Progenitors of Type IIb Supernovae. I. Evolutionary Pathways and Rates

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Abstract

Type IIb supernovae (SNe) are important candidates to understand mechanisms that drive the stripping of stripped-envelope (SE) supernova (SN) progenitors. While binary interactions and their high incidence are generally cited to favor them as SN IIb progenitors, this idea has not been tested using models covering a broad parameter space. In this paper, we use non-rotating single- and binary-star models at solar and low metallicities spanning a wide parameter space in primary mass, mass ratio, orbital period, and mass transfer efficiencies. We find that our single- and binary-star models contribute to roughly equally, however small, numbers of SNe IIb at solar metallicity. Binaries only dominate as progenitors at low metallicity. We also find that our models can account for less than half of the observationally inferred rate for SNe IIb at solar metallicity, with computed rates \( \lesssim 4\% \) of core-collapse (CC) SNe. On the other hand, our models can account for the rates currently indicated by observations at low metallicity, with computed rates as high as 15\% of CC SNe. However, this requires low mass transfer efficiencies (\( \lesssim 0.1 \)) to prevent most progenitors from entering contact. We suggest that the stellar wind mass-loss rates at solar metallicity used in our models are too high. Lower mass-loss rates would widen the parameter space for binary SNe IIb at solar metallicity by allowing stars that initiate mass transfer earlier in their evolution to reach CC without getting fully stripped.

Key words: binaries: general – stars: evolution – stars: general – stars: massive – supergiants – supernovae: general

1. Introduction

CC SNe are explosions marking the deaths of stars with zero-age main-sequence (ZAMS) masses \( \gtrsim 8M_\odot \) (see, e.g., Smartt 2009, for a recent review). Depending on the absence or presence of hydrogen lines in the supernova spectrum, SNe are classified as Type I or Type II, respectively. The absence of hydrogen features in a Type I CC SN spectrum is attributed to a progenitor star that lacks its outer hydrogen layers. SN IIb progenitors exhibit “mild” stripping of their outer layers, initially exhibiting prominent hydrogen spectral features that weaken and disappear in the weeks following explosion. Type I CC (also known as Type Ibc) and SNe IIb are therefore also referred to as SE SNe. The mechanisms that drive the stripping and regimes in which they dominate are still open questions. The leading candidates are close binary interactions (e.g., Podsiaowski et al. 1992; Yoon et al. 2010, 2017), stellar winds (e.g., Woosley et al. 1993; Georgy et al. 2012; Groh et al. 2013b; Soker 2017), stellar rotation (e.g., Georgy et al. 2012; Groh et al. 2013a, 2013b), and nuclear burning instabilities (e.g., Arnett & Meakin 2011; Strotjohann et al. 2015).

Binary interactions were initially the favored channel to strip stars due to the high observed binarity of Wolf–Rayet (WR) stars (Kuhi 1973). However, with spectroscopic UV observations indicating strong stellar winds, sufficient to strip stars (Chiosi et al. 1978), they became the preferred channel. The trend is now appearing to be reversing, with binary interactions gaining traction as the preferred formation channel. This is due to a variety of pieces of evidence. First, clumping in stellar winds suggest that currently used mass-loss rates are too high; hot wind mass-loss rates are lower by a factor of 2–3 than those typically used in stellar evolution calculations (Smith 2014; but also see Vink & Gräfener 2012). Second, recent observations indicate that massive stars are predominantly part of close binary systems (Sana et al. 2012; Kubulnicky et al. 2014; Moe & Di Stefano 2017). Third, observed SE SN rates are too high to be explained solely by single-star evolution (Smith et al. 2011). Fourth, pre-SN masses estimated from light curves indicate lower ZAMS mass for SE SN progenitors than those that produce WR stars via the single-star channel (Lyman et al. 2016; Prentice et al. 2019). Finally, in many cases circumstellar medium densities for SE SNe inferred from X-ray/radio observations indicate pre-SN mass-loss rates higher than WR winds (Wellons et al. 2012; Drout et al. 2016), implying additional mass-loss processes being active close to CC.

Type IIb SNe are of particular interest in understanding formation channels to SE SNe because of a few reasons. First, they are the only class within the group that has several (five) identified progenitors. Second, there is evidence for the presence of a binary companion to the progenitor in three cases (Folatelli et al. 2014a; Fox et al. 2014; Ryder et al. 2018). Finally, SNe IIb are quite abundant, accounting for 10\%–12\% of all CCSNe and 30\%–40\% of all SE SNe (Li et al. 2011; Smith et al. 2011; Shiverers et al. 2017).

SN 1993J is the prototypical SN IIb. A progenitor candidate was identified in ground-based pre-explosion images by Aldering et al. (1994). They also found that its SED had a blue component, which they attributed to either an OB association or a binary companion. Late-time observations of the region have provided stronger evidence for the presence of a putative companion star (Maund et al. 2004; Fox et al. 2014). SN 1993J is the best-studied SN IIb to date, in part due to its proximity, as it is the subject of several observational and theoretical investigations. Since 1993, putative progenitors of
four more SNe IIb have been identified in pre-explosion images: SN 2008ax (Crockett et al. 2008; Folatelli et al. 2015), SN 2011dh (Maund et al. 2011; Van Dyk et al. 2011; Benvenuto et al. 2013), SN 2013df (Van Dyk et al. 2014; Maeda et al. 2015), and SN 2016gkg (Kilpatrick et al. 2017; Tartaglia et al. 2017; Bersten et al. 2018). There is also evidence for binary companions to the progenitors of SN 1993J (Fox et al. 2014), SN 2001ig (Ryder et al. 2018), and SN 2011dh (Folatelli et al. 2014a). The Galactic supernova remnant, Cassiopeia A, is known to be the result of an SN IIb from light echo spectra (Krause et al. 2008; Rest et al. 2011). However, there is no companion even at deep limits (Kerzendorf et al. 2019; Kochanek 2018).

With the discovery of more events, there were efforts, both observational and theoretical, to understand the population of SNe IIb. On the observational side, Chevalier & Soderberg (2010) studied a sample of SNe IIb and suggested that they can be further classified into two sub-types based on their radio SN shock velocities; compact and extended SNe IIb progenitors exhibit high and low velocities, respectively. However, this suggestion was quickly challenged by the discovery of SN 2011dh exhibiting both rapidly expanding radio shells (Soderberg et al. 2012) and an extended yellow supergiant progenitor (Folatelli et al. 2014a). Folatelli et al. (2014b) suggested that some SNe Ib/c were spectroscopically more similar to SNe IIb. More recently, Liu et al. (2016) found a continuum in the signatures of SN IIb and Ib spectra.

Most early theoretical investigations into progenitors of and evolutionary pathways to Type Ib focused on SN 1993J (e.g., Podsiadlowski et al. 1993; Woosley et al. 1994; Maund et al. 2004; Stancliffe & Eldridge 2009). Yoon et al. (2010) and Dessart et al. (2011) studied progenitors of Type Ib/c SNe arising as a result of mass transfer in close binary systems and found that some of their Type Ib SN progenitors exploded with small amounts of residual hydrogen. They suggested that these progenitors may be classified as SNe IIb if detected soon after explosion. Georgy (2012) and Groh et al. (2013a) used solar-metallicity single-star, non-rotating and rotating models and identified their 20–25M\(_\odot\) rotating models as potential SN IIb progenitors.

