined by the errors; (iii) allowing the reddening law parameter to vary in \( 2 \leq R_V \leq 6 \) and keeping \( E(B - V) \) at the nominal value; and (iv) allowing both \( R_V \) and \( E(B - V) \) to vary within the ranges described above. For each computed evolutionary endpoint and each dust extinction approach we find the distance \( d \) (within the distance estimates of each SN) which minimises the \( \chi^2 \) in Equation (2), as long as the upper limits as detailed in Table 3 are not violated.

The comparison between the computed magnitudes for the best-fitting models and the observed magnitudes for all SN progenitors is presented in Figure 4. For the progenitors of SN 2008ax, iPTF13bvn

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2 While writing this paper, new photometry for SN 2019yvr was published by Sun et al. (2022). This photometry is very similar to that of Kilpatrick et al. (2021b) in the three shorter-wavelength filters, and is slightly fainter in F814W. This difference will have a negligible effect on our results and conclusions and therefore we stay with the Kilpatrick et al. (2021b) data.

3 While both wind schemes cannot be correct simultaneously, we pool all tracks together so that our analysis will cover as much of the progenitor property parameter space as possible, and also to allow us to directly compare the suitableness of the two schemes.
Figure 1. Hertzsprung–Russell diagram for the stellar evolution endpoints of the primary star in all computed models.

Figure 2. Stellar radius as a function of total hydrogen mass for the stellar evolution endpoints of the primary star in all computed models.

Figure 3. Mean effective mass transfer efficiency as a function of initial orbital period for the different mass ratio regimes, where $Q \equiv M_2/M_1$ is the mass ratio. Each point is an average over all initial primary masses and both wind schemes and the error bars denote the standard deviation. The points for the longest initial orbital periods and lowest companion masses are not shown because of a very low success rate of simulations for those initial conditions, with most of the evolutionary tracks entering CEE phases.

and SN 2016gkg a good fit is easily found for all approaches. The UV excess of the SN 1993J progenitor is not reproduced well in any model. For SN 2011dh, allowing $R_V$ and $E(B-V)$ to vary significantly improves the best fit, while for SN 2013df just varying $R_V$ helps. For the progenitor of SN 2019yvr, allowing either $R_V$ or $E(B-V)$, or both, to vary allows a better fit compared to keeping $R_V$ and $E(B-V)$ fixed.

We repeated the analysis for our two Type Ib’s, SN 2019yvr and iPTF13bvn, a couple of times, limiting the model set once to evolutionary endpoints with $M_H < 0.033 M_\odot$, and a second time with $M_H < 0.001 M_\odot$. The result for SN 2019yvr with the $M_H < 0.033 M_\odot$ constraint is shown in Figure 5, where a good fit is possible if both $R_V$ and $E(B-V)$ are allowed to vary. When aggravating the constraint to $M_H < 0.001 M_\odot$, no reasonable fits are found for SN 2019yvr. For iPTF13bvn, requiring $M_H < 0.033 M_\odot$ has no effect on the best-fitting models, while taking $M_H < 0.001 M_\odot$ markedly reduces the quality of the best-fitting models, increasing $\chi^2$. For iPTF13bvn, the best-fitting models with fixed $R_V$ have $M_H <
0.033 $M_\odot$, while allowing $R_V$ to vary results in better fits for models with $M_H < 0.044 M_\odot$ and higher $R_V$. Requiring $M_H < 0.001 M_\odot$ has a smaller effect on the fit quality for the iPTF13bvn $F$ photometry than the same requirement for iPTF13bvn $E$.

To show not only the best-fitting models but all those with relatively low $\chi^2$, we colour-code all models according to their computed $\chi^2$, in Figure 6, for the seven SNe. For the computation of $\chi^2$ as marked in Figure 6 we chose the fourth approach to dust extinction, as described above, allowing both $R_V$ and $E(B-V)$ to vary. The details for all best-fitting models are presented in Table 4.
Table 4. Details of best-fitting models.

