The evolution toward the observational features of the stripped envelope type IIb Supernovae in the binary system

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Abstract Supernovae IIb has been believed to originate from the core collapse supernova that has a thin hydrogen left in their outer envelope. The mass transfer via Roche lobe overflow can significantly change the nucleosynthesis and surface chemical elements of the progenitor of the supernovae IIb. We aim to explore what condition for a close binary can meet with the observational features of the Type IIb Supernovae. We find that the observed low mass Type IIb cannot be produced by the low mass isolated star with $M < 20M_\odot$ due to the existence of a thick hydrogen envelope regardless of rotation. Binaries dominate as progenitors at mass interval (i.e., $M < 20M_\odot$) as considered in this paper. The primary 16$M_\odot$ with the companion 14$M_\odot$ in the binary system with the region of $\sim 10$ days < $P_{\text{orb}}$ < 720 days can reproduce observational features of IIb Supernovae (i.e., $T_{\text{eff}}$, $\log L/L_\odot$, $M_{\text{He}}$, $M_{\text{H}}$, etc.). With the decreasing of the hydrogen-rich envelop mass, the radius of the progenitor falls down. The associated types of the IIb supernovae progenitor from the RSG, YSG to BSG is closely related to the amount of hydrogen left in the envelopes. Rotation can brings the productions of the CNO reaction to the stellar surface at an early phase, which would explain the nitrogen-rich circumstellar material of SN 1993J and can also explain the large He/H ratio of the supernovae ejecta. Rotation can increase the corresponding region of the orbital period which can produce SN IIb.

Key words: stars: close binaries—stars: rotation—stars: abundances—stars: evolution
1 INTRODUCTION

The IIb Supernovae has an initial faint hydrogen emission in its spectrum. However, at the subsequent stage, the hydrogen line can not be detected by the observers. There is also a second peak in the light curve, whose spectrum is closer to a Type Ib supernova. This fact indicates that as the ejecta expands, the hydrogen layer rapidly becomes more transparent and displays the deeper layer. The physical mechanisms that drive the stripping of the hydrogen envelope and the parameter regimes in which they dominate the formation of SN IIb are still open questions. There are four evolutionary channels which can reproduce a progenitor of type IIb supernova. They are the single star evolution, RLOF scenario (Sravan et al. 2019; Gilkis et al. 2019), the binary evolution channel with grazing envelope evolution (GEE) (Torrey et al. 2019), and fatal common envelope evolution (where the secondary star merges with the core of the giant primary star) (CEE) (Soker 2017; Lohev et al. 2019). The progenitor of IIb Supernovae might be a more massive star ($\geq \sim 30\, M_\odot$) that stripped the hydrogen envelope via strong stellar winds. By studying the evolution of massive single stars, Georgy et al. (2012) have found a suitable progenitor born with $20\, M_\odot$ and ending with the correct core mass, hydrogen content, luminosity, and color to explain the complete set of observations of SN 2008ax. Groh et al. (2013) reinterpreted the final stage of the rotating model as a LBV star and suggested that LBVs may be the progenitors of some core collapse SNe. However, the observed stripping envelope SN rates are too high to be explained solely by single star evolution. Moreover, wind clumping in stellar winds implies that the lower wind loss rate is not conducive to the production of SN IIb.

Most of the hydrogen-rich envelope is lost by the interaction with the companions in a binary system, leaving a core composed almost entirely of helium ($2M_\odot < M_{\text{He}} < 6M_\odot$) (RLOF scenario). The stellar evolution of the isolated star requires a very precise adjustment of the initial parameters in order to leave a thin hydrogen envelope before the explosion. The binary evolutionary channel of SN IIb can be strengthened by two main reasons. First, mass loss can be much more naturally interpreted by the Roche lobe overflow. Secondly, the foundation of the companion star in SN 1993J and SN 2001ig, can highlight the binary channel. The fatal CEE scenario can also account for some SNe IIb. A low mass main sequence secondary star inspirals inside the giant envelope of the massive primary star and removes most of the giant envelope before it merges with the giant core. However, it has several uncertainties in the calculations, such as, the outcome of the CEE, the merger process, and wind mass-loss rate. In this scenario, there are some physical processes involving the ejection of common-envelope (Podsiadlowski et al. 1992; Yoon et al. 2010, 2017), thermal nuclear reaction instabilities (Arnett & Meakin 2011; Strotjohann et al. 2015), stellar evolution with rotation (Groh et al. 2013; Soker 2017), and mass removal via strong winds (Heger et al. 2003; Woosley et al. 1994; Georgy et al. 2012; Groh et al. 2013; Soker 2017). Torrey et al. (2019) have introduce an enhanced mass loss due to jets that the secondary star might launch, and find that the enhanced mass loss brings the binary system to experience GEE and form a progenitor of type IIb supernovae. The GEE is an additional mass transfer scenario, different from the RLOF scenario, and hence expands the binary parameter space that can lead to SNe IIb. At
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present, it is an important task to construct a detail model which can explain the observational features of the stripped envelope type IIb Supernovae.

Axis rotation is a very important physical process which need to be fully considered in the evolution of massive stars (Maeder & Meynet 2012; Langer 2012). Rapid rotation can trigger strong stellar winds and it can eliminate a large amount of material from the stellar surface. The faster the rotational speed, the larger the stellar wind. Note that rapid rotation can drive various instabilities in the star. In particularly, meridional circulations and shear turbulence can transfer the angular momentum and mix chemical species in the star (Song et al. 2013, 2016). The mixing of chemical elements might be the most important effect of rotation in massive stars (Mathis & Zahn 2004; Zahn 1992). Thus, fresh nitrogen and helium can appear on the stellar surface and constantly become more abundant over time during the main sequence (Maeder & Meynet 2000, 2012).

Interacting binary can change the structure of supernova progenitors dramatically. A famous example is SN1987A. Its surrounding ring can be ascribed to the binary interaction (Podsiadlowski & Joss 1989). SN 1993J and SN 2011dh are IIb Supernovae and they have experienced a significant mass loss (Van Dyk et al. 2011). These models often require the primary to flow the matter to the companion at different stages of its evolution. The channel of the binary system can give rise to low mass of type IIb supernovae progenitor and the survival of a massive companion near the supernova remnant. In contrast to the isolated counterparts, these characteristics can fit with the observations of the type IIb SN1993J.

In this paper, we intend to explore what conditions can succeed in produce the SNe IIb in the close binary evolution scenario. We aim to explore the following questions in the binary scenario: 1) how rotation has an important impact on the formation of SNe IIb, 2) how surface nitrogen abundance of the progenitor star evolve with evolutionary age, 3) what controls the residual hydrogen under the influence of the mass transfer due to Roche Lobe overflow (RLOF), 4) what is the relationship between SN IIb with other types of supernovae, such as SNe IIP, IIL and Ib/c, 5) how the internal structure of the deep core may be influenced by rotation and RLOF and 6) how different theoretical models can explain the surface parameters of SN IIb, such as the masses of hydrogen envelopes and helium core, the pre-explosion images, the stellar radii and mass loss rate.

