Type IIb supernova progenitors by fatal common envelope evolution

Noam Lohev\(^1\)*, Efrat Sabach\(^1\)†, Avishai Gilkis\(^2\)‡, Noam Soker\(^{1,3}\)§

\(^{1}\) Department of Physics, Technion - Israel Institute of Technology, Haifa 3200003, Israel
\(^{2}\) Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK
\(^{3}\) Guangdong Technion Israel Institute of Technology, Shantou, Guangdong Province 515069, China

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ABSTRACT

From stellar evolution simulations (using MESA) we conclude that the fatal common envelope evolution (CEE) channel for the formation of type IIb core collapse supernova (SNe IIb) progenitors, can indeed account for some SNe IIb. In the fatal CEE channel for SNe IIb a low mass main sequence secondary star spirals-in inside the giant envelope of the massive primary star and removes most of the giant envelope before it merges with the giant core. The key ingredient of the scenario studied here is that the tidally destroyed secondary star forms a new giant envelope. The mass-loss process in a wind during the evolution from the merger process until core collapse, i.e., until the explosion, leaves little hydrogen mass at explosion as inferred from observations of SNe IIb. In the case of a massive primary star with a zero age main sequence mass of \(M_{\text{ZAMS}} = 16 M_\odot\) that during its giant phase swallows a main sequence star of mass \(M_2 = 0.5 M_\odot\), we find at explosion a hydrogen mass of \(M_{\text{env}} = 0.085 - 0.09 M_\odot\), weakly depending on the rotation we assume. We find a similar value for \(M_{\text{ZAMS}} = 12 M_\odot\).

Key words: stars: stars: supernovae: general — binaries: close — accretion disks

1 INTRODUCTION

Massive stars explode as core-collapse supernovae (CCSNe) with varying amounts of hydrogen in their envelope. Those that have envelopes with a small amount of hydrogen show strong hydrogen lines at early times and very weak hydrogen lines, or even none, at later times. These are classified as Type IIb supernovae (SN IIb). Sravan et al. (2019) take the mass of the hydrogen-rich envelope of the progenitor at the onset of explosion to be \(0.01 M_\odot \leq M_{\text{H,env}} \leq 1 M_\odot\), while others take somewhat narrower ranges of \(M_{\text{H}} \approx 0.03 - 0.5 M_\odot\) (e.g., Woosley et al. 1994; Meynet et al. 2015; Yoon et al. 2017).

Studies estimate the fraction of SNe IIb out of all CCSNe to be \(f_{\text{IIb}} \approx 11\%\) (e.g., Smith et al. 2011; Shivvers et al. 2017; Graur et al. 2017). In a recent population synthesis study Sravan et al. (2019) take \(f_{\text{IIb,L}} \approx 20\%\) in low-metallicity stellar populations and \(f_{\text{IIb,H}} \approx 10 - 12\%\) in high-metallicity stellar populations. Sravan et al. (2019) study both single and binary stellar evolutionary routes and find that the two contribute about equally to the population of SNe IIb progenitors. However, the combined contribution of single and binary systems in their calculations is about a factor of three or more lower than the observed rate of SNe IIb (also Sravan 2016).

In the present study we focus on binary stellar evolution. Observations support the notion that, at least a large fraction of, SNe IIb come from binary stellar interactions. Kilpatrick et al. (2017) could fit a binary model for the progenitor of SN 2016gkg where the mass of the primary star at explosion was \(M_{1,f} = 5.2 M_\odot\), after it lost most of its mass in a binary interaction. The initial masses were \(M_{1,i} = 15 M_\odot\) and \(M_{2,i} = 1.5 M_\odot\) and the initial period was \(P_i = 1000\) days. Other examples include Benvenuto et al. (2013) who fit a binary progenitor for the SN IIb 2011dh, and the recent paper by Nakaoka et al. (2019) who fit a binary model to the SN IIb 2017cdd. Podsia\l{}owski et al. (1993) suggested that the progenitor of SN IIb 1993J was a binary system. Later Aldering et al. (1994) supported this suggestion from the photometry of this SN IIb. Fox et al. (2014) use the flattened circumstellar matter around SN 1993J (Matheson et al. 2000) to argue for a stellar binary progenitor.

Claeys et al. (2011) study a mass transfer scenario by expanding the work of Stancliffe & Eldridge (2009). They find that the binary evolution they consider can explain only about five percent of all SNe IIb, but this fraction increases
if the companion accretes only a small fraction of the mass that is lost from the binary system (see also Ouchi & Maeda 2017), and if the mass outflow carries relatively low angular momentum.