| SN    | $M_1/M_0$ | $M_2/M_0$ | $P_i/d$ | $M_3/M_0$ | $M_4/M_0$ | log($T_{\text{eff}}$/K) | log($L/L_\odot$) | $R_V$ | $E(B - V)$/mag | wind | ST$^a$ |
|-------|-----------|-----------|---------|-----------|-----------|--------------------------|------------------|-------|----------------|------|--------|
| 1993J | 16        | 15        | 1219    | 5.43      | 0.114     | 3.71                     | 5.07             | 3.1   | 0.1935        |      | YSG    |
| 1993J | 16        | 15        | 1219    | 5.43      | 0.114     | 3.71                     | 5.07             | 3.1   | 0.2145        |      | YSG    |
| 1993J | 19        | 18        | 669     | 6.47      | 0.233     | 3.7                      | 5.17             | 5.3   | 0.1935        |      | YSG    |
| 1993J | 19        | 18        | 669     | 6.47      | 0.233     | 3.7                      | 5.17             | 6     | 0.1458        |      | YSG    |
| 2008ax| 13        | 5         | 60      | 3.59      | 0.016     | 4.16                     | 4.81             | 3.1   | 0.3           | V17  | BSG    |
| 2008ax| 22        | 8         | 110     | 7.14      | 0.02      | 4.22                     | 5.29             | 3.1   | 0.35          |      | YSG    |
| 2008ax| 11        | 7         | 367     | 2.72      | 4 x 10^{-5}| 4.1                      | 4.54             | 2     | 0.3           | NL00 | HeG    |
| 2008ax| 22        | 8         | 110     | 7.14      | 0.02      | 4.22                     | 5.29             | 2.5   | 0.378         |      | BSG    |
| 2011dh| 14        | 9         | 367     | 4.3       | 0.043     | 3.83                     | 4.93             | 3.1   | 0.07          | V17  | YSG    |
| 2011dh| 14        | 9         | 367     | 4.3       | 0.043     | 3.83                     | 4.93             | 3.1   | 0.1129        |      | YSG    |
| 2011dh| 14        | 9         | 367     | 4.3       | 0.043     | 3.83                     | 4.93             | 4.8   | 0.07          |      | YSG    |
| 2011dh| 22        | 8         | 2223    | 7.64      | 0.142     | 3.81                     | 5.3              | 4.8   | 0.1385        |      | YSG    |
| 2013df| 12        | 8         | 669     | 3.46      | 0.065     | 3.66                     | 4.76             | 3.1   | 0.9968        |      | RSG    |
| 2013df| 12        | 8         | 669     | 3.46      | 0.065     | 3.66                     | 4.76             | 3.1   | 0.1016        |      | RSG    |
| 2013df| 13        | 12        | 669     | 4.04      | 0.126     | 3.64                     | 4.87             | 5.6   | 0.9968        |      | RSG    |
| 2013df| 13        | 12        | 669     | 4.04      | 0.126     | 3.64                     | 4.87             | 5.6   | 0.1063        |      | RSG    |
| iPTF13bvnE| 25  | 9         | 60      | 8.54      | 0.028     | 4.34                     | 5.4              | 3.1   | 0.1237        |      | BSG    |
| iPTF13bvnE| 25  | 9         | 60      | 8.54      | 0.028     | 4.34                     | 5.4              | 3.1   | 0.1242        |      | BSG    |
| iPTF13bvnE| 25  | 9         | 60      | 8.54      | 0.028     | 4.34                     | 5.4              | 2.2   | 0.1237        |      | BSG    |
| iPTF13bvnE| 25  | 9         | 60      | 8.54      | 0.028     | 4.34                     | 5.4              | 2     | 0.14          |      | BSG    |
| iPTF13bvnE| 14  | 12        | 10      | 4.1       | 0.029     | 4.13                     | 4.9              | 3.1   | 0.1237        |      | BSG    |
| iPTF13bvnE| 14  | 12        | 10      | 4.1       | 0.029     | 4.13                     | 4.9              | 3.1   | 0.1242        |      | BSG    |
| iPTF13bvnE| 16  | 10        | 201     | 5.16      | 0.044     | 4.17                     | 5.05             | 5.9   | 0.1237        |      | BSG    |
| iPTF13bvnE| 16  | 10        | 201     | 5.16      | 0.044     | 4.17                     | 5.05             | 6     | 0.1283        |      | BSG    |
| 2016kg| 22       | 14        | 110     | 7.23      | 0.038     | 3.96                     | 5.29             | 3.1   | 0.1071        |      | YSG    |
| 2016kg| 22       | 8         | 367     | 7.22      | 0.034     | 4                      | 5.29             | 3.1   | 0.1581        |      | YSG    |
| 2016kg| 22       | 21        | 60      | 7.21      | 0.037     | 3.97                     | 5.29             | 6     | 0.1071        |      | YSG    |
| 2016kg| 25       | 22        | 60      | 8.55      | 0.045     | 4.05                     | 5.4              | 6     | 0.1517        |      | YSG    |
| 2019yr| 12       | 11        | 110     | 3.3       | 0.03      | 3.73                     | 4.73             | 3.1   | 0.53          | V17  | YSG    |
| 2019yr| 19       | 12        | 201     | 5.82      | 0.051     | 3.83                     | 5.14             | 3.1   | 0.7903        |      | YSG    |
| 2019yr| 22       | 8         | 2223    | 7.64      | 0.142     | 3.81                     | 5.3              | 5.6   | 0.53          |      | YSG    |
| 2019yr| 19       | 12        | 201     | 5.82      | 0.051     | 3.83                     | 5.14             | 3.2   | 0.7766        |      | YSG    |