Clayes et al. (2011) performed the first parameter space search for single and binary progenitors of SNe IIb using detailed evolutionary calculations. However, they restricted their binary parameter space to initial primary masses 15M\(_\odot\)–30M\(_\odot\), initial secondary masses 10M\(_\odot\)–15M\(_\odot\), initial orbital periods 800–2100 days, and solar metallicity. While they were able to analyze various evolutionary pathways to SNe IIb and their outcomes, they were unable to compute robust relative rates because of their limited parameter space coverage. As we show in this paper, the parameter space for binary SNe IIb varies significantly with initial primary mass. Another limitation is that they restrict their analysis to progenitors that explode with 0.1–0.5M\(_\odot\) of residual hydrogen envelope. This excludes the group of more compact SN Ib progenitors suggested from analyses of SN IIb light curves (Morales-Garoffolo et al. 2014; Tartaglia et al. 2017; Bersten et al. 2018) and detailed non-LTE radiation hydrodynamical calculations (Dessart et al. 2018). Recently, Yoon et al. (2017) undertook a wide parameter space search for binary Type Ib and Ib SN progenitors using detailed evolutionary calculations, varying the initial primary-star mass from 10 to 18M\(_\odot\), initial orbital period from 10–3000 days, but keeping the initial mass ratio (=0.9) and mass transfer efficiency (=0.2) constant. They analyze SN Ib progenitors at two different metallicities, Z = 0.007 and solar, and show that the parameter space for SNe IIb broadens significantly when lowering metallicity and that its effect is roughly analogous to lowering the wind mass-loss rate. However, their parameter space coverage precludes them from computing case C SNe IIb (mass transfer after core helium exhaustion), SN IIb relative rates, and statistical progenitor properties.

Motivated by these gaps in theoretical analyses, in a two-paper study, we investigate the progenitors (their evolutionary pathways, rates, and properties) of SNe IIb (henceforth referred to as SNe IIb) using a comprehensive parameter space coverage and statistical analysis. Our study yields a comprehensive database of full evolutionary histories of non-rotating single- and binary-star progenitors of SNe IIb at solar and sub-solar metallicities. This paper is dedicated to investigating the parameter space and evolutionary pathways to SNe IIb. In addition, our parameter space coverage allows us to compute theoretical SN IIb rates. The second paper will be dedicated to investigating the observable properties of SN IIb progenitors presented here.

This paper is organized as follows. In Section 2, we provide a detailed description of our models. In Section 3, we discuss key evolutionary channels, and governing physics, toward SNe IIb. In Section 4, we describe the parameter space for SN IIb progenitors at solar and sub-solar metallicities. In Section 5, we provide theoretical rates for SNe IIb as a fraction of CC SNe. We discuss our results and conclude in Section 6. We present numerical tests in the Appendix.

2. Stellar Models

We use Modules for Experiments in Stellar Astrophysics (MESA Release 9575; Paxton et al. 2011, 2013, 2015, 2018) to compute a large grid of non-rotating single- and binary-star models at solar (Z\(_\odot\)) and 1/4 solar (which we henceforth refer to as “low metallicity”) metallicities. We choose the latter to represent nearby low-metallicity environments, i.e., between the Large and Small Magellanic Cloud metallicities. We adopt the value\(^4\) of Z\(_0\) = 0.02 to allow comparison of our results with earlier studies. We assume that helium abundance increases linearly from its primordial value Y = 0.2477 (Peimbert et al. 2007) at Z = 0.0 to Y = 0.28 at Z = 0.02 (Brott et al. 2011) and compute radiative opacities using tables from the OPAL project (Iglesias & Rogers 1996). In the following, we summarize the properties of our models.

We use the basic.net, co_burn.net, and approx21.net nuclear networks in MESA. The basic.net network includes eight isotopes \(^1\)H, \(^3\)He, \(^4\)He, \(^{12}\)C, \(^{14}\)N, \(^{16}\)O, \(^{20}\)Ne, and \(^{24}\)Mg to model both hydrogen and helium burning, with missing isotopes in the PP and CNO chains being accounted for by assuming equilibrium abundances. The co_burn.net network adds \(^{28}\)Si as well as various reactions relevant to carbon and oxygen burning, while the isotope network approx21.net includes an \(\alpha\) chain up to \(^{56}\)Ni and is meant to model late burning stages. We have verified that our results are not sensitive to our choice of nuclear network, with larger networks producing equivalent results. Reaction rates are taken from Angulo et al. (1999) and Caughlan & Fowler (1988), with preference given to the latter for rates reported in both.

\(^4\) We note that the exact value of Z\(_0\) is not settled (see, e.g., Asplund et al. 2009; Vagnozzi et al. 2017).
We model convection using the standard mixing-length theory (MLT; Böhm-Vitense 1958; Cox & Giuli 1968), adopting the Ledoux criterion, with the mixing-length parameter, \( \alpha_{\text{MLT}} \), set to 1.5 which is the MESA default. Calibrations done for low and intermediate-mass stars indicate values closer to \( \alpha_{\text{MLT}} = 2 \) (see Stancliffe et al. 2016), but these differences do not have a significant impact on our results; testing some of our SN Iib models using \( \alpha_{\text{MLT}} = 2 \) leads to differences in progenitor pre-SN effective temperatures of only \( \pm 10\% \). During late stages of massive star evolution, regions in convective envelopes can approach the Eddington limit with convective velocities nearing sound speed, which is inconsistent with the assumptions of standard MLT. Since the treatment of the physics in these regimes is a subject of active research, we currently employ a different treatment of convection in MESA, known as MLT++ (Section 7.2 in Paxton et al. 2013), which artificially reduces the super-adiabacity in these regions, implying unspecified additional energy transport.

We include step overshooting by extending the hydrogen-burning convective core boundary determined by the Ledoux criterion by 0.335 of \( H_\odot \) (Brott et al. 2011). This value was calibrated using observations of LMC stars with masses \( \sim 15M_\odot \), making it a more appropriate choice compared to smaller values derived from intermediate-mass eclipsing binaries (Stancliffe et al. 2015). We assume negligible overshooting for all other convective regions. Semi-convection occurs when a region that is unstable according to the Schwarzschild criterion is stabilized by a composition gradient. It has an important yet ill-constrained effect on the evolution of massive stars (Langer 1991). MESA uses the formulation of Langer et al. (1983) to model semi-convection. We adopt the value of the dimensionless free-parameter \( \alpha_{sc} \) to be 1.0 (Yoon et al. 2006). Similarly, thermohaline mixing can also cause additional mixing by rendering a region that is stable according to the Ledoux criterion unstable due to a negative composition gradient. This phenomenon has an important effect on the evolution of accretors in close binary systems (e.g., Stancliffe et al. 2007). MESA uses the formulation of Kippenhahn et al. (1980) to model thermohaline mixing. We adopt the value of the dimensionless free-parameter \( \alpha_t \) to be 1.0.

We use luminosity, effective temperature (\( T_{\text{eff}} \)), surface hydrogen mass fraction (\( X_{\text{surf}} \)), and metallicity-dependent stellar winds. When \( T_{\text{eff}} \geq 1.1 \times 10^4 \text{K} \), we adopt the prescription of Vink et al. (2001) when \( X_{\text{surf}} \geq 0.4 \) and that of Nugis & Lamers (2000) otherwise. When \( T_{\text{eff}} \leq 10^4 \text{K} \), we adopt the prescription of de Jager et al. (1988) scaled by \((Z/Z_\odot)^{0.85}\), to match the metallicity scaling of Vink et al. (2001), where \( Z \) is the initial metallicity of a model. For comparison, the prescription of Nugis & Lamers (2000) scales as the square-root of surface metallicity. When \( 10^4 \text{K} < T_{\text{eff}} < 1.1 \times 10^4 \text{K} \), we interpolate between the results for \( T_{\text{eff}} \geq 1.1 \times 10^4 \text{K} \) and \( T_{\text{eff}} \leq 10^4 \text{K} \). This wind mass-loss recipe is similar to the “Dutch” wind mass-loss scheme in MESA, except for the metallicity dependence adopted for de Jager et al. (1988).

We use the binary module of MESA to model binary stars. The mass lost from the primary due to Roche-lobe overflow (RLO) is computed following the prescription of Kolb & Ritter (1990) and is transferred to the secondary with an efficiency (ratio of mass accreted by the secondary to the mass transferred via RLO by the primary), \( \epsilon_c \), that we assume to be constant during the entire evolution. We assume that the remaining mass is lost from the vicinity of the accretor as its stellar winds. Stellar winds are assumed to carry away the specific angular momentum of the mass losing stars. We require that primaries transfer at least 1% of their initial mass in RLO to qualify as “binaries.” This is to exclude effectively noninteracting binary-star models that largely resemble their single star analogs. We show in Section 5 that the exact criterion for selecting “binaries” does not affect our inferences for progenitor channels and derived rates significantly. Finally, we assume all initial orbits to be circular.