2 THE INITIAL MODEL PARAMETERS USED IN THE CALCULATIONS.

We make using of the MESA code to investigate the evolution of the progenitor of SN IIb (Paxton et al. 2011, 2013, 2015, 2018). We adopt the Schwarzschild criterion to dominant the size of the convective zone. The mixing length can be given by \( l_m = 1.5H_P \), where \( H_P \) denotes the pressure scale height. An overshooting parameter of 0.12 pressure scale heights is considered as the standard value. We set the initial chemical composition to be solar one (i.e., \( X = 0.7, Y = 0.28, Z = 0.02 \)) (Peimbert et al. 2007; Brott et al. 2011). We have included the basic.net, coburn.net, and approx21.net nuclear networks in MESA. Our initial models are composed of one or two zero-age main sequence components with various parameters which have listed in Table 1. The efficiency
Table 1: The initial model parameters used in the calculations.

<table>
<thead>
<tr>
<th>Models</th>
<th>$M_{1,\text{ini}}$</th>
<th>$M_{2,\text{ini}}$</th>
<th>$V_{1,\text{ini}}$</th>
<th>$V_{2,\text{ini}}$</th>
<th>$P_{\text{orb,ini}}$</th>
<th>$R/R_{\odot}$</th>
<th>TP</th>
<th>$M_{\text{He}}$</th>
<th>$M_{\text{H}}$</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>16</td>
<td>..</td>
<td>0</td>
<td>..</td>
<td>881</td>
<td>RSG</td>
<td>4.824</td>
<td>7.821</td>
<td></td>
<td>IIP</td>
</tr>
<tr>
<td>S2</td>
<td>16</td>
<td>..</td>
<td>350</td>
<td>..</td>
<td>912</td>
<td>RSG</td>
<td>5.076</td>
<td>7.408</td>
<td></td>
<td>IIP</td>
</tr>
<tr>
<td>S3</td>
<td>20</td>
<td>..</td>
<td>0</td>
<td>..</td>
<td>1071</td>
<td>RSG</td>
<td>6.431</td>
<td>7.960</td>
<td></td>
<td>IIP</td>
</tr>
<tr>
<td>S4</td>
<td>20</td>
<td>..</td>
<td>350</td>
<td>..</td>
<td>885</td>
<td>RSG</td>
<td>7.402</td>
<td>3.444</td>
<td></td>
<td>IIP</td>
</tr>
<tr>
<td>S5</td>
<td>25</td>
<td>..</td>
<td>0</td>
<td>..</td>
<td>1047</td>
<td>RSG</td>
<td>8.668</td>
<td>7.802</td>
<td></td>
<td>IIP</td>
</tr>
<tr>
<td>S6</td>
<td>25</td>
<td>..</td>
<td>350</td>
<td>..</td>
<td>870</td>
<td>RSG</td>
<td>9.466</td>
<td>4.411</td>
<td></td>
<td>IIP</td>
</tr>
<tr>
<td>B1</td>
<td>16 14</td>
<td>0</td>
<td>0</td>
<td>3.00</td>
<td>15 BSG</td>
<td>3.039</td>
<td>0.000</td>
<td>Ib</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>16 14</td>
<td>0</td>
<td>0</td>
<td>10.00</td>
<td>6 BSG</td>
<td>4.233</td>
<td>0.131</td>
<td>IIb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>16 14</td>
<td>0</td>
<td>0</td>
<td>110.00</td>
<td>223 YSG</td>
<td>4.274</td>
<td>0.153</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>16 14</td>
<td>0</td>
<td>0</td>
<td>300.00</td>
<td>426 RSG</td>
<td>4.379</td>
<td>0.234</td>
<td>IIb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>16 14</td>
<td>0</td>
<td>0</td>
<td>720.00</td>
<td>676 RSG</td>
<td>4.399</td>
<td>1.015</td>
<td>IIL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B6</td>
<td>16 14</td>
<td>0</td>
<td>0</td>
<td>1000.00</td>
<td>741 RSG</td>
<td>4.399</td>
<td>1.015</td>
<td>IIL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B7</td>
<td>16 14</td>
<td>350</td>
<td>350</td>
<td>300.00</td>
<td>3 BSG</td>
<td>4.700</td>
<td>0.000</td>
<td>Ib</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B8</td>
<td>16 15</td>
<td>0</td>
<td>0</td>
<td>1100</td>
<td>565 RSG</td>
<td>5.0</td>
<td>0.4</td>
<td>IIb</td>
<td></td>
<td></td>
</tr>
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</table>

Each column means something as follows. The symbol S represents the isolated star while the symbol B indicates the binary system. $M_{1,\text{ini}}$: the initial mass of the primary in unit of $M_{\odot}$; $M_{2,\text{ini}}$: the initial mass of the companion; $V_{1,\text{ini}}$: the initial rotational velocity on the equator for the primary; $V_{2,\text{ini}}$: the initial rotational velocity on the equator for the secondary; $P_{\text{orb,ini}}$: the initial orbital period; $R/R_{\odot}$: the radius of the progenitor supernovae; TP: The type of the progenitor supernovae; $M_{\text{He}}$: the helium core mass at the core carbon exhaustion; $M_{\text{H}}$: the hydrogen envelope mass at the core carbon exhaustion. ST: Supernovae type.

Table 2: The observations of SN 1993J and the theoretical values in models B4 and B8.

<table>
<thead>
<tr>
<th>Observations</th>
<th>Model B4</th>
<th>Model B8</th>
</tr>
</thead>
<tbody>
<tr>
<td>log $T_{\text{eff},1}$</td>
<td>3.63 ± 0.05</td>
<td>3.63</td>
</tr>
<tr>
<td>log $L_1/L_{\odot}$</td>
<td>5.1 ± 0.3</td>
<td>4.89</td>
</tr>
<tr>
<td>log $T_{\text{eff},2}$</td>
<td>4.3 ± 0.1</td>
<td>4.5</td>
</tr>
<tr>
<td>log $L_2/L_{\odot}$</td>
<td>5.0 ± 0.3</td>
<td>4.82</td>
</tr>
<tr>
<td>$R/R_{\odot}$</td>
<td>~ 600</td>
<td>426</td>
</tr>
<tr>
<td>$M = 2 - 6 \times 10^{-6} M_{\odot}/yr$</td>
<td>$2.58 \times 10^{-6} M_{\odot}/yr$</td>
<td></td>
</tr>
<tr>
<td>$M_{\text{H}} = 0.15 - 0.4 M_{\odot}$</td>
<td>$0.234 M_{\odot}$</td>
<td></td>
</tr>
<tr>
<td>$M_{\text{He}} = 2.8 - 6 M_{\odot}$</td>
<td>$4.379 M_{\odot}$</td>
<td></td>
</tr>
</tbody>
</table>

1) The observational data of the progenitor SN 1993J is taken from the references (Woosley et al. 1994; Maund et al. 2004).
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according to (Nugis & Lamers 2000). The opacities are computed from the OPAL tables (Iglesias & Rogers 1996).