Notes. For each SN the first line is for fixed $R_V$ and $E(B - V)$, the second line is for fixed $R_V$ and variable $E(B - V)$, the third line is for variable $R_V$ and fixed $E(B - V)$ and the fourth line is for variable $R_V$ and $E(B - V)$. Models which have $X_e > 0.4$ in the wind column did not have any point in their evolution where $T_{\text{eff}} > 10000$ K and $X_e < 0.4$, and therefore neither the NL00 wind scheme nor the V17 was employed. $^a$ Stellar Type (defined in Section 4.1).

Figure 5. Computed magnitudes for best-fitting models compared to the observed magnitudes, showing only models with $M_4 < 0.033 M_0$ allowed for SN 2019yr.

4.3 Monte Carlo realisations

We employ a Monte Carlo realisations approach to estimate the sensitivity of the observations to the progenitor properties. For each SN progenitor, we generate 100 mock observations by assuming a normal distribution for each observable with the nominal value as the mean and the error as the standard deviation. For each generated mock observation, we find the evolutionary endpoint and distance which minimise $\sum (m_{\text{obs,mock}} - m_{\text{obs}})^2$, where $m_{\text{obs,mock}}$ are the mock observation magnitudes. Similarly to Section 4.2, we employ four different approaches to dust extinction. The best-fitting models obtained using the fourth dust extinction approach, where both $R_V$ and $E(B - V)$ are allowed to vary, are presented in Figure 7. Each panel shows the observed magnitudes as well as all 100 synthetic photometry models that were found to fit best the mock observations generated as described above. Each synthetic photometry model represents one evolutionary endpoint, with adjustments according to dust and distance. One endpoint can appear numerous times, with different distance and dust values. By counting the number of appear-
Figure 6. Hydrogen mass as a function of effective surface temperature for the primary star in all models, with colours denoting the value of $\chi^2 - \chi^2_{\text{min}}$. Each evolutionary endpoint is marked with a circle whose size is proportional to the stellar radius.

Ance of an evolutionary endpoint (out of 100) we derive statistics for the derived progenitor properties, such as effective surface temperature, luminosity, total hydrogen mass and radius, as well as evolutionary parameters like mass transfer efficiency and wind mass-loss rates. For example, we find that the progenitors of SN 1993J and SN 2016gkg prefer a high mass transfer efficiency ($\approx 0.9$), while SN 2008ax, SN 2011dh and SN 2013df prefer a lower mass transfer efficiency ($< 0.35$). No strong preference was found for the progenitors of the Type Ib events iPTF13bvn or SN 2019yvr.

All model magnitudes plotted in Figure 7 are the combinations...
Figure 7. Observed pre-explosion magnitudes (thick black lines with error bars) and upper limits (black triangles) compared to best-fitting models to mock observations generated by Monte Carlo realisations (thin grey lines).

of contributions from the primary star and from its companion. The contribution of the companion alone is of interest when considering post-SN observations, whether these have already been done, or will be obtained in the future. We plot the computed companion magnitudes in the best-fitting models for SN 2019yvr in Figure 8 (the computed companion magnitudes for the five SNe with post-SN upper limits are presented in Appendix B), and show the mean and error of our predicted magnitudes for the companion in each filter wavelength. We predict the surviving companion to have an apparent magnitude between 32 and 27 Vega magnitudes.