We start the evolution of every star at the ZAMS. We terminate the evolution if any one of these conditions are met: (1) the central carbon mass fraction drops below \( 10^{-6} \) for solar-metallicity models and \( 10^{-3} \) for low-metallicity models, in which case we assume the star has reached CC\(^5\) (2) if the hydrogen-envelope mass drops below 0.01\(M_\odot\), in which case we assume the star is stripped and will explode as a Type Ibc SN, or (3), in binaries, the system evolves into contact, in which case we assume a merger ensues. We assume the surface properties of the star at this stage match the pre-SN state. While this is plausible, recent work suggests that waves can efficiently transport energy outwards during core neon and oxygen burning stages. This could result in outbursts and large fluctuations in surface properties of the star in the years or months leading to CC (Quataert & Shiode 2012; Shiode & Quataert 2014; Fuller 2017).

Regarding convergence of our models, MESA uses adaptive timestep and spatial resolution, and our setup is such that our runs typically take \( \sim 5000 \) timesteps and \( \sim 2000 \) mesh points. To test convergence, for some of our SN Iib progenitors, we have verified that approximately doubling both the temporal and spatial resolution does not modify our results.

In the following subsections and Table 1, we summarize the parameter space for our single- and binary-star models at solar and low metallicities. All of our models including MESA input files needed to reproduce them are available at zenodo.org/record/3332831#.XSJnelA+pA3g.

### 2.1. Solar-metallicity Models

We compute solar-metallicity single-star models with initial mass, \( \log_{10}(M_{\text{ZAMS}}/M_\odot) = 1.2-1.5 \) (\( M_{\text{ZAMS}}/M_\odot \approx 16-31.5 \)) in intervals of 0.0005 dex.

We compute solar-metallicity binary-star models with initial primary mass, \( \log_{10}(M_{\text{ZAMS,1}}/M_\odot) = 1.0-1.4 \) (\( M_{\text{ZAMS,1}}/M_\odot \approx 10-25 \)) in intervals of 0.02 dex, initial mass ratio, \( q_{\text{ZAMS,2}}=M_{\text{ZAMS,2}}/M_{\text{ZAMS,1}}=0.225-0.975 \) in intervals of 0.05, and initial orbital period, \( \log_{10}(P_{\text{orb, ZAMS}}/\text{day}) = 2.5-3.8 \) (\( P_{\text{orb, ZAMS}}/\text{day} \approx 316-6310 \)) in intervals of 0.02 dex. We only consider case B or later mass transfer (i.e., mass transfer after core hydrogen exhaustion) in this work; a systematic investigation of case A mass transfer (i.e., mass transfer before core hydrogen exhaustion) toward SNe Iib is beyond the scope of this paper and would be an interesting line of future investigation. As a result, the upper limit on the initial primary mass is set to the mass of the most massive single-star model that is stripped by its own stellar winds (\( M_{\text{ZAMS}} = 25.6M_\odot \)), since case B or later mass transfer will only result in additional mass loss as the core is already established

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\(^5\) After modeling our solar-metallicity models, we found we could stop the evolution of our models earlier and used it in our low-metallicity models. See the Appendix where we evolve representative solar- and low-metallicity models to advanced nuclear burning stages.
in these models. We compute the models for $\epsilon = 1.0$ (fully conservative mass transfer), 0.5, 0.1, and 0.01.

Models with $\epsilon = 0.5$ and 0.1 are the same as those analyzed in Sravan et al. (2018), where we show that they successfully reproduce the observed properties of the progenitor of SN 2016gkg derived from pre-explosion photometry and its light curve.

### 2.2. Low-metallicity Models

We compute low-metallicity single-star models with initial mass, $\log_{10}(M_{ZAMS}/M_{\odot}) = 1.4$–1.7 ($M_{ZAMS}/M_{\odot} \approx 25$–50) in intervals of 0.0005 dex. Within this mass range, only models with initial masses $>40M_{\odot}$ lose enough of their hydrogen envelopes to qualify as SN IIb progenitors, but at low metallicities, these are expected to directly collapse into black holes rather than explode as SNe (Heger et al. 2003).

We compute low-metallicity binary-star models with the same initial primary masses and initial mass ratios as at solar. However, we compute a broader range in initial orbital period than at solar metallicity, $\log_{10}(P_{\text{orb},ZAMS}/\text{day}) = 1.0$–3.7 ($P_{\text{orb},ZAMS}/\text{day} \approx 10$–5012), because of the wider parameter space that leads to SN IIb at low metallicity. In addition, we use coarse (0.1 dex) and fine (0.02 dex) intervals for initial orbital periods below and above $\log_{10}(P_{\text{orb},ZAMS}/\text{day}) = 2.7$ ($P_{\text{orb},ZAMS} \approx 501$ days), respectively, to reduce computational demand for modeling short orbital period binaries (experiencing early case B mass transfer) while adequately resolving long orbital period binaries (experiencing late case B and case C mass transfer). As for solar metallicity, our coverage of the range in orbital periods does not capture case A mass transfer. We limit the initial primary mass to $M_{ZAMS,1} \approx 25M_{\odot}$, even though our single-star models at low metallicity retain large envelopes at this mass and can potentially lead to SNe IIb after mass transfer, to reduce computational demand. In addition, we show in Section 5 that potential SN IIb progenitors with $M_{ZAMS,1} \gtrsim 25M_{\odot}$ are relatively very few and do not affect our inference for SN IIb progenitors significantly. We compute all of the aforementioned low-metallicity models for $\epsilon = 0.5$ and 0.1. We do not use $\epsilon = 1.0$ and 0.01, because, as we show in Section 4, the parameter spaces at $\epsilon = 0.01$ and 0.1 are quite similar and the parameter space at $\epsilon = 1.0$ is quite small at solar metallicity. In addition, mass transfer is expected to be nonconservative due to rapid spin-up of the secondary to critical rotation during mass transfer (Packet 1981; Petrovic et al. 2005; Ritchie et al. 2012, also see Popham & Narayan 1991 for a counter argument).

### 2.3. Model Definitions

We introduce a couple of definitions to aid our discussion of SN IIb progenitors.

First, we define which pre-CC models are interpreted as SN IIb progenitors. The connection between the pre-SN progenitor structure and the explosion’s spectroscopic properties is a subject of ongoing investigation (e.g., Dessart et al. 2018). Therefore, here we adopt a conservative criterion using the pre-SN hydrogen-envelope mass to define an SN IIb progenitor. Specifically, models with primaries that reach CC with residual hydrogen-envelope mass $0.01M_{\odot} \leq M_{\text{H,env,preSN}(1)} \leq 1M_{\odot}$ are defined as SN IIb progenitors. This is our “fiducial SN IIb progenitor definition.”

Our adopted definition was chosen to be a conservative one. Inferred hydrogen-envelope masses for SNe IIb with detected progenitors are $<0.5M_{\odot}$ (Woosley et al. 1994; Houck & Fransson 1996; Bersten et al. 2012; Morales-Garoffolo et al. 2014; Arcavi et al. 2017; Bersten et al. 2018). These SNe IIb represent those with the most massive, and thus most extended (Yoon et al. 2017), envelopes, as more compact progenitors would be harder to detect. In addition, the inferred hydrogen-envelope masses from a larger population SNe IIb are also $<0.5M_{\odot}$ (Bufano et al. 2014; Morales-Garoffolo et al. 2015; Fremling et al. 2019).

We also test the effect of changing the “fiducial definition” of SN IIb progenitors in later sections by applying a tighter cut on the residual hydrogen-envelope mass ($0.01M_{\odot} \leq M_{\text{H,env,preSN}(1)} \leq 0.5M_{\odot}$) and the helium core mass ($2M_{\odot} \leq M_{\text{He,core,preSN}(1)} \leq 6M_{\odot}$; Nomoto et al. 1993; Woosley et al. 1994; Morales-Garoffolo et al. 2014; Ergon et al. 2014, 2015; Folatelli et al. 2015). These constraints are motivated by values derived for SNe IIb with detected progenitors, computed by analyzing their light curves numerically (using hydrodynamical models), analytically or semi-analytically.