We include various rotationally induced instabilities that lead to the mixing of chemical elements, such as the meridional circulation, secular and dynamical shear instabilities, and the Goldreich-Schubert-Fricke instability. The rotational mixing due to these hydrodynamical instabilities have been considered as a diffusive process according to the reference (Heger et al. 2000; Peng et al. 2022). The diffusion coefficients are included in the diffusion equation and they are adopted for the transportation of both the angular momentum and the chemical elements. The rotational mixing due to these hydrodynamical instabilities are decreased by a factor $f_c = 0.0228$. This parameter has been corrected to meet with the observed nitrogen abundances versus the projected rotational velocities for the samples in the Large Magellanic Cloud (Arnett & Meakin 2011). The inhibition effect of the mean molecular weight gradients on the efficiency of rotational mixing processes can be regulated by the factor $f_\mu$. We make using of a value $f_\mu = 0.1$ as in the reference (Yoon et al. 2006) who corrected this factor to be consistent with the observed surface helium.

We treat the model to be a SNe II P or SNe II L when the final hydrogen envelope mass is greater than $0.5M_\odot$. Actually, together with extinction and distance uncertainties in progenitor data, it is very difficult to derive an accurate hydrogen envelope mass from the pre-explosion imaging. The amount of hydrogen left in the envelope at the time of explosion is closely related to the mass-loss rate and it also likely involves binary interaction. The weakening of the hydrogen lines of the SN IIb implies that the SN IIb progenitor has a tiny hydrogen envelope mass at the time of explosion, $M_H \approx 0.03 - 0.5M_\odot$ (Woosley et al. 1994; Meynet et al. 2015; Yoon et al. 2017), with a possible smaller mass limit of even down to $M_H \approx 0.01M_\odot$ (Dessart et al. 2011; Eldridge et al. 2018). Sravan et al. (2018) have set the hydrogen envelope of the SN IIb progenitor at the onset of explosion to have a mass of $0.01M_\odot < M_H < 1.0M_\odot$ in their population synthesis investigation. Recently, Gilkis & Arcavi (2022) quantify this uncertainty and discovered that available data are consistent with a proposed type Ib-IIb hydrogen mass threshold of $M_H \approx 0.033M_\odot$, implying that even type Ib progenitors are not pure helium stars. When the hydrogen envelope mass is less than $0.033M_\odot$, the star explodes as SNe Ib or Ic. Models with hydrogen envelope mass between $0.033M_\odot$ and $0.5M_\odot$ are considered as SN IIb progenitors in this paper.

The final evolutionary outcomes for the isolated star and the primary in the binary system are also summarized in Table 1. The binary orbit is circular and the Roche lobe radius is taken from the reference (Eggleton 1983). We chose several initial orbital periods as the different type of mass transfer via RLOF. Case A mass transfer occurs during the main sequence phase ($P_{\text{orb}} = 3.0$ days) while Case B mass transfer happens after core H-exhaustion but before the He-ignition in the core ($P_{\text{orb}} = 10.0$ days. Case C mass transfer starts during the core He-burning ($P_{\text{orb}} >\sim 20.0$ days). The progenitors are classified into the different type according to their effective temperature and surface hydrogen mass fraction, as follows: Red supergiant (RSG): $T_{\text{eff}} < 4.8kK, 0.01 \leq X_s$; Yellow supergiant (YSG): $4.8kK < T_{\text{eff}} < 7.5kK, 0.01 \leq X_s$; Blue supergiant (BSG): $7.5kK < T_{\text{eff}} < 55kK, 0.01 \leq X_s$. 


Fig. 1: (a) Evolutionary tracks of the isolated stars with initial masses of $16M_\odot$, $20M_\odot$, and $25M_\odot$ in Hertzsprung-Russell diagram. (b) Evolutionary tracks of the primary with the initial mass of $16M_\odot$ in the binary system with the initial orbital periods ranging from 3 days to 1000 days. (c) The mass of hydrogen envelope varies with the effective temperature for all isolated stars. (d) The mass of hydrogen envelope varies with the effective temperature for the primary $16M_\odot$ in all computed binary models.

3 RESULTS OF NUMERICAL CALCULATIONS

3.1 The evolutionary tracks in the Hertzsprung-Russell diagram

Panel (a) in Fig. 1 illustrates the HR diagram for all models, grouped by mass and rotation in single stars. At the beginning of evolution, the relation between temperature and stellar mass is $T_{\text{eff}} \propto M^{0.5-0.6}$. Therefore, the higher the stellar mass, the higher the effective temperature. The effective gravity can be significantly decreased by the centrifugal force which can be affected by the internal transportation of the spin angular momentum from the interior to the surface. Therefore, the star under the influence of rotation displays the surface luminosity characteristics of a lower-mass non-rotating one. The star, therefore, shifts towards lower luminosity and effective temperature when the initial rotational velocity increases. This is also because rapid rotation increases the stellar volume and the mean radius of a star, which results in a lower effective temperature than the non-rotating counterpart. This effect is considered as the dynamical effect of the rotation.

The rotationally driven mixing can also increase the hydrogen convective core, causing the evolutionary track more luminous and redder. Moreover, the opacity in the hydrogen envelope can be reduced by the increase of helium in the subsequent evolution. This process can cause the star to be more compact and higher effective temperature. The tracks shift upward and to the left.
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Fig. 2: Evolutionary tracks of two component stars with the initial mass of $16M_\odot$ in the binary systems B4 and B8.

Fig. 3: (a) The surface helium mass fraction varies with the effective temperature for all single stars. (b) The surface helium mass fraction varies with the effective temperature for the primary star $16M_\odot$ in all binary models. (c) The surface mass fraction ratio of nitrogen to carbon varies with the effective temperature for all single stars. (d) The surface mass fraction ratio of nitrogen to carbon varies with the effective temperature for the primary star $16M_\odot$ in all binary models.

before bending to the right in the HR diagram when the initial rotational velocity become higher (Maeder & Meynet 2000, 2012; Chieffi & Limongi 2013). After that, the star evolves toward the lower effective temperature. This is the consequence of the increase the mean molecular weight. The post main sequence luminosity of the rapidly rotating star is larger, by about a factor of
Fig. 4: (a) The surface hydrogen mass fraction varies with the evolutionary age for all isolated stars. (b) The surface hydrogen abundance varies with the evolutionary age for the primary $16M_\odot$ in all binary models. (c) The mass of helium cores varies with the evolutionary age for single stars. (d) The mass of helium cores varies with the evolutionary time for the primary $16M_\odot$ in all binary models.