The likelihood distributions for the stellar radius and the hydrogen mass, for the fourth dust extinction approach as described in Section
Table 5. Effective surface temperature, luminosity, total hydrogen mass and stellar radius and their standard deviations, and occurrences of stellar types (defined in Section 4.1) and wind schemes in fits to Monte Carlo realisations.

| SN     | log$_{10}(T_{\text{eff}}/K)$ | log$_{10}(L/L_\odot)$ | log$_{10}(M_1/M_\odot)$ | log$_{10}(R/R_\odot)$ | RSG | YSG | BSG | HeG | WR | $X_e \geq 0.4$ | V17 | NL00 |
|--------|-----------------------------|-----------------------|--------------------------|-----------------------|-----|-----|-----|-----|----|----------------|-----|------|
| 1993J  | $3.71 \pm 0.01$             | $5.07 \pm 0.04$       | $-0.95 \pm 0.08$         | $2.63 \pm 0.03$       | 0   | 0   | 0   | 0   | 0  | 0              | 0   | 0    |
| 2008ax | $4.1 \pm 0.16$              | $4.8 \pm 0.34$        | $-5.26 \pm 6.38$         | $1.72 \pm 0.17$       | 0   | 0   | 75  | 0   | 22 | $3 \pm 25$    | 0   | 0    |
| iPTF13bvn | $2.09 \pm 0.15$        | $3.23 \pm 0.29$       | $-1.36 \pm 0.24$         | $2.41 \pm 0.07$       | 68  | 16  | 0   | 0   | 0  | 0              | 0   | 0    |

Note. For each SN the first line is for fixed $R_V$ and $E(B-V)$, the second line is for fixed $R_V$ and variable $E(B-V)$, the third line is for variable $R_V$ and fixed $E(B-V)$ and the fourth line is for variable $R_V$ and $E(B-V)$.

Figure 8. Computed magnitudes of the companion star from our Monte Carlo best-fitting models for SN 2019yvr, obtained with variable $E(B-V)$ and $R_V$. The mean computed surviving magnitudes of the companion and their standard deviation are shown in light blue.

4.2, are presented in Figure 9. The likelihood distribution of all models is also shown, for reference. This is simply the number of computed models in each bin, i.e., all models are assumed equally likely. We do not convolve these results with the various observational estimates of the probability distributions of initial masses (e.g., Kroupa 1995; Salpeter 2001), or binary parameters such as mass ratios or orbital periods (e.g., Sana et al. 2012; Moe & Di Stefano 2017). The likelihood distributions of the progenitor properties are computed by counting the number of best-fitting models out of the 100 obtained from fitting the Monte Carlo realisations of the observations.

In Figure 10 we present the stellar radii and hydrogen masses and their standard deviations for all four dust extinction approaches and for all SN progenitors except SN 2008ax and iPTF13bvn, for which the possibility of hydrogen-free progenitors (Table 5) causes an extremely large variance in the hydrogen mass estimate. The luminosity and effective surface temperature and their standard deviations are presented in Figure 11. Each SN progenitor is plotted four times, for the four different dust extinction approaches. The progenitors of SN 1993J and SN 2013af are the coolest and largest, while those of SN 2008ax and iPTF13bvn are the hottest and most compact. The progenitor of SN 2016kg is relatively compact, in agreement
with Arcavi et al. (2017). The properties derived for the progenitor candidate of SN 2019yvr show the highest sensitivity to the assumptions on dust, especially the luminosity and the total hydrogen mass, with the derived effective surface temperature and radius less affected. The effective surface temperature, luminosity, leftover hydrogen mass and stellar radius (and their standard deviations), and the numbers of occurrences of stellar types and wind schemes, are listed in Table 5.

For each endpoint we computed the mass lost from the system in the last $\approx 1000$ yr of the evolution to derive an average mass-loss rate. In Figure 12 we compare the distribution of the average mass-loss rate in the best-fitting models for each SN to constraints on mass lost in the last 10-10000 yr before the explosion obtained from obser-
Figure 10. Mean progenitor stellar radius vs. mean hydrogen mass and their standard deviations. The primary components in all computed stellar models are also shown, for reference.

Figure 11. Mean luminosity and mean effective surface temperature with their standard deviations for all SN progenitors. The primary components in all computed stellar models are also shown, for reference.
10000 K is computed by the V17 or NL00 prescription if V01 prescription otherwise (see Sections 2.1.2 and 4.1).