Second, in addition to the case C binaries defined earlier, we introduce a further distinction between binaries experiencing case B mass transfer:

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**Table 1**

Initial Properties of Solar- and Low-metallicity Models

| Type            | Property                           | Solar Metallicity | Low Metallicity |
|-----------------|------------------------------------|-------------------|-----------------|
|                 |                                     | min   | max   | Interval | min   | max   | Interval |
| Single Stars    | $\log_{10}(M_{ZAMS}/M_{\odot})$    | 1.2   | 1.5   | 0.0005   | 1.4   | 1.7   | 0.0005   |
| Binary Stars    | $q_{ZAMS}$                         | 1.00  | 1.40  | 0.02     | 1.00  | 1.40  | 0.02     |
|                 | $\log_{10}(P_{\text{orb}}/\text{day})$ | 0.225 | 0.975 | 0.05     | 0.225 | 0.975 | 0.05     |
|                 |                                     | 2.5   | 3.8   | 0.02     | 2.7   | 3.7   | 0.02     |

Notes.

(1) $M_{ZAMS,1}$: Initial primary mass.

(2) $q_{ZAMS} = M_{ZAMS,2}/M_{ZAMS,1}$: Initial mass ratio.

(3) $P_{\text{orb}}$: Initial orbital period.

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6 The hydrogen-envelope-helium core boundary is defined as the outermost point where the hydrogen mass fraction $\leq 0.01$ and the helium mass fraction $>0.1$.
increasing ZAMS mass leads to a progression to more stripped SN types: more stripped progenitors due to stronger winds. At solar metallicity, center of the star, respectively. Increasing ZAMS mass and metallicity leads to stars at solar and low metallicities. The circles, triangles, and squares denote here would explode as SNe II. Note that we stop the evolution of the 40 M$_\odot$ solar-metallicity model when it strips (see Section 2).}

1. Case early-B (EB): models initiating mass transfer while the primary is crossing the Hertzsprung Gap (HG)$^9$: the time between exhausting hydrogen in its core and the start of its rise on the giant branch
2. Case late-B (LB): models initiating mass transfer after the primary begins its rise on the giant branch but before it exhausts helium in its core

Once again, case C binaries are those where the primary initiates mass transfer after core helium exhaustion.

3. Evolutionary Channels of SN Ib progenitors

In this section, we discuss single and binary evolutionary channels toward SNe Ib at solar and low metallicity, with a special emphasis on the effect of mass ratio and mass transfer efficiency, especially at low metallicities. We briefly summarize results from earlier work for context and completeness. Also, we only focus on discussing previous work that used self-consistent stellar evolution models for consistency.

3.1. Single SN Ib progenitors

Figure 1 shows H–R tracks for single stars at solar and low metallicity. It demonstrates two well-understood phenomena related to producing single stripped stars. First, increasing ZAMS mass drives stronger winds and results in more stripped progenitors. Second, lowering metallicity drives weaker winds and results in less stripped progenitors.

Our single-star solar-metallicity models transition from SN II to SN Ib at ZAMS mass of 22M$_\odot$, then to SN Ibc at ZAMS mass of 26M$_\odot$ (see definitions in Sections 2 and 2.3). In Figure 1, the 23 M$_\odot$ model is an SN Ib progenitor. At low metallicity, none of our models lose enough of their envelope to explode as SE SNe. We emphasize that the mass range leading to a given SN type at any metallicity is strongly dependent on the wind mass-loss prescription used and these are known to be quite uncertain (see also discussion in Section 6.2).

3.2. Binary SN Ib progenitors

Figure 2 shows typical evolutionary pathways via case EB, LB, and C mass transfer to SNe Ib at low metallicity. These channels also exist at solar metallicity; however, case EB mass transfer channels are strongly suppressed, as in several cases stronger winds remove the remaining hydrogen envelope after detachment (Yoon et al. 2017). Case C mass transfer is only possible for a narrow range in initial primary mass (see also Section 4). This is because only lower primary masses can expand significantly after core helium exhaustion. Despite their rarity, case C SNe Ib warrant discussion because they have the attractive property of having recently undergone or still undergoing mass transfer at CC. Recent studies indicate that many SNe Ib experience strong mass loss close to CC (e.g., Kamble et al. 2016). This channel was also initially suggested as the likely progenitor of the prototypical SN Ib: 1993J (Podsiadlowski et al. 1993; Maund et al. 2004).

Many of these channels were first discussed for solar-metallicity models by Claey et al. (2011). However, unlike this work, Claey et al. (2011) also found channels to SNe Ib via case A and EB mass transfer.$^8$ The difference in outcomes is largely due to the adopted wind mass-loss prescription. Claey et al. (2011) adopted the prescription of de Jager et al. (1988) during the entire stellar evolution, which is about two orders of magnitude lower than our WR mass-loss prescription of Nugis & Lamers (2000) and drives most of the stripping in our case. More recently, Yoon et al. (2017) extended the analysis for SN Ib progenitors to low metallicity. They found a significant difference in the availability of case EB mass transfer channels toward SNe Ib between solar and low metallicities. Specifically, though after the mass transfer phase primary stars at both metallicities detach with similar amounts of hydrogen envelope, strong winds at high metallicity strip many of them before CC. This results in a sharp narrowing of the parameter space for binary SNe Ib at solar metallicity as case EB binaries span ~2 orders of magnitude in initial orbital period. We show the full parameter space of binary SNe Ib as a function of metallicity (including mass transfer efficiency and mass ratio) in Section 4 and quantify the effect of the above mentioned phenomenon on theoretical SN Ib rates in Section 5.

Our parameter space coverage allows us to investigate the effect of mass ratio and mass transfer efficiency on binary SN Ib channels at both solar and low metallicities. We find that the viability of all three channels mentioned above (case EB, LB, and C) increases with increasing initial mass ratio and decreasing mass transfer efficiency. We find that mass transfer efficiency plays an important role for the viability of case EB SNe Ib. The left and right panels of Figure 3 show the difference in evolution when mass transfer begins early and late on the HG for different $\epsilon$ values. The primary in these models initiates mass transfer on its thermal timescale, which is shorter later on the HG (Wellstein et al. 2001). In late EB mass transfer scenarios (right panels), if $\epsilon$ $

$^9$ The HG is defined as the phase after core hydrogen exhaustion to the point where the star dips to a minimum luminosity before rising on the giant branch.

$^8$ They also did not find channels to SNe Ib via case C mass transfer, but this was due to their adopted upper limit on the residual hydrogen-envelope mass (0.5M$_\odot$) for defining SN Ib progenitors.
is high enough that accretion occurs significantly faster than the thermal timescale of the secondary, then the binary will enter contact. Given the wide parameter space spanned by case EB binaries, this phenomenon has an important secondary effect on the parameter space and rates for SNe IIb.

4. Results on SN IIb Progenitor Populations

In this section, we discuss the parameter space for single and binary SN IIb progenitors at solar and low metallicities. For binary systems, we focus our discussion on the effect of mass ratio and mass transfer efficiency, especially at low metallicity.

4.1. Single SN IIb Progenitors

At solar metallicity, single stars with initial mass \( M_{\odot} \) (ZAMS) = 1.3445–1.409 (ZAMS/M_\odot \approx 22–26) are SNe IIb progenitors according to our fiducial definition (primaries that reach CC with residual hydrogen-envelope mass 0.01M_\odot \leq M_{\text{He,preSN}(1)} \leq 1M_\odot). At low metallicity, our most massive model (ZAMS \approx 50M_\odot) barely gets stripped enough to be labeled an SN IIb progenitor. However, we expect that stars as massive as these (helium core masses \( \gtrsim 26M_\odot \)) will not experience successful explosions but will instead collapse directly into black holes (Fryer 1999). We adopt this assumption for the remainder of this work.