Soker (2017) takes the above properties, of low accretion mass by the companion, of low angular momentum of the ejected mass, and of a flattened mass loss, as supporting evidence for the grazing envelope evolution (GEE) scenario for the progenitors of some SNe IIb. In the GEE the companion grazes the giant envelope and launches jets. The jets remove mass from the envelope. Some of these properties, such as mass ejection and a flattened outflow, are shared with post-asymptotic giant branch intermediate binaries (post-AGBIBs; e.g., Kastner et al. 2010; Van Winckel 2017a), where observations in some systems find the main sequence (MS) companion that closely orbits the post-AGB star to launch jets (e.g., Witt et al. 2009; Gorlova et al. 2012; Thomas et al. 2013; Gorlova et al. 2015; Van Winckel 2017b). The GEE is an additional mass transfer scenario, different from the Roche-lobe overflow scenario, and hence expands the binary parameter space that can lead to SNe Ib.

We suggest that binary stellar evolution explains most, or even all, SNe Ib. For that to be the case we add two more evolutionary channels in addition to the Roche-lobe overflow scenario that most studies, e.g., Sravan et al. (2019), consider. The first evolutionary channel, as we described above, is the GEE as proposed by Soker (2017) and that Naiman et al. (2019) further study in a recent paper. In the second evolutionary channel a MS companion ejects all, or most, of the original hydrogen-rich envelope of the SN Ib progenitor, but then it suffers a fatal merger with the core of the giant. The companion is destroyed on the core and turns to be the new low-mass hydrogen-rich envelope of the massive star. This fatal common envelope evolution (CEE) scenario for SNe Ib is the subject of the present study.

There are different types of mergers of a core of a giant star with the more compact secondary star, sometimes resulting in a fatal destruction of the companion on the core (for a review of some fatal CEE evolutionary channels see Soker 2019). The companion itself can be a substellar object, like a brown dwarf (e.g., Hargaz & Soker 1994; Siess & Livio 1999), a MS star, e.g., as in some scenarios for the progenitor of SN 1987A (e.g., Chevalier & Soker 1989; Podsiadlowski et al. 1990; Menon & Heger 2017; Urushibata et al. 2018; Menon et al. 2019) or, as in a scenario for unusual nucleosynthesis (Ivanova & Podsiadlowski 2002), a white dwarf (e.g., Ilkov & Soker 2012 for the core degenerate scenario of Type Ia supernovae), or a neutron star. The merger of a neutron star with the core can be a very violent event and lead to a supernova-like event that is termed a common envelope jets supernova (Soker & Gilkis 2018). The merger of the two cores of two giants can lead to a bright transient event with the breakup velocity, i.e., we set.

To assess the role of rotation in our scenario we examine two cases. We simulate one case without rotation along the entire evolution, and one case with rotation. In the case with rotation the ZAMS equatorial velocity is \( v_{\text{rot,zams}} = 100 \text{ km s}^{-1} \). Spin-down is included by way of angular momentum being carried away by the stellar wind, with the mass-loss rate following de Jager et al. (1988) when \( T_{\text{eff}} \leq 10^4 \text{ K} \), according to Vink et al. (2001) when \( T_{\text{eff}} \geq 11^4 \text{ K} \), and interpolating in between. We do not include the spin-up of the giant envelope when the secondary star spirals-in.

The material accreted in the merger-mimicking phase has a specific angular momentum of \( j_{\text{acc}} = 4 \times 10^{18} \text{ cm}^2 \text{s}^{-1} \), resulting in an equatorial rotation velocity of about 10\% of the breakup velocity, i.e., we set the post-merger rotation velocity to 4.8 km s\(^{-1}\). As we describe below the initial rotation velocity has very small influence on the final hydrogen mass in the envelope at core collapse (explosion).

### 3 MASS REMOVAL

We first describe the evolution of a star with a ZAMS mass of \( M_{\text{ZAMS}} = 16M_\odot \) and with rotation (\( v_{\text{rot,zams}} = 100 \text{ km s}^{-1} \); see section 2). We assume that after the star undergoes its
we present the simulation without rotation the hydrogen mass is 0 with rotation has a hydrogen mass of 0 the mass of the secondary star, the giant in our simulation within a time of about 2000 years at a constant rate. The mass coordinate is \( M_r \) large expansion it swallows a secondary star of mass \( M_2 \) and in the lower panel we present the radius (orange-thick line) and density profile (blue-thin line) as a function of mass.

large expansion it swallowing a secondary star of mass \( M_2 \approx 10 M_\odot \). In particular, here we take \( M_2 = 0.5 M_\odot \) to enter the giant star envelope when the giant radius reaches a maximum value of \( R_1 = 848 R_\odot \). In Fig. 1 we present the primary stellar model at that stage, when we assume that the secondary star enters the giant envelope and spirals-in, and hence we start to rapidly remove envelope mass.

The core tidally destroys the secondary star at a radius \( r_T \) where the average density of the secondary star is about equal to the average density of the primary star inner to that radius. We find this radius to be about \( r_T \approx 1.5 R_\odot \). The mass coordinate is \( M(1.5 R_\odot) = 4.8 M_\odot \). We first need to ensure that the companion can in principle remove the envelope above that radius. In Fig. 2 