~ 2.2, than that of a non-rotating counterpart. The reason is that rotational mixing leads to a more massive helium core. This fact indicates that rotating models will be faced with a violent collapse that heats the central core up to a higher density and temperature.

By core contraction after core helium exhaustion, non-rotating single stars spend their last evolutionary phases as red supergiants. Enhanced mass loss by rotation implies that tracks for the stars do not attain as far to the right position of the HR diagram as they do for non-rotating stars. The larger helium core in rotating stars can result in faster red-ward transition from blue supergiants to red supergiants, and hence, a larger mass loss rate can be induced by the increased luminosity. Therefore, the model S6 slightly shifts toward the higher effective temperature after the red supergiant star.

Comparing the our models of single stars with the counterparts in Georgy et al. (2012), the evolutionary track on the HRD is similar, but not identical, to that of stars that start on the ZAMS with a mass region of 15-20 $M_\odot$. For example, Georgy et al. (2012) have obtained that the track of a rotating 20 $M_\odot$ model has a H-content in the ejecta of 0.02 $M_\odot$, and a CO-core mass of 4.73 $M_\odot$. The corresponding hydrogen envelope mass at explosion is much less than our model S4. The main difference might ascribe to the treatments of the convective overshooting and
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Fig. 5: (a) The rate of mass-transfer via the RLOF varies with the evolutionary age in the models B1, B2, B4. (b) The variation of stellar radius with its stellar mass in the single and binary models. The dotted lines correspond to the Roche lobe in three binary models.

initial rotational velocities. The model of Georgy et al. (2012) remove most of the envelope, the star becomes somewhat bluer than our model S4 that suffer no rapid mass loss.

We display in Fig. 1(b) that the evolutionary tracks of the primary star with the initial mass of 16M⊙ in the binary system with the initial orbital periods ranging from 3 days to 1000 days. Since the orbital period in model B1 with \( P_{\text{orb}} = 3.0 \) days is so short that the primary star can go through the first event of RLOF during core hydrogen burning. The primary maintains at semi-detached state up to the core hydrogen exhaustion. The primary star transfers mass to the companion star so its luminosity falls down rapidly. The primary star deviates from thermal equilibrium. When the rate of mass transfer via RLOF become lower, the stars have enough time to adjust and attain both hydrostatic and thermal equilibrium again. Because of the expansion of the envelope, the primary star occurs the second episode of RLOF up the core helium burning. In the subsequent evolution, the strong stellar wind decreases the hydrogen envelope mass gradually, and the star shifts towards the higher effective temperature in the HR diagram. The shell of hydrogen burning can be extinguished and removed readily. Then, most of core helium is depleted during the blue excursion. When the core helium is burned out, the burning of helium in the shell can cause the star to expand again. At the same time, the deep layers can experience the advanced nuclear reactions before the final collapse. The stellar mass is only 3.04M⊙ when it exploded. The star is absent of hydrogen at all. Therefore, the primary finally appears as a BSG and explode as a SN Ib. It is worth noting that this star is not a SN Ic because the progenitor has a 1.47M⊙ helium envelope. The type Ic supernovae has a small helium envelope mass (MHe < 0.1M⊙). The current orbital period of the system is about 51.6 days and two components are clearly separated because of mass transfer.

In this system, the secondary has obtained a part of the transferred mass, being of 18.87M⊙. The companion star still burns hydrogen at its core. Because there is a large amount of matter
which can transfer from the primary, the central core of the secondary can be enlarged by the structural readjustment. The reason is that the central temperature and the convection core become larger when the central pressure is increased by the mass accretion. Fresh hydrogen above the previous core can be mixed by the convection and the central hydrogen abundance can be increased accordingly. The star is rejuvenated and then behaves like a younger star. The star does not shift further from the position of the zero age main sequence. It is not full of its Roche lobe. Another important feature of the companion star is that its internal structure is significantly different from the single star of the same mass. The companion star is appreciably over-luminous because of the mass accreting when the primary explodes. One of the observational counterpart of binary SN Ib progenitors is HD 45166. The system is made up a enriched helium 4.2$M_\odot$ primary star with $R \approx 1.0 R_\odot$ and a companion star which evolves on the main sequence. The system has an orbital period of 1.596 days (Boian & Groh 2018). However, the observed low-mass ($M = 3 - 5 M_\odot$) helium star can displays a higher effective temperature and become visually very faint on the evolution of the core helium burning. However, the star become cooler and more luminous at the final evolutionary stage because there exists a rapidly expanding envelope.

Let us consider the same initial mass 16$M_\odot$ as in the binary system B2 but with an initial orbital period of 10 days. The system goes through the first event of the RLOF after the main sequence. The primary can transport most of its mass to the companion at the beginning of the core helium burning (Case B mass transfer). More hydrogen can be retained after RLOF in the model B2 in contrast to the model B1. The reason is that the stripping process becomes less efficient in an initial wider system. After the mass transfer process, the stripped primary shrinks and attempts to reach a new thermal equilibrium. At the same time, the helium burning has already ignited in the convective core. From the minimum value of the luminosity, the main mechanism of structural adjustment is the carbon burning. The primary star in the initial tighter system B1 become hotter and more compact than the one in model B2 because the model B1 has a slight hydrogen envelope. Thus this process can reduce significantly the radius of the primary. The model B1 has a mass of 3.12$M_\odot$ at core helium exhaustion. After that the star loses all of its remaining hydrogen envelope because of strong stellar winds. Model B2 has a mass of 4.39$M_\odot$ and a hydrogen envelope mass of 0.17$M_\odot$. Then, it also can form a large blue excursion because there is a helium burning in the core. The track returns to the low effective temperature and finally blows up, going through all the rest nuclear burning. The progenitor of the supernova has a outermost hydrogen envelope of 0.13$M_\odot$ and the total mass of this star is 4.36$M_\odot$. This is a YSG progenitor that explodes as a type IIb supernovae. For the system B2, the rate of mass transfer is larger than the one in the system B1. This is because the thermal timescale of the star become much shorter at the moment that the RLOF begins. Therefore, the final orbital period of the system is about 89 days.