Progenitors of Type Ib SNe (iPTF13bvn and SN 2019yvr) contain less hydrogen in their envelopes compared to all the Type Ib progenitors. If this is the case, the tension between the Type Ib classification of SN 2019yvr and its progenitor properties, as claimed by Kilpatrick et al. (2021b), is lessened.

The binary progenitor models considered by Kilpatrick et al. (2021b) were computed with the mass code (Eldridge et al., 2017), with the best-fitting models resulting from CEE of systems in which the companion has a significantly lower mass than the primary star. Our models do not cover this part of the parameter space, and have initial companion masses $M_2 > 0.35M_\odot$. However, we do find reasonable fits in the part of the parameter space that we do cover, where mass transfer is stable. The disparate results obtained by using two separate stellar evolution codes might arise from the relation between the hydrogen mass and the envelope radius being sensitive to certain aspects of the code, like the EOS and opacities. We defer the expansion of our parameter space to include CEE to a future study.

Kilpatrick et al. (2021b) discuss the possibility that the progenitor of SN 2019yvr had a radiation dominated inflated envelope. Our models include the MLT++ treatment of MESA, which suppresses super-Eddington regions stabilized by density inversions in an inflated envelope. If MLT++ is disabled, an inflated envelope can form near the end of the computed stellar evolution, with a large radius and a smaller hydrogen mass compared to that obtained with the MLT++ treatment. This further reduces the tension between the progenitor properties of SN 2019yvr and its Type Ib classification, though the feasibility of this scenario depends on the stability of density inversions in stellar envelopes.

Our analysis and hydrogen mass estimates are derived solely from the progenitor photometry, and are independent from the explosion characteristics and the observed SN spectra. However, we did check the implications of limiting the progenitor models included in finding a best fit according to theoretical SN computations. When taking the threshold of $M_{\text{Hmin,IIb}} \approx 0.033 M_\odot$ given by Hachinger et al. (2012), we find no significant reduction in the quality of the fits for iPTF13bvn and SN 2019yvr. However, when taking a threshold of $M_{\text{Hmin,IIb}} \approx 0.001 M_\odot$ (consistent with Dessart et al., 2011), we find it difficult to fit any model to the progenitor of SN 2019yvr, and the quality of the fits for the progenitor of iPTF13bvn are reduced. We can therefore claim that our analysis favors the higher value for the threshold hydrogen mass differentiating between Type Ib and Type Ib SNe. Speculating further, it is possible that most Type Ib SNe are actually hydrogen deficient but not hydrogen free, and that theoretical “pure helium stars” might not be required for progenitors of Type Ib SNe.

5 DISCUSSION

5.1 Progenitor properties

We find that the effective surface temperatures of the SN progenitors are well constrained by the photometry, in general agreement with earlier studies (Table 6). Yoon et al. (2017), for example, classify the progenitors of SN 2008ax and SN 2016gkg as BSGs, the progenitor of SN 2011dh as a YSG, and the progenitors of SN 1993J and SN 2013df as RSGs. Our results are almost the same (Table 4), with the only exception the progenitor temperature for SN 1993J as a YSG. However, the effective surface temperature for SN 1993J is found very near the boundary between the definitions of RSGs and YSGs, and within the uncertainty a classification of RSG is acceptable (Table 5).

The progenitor of iPTF13bvn is classified as a BSG, and it is consistently hotter than all other progenitors. For SN 2019yvr, we find a YSG progenitor, with an effective surface temperature almost identical to that of the progenitor of SN 2011dh (Tables 4 and 5).

While the effective surface temperature is not much affected by the assumptions on dust extinction, the luminosity experiences more variance. This is especially the case for SN 2019yvr, which is the most heavily extinguished SN. Because of the non-trivial relation between the hydrogen mass and the progenitor size (Figure 2), the uncertainty in luminosity results also in an uncertainty in the hydrogen mass. Within the uncertainties, it is plausible that the two
largest freedom in the dust extinction parameters. It is possible that
allowing an even lower mass transfer efficiency than that resulting
from our prescription would have eased the fitting procedure.