We also explore the effect of adopting different criteria for defining SN IIb progenitors as the mapping between progenitor structure and ensuing SN spectra is not clear. Adopting the cut \( 0.01M_\odot \leq M_{\text{He,preSN}(1)} \leq 0.5M_\odot \) for defining SN IIb progenitors, only models with ZAMS \approx 23–25.5M_\odot at solar metallicity qualify as SN IIb progenitors. Applying the \( 2M_\odot \leq M_{\text{He,preSN}(1)} \leq 6M_\odot \) cut qualifies no single stars, either at solar or low metallicity, as SN IIb progenitors: \( M_{\text{He,preSN}(1)} = 9.5M_\odot \) for the least massive SN IIb progenitor (using our fiducial definition) at solar metallicity. This fact has been noted several times in the literature to motivate the need for additional mass-loss mechanisms (including binary interactions) to create SN IIb progenitors at lower ZAMS masses (e.g., Lyman et al. 2016; Prentice et al. 2019).

Claeys et al. (2011) found single SN IIb progenitors with ZAMS masses \( \sim 33M_\odot \). This is again due to the difference in adopted wind mass-loss prescription, where their formulation is two orders of magnitude lower than ours. Lowering wind mass-loss rates increases the minimum ZAMS mass that produces SNe IIb.

4.2. Binary SN IIb Progenitors

Figures 4 and 5 show the parameter space for binary SN IIb progenitors using our fiducial definition (primaries that reach CC with residual hydrogen-envelope mass 0.01M_\odot \leq M_{\text{He,preSN}(1)} \leq 1M_\odot) at solar and low metallicity, respectively.

Case LB mass transfer toward SNe IIb are the dominant production scenarios at solar metallicity. However, case C mass transfer channels, though observationally interesting, have not previously been discussed in the context of a parameter space analysis. As expected, case C SNe IIb are limited to lower initial primary masses and arise from a small range in initial orbital periods that shrinks with increasing initial primary mass. Case C SNe IIb are also favored for lower initial mass ratios (qZAMS \lesssim 0.65).

The parameter space for binary SNe IIb increases dramatically with decreasing metallicity. This is due to channels to SNe IIb via case EB mass transfer that are only viable at low metallicity (see Section 3). Due to the large change in primary radius that occurs when crossing the HG, the range of initial orbital periods that permit mass transfer during this phase is very large. The difference in parameter space due to metallicity has a primary dominant effect on theoretically computed SN IIb rates (see Section 5).
Once again, we explore the effect of adopting different criteria for defining SN IIb progenitors. For example, the SN IIb parameter space with $q_{\text{ZAMS}} \lesssim 0.4$ is almost entirely progenitors with $M_{\text{He,env,preSN}} \lesssim 0.5 M_\odot$ at both metallicities. Case EB SNe IIb also dominantly have $M_{\text{He,env,preSN}} \lesssim 0.5 M_\odot$. Applying the cut $2M_\odot \lesssim M_{\text{He,core,preSN}} \lesssim 6M_\odot$ effectively excludes the parameter space above $M_{\text{ZAMS,1}} \approx 16 M_\odot$ at both metallicities. This is because the core is already established before the onset of interaction in the binary models considered in this work (see Section 2.1). Finally, while it is difficult to directly compare our results to those of Claeyts et al. (2011) and Yoon et al. (2017) due to differences in modeled binary parameters, definitions for SNe IIb progenitors, and adopted physics in stellar modeling, there is broad agreement with respect to all of the above results.

### 4.2.1. Effect of Mass Transfer Efficiency

Mass transfer efficiency plays an important role in shaping the parameter space toward SNe IIb, especially at low metallicity. The gap in the parameter space between $\log_{10}(P_{\text{orb,ZAMS}}/\text{day}) \approx 1.5$ (2–3) at low metallicity when $\epsilon = 0.5$ in Figure 5 is due to the occurrence of contact in these binaries (see Section 3 and Figure 3 for details). In other words, low-metallicity EB SN IIb are favored at lower $\epsilon$. Also, overall, the parameter space for SNe IIb decreases with increasing $\epsilon$ at both metallicities. This is because of increasing likelihood of contact in the binaries when the secondary is unable to thermally relax with its acquired mass at higher $\epsilon$ (Braun & Langer 1995) and the decreasing stabilizing effect of orbit widening (from loss of angular momentum) due to inefficient mass transfer.

Interestingly, for the subset of high initial mass ratio ($q_{\text{ZAMS}} = 0.975$) EB SNe IIb at low metallicity, higher $\epsilon$ has the opposite effect, i.e., it helps avoid contact. Specifically, in models with $\epsilon = 0.1$, the secondary accretes relatively small amounts of mass when it is close to the terminal main sequence, with a negligible effect on its evolution, and expands as it leaves the main sequence and enters contact while on the HG. However, in models with $\epsilon = 0.5$, the secondary accretes enough mass to rejuvenate as a main-sequence star, allowing the primary to evolve to CC while the secondary is still on the main sequence. This phenomenon results in the absence of several case EB SNe IIb in the topmost-right panel of Figure 5, as compared to the topmost-left panel of the same figure.

Notably, whether binaries with $\epsilon = 1.0$ and high mass ratios ($q_{\text{ZAMS}} \gtrsim 0.7$) at high metallicity are able to avoid contact depends sensitively on their evolutionary history, which dictates whether convective mixing in the secondary is able to carry the accreted material to the core, allowing them to rejuvenate and contract. Specifically, rejuvenation occurs over a series of discrete events where the convective core grows in mass and merges with an outer convection zone. The discrete nature of this process leads to non-monotonic behavior in terms of the initial parameters, resulting in the patchy distribution that

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**Figure 3.** H–R diagrams showing the difference in evolution of representative low-metallicity binary-star models that initiate mass transfer early (left panel) or later on the HG due to mass transfer efficiency (0.5, top and 0.1, bottom). Line colors, line weights, and symbols have the same meaning as in Figure 2. In these models, mass transfer occurs on the thermal timescale of the primary (which is inversely proportional to the primary radius). When the primary transfers mass later on the HG (right panels) at higher accretion efficiencies, the secondary approaches a limit, acquiring mass significantly faster than its thermal timescale (model in the top-right panel). This results in the radius of the secondary increasing dramatically and the binary entering a contact phase.
4.2.2. Effect of Mass Ratio

The parameter space for SNe IIb generally decreases with $q_{\text{ZAMS}}$ due to increasing likelihood of contact in the binaries. At the onset of mass transfer, if $q = M_{\text{accretor}}/M_{\text{donor}} \lesssim 1$, the orbit shrinks in response to further mass transfer (with lower mass ratios resulting in faster shrinkage) causing the system to undergo unstable mass transfer. However, if $q \gtrsim 1$, the orbit expands, stabilizing further mass transfer, allowing the primary to evolve to CC. The exact boundary that separates the two scenarios depends on the mass transfer efficiency, e.g., for conservative mass transfer it is $q = 1$ (Tauris & van den Heuvel 2006). Similarly, the parameter space decreases more with $q_{\text{ZAMS}}$ at lower $\epsilon$, as more material leaving the system carrying its orbital momentum causes the orbit to shrink faster, promoting conditions for the development of contact or unstable mass transfer.

However, in binaries with $q_{\text{ZAMS}} \lesssim 0.5$, higher values of $\epsilon$ can cause the mass ratio to flip thereby facilitating stable mass transfer. This results in the break in the parameter space trend at $\epsilon = 0.1$ in the lowermost panel series of Figure 4. At $\epsilon = 0.1$, several accretors that managed to avoid contact at $\epsilon = 0.01$, overflow their Roche lobes. However, at even higher values of $\epsilon$, the initial mass transfer phase causes the mass ratio to rapidly flip, leading to the expansion of the orbit on further mass transfer, allowing them once again to avoid contact.