In the system B6 with a longer initial orbital period of 1000 days can give rise to Case C mass transfer. The RLOF occurs at a central helium fraction of 0.974. The occurrence of Case C mass transfer is closely related to the evolution of stellar radius. One can find that the peak value of the mass transfer rate via RLOF can reach $6.6 \times 10^{-3} M_\odot/yr$. The carbon can be ignited at the
The evolution toward the stripped envelope type IIb Supernovae

subsequent stage and results in a higher luminosity. When the explosion occurs, the progenitor has a mass of $5.414 \, M_{\odot}$ whereas its companion grows to $18.139 \, M_{\odot}$. This model can account for the luminosity of type SN IIL progenitor in the HR diagram. Furthermore, one also notice that both extended blue loops and blueward excursions can be increased by rotation in the binary system B7.

3.2 Compare with the other binary work

Our theoretical results differ from the other work for modeling the progenitor of SN 1993J. Claeys et al. (2011) also found channels to SNe IIb via Case A and early Case B mass transfer. The difference in two results is slightly large due to the adopted wind mass-loss prescription. Claeys 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 IIb progenitors to low metallicity. They have found a significant difference in the availability of early Case B mass transfer channels toward SNe IIb between solar and low metallicities. The circumstance with lower metallicity is prone to generate the more compact blue progenitors and can remain less hydrogen mass at SN explosion. Sravan et al. (2019) investigated the effect of mass ratio and mass transfer efficiency on binary SN IIb channels at both solar and low metallicities. They find that the viability of the evolutionary channels mentioned above increases with increasing initial mass ratio and decreasing mass transfer efficiency.

So far, five SN IIb progenitor candidates have been identified in pre-explosion images: SNe 1993J, 2008ax, 2011dh, 2013df, and 2016gkg. They are the important fundamental factors for constraining the evolution of SN IIb progenitors. In order to compare the theoretical results with observations, we have marked the position of five SN IIb in the HR diagram. There are also some evidences for binary companions to the progenitors of SN 1993J, SN 2001ig, and SN 2011dh. At present, only the effective temperature and luminosity of the companion star of SN 1993J have been identified. They are listed in Table 2. The observational position of two component stars in the HR diagram can provide us with a good tool to restrain the theoretical model and the evolutionary characters. The evolution of two components in the HR diagram can be traced by the model B4. At the time of SN explosion, the primary star fits well with the the pre-explosion observations (i.e., $\log L/L_{\odot} = 5.1 \pm 0.3$, $\log T_{\text{eff}} = 3.63 \pm 0.05$). However, the secondary star in model B4 is approximately consistent with observations. The secondary has the right luminosity to match the observations, but it is too blue. The star is shifted to a higher effective temperature by just $\triangle \log T_{\text{eff}} = 0.1$ (cf., Table 2). Stancliffe & Eldridge (2009) have proved that it is extremely difficult to obtain the secondary in the right place in the HR diagram. The observational position indicates that the secondary is extremely close to (or just beyond) the end of its main sequence. They find that this can only be done in a very narrow range in initial masses and periods. The position of the companion star also heavily depends on the value of the accretion efficiency $\beta$ (Benvenuto et al. 2013). The effective temperature and luminosity of the companion star of SN
1993J decrease for lower accretion efficiencies. Stancliffe & Eldridge (2009) have noticed that if mass transfer is conservative, the observations can be reproduced by a system consisting of a 15 M$_\odot$ primary and a 14 M$_\odot$ secondary in an orbit with an initial period of 2100 days. However, they used a high metallicity model with $Z = 0.04$. We simulate the system of SN 1993J composing of a 16 M$_\odot$ primary and a 15 M$_\odot$ secondary in an orbit with an initial period of 1100 days. The metallicity is $Z = 0.04$ and the accretion efficiency is set to be $\beta = 0.15$. The final positions for two components in the HR diagram are well fit with the observations (cf., Table 2 and Fig. 2.).

3.3 The variation of the hydrogen envelope mass

Panels (c) and (d) in Fig. 1 illustrate the mass of hydrogen envelope varies with the effective temperature in the isolated star and the primary in binaries. The hydrogen envelope mass is an important criterion for distinguishing from various types of supernovae. In the single star scenario, all models finally explodes as red supergiants because of the existence of the thick hydrogen envelope (cf., Panel (a) in Fig. 1). The fact indicates that stellar winds are too weak to remove the hydrogen envelope. Actually, an evolution to the blue after the red supergiant star occurs when the core mass fraction is greater than a low limit value about 70% of the stellar mass. This implies that the yellow or blue supergiant will has a hydrogen envelope that is less than about 30% of the total mass. In the binary scenario, the physical mechanisms of the mass loss via the RLOF are governed by the orbital separation and the stellar radius. The rate of mass transfer via RLOF heavily depends on the the radius excess (i.e., the difference of stellar radius and the radius of the Roche lobe). The mass transfer terminates when the radius of the primary is smaller than its Roche lobe. Interestingly, depending on two different physical mechanism for the mass removal, the stellar structure is quite different at the pre-supernova stage. Our results display that mass transfer via RLOF can give rise to a much thinner hydrogen envelope than stellar winds. The smaller the orbital period, the less the hydrogen envelope. There is a decreasing trend of the hydrogen envelope mass in the sequence from the IIP, III to IIb. The SN IIb progenitor has a tiny hydrogen envelope mass at the time of explosion, $M_H \simeq 0.033 - 0.5M_\odot$. When the hydrogen envelope mass is lower this mass region, the progenitor would be a WN star that would produce an SN Ib. The leftover hydrogen envelope mass in the envelope has an important impact on progenitor properties, such as temperature and photospheric radius, in non-trivial ways. In fact, a peak in progenitor envelope mass translates to a peak in radius, and vice versa. The extended model produces a pronounced spike at the early stage (at the time of 5 days after the SN explosion) of the observed bolometric light curves of the SN IIb while the compact progenitor displays a much weaker bump. The difference is mostly due to the extra amount of energy required to expand a more compact structure. Moreover, the more extended the progenitor structure, the higher the luminosity and temperature of the emitting region right after shock breakout, and the slower the subsequent decline (Bersten et al. 2012).

We find that for $M_H >\sim 0.1M_\odot$, with the decreasing of the leftover hydrogen envelope, the stellar radius become smaller while the effective temperature become larger. This difference might be a way to distinguish between the isolated and the binary channels for producing yellow or red
progenitors of supernovae (cf. Table 1). However, for $M_H < \sim 0.1M_\odot$, the evolution of the radius has no relevance to the mass of hydrogen envelope but is closely related to the expansion of the helium envelope. Thus, the relationship between SN IIb and other types of supernovae, such as SNe IIP, IIL and Ib/c strongly depends on the hydrogen envelope leftover.