5.3 Wind mass loss

We find that the best-fit models have a preference not to include the 
NL00 mass-loss prescription (Table 4 and Table 5). In one case 
for SN 2008ax where the best-fit model was evolved with the NL00 
prescription, the leftover hydrogen mass is too low to qualify as a 
Type Ib SN. Optically thin winds are more favorable in producing 
Type Ib and Type Iib SN progenitors, and optically thick WR-
like winds do not result in progenitor properties as observed for these SNe. However, the sample size is rather small, with only five 
Type Iib SN progenitors identified, and only two for Type Ib SNe (with SN 2019yvr still too recent to confirm its progenitor). Still, the 
role of the assumed mass-loss rate during the post-RLOF stage is 
crucial, as already asserted by Gilkis et al. (2019).

Björklund et al. (2021) give a revised mass-loss prescription for 
O-type stars in the Galaxy and the Magellanic Clouds, which is 
genерally lower than Vink et al. (2001), and also with no bi-stability 
jump. For WR stars, the rate prescription given by Nugis & Lamers 
(2000) is outdated compared to the prescriptions given by Hainich 
et al. (2014) and Tramper, Sana & de Koter (2016), which have been 
adopted by Yoon (2017) and Woosley (2019). For RSGs, Beasor et al. 
(2020) derive mass-loss rates which are significantly lower than the 
dJ88 prescription that we use. Our models include binary 
interactions and in many cases mass loss occurs through RLOF dur-
ing cool phases, but a lower RSG mass-loss rate might still have an 
effect. However, we expect this effect to be most pronounced for 
hydrogen-rich Type IIP SNe, which we do not discuss here.

Late-time post-SN observations indicate that interaction with cir-
cumstellar material takes place, and the mass loss preceding the SN 
can be estimated. We compare the observational constraints for the 
six earlier SNe to the derived mass-loss rate (averaged over the last 
1000 yr of evolution) in our best-fitting Monte Carlo models (Figure 
12) and find a general agreement in most cases. Our models tend 
to underestimate the mass-loss rate, and this is especially the case 
for SN 1993J and SN 2013df. The mass lost in the late evolutionary 
stages is mostly from stellar winds, and not from RLOF. Significant

mass loss from the system by inefficient RLOF mass transfer occurs 
only at early evolutionary stages, when the mass of the envelope is 
large. Although many evolutionary endpoints fill their Roche lobe, 
by this stage the mass ratio has usually been inverted, and the mass 
transfer rate is and almost fully conservative according to our 
prescription for the mass transfer efficiency.

5.4 Metallicity

As stated in Section 2.1, the metallicity in all our stellar evolution 
simulations is $Z = 0.019$, which is close to Solar. Metallicity can 
affect the evolution through opacity, with lower metallicity models 
reaching smaller radii and therefore losing less of their envelope 
through RLOF (Göttberg, de Mink & Groh 2017). Remaining hy-
drogen can lead to a large radial expansion prior to core collapse 
(Laplace et al. 2020), with a tenuous low-mass envelope, as sug-
gested for some Type Ib SNe (e.g., SN 2011dh; Bersten et al. 2012). 
Another effect of a lower metallicity is reduced mass-loss rates, with 
all three hot-wind rates used in our simulations (NL00, V01, V17) 
strongly depending on metallicity.

Solar metallicity is inferred for the progenitors of SN 2011dh 
(Maund et al. 2011), SN 2013df (Van Dyk et al. 2014), iPTF13bvn 
(Fremling et al. 2016) and SN 2016ckg (Bersten et al. 2018). The 
metallicity of the progenitor of SN 1993J is suggested to be between 
the Large Magellanic Cloud and Solar. For SN 2019yvr, Kilpatrick et al. 
(2021b) assume Solar metallicity for the progenitor, while Sun et al. 
(2022) derive a slightly lower metallicity. We conclude that the metallicity 
used in our simulations is consistent with what is known for the SN 
progenitors that we study.