5. SNe IIb Relative Rates

We use models discussed in previous sections to compute SN IIb relative rates (fractions) at solar and low metallicities. In the following, we outline our assumptions for the computation of SN rates.
We assume that the minimum ZAMS mass to undergo CC\footnote{Siess (2007) and Doherty et al. (2015) suggest a higher value of \(10-12M_\odot\) than \(8M_\odot\) used here, depending on metallicity and initial mass ratio.} is \(8M_\odot\) (Woosley et al. 2002;Smartt 2009). Following Heger et al. (2003), at solar metallicity, we do not consider an upper mass limit for stars to explode as SNe, assuming that even stars that form black holes explode as fallback SNe. Also based on the results of Heger et al. (2003), for our low-metallicity models, we consider stars with initial masses in excess of \(40M_\odot\) to directly collapse to black holes rather than explode as SNe. We adopt a power-law distribution for the initial mass ratio, \(q_{\text{ZAMS}}\):\footnote{Note that, though the distributions of Sana et al. (2012) and Kobulnicky et al. (2014) for the initial mass ratio, \(q_{\text{ZAMS}}\), are only valid up to \(q_{\text{ZAMS}} = 3.0\), we use \(q_{\text{ZAMS}} \leq 3.8\) in our calculations for the initial mass ratio distribution.}

\begin{equation}
    f(q_{\text{ZAMS}}) = (q_{\text{ZAMS}})^{\beta}.
\end{equation}

We assume that \(0.2 \leq q_{\text{ZAMS}} \leq 1.0\) (Kobulnicky et al. 2014). Finally, we assume a power-law distribution for the initial orbital period, \(\log_{10} P_{\text{orb,ZAMS}}\):\footnote{Kroupa (2001) and Schneider et al. (2018) use a power-law distribution for the initial orbital period.}

\begin{equation}
    f(\log_{10} P_{\text{orb,ZAMS}}) = (\log_{10} P_{\text{orb,ZAMS}})^{\gamma}.
\end{equation}

We assume that it is valid \(0.15 \leq \log_{10} (P_{\text{orb,ZAMS}}/d) \leq 3.80\) (the upper limit on the initial orbital period modeled in this work). Note that while massive binary properties are observed to be relatively insensitive to metallicity only between solar and Large Magellanic Cloud metallicities (and initial orbital periods from 1 to 1000 days; Almeida et al. 2017), we assume that they are preserved down to a fourth-solar.

We use several values of \(f_{\text{bin}}, \alpha, \beta, \gamma\). For \(f_{\text{bin}}\), we use 0.25, 0.5, 0.65, and 0.8. The first two are to allow comparison of our results against those of Claeys et al. (2011), while the last two are the upper and lower limits on \(f_{\text{bin}}\) found by Kobulnicky et al. (2014; note that Sana et al. (2012) find \(f_{\text{bin}} \sim 0.7\) for Galactic O-stars). For \(\alpha\), we use 1.6, 2.3, 3.0 to capture the 1σ range in \(\alpha\) found by Kroupa (2001; see also Schneider et al. 2018). For \(\beta\), we use \(-1.0\) (negative values of \(\beta\) favor binaries with low \(q_{\text{ZAMS}}\) or unequal binary component masses) and \(0.0\). \(\beta = 0.0\) is according Sana et al. (2012), Kobulnicky et al. (2014) and \(\beta = -1.0\) is to allow comparison of our results against those of Claeys et al. (2011). For \(\gamma\), we use 0.0 and \(-0.22\). The former is Öpik’s law (Opik 1924), while the latter is according Kobulnicky et al. (2014). Note that, though the distributions of Sana et al. 2012 and Kobulnicky et al. (2014) are only valid up to \(P_{\text{orb,ZAMS}} = 2000\) and \(3300\) days, respectively, we assume that they hold up to \(\approx 6310\) days. However, we note that we find good agreement with SN IIb rates computed using the distributions of (Moe & Di Stefano 2017, discussed next) that are valid for larger values of \(P_{\text{orb,ZAMS}}\).

In addition to the simple distributions discussed above, we also consider recent distributions derived by Moe & Di Stefano (2017) to calculate SN IIb rates. We simulate a large population of single and binary stars with initial (binary systems), primary mass \(M_{\text{ZAMS}} \geq 8M_\odot\), using a Monte Carlo technique and match the sampled initial properties to our model grids to compute rates. For the distribution of Moe & Di Stefano (2017), an IMF needs to be assumed. We assume a Salpeter IMF with different values of \(\alpha = 1.6, 2.3, \) and \(3.0\).

As we do not model the evolution of secondaries after the primary undergoes CC, we consider two extreme cases in order to bracket our rates: either all of them explode as SNe of a type other than IIb (which is the lower limit on our predicted SN IIb rates), or that none of them explode as SNe (which is the upper limit on our predicted SN IIb rates). While it is possible that the secondaries explode as SNe IIb, we expect their contribution to be at most equal to that of single stars. After the first SN explosion, more than \(\approx 80\%\) of systems are expected to become unbound due to the kick on the newly formed neutron star (Renzo et al. 2019), such that the companion would evolve as an effectively single star. Of the few systems that remain bound, RLO is expected to lead to unstable mass transfer and a merger due to the extreme mass ratio between the neutron star and the massive donor.

Figure 5. Parameter space for binary SN IIb progenitors at low metallicity. Horizontal panels show models with representative \(q_{\text{ZAMS}}\) (noted to the top-left in the left-most panels) demonstrating how the parameter space changes with \(q_{\text{ZAMS}}\). The left and right vertical panels show models with mass transfer efficiency, \(\epsilon = 0.5\) and 0.1, respectively. The colored and dotted regions have demonstrating how the parameter space changes with \(q_{\text{ZAMS}}\), \(f_{\text{bin}}, \alpha, \beta, \gamma\), \(\Omega_{\text{orb,ZAMS}}, \Omega_{\text{ZAMS}}\), and initial mass ratio, \(q_{\text{ZAMS}}\), \(f_{\text{bin}}, \alpha, \beta, \gamma\), \(\Omega_{\text{orb,ZAMS}}, \Omega_{\text{ZAMS}}\), and initial mass ratio, \(q_{\text{ZAMS}}\).
5.1. Single and Binary SN IIb Rates at Solar and Low Metallicity

Table 2 summarizes our results for SN IIb relative rates. Tables 3 and 4 list single- and binary-star (with $\epsilon = 0.5$ and 0.1) SN IIb rates at solar and low metallicity, respectively, for all values for $f_{\text{bin}}$, $\alpha$, $\beta$, and $\gamma$ and four definitions for SN IIb progenitors (see Section 3), namely:

1. $0.01 M_\odot \leq M_{\text{env,preSN}(1)} \leq 1 M_\odot$ (“fiducial definition”),
2. $0.01 M_\odot \leq M_{\text{env,preSN}(1)} \leq 0.5 M_\odot$,
3. $0.01 M_\odot \leq M_{\text{env,preSN}(1)} \leq 1 M_\odot$ and $2 M_\odot \leq M_{\text{He,core,preSN}(1)} \leq 6 M_\odot$, and
4. $0.01 M_\odot \leq M_{\text{env,preSN}(1)} \leq 0.5 M_\odot$ and $2 M_\odot \leq M_{\text{He,core,preSN}(1)} \leq 6 M_\odot$.

Values shown in the tables correspond to lower limits on SN IIb rates, where we assume that all secondaries explode as SNe of a different type. The upper limit on SN IIb rates, assuming that none of the secondaries explode as SNe, can be obtained by multiplying the rates by $(1 + f_{\text{bin}})$.

Table 5 lists single- and binary-star (with $\epsilon = 0.5$ and 0.1) SN IIb rates at solar and low metallicity computed using the distributions of Moe & Di Stefano (2017) for all values of $\alpha$ and all four definitions for SN IIb progenitors. For these, we compute and quote lower and upper limits on the rates, assuming that all or none of the secondaries explode as SNe, respectively. These rates are typically 2–5 times lower than those from our “fiducial distributions” (using $f_{\text{bin}} = 0.88$; computed value for our simulated population).

The computed rates increase by <0.01% when we require that primary stars transfer at least 0.1% (instead of 1%) of their initial mass in RLO to qualify as a “binary.” The low-metallicity rates are more strongly robust to this definition; there are relatively few mildly interacting binaries at low metallicity. As mentioned in Section 2.2, we limit the initial primary mass to $M_{\text{ZAMS,1}} \approx 25 M_\odot$ in our low-metallicity models even though the corresponding single-star models retain large envelopes. If we assume that all binaries in the unmodeled parameter space lead to SNe IIb (i.e., $M_{\text{ZAMS,1}} \gtrsim 25 M_\odot$, $q_{\text{ZAMS}} = 0.4–1.0$, and $\log_10(P_{\text{rot,ZAMS}}/$ day) = 3.0–3.7), they would contribute at most 2.7% in rates for the most favorable priors and assuming that no secondaries lead to SNe.