3.4 The evolution of the surface chemical element

Panels (a-b) in Fig. 3 illustrate that the chemical enrichments vary as the evolutionary age in isolated stars and the primary in the binaries with various initial orbital periods. In non-rotating stars S1, S3, and S5, chemical mixing occurs only in the core due to convection and convective overshooting. However, these stars do not develop the convective envelope during the core hydrogen burning. Therefore, there is no other physical mechanisms which can bring nuclear material to the surface. Panels (a) and (b) in Fig. 4 display the evolution of the hydrogen abundance for single stars and the binary system with various orbital periods. One can find that the surface hydrogen abundance in non-rotating single stars drops slightly at the core hydrogen exhaustion. This indicates that the convective dredge-up can increase the helium and other heavy elements (i.e., $^{14}$N) from the deep layers to the surface. We find in Panels (a) in Fig. 4 that during the post-main sequence, surface hydrogen in model S1 drops from 0.7 to 0.65 while it falls down from 0.65 to 0.45 in model S5. This implies that the convective dredge-up is more efficient in the more massive star than the one in the less massive counterpart.

Rapid rotation in a star can give rise to the meridional circulation and the shear turbulence, which can mix nuclear products from the convective core all the way up to the surface in the models S2, S4, and S6. The first element to illustrate an enriched abundance is nitrogen, produced by the CNO cycle while the carbon is depleted during the main sequence. Rotation-induced mixing can also bring central helium to the surface while the hydrogen in the envelope can be transferred to the core (cf., panel a in Fig.4). One can find that the helium and the ratio of nitrogen to carbon N/C go up while surface hydrogen reduces with the increase of stellar mass and initial rotation velocity (Song et al. 2018). This can also result in a higher He/H ratio. However, the helium enrichment on the surface is much slower than the nitrogen abundance, as the inner helium gradient is much smaller than the nitrogen gradient(cf., panels a and c). A steeper nitrogen gradient is beneficial to give rise to nitrogen diffusion. The ratio of N/C goes up with the evolutionary age because more new nuclear reaction products can reach the surface. Therefore, rotation brings CNO products to the surface at an early time in contrast to the non-rotating counterpart. Rotational mixing is the strongest at the main sequence phase because the rotational velocity can maintain a higher value. At the post main sequence stage, the star can be spinned down by the stellar expansion, or it loses spin angular momentum significantly via strong stellar winds. Although rotational mixing can be decreased slightly, nitrogen enrichment is obvious because of the combined effect of the convective dredge-up and the enhanced wind. The convection region can extend to the upper region above the hydrogen burning shell.
The strong RSG wind can also expose the enriched nitrogen layer. Much of the difference in the chemical structure of the rotating pre-supernova and non-rotating one arises during the evolution of the main sequence evolution. The lifetime of the advanced stage is too short to allow significant effects for most rotational instabilities. Including rapid rotation in the progenitor model has many advantages. It can explain the N-rich circumstellar material. For example, the ultraviolet line of SN 1993J is wide with a box shape, originating from the ejections and a cold and dense shell. The shape of the line is well fitted by a fast moving shell with inner velocity $\approx 7000\, \text{Km/s}$. A strong signal of nitrogen enrichment is noticed in the shell, with the ratio of $N/C \approx 12.4$ in SN IIb 1993J. The ejecta of SN 1987A, with a velocity of $\geq 30,000\, \text{km/s}$, has an unexpected large He/H ratio of 0.2 by number, i.e., $Y = 0.4$. The high ratio of nitrogen to carbon in the ejecta of Supernova 1993J can be easily explained because the rotational mixing can bring central nitrogen to the surface and take the fresh carbon in the envelope to the central core. The large He/H ratio can be reproduced by rotational mixing which can bring the helium from the core to the surface. Furthermore, the non-spherical structure implies that the star had a strong aspherical wind, probably because of rapid rotation at the phase of red supergiants.

In contrast to single stars, the enrichment of N/C and helium in the primary star can attain a higher value and heavily depends on the orbital period. For example, the quantity $\log \frac{N}{C}$ increases from -0.53 to 2.14 for model B1 while it goes up from -0.53 to 1.92 for model B3. Therefore, nitrogen enrichment can attain the highest value during the first episode of RLOF in the tightest system B1. The main reason is that the hydrogen burning shell can be revealed early because the more hydrogen envelope can be removed by RLOF. The rotating binary system B7 can reach a larger value of nitrogen before RLOF due to the efficient rotational mixing. At the end of evolution, the quantity $\log \frac{N}{C}$ decreases rapidly because the carbon can be produced by $3\alpha$ in the bare helium core. Moreover, nitrogen can be depleted by the nuclear reaction $^{14}\text{N}(\alpha, \gamma)^{18}\text{O}$. 

3.5 The evolution of the helium core mass

Panels (c) and (d) in Fig. 4 illustrate the helium core varies with the time for the isolated star and the binary system with various orbital period. Single star models suggest that SN IIb arise in stars of modestly low mass, about $< 20\, \text{M}_{\odot}$ solar masses. The more massive initial star can give rise to the larger helium core ($> 6.0\, \text{M}_{\odot}$). This provides us a clear clue of the initial low mass of the progenitor in the binary system because the mass of the collapsing core is only several solar masses. Moreover, the thick hydrogen envelope of low-mass stars must be removed by the mass transfer via the RLOF. Regardless of a single or binary star, rotation can significantly increases the helium core mass because the convective core at the stage of the main sequence can be significantly enlarged by the rotational mixing. As the hydrogen shell burning surrounding the core consumes hydrogen and produces the helium ash falling to the core, the helium core mass grows slowly. However, the developing of the helium core can be greatly restricted by the RLOF because the hydrogen burning shell may be extinguished or eliminated by mass transfer via RLOF. The tighter
the binary system, the smaller the helium core mass. This indicates that the helium core of model B1 is most affected by the RLOF.

Actually, the helium core mass can essentially determine the type of supernova events. The light curve of SN 1993J was well fitted by the model with an explosion of a helium core mass of $4 - 5M_{\odot}$ and a residual low mass hydrogen envelope (of around $0.2M_{\odot}$) (Nomoto et al. 1993; Woosley et al. 1994, 1993). The low mass progenitor with a radially extended $\sim 500R_{\odot}$ hydrogen envelope is required to give rise to the initial sharp peak in the light curve and this qualitatively explains the transformation of the spectral evolution from a SN II to a SN Ib.

The timing of the second SN peak of the light curve imposes an important constraint on the helium core mass. More massive helium stars reach the light curve maximum at later times because the heat produced by radioactive decays takes a longer time to diffuse out. The wind mass-loss rate of a single main sequence mass $\geq 30M_{\odot}$ is large enough to remove the hydrogen envelope and this star can generate SN IIb (Heger et al. 2003; Georgy et al. 2009). However, this type of star has a helium core mass $\geq 8M_{\odot}$ previous to the explosion. A $8M_{\odot}$ helium core is too massive to produce the second maximum at $\sim 20$ days as observed for SN 2011dh, even assuming the most extreme $^{56}$Ni mixing (Bersten et al. 2012). As a result, the helium core mass region of SN IIb is about 2.0-6.0 $M_{\odot}$ which has been listed in Table 2.