6 SUMMARY AND CONCLUSIONS

We have systematically investigated the properties of Type Ib and 
Type Iib SN progenitors by using detailed binary stellar evolution 
simulations, synthetic photometry, and Monte Carlo random realisations 
of the observations. We validate our analysis by comparing the 
derived progenitor properties to previous studies, finding a general

| SN         | $\log_{10}(T_{\text{eff}}/K)$ | $\log_{10}(L/L_\odot)$ | $\log_{10}(T_{\text{eff}}/K)_{\text{literature}}$ | $\log_{10}(L/L_\odot)_{\text{literature}}$ |
|------------|-------------------------------|------------------------|-----------------------------------------------|-----------------------------------------------|
| SN 1993J (Ib) | 3.73 ± 0.02                  | 5.19 ± 0.17            | 3.63 ± 0.05                                    | 5.1 ± 0.3                                    |
| SN 2008ax (Ib) | 4.16 ± 0.1                   | 4.95 ± 0.22            | 4.09 ± 0.21                                    | 4.855 ± 0.445                                |
| SN 2011dh (Iib) | 3.79 ± 0.01                  | 4.92 ± 0.18            | 3.779 ± 0.02                                   | 4.945 ± 0.045                                |
| SN 2013df (Ib) | 3.64 ± 0.01                  | 4.87 ± 0.04            | 3.628 ± 0.01                                   | 4.94 ± 0.06                                  |
| SN 2016ckg (Iib) | 4.02 ± 0.11                  | 5.28 ± 0.16            | 3.978 ± 0.15                                   | 4.985 ± 0.335                                |
| iPTF13bvn (Ib) | 4.29 ± 0.09                  | 5.26 ± 0.16            | 4.06 ± 0.04                                    | 4.6 ± 0.1                                    |
| iPTF13bvn (Ib) | 4.18 ± 0.1                   | 5.01 ± 0.28            | 4.06 ± 0.04                                    | 4.6 ± 0.1                                    |
| SN 2019yvr (Ib) | 3.83 ± 0.05                  | 5.19 ± 0.17            | 3.833 ± 0.025                                  | 5.3 ± 0.2                                    |

Notes. The literature values for the five Type Ib progenitors are taken from Yoon et al. (2017), who compiled results from several sources (Aldering et al. 1994; Maund et al. 2004, 2011; Van Dyk et al. 2011, 2014; Bersten et al. 2012; Folatelli et al. 2015; Arcavi et al. 2017; Kilpatrick et al. 2017; Tartaglia et al. 2017). The literature values for iPTF13bvn are taken from Eldridge & Maund (2016). Our higher temperature for the progenitor of this event is more consistent with that of Bersten et al. (2014) and our higher luminosity is due in part to our larger assumed distance. The literature values for SN 2019yvr are taken from Kilpatrick et al. (2021b). Our $T_{\text{eff}}$ and $L$ estimates are for variable $E(B - V)$ and $R_V$ (fourth row for each SN in Table 5).
agreement with massive stars partially stripped by binary interaction as the progenitors of Type Ib and Type IIb SNe. We apply a uniform analysis to all seven known Type Ib and Type IIb SN progenitors (six confirmed, one candidate) to establish a coherent picture of their evolution.

Several key points are emphasised:

(i) A small amount (mass) of hydrogen has a significant effect on the progenitor radius (Figure 2). The relation between $M_H$ and $R$ is non-trivial, with less luminous stellar models reaching larger radii for a certain hydrogen mass. Owing to the uncertainty in both the distance to the host galaxy and the amount of dust extinction, there is therefore a non-negligible error on the derived hydrogen mass (Figure 10).

(ii) According to our analysis it is plausible that the progenitors of iPTF13bvn and SN 2019yvr contained less hydrogen than all known Type IIb SN progenitors, alleviating the proposed tension between the Type Ib classification of SN 2019yvr and its progenitor properties (Kilpatrick et al. 2021b), and mitigating the need for special scenarios to get rid of the progenitor envelope in the short duration between the pre-explosion observation and the SN itself. Our results are in tentative agreement with a mass threshold for a Type Ib appearance close to $M_{H,\text{min,ib}} \approx 0.033 M_\odot$ (Hachinger et al. 2012), but inconsistent with the findings of Dessart et al. (2011) that even $0.001 M_\odot$ of hydrogen in the exploding envelope would be enough to result in a type IIb SN.

(iii) The best-fitting models prefer evolutionary pathways which include optically thin winds (Vink et al. 2001; Vink 2017) rather than optically thick WR-like winds (Nugis & Lamers 2000), and a non-negligible leftover hydrogen mass. Even for the Type Ib SN progenitors, the progenitor is not a “pure helium star”, but is probably more accurately classified as a CSG. The assumptions on post-RLOF wind mass loss are therefore crucial for understanding the evolution towards Type Ib and Type IIb SNe (Gilkis et al. 2019).