In Table 2, we report conservative ranges for theoretical SNe IIb relative rates. The lower limits are the smallest values from Tables 3 and 4 and assuming that all secondaries explode as SNe of a type other than IIb, while the upper limits are the largest values from those tables and assuming that no secondaries explode as SNe. Therefore, values in Table 2 span the range of theoretical SN IIb rates obtained by varying prior distributions of single- and binary-star birth properties and structural criteria for defining SN IIb progenitors.

We note that our binary SN IIb rates at low metallicity represent lower limits, as we do not compute progenitors arising via case A mass transfer. We do not expect SN IIb progenitors via case A mass transfer at solar metallicity because their residual hydrogen envelope after the mass transfer phase will be roughly as massive as that for binary stars that initiate mass transfer on the HG (Götberg et al. 2017) and will therefore also be stripped by winds before CC.

Overall, our model (single and binary) SNe IIb contribute to 0%–4.1% and 0.4%–15% of all CC SNe at solar and low metallicity, respectively. The SN IIb rate from observations is ~11% (Li et al. 2011; Smith et al. 2011; Graur et al. 2017) at high metallicity. Our solar-metallicity models can account for less than half the observationally inferred rate at high metallicity. On the other hand, there is evidence that SN IIb rates may be higher in galaxies less massive than the LMC (Arcavi et al. 2010; Graur et al. 2017). Note that observationally inferred rates as a function of galaxy mass/metallicity should be interpreted with caution as they are affected by small sample sizes. However, if this trend holds up in future investigations using large sample sizes, our models can account for the implied SNe IIb rates at low metallicity. However, this is only true for models with low mass transfer efficiency.

Applying the most restrictive criteria for defining SN IIb progenitors [$M_{\text{env,preSN}(1)} \leq 0.5 M_\odot$ and $2 M_\odot \leq M_{\text{He,core,preSN}(1)} \leq 6 M_\odot$], makes the disagreement between theoretical (0.1%–1.4%) and observed rates at solar metallicity worse. At low metallicity, however, though theoretical rates (0.5%–12%) also decrease, our most optimistic rates are still consistent with observed rates. An analogous result was also found by Lyman et al. (2016), who found that low-metallicity binaries with primary masses 8–20$M_\odot$ can explain the observed distribution of SN IIb (and also SE SN generally) ejecta masses.
### Table 3
SN Ib Relative Rates at Solar Metallicity

| \( f_{\text{bin}} \) | \( \alpha \) | \( \beta \) | \( \gamma \) | \( M_{\text{He core}} \leq 0M_{\odot} \) | \( M_{\text{He env}} \leq 1.0M_{\odot} \) | \( M_{\text{He env}} \leq 0.5M_{\odot} \) | \( M_{\text{He env}} \leq 1.0M_{\odot} \) | \( M_{\text{He env}} \leq 0.5M_{\odot} \) |
|---|---|---|---|---|---|---|---|---|
| \( \geq 0 \) | \( 0 \) | \( 0.2 \) | \( 0.3 \) | \( 0.4 \) | \( 0.5 \) | \( 0.6 \) | \( 0.7 \) | \( 0.8 \) |
| \( = 0 \) | \( 0.1 \) | \( 0.2 \) | \( 0.3 \) | \( 0.4 \) | \( 0.5 \) | \( 0.6 \) | \( 0.7 \) | \( 0.8 \) |
| \( \leq 1 \) | \( 0.0 \) | \( 0.1 \) | \( 0.2 \) | \( 0.3 \) | \( 0.4 \) | \( 0.5 \) | \( 0.6 \) | \( 0.7 \) |
| \( \leq 2 \) | \( 0.0 \) | \( 0.1 \) | \( 0.2 \) | \( 0.3 \) | \( 0.4 \) | \( 0.5 \) | \( 0.6 \) | \( 0.7 \) |
| \( \leq 3 \) | \( 0.0 \) | \( 0.1 \) | \( 0.2 \) | \( 0.3 \) | \( 0.4 \) | \( 0.5 \) | \( 0.6 \) | \( 0.7 \) |

**Note.** \( f_{\text{bin}} \) is fraction of binary systems, and \( \alpha \), \( \beta \), and \( \gamma \) are parameters for the priors on the initial mass, \( \log_{10} M_{\text{ZAMS}} \), initial mass ratio, \( q_{\text{ZAMS}} \), and initial orbital period, \( P_{\text{orb}} \), respectively (see Equations (1), (2), and (3)). SN Ib rate is defined as fraction of SNe Ib versus all CC SNe percent.

1. \( M_{\text{He core}} \equiv M_{\text{He core, post SN(1)}} \): Residual hydrogen-envelope mass in the progenitor at CC.
2. \( M_{\text{He env}} \equiv M_{\text{He env, post SN(1)}} \): Helium core mass of the progenitor at CC.
6. Discussions and Conclusions

6.1. Summary of Results

In this paper, we use non-rotating single- and binary-star models at solar and low metallicities covering a broad parameter space (see Table 1) to investigate evolutionary channels and parameter space for progenitors of SNe IIb. We find that metallicity and mass transfer efficiency play important roles in shaping the parameter space toward SNe IIb. Both of these affect the evolution of case EB binaries (binaries that initiate MT on the HG), where lower metallicities and mass transfer efficiencies are favorable for the production of SNe IIb. Since the range of binary
Table 5
SN IIb Relative Rates at Solar and Low Metallicities Using 10^6 Single and Binary Stars Generated from Distributions of Moe & Di Stefano (2017)

| Z   | α     | M_{He core} ≥ 0M_⊙ | M_{He core} ≤ 1.0M_⊙ | M_{He core} ≤ 0.5M_⊙ | M_{He core} ≤ 1.0M_⊙ | M_{He core} ≤ 0.5M_⊙ |
|-----|-------|---------------------|------------------------|------------------------|------------------------|------------------------|
|     |       | single              | binary                 | single                 | binary                 | single                 | binary                 |
|     |       | e = 0.5             | e = 0.1                | e = 0.5                | e = 0.1                | e = 0.5                | e = 0.1                |
| 1.6 | 0.0   | 0.81-1.6            | 2.8-5.3                | 0.0                    | 0.73-1.4               | 2.6-5.1                | 0.0                    | 0.67-1.3               | 2.2-4.3               | 0.0                    | 0.64-1.2               | 2.2-4.2               |
| 2.3 | 0.0   | 0.8-1.5             | 2.6-5.0                | 0.0                    | 0.72-1.4               | 2.5-4.8                | 0.0                    | 0.67-1.3               | 2.2-4.2               | 0.0                    | 0.64-1.2               | 2.2-4.1               |
| 3.0 | 0.0   | 0.83-1.6            | 2.7-5.0                | 0.0                    | 0.77-1.4               | 2.6-4.8                | 0.0                    | 0.74-1.4               | 2.3-4.4               | 0.0                    | 0.71-1.3               | 2.3-4.2               |

Note. Table notes and notation same as in Table 3. The lower (upper) limit on rates is from assuming that all (none) of the secondaries explode as SNe.
configurations that lead to case EB mass transfer is very wide, these binaries have a strong effect in shaping the parameter space and, therefore, rates for SNe Iib.

We use our models to compute theoretical SN IIb rates and compare them to observationally constrained values. We attempt to account for the uncertainties in the prior distributions of single- and binary-star birth properties and criteria used to define SN IIb progenitor structures by spanning possible values for them. This allows us to investigate to what extent our models are a priori able to explain observed SN IIb rates.

We find that solar-metallicity single- and binary-star models, by themselves or together, account for less than half of the observed SN IIb rate at solar metallicity. Our most optimistic rate is inconsistent within 2σ of the observationally inferred rates. Also, at high metallicity, singles and binaries contribute to roughly equal numbers (singles slightly more) of SNe IIb. At low metallicity, however, our models can account for the implied rate. Here, binaries are the sole producers of SNe IIb. The group of case EB binary SNe IIb (which in turn is courtesy of lower wind mass-loss rates at low metallicity) is responsible for this change. Further, even using our most restrictive criterion on an SN IIb progenitor structure, theoretical rates at low metallicity are still consistent with observed rates within the reported uncertainties (though these are quite large).