Our model suggested the primary with an initial mass about $16M_{\odot}$ turns into a helium core-burning red supergiant. It fills with its Roche lobe and transfers about $10M_{\odot}$ during RLOF. A part of the remanent hydrogen envelope can be eliminated by the strong stellar wind.

3.6 The evolution of the rate of mass transfer

Panel (a) in Fig. 5 shows the rate of mass transfer via RLOF varies with the evolutionary time in the binary systems B1, B2, and B4. As matter flows from the more massive star to the less massive companion star in model B1 the orbital separation becomes short. The transfer of an amount of mass leads to shrinking of the donor radius, moving it back within its Roche lobe. Moreover, the shrinkage of the Roche lobe of the primary indicates that it can transport mass at a maximum rate of $\sim 2 \times 10^{-4}M_{\odot}\text{yr}^{-1}$ (cf., Panel (b) in Fig. 5). Due to this high rate of mass transfer, the thermal equilibrium is broken. The orbital separation stops shrinking when the star becomes the less massive of the two. From now on, continuing mass transfer will increase the orbital separation. The primary star which remains on the main sequence, is still filling of its Roche lobe so it keeps flowing matter to the secondary, albeit at a lower rate $< 3 \times 10^{-6}M_{\odot}\text{yr}^{-1}$. At the evolutionary age of 9.6 Myr, the primary has lost about $7.33M_{\odot}$ so $M_1 = 8.67M_{\odot}$ and $M_2 = 17.53M_{\odot}$. Therefore, the rate of mass transfer has been decreased to the nuclear timescale of the primary. The mass transfer ceases at the end of the main sequence because the stellar radius shrinks briefly. At the subsequent hydrogen shell fusion phase, the star expands again and the resulting high-mass transfer rate $\sim 4 \times 10^{-4}M_{\odot}\text{yr}^{-1}$ happens in the Kelvin-Helmholtz timescale.

The primary in model B2 is filled with its Roche lobe, when it crosses the Hertzsprung gap during the hydrogen-shell fusion phase, and starts to transport matter to the secondary star. The
expansion of the primary occurs on the Kelvin-Helmholtz timescale. As the orbit shrinks, this brings about a higher rate of mass transfer \( \dot{M}_R \sim 3.0 \times 10^{-3} M_\odot \text{yr}^{-1} \) in contrast to the model B1 and a steep drop in luminosity in HR diagram. The reason is that the mass transfer is so rapid that the star deviates from the thermal equilibrium. Simultaneously, the central core cannot produce enough nuclear energy to keep pace with the expansion of the envelope, so the luminosity of the star drops dramatically during RLOF.

When the donor in model B4 evolves on the Hayashi line, mass transfer occurs. The rate of mass transfer is expected to be unstable because the red supergiant star has developed a deep convective envelope. This will lead to rapid shrinking of both the orbital separation and the size of the Roche lobes, while the donor star keeps expanding. This results in a very high rate of mass transfer of \( \sim 1.0 \times 10^{-2} M_\odot \text{yr}^{-1} \) and thus the companion has no time to adjust. The mass transportation flows in the dynamical timescale. Unstable mass transfer via RLOF generally results in the formation of a common envelope but the model B4 does not. The main reason is that the high initial mass ratio \( M_2/M_1 \) can cause the system to avoid this phase. The accreting process happens after the secondary star has left the main sequence. This will increase its total envelope mass relative to its core mass. The secondary star is more likely to burn helium as BSGs, instead of RSGs. The secondary star may explode as BSG just like SN 1987A. One can find in panel (b) of Fig. 1 that the binary system with the orbital period region of 110 days < \( P_{\text{orb}} \) < 720 days can evolve into the observational RSGs (i.e., \( 3.58 < \log T_{\text{eff}} < 3.8; 4.72 < \log L/L_\odot < 5.4 \)) progenitor of type IIb Supernovae. Rotation can shift the region of the orbital period toward the higher value because it tends to increase the mass loss. The effect of rotation on the range of the initial orbital period will be discussed in future work.

The less massive single star (i.e., \(< \sim 25 M_\odot \)) ends their lifetime as red supergiants (cf., Table 1) while the more massive single ones (i.e., \( > \sim 25 M_\odot \)) evolves into yellow-blue supergiants. Yellow or blue supergiants progenitors can be produced by strong mass losses occurring at the stage of red supergiants. For example, the high mass loss can be triggered by the interaction between the radiation and the dust. Rotational mixing enhances the stellar luminosity and thus favours a more efficient mass loss. Also yellow/blue supergiants may be produced by RLOF in a binary channel. In this binary case, RLOF does not necessarily merely happens at the red supergiant stage. It can occur at more earlier phase. A very good example is given by the case of SN 2011dh. The observations indicate that SN 2011dh is a YSG which represents a great challenge to the evolution of the isolated star. If the progenitor star were a single star, for it to attain the pre-supernova as a YSG, it would have suffered from a very strong stellar wind. The evolutionary track is very sensitive to the stellar wind and the RSG wind need to be increased enormously. If the progenitor of SN 2011dh is a member of the binary system, we can naturally explain the main observational features of this star without increasing the stellar wind.
3.7 The evolution of stellar radii

Panel (b) in Fig. 5 shows that the stellar radius changes with the evolutionary age for isolated stars and the primary stars in binarities. The radius goes up slightly during the core hydrogen burning. The more massive star S6 has a larger radius because the mass-radius relationship scales with $R \propto M^{0.46}$ at $Z = 0.02$. In contrast to the non-rotating counterpart S1, rotation can help the star can attain a larger size in model S6. The reason is that the centrifugal force becomes stronger at the equator than the pole. The star turns into the oblate and the mean radius increases accordingly. When the single star crosses the Hertzsprung gap before core helium ignition, it swells strongly. It tends to expand slightly after helium core burning. The radius of single stars can attain a maximum value of $\sim 10^3 R_\odot$. One can notice that the total amount of mass loss is larger at the stages of both the main sequence and red supergiants. This is because the lifespan of the core hydrogen burning is the longest during the whole evolution. Moreover, the stellar wind of red supergiants can attain a high value of $\sim 10^{-5} M_\odot$/yr.