(iv) We predict that a faint ($V$-band apparent magnitude of $\approx 30$) companion will remain and that the YSG progenitor candidate will disappear in future observations of SN 2019yvr. We note that there are alternative scenarios, such as a hot progenitor reddened by an optically-thick wind (Jung, Yoon & Kim 2021), which will also result in the progenitor candidate disappearing in the future, or that the YSG is a companion to the true progenitor (Sun et al. 2022), in which case a luminous counterpart will remain at the SN site in future observations.

The differences between progenitors of Type Ib and Type IIb SNe might offer a valuable opportunity to test key points in SN physics in the evolution of massive stars. Processes such as stellar winds, mass transfer in binaries and CEE might be crucial for analysing the progenitors of CCSNe. In our study we made use of one set of stellar models, where only one key aspect, post-RLOF winds, was explored (and to a lesser extent also the mass transfer efficiency). Even so, we find distinct implications for the assumed mass loss prescription. In future studies our systematic approach can be expanded to investigate additional stellar evolution issues, to cover a larger parameter space of initial conditions, and also to include constraints from the SN explosion and additional post-SN constraints.

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DATA AVAILABILITY STATEMENT

The code and input files necessary to reproduce our simulations and associated data products are available at https://doi.org/10.5281/zenodo.5897214.

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APPENDIX A: COVERAGE OF SPECTRAL GRIDS

Here we present the physical properties associated with all spectra used for the generation of synthetic photometry. In Figure A1 we show the luminosity and effective surface temperature for which Pickles (1998) spectra are available and mark the points used to generate synthetic photometry. In Figure A2 we show the gravity and effective surface temperature for which we have TLUSTY spectra and specify the region for which a one-dimensional interpolation is described in Section 2.2 is performed. In Figure A3 we show the transformed radius and effective surface temperature for which we have row synthetic spectra and the stellar models for which WR spectra are used for synthetic photometry generation.

APPENDIX B: COMPANION MAGNITUDES

Here we present the flux contribution of the companion star in our models. In Figure B1 we present the computed magnitudes (generated from the synthetic photometry) decomposed to the two stellar components in each best-fitting model. The flux contribution of the companion star is usually a few percent of the total flux in all filters, with the highest contribution in the bluest filter. For the case of SN 1993J the contribution in the filter reaches about a third of the total flux (Figure B2).

In Figure B3 we plot the magnitudes of the companion star from our Monte Carlo best-fitting models compared to the available post-SN limits. We do this for the SNe with post-SN measurements listed in Table 3.
Figure A1. Luminosity and effective surface temperature for which spectra are available (from Pickles 1998, shown as yellow circles) and for all computed models with $T_{\text{eff}} \leq 10^4.95$ K (primaries shown as blue dots and companions as orange crosses). The dash-dotted black line connects the sequence of spectra used for synthetic photometry interpolation.

Figure A2. Gravity and effective surface temperature for which TLUSTY synthetic spectra are available (O-star grid points shown as yellow squares, B-star grid points shown as purple circles) and for all computed models in the range $10^{3.5}$ K $\leq T_{\text{eff}} \leq 10^{5}$ K (primaries shown as blue dots and companions as orange crosses). Models beyond the grid limits (black line) with $15$ kK $\leq T_{\text{eff}} \leq 55$ kK are assigned synthetic photometry by interpolation between the grid points marked by maroon asterisks.
Figure A3. Transformed radius (Eq. 1) and effective surface temperature for which rowr synthetic spectra are available and for progenitor models with $T_{\text{eff}} > 55\,\text{kK}$ (models with $X_\text{H} \geq 0.05$ obtained with the V17 mass-loss rate marked as orange pluses, models with $X_\text{H} \geq 0.05$ obtained with the NL00 mass-loss rate marked as yellow crosses and models with $X_\text{H} < 0.05$ marked as green asterisks).
Figure B1. Computed magnitudes for best-fitting models, obtained with variable $E(B - V)$ and $R_V$, decomposed to the two stellar components.
Figure B2. The flux contribution from the companion in best-fitting models.
Figure B3. Computed magnitudes of the companion star from our Monte Carlo best-fitting models, obtained with variable $E(B-V)$ and $R_V$, and observational data (where available). Most of the observed late-time flux of SN 1993J is attributed to the (still fading) SN remnant (Fox et al. 2014), with perhaps only some of the UV flux resulting from the companion.