If wind mass-loss rates are lower than those used in our models (which may be the case as discussed in Section 6.2), it might be instructive to compare observed rates at high metallicity to our low-metallicity models (Yoon et al. 2017). We find that rates for our low-metallicity and low mass transfer efficiency models are consistent with observed rates at high metallicity. This is true even after using our most restrictive definition of an SN IIb progenitor structure. However, this requires $f_{\text{bin}} > 0.5$ and priors favoring equal mass binaries and favoring a flat orbital period distribution to be consistent within reported uncertainties for observationally inferred rates. We discuss implications of this in Section 6.3.

6.2. Implications of Assumed Physics

Although we have tried to be conservative in our predicted upper and lower limits for rates, it is instructive to point out additional physical uncertainties in our models.

Wind mass-loss rates have an important effect on single- and binary-star channels toward SNe Iib. Stellar winds in our MESA models are computed using different wind mass-loss prescriptions at various evolutionary phases. WR mass-loss rates have the strongest impact on evolutionary outcomes. However, these rates are also known to be quite uncertain, particularly for low mass WR stars. Most estimates, including those used in this work are expected to be overestimated due to clumping in the winds (Smith 2014). Lower wind mass-loss rates would expand the parameter space for binary SNe Iib (Yoon et al. 2017; Gilkis et al. 2019). In addition, though it is commonly assumed that mass-loss rates from red supergiants decrease with metallicity, some studies suggest that they are more or less metallicity independent (van Loon 2000; van Loon et al. 2005; Goldman et al. 2017). If this is the case, we would expect low-metallicity single stars to produce SN Iib at a relative rate similar to that of high-metallicity single stars.

Another important point is that we have not included stellar rotation. Rotation is thought to play an important role in massive star evolution, with very rapidly rotating stars even being predicted to evolve chemically homogeneously due to rotationally enhanced mixing (Maeder 1987). Rotationally enhanced mass-loss rates can also reduce the minimum mass required for a single star to remove its hydrogen envelope (Meynet & Maeder 2003), thus increasing the rate of SN Iib progenitors from single stars. However, Groh et al. (2013a) found that the initial mass range that produces SNe Iib does not change much for their rotating models with $V_{\text{rot}} \sim 250 \text{ km s}^{-1}$. Further, observations show that the bulk of the massive star population rotates at lower velocities (Ramírez-Aguudeco et al. 2013, 2015), and that stars rotating at faster rates can potentially be accounted for in terms of spun-up secondaries in post-mass transfer systems (de Mink et al. 2013). Properly assessing the impact of rotation, along with the effect of tides and eccentricity (which is likely small due to the wide orbits considered here) would require future calculations that include these effects, but they are beyond the scope of the present study.

6.3. Key Takeaways and Future Directions

Our results have the following implications for progenitor channels to SNe Iib. In order to account for the observationally inferred SN Iib rates

1. Solar-metallicity wind mass-loss rates need to be lower than those used in our models: lower wind mass-loss rates increase the contribution of binaries to SNe Iib, by populating the parameter space available via case EB mass transfer, while driving down the contribution from single stars.

2. Low mass transfer efficiencies are needed: this allows case EB accretors to thermally adjust to the transferred mass and avoid contact.

We note that it is likely that even after accounting for robust mass-loss rates, the uncertainty in prior distributions of stellar birth properties and SN Iib definitions will still pose significant challenges for comparing theoretical models to observations. Therefore, in order to address the question of SNe Iib progenitors, we need four pieces of information: (1) accurate determinations of mass-loss rates for stripped stars as a function of metallicity, (2) constraints on structural properties of SN Iib progenitor stars, (3) robust distributions for single- and binary-star birth properties, and (4) the observational side, SN Iib rates as a function of metallicity. An exploration of case A mass transfer toward SNe Iib at low metallicity and merger channels would also be worthwhile.

In this paper, we focused on understanding the evolutionary channels and parameter space of SN Iib progenitors. In a follow-up paper, we will focus on using our models to draw statistical comparisons to all three independent observational probes into SN Iib progenitors: (1) direct progenitor detections in archival images, (2) progenitor structure and explosion parameters from analyzing multi-band light curves, and (3) circumstellar medium properties from X-ray/radio observations. The aim would be to confirm that our models are able to reproduce the full range of observational constraints for SNe Iib, that the results of such comparison is consistent with conclusions in this paper, and finally, to identify regions in the observational parameter space that are implied from our models but remain unprobed by observations to help guide observing strategies.

The advent of high-cadence surveys like the ZTF (Bellm 2014; Bellm & Kulkami 2017), ASSA-SN (Kochanek et al. 2017),
DLT40 (Valenti et al. 2017), KAIT (Filippenko et al. 2001), and, at the turn of the decade, LSST (Tyson 2002; Ivezić et al. 2019) have created the need for a comprehensive database of theoretical models to provide reliable progenitor characterization and in the case of binary progenitors, their companions. Conversely, the wealth of data that will be available will provide unprecedented statistics on progenitor properties, along with their dependence on properties such as host galaxy metallicity. Efforts such as the one undertaken here are therefore imperative in order to understand the physics of massive star evolution.

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Appendix
Numerical Tests

We stop the evolution of our single- and binary-star models close to core carbon depletion (according to the definitions in Section 2) and assume that their global characteristics of interest when investigating SN IIb progenitors are roughly the same at CC. To confirm that this is indeed the case, we run representative binary-star models at solar (case LB mass transfer type) and low (case EB mass transfer type, also investigated in Section 3 and Figure 3) metallicity until central silicon mass fraction in the primary drops below $10^{-6}$ (at which point the models are a few hours from CC). We then check whether the primary hydrogen envelope and helium core mass and H–R locations of both components differ significantly at this later evolutionary stage.

Figure 6 shows the result of this test. We find that both models have converged by the fiducial evolutionary stopping criterion used in this work to that at the more advanced evolutionary stage for all properties relevant to our investigation.

**Figure 6.** Left panels: H–R diagrams showing evolution of representative solar- (top panel) and low- (bottom panel) metallicity binary-star models to core silicon exhaustion. Line colors and weights have the same meaning as in Figure 2. Right panels: evolution of primary hydrogen envelope (solid line) and helium core mass (dashed line) as a function of binary age for the corresponding models on the left. In all panels, crosses (stars) denote the point where carbon (silicon) is exhausted in the core of the primary. The properties of all models have converged to those very near CC by the fiducial evolutionary stopping criterion used in this work.

\[ M_{ZAMS,1} = 15.8 \, M_\odot \]
\[ \epsilon = 0.1 \]
Van Dyk, S. D., Zheng, W., Brink, T. G., et al. 2018, ApJ, 860, 90
Van Dyk, S. D., Zheng, W., Fox, O. D., et al. 2014, AJ, 147, 37
van Loon, J. T. 2000, A&A, 354, 125
van Loon, J. T., Cioni, M.-R. L., Zijlstra, A. A., & Loup, C. 2005, A&A, 438, 273
Vink, J. S., de Koter, A., & Lamers, H. J. G. L. M. 2001, A&A, 369, 574
Vink, J. S., & Gräfener, G. 2012, ApJL, 751, L34
Wellons, S., Soderberg, A. M., & Chevalier, R. A. 2012, ApJ, 752, 17
Wellstein, S., Langer, N., & Braun, H. 2001, A&A, 369, 939
Woosley, S. E., Eastman, R. G., Weaver, T. A., & Pinto, P. A. 1994, ApJ, 429, 300
Woosley, S. E., Heger, A., & Weaver, T. A. 2002, RvMP, 74, 1015
Woosley, S. E., Langer, N., & Weaver, T. A. 1993, ApJ, 411, 823
Yoon, S.-C., Dessart, L., & Clocchiatti, A. 2017, ApJ, 840, 10
Yoon, S.-C., Langer, N., & Norman, C. 2006, A&A, 460, 199
Yoon, S.-C., Woosley, S. E., & Langer, N. 2010, ApJ, 725, 940