The evolution of radius in the binary has two important features. Firstly, the radius is constrained within the Roche lobe and is smaller than the single counterpart. The radius of the Roche lobe strongly depends on the orbital separation between two components and is less correlation with the mass ratio. Thus, the shorter the initial orbital period, the smaller the restrained stellar radius in the Roche lobe. Secondly, the radius expansion is non-monotonic and follows by a contraction and re-expansion phase. This feature is associated with the process that the primary star attempts to restore thermal equilibrium after RLOF. In order to enter the observed effective temperatures range (i.e., 3.6 and 4.1 in logarithm) of type IIb supernovae progenitor, the hydrogen envelope mass must be between 0.033 and 0.5 $M_\odot$. SN 1993J and SN 2013df are the RSG type SN IIb and their radii are $\sim 600 R_\odot$. The corresponding hydrogen envelope mass is $M_H = 0.2 - 0.4 M_\odot$. SN 2011dh (YSG progenitor, $\sim 200 R_\odot$) has the mass of hydrogen envelope of $M_H \sim 0.1 M_\odot$ while SN 2008ax (BSG progenitor, $30 - 50 R_\odot$) has a mass of hydrogen envelope of $M_H \sim 0.06 M_\odot$ (Yoon et al. 2017). This indicates that when the hydrogen envelope mass of the progenitor falls down, its radius decreases accordingly. The star become hotter and more compact. The mass of the residual hydrogen in the stellar envelope is clearly continuous, which also indicates the continuous transformation of the associated types of the SN IIb progenitor from the RSG, YSG to BSG.

We see large differences between an initial tight model B1 and a single star model S1 in the last evolutionary phase. The radius of the single model S1 can attain a maximum $870 R_\odot$ whereas it reaches $7.94 R_\odot$ in model B1. The smaller radius of the SN progenitor implies that the star might be a component star of the binary system. The radius of supernovae IIb covers the region form $\sim 50 R_\odot$ of the BSG progenitor to $\sim 600 R_\odot$ the RSG progenitor.

The mass-loss rate just before the explosion contains important information about their evolutionary paths. The mass-loss property is reflected in the density of circumsolar matter. Maeda et al. (2015) have noticed that there exists a close relationship between the progenitor radius and the average mass-loss rate shortly before the explosion. They have presented that more extended progenitors ($\sim 600 R_\odot$; e.g., 1993J, 2013df) have a very large mass-loss rate of $\sim 10^{-5} M_\odot$/yr before
the explosion, while less extended progenitors (∼ 200R⊙; e.g., SN 2011dh) have a moderate mass-loss rate (∼ 3 × 10^{-6}M⊙/yr). Ouchi & Maeda (2017) has explained that less extended progenitors have not only a smaller envelope mass to transfer but a larger value of equilibrium index ξ_{eq}. The larger ξ_{eq} means that the progenitor shrinks faster in response to the mass loss. However, mass loss rates can attain as high as ∼ 10^{-4}M⊙/yr from some red supergiants which have been reported van Loon et al. (2005). It may also be possible that this extensive mass loss for the more extended progenitors can be explained by a red supergiant with strong stellar winds after RLOF in our models B4 and B8. In model B4, the radius of the primary has a value of 426R⊙ and its stellar wind is 2.58 × 10^{-5}M⊙/yr (RSG progenitor of Supernovae IIb). In the theoretical model B3, the radius of the primary has a value of 223R⊙ and its stellar wind is 3.4 × 10^{-6}M⊙/yr (YSG progenitor of Supernovae IIb). These theoretical results in model B4 can be approximately consistent with the observations of the type IIb Supernovae 1993J (cf. Table 2).

4 CONCLUSION AND SUMMARY

Type IIb supernovae can be produced by the stellar winds but the intensity of stellar winds need to be well regulated. Therefore, it is very difficult for the less massive star (i.e., < 20M⊙) to give rise to the type IIb supernovae. Mass transfer in the binary system gives us an alternative channel for mass loss. Interacting binaries can naturally interpret the presence of the relatively low-mass IIb supernovae. In particular, a binary evolutionary channel might allow the formation of yellow or blue supergiant stars to originate from the relatively less massive star. In order to enter the observed effective temperature range between (in logarithm) 3.58 and 3.8 of the progenitor, the hydrogen envelope mass must be located in the range between 0.033 and 0.5 M⊙. The primary 16M⊙ with the companion 14M⊙ in the binary system with the initial orbital period region of 10 days < P_{orb} < 720 days can evolve into the observational regions of type IIb supernovae. The type of the progenitor (i.e., BSG, YSG, and RSG progenitors of SN IIb) is closely bound up with the initial orbital period. The BSG type SN IIb progenitor originates from the system with an initial P_{orb} ∼ 10 days while the YSG progenitor evolves from the system with an initial P_{orb} ∼ 100 days. The RSG progenitor is from the system with 300 days < P_{orb} < 700 days. An initially tighter system leads to a larger peel of the hydrogen envelope via RLOF. With the decreasing of the mass of the hydrogen envelope, the radius of the progenitor falls down accordingly. The star became hotter and more compact.

It is extremely difficult for the system with an initial orbital period P_{orb} > 700 days to produce a type Ib/c supernova without the hydrogen envelope (or even a type IIb supernova) in our RLOF scenario because the residual hydrogen envelope is sufficiently large. The star can stay the RSG structure and explode as SN IIP. However, other evolutionary channels (i.e., CEE etc.) or mass transfer implementations might change the evolutionary state in the initial wider system. It might be possible to reproduce the large radii type IIb supernovae in some other codes which have employed the different physical factors or processes. This study is beyond the scope of this paper which focuses on the progenitor evolution of SN IIb via the our RLOF scenario. Case B/C mass
transfer in this orbital region can make the helium core to be covered with a small amount of hydrogen envelope. Because the duration of Case B/C mass transfer is very short, a thick hydrogen envelope of $M_H > 0.033 M_\odot$ can be retained in the envelope. The envelope mass is larger than the one which is calculated from the binary model B1. Such a primary star may ultimately blow up as a type SN IIb 1993J, with a much extended envelope ($10^{13} - 10^{14}$cm). Case A mass transfer in model B1 can produce SN Ib because it is absent of hydrogen envelop.

Rapid rotation can produce three favorable conditions to generate SN IIb. Firstly, rapid rotation can enlarge the helium core mass significantly and thus reduce the hydrogen envelope mass accordingly. Secondly, rotation can shift the lowest limit of the initial orbital period which can produce SN Ib to a higher value because the centrifugal force tends to increase the mass loss via stellar winds. For a rapidly rotating component in the binary system, a less hydrogen envelope mass, therefore, need to be removed by the RLOF. Finally, rapid rotation significantly affects the stellar radius. Moreover, the transformation between spin angular momentum and the orbital angular momentum can affect slightly the orbital separation and the size of the Roche lobe. These variations have a very important impact on the rate of mass transfer via the RLOF because the mass transfer rate is closely related to the radius excess (i.e., the difference between stellar radius and the Roche lobe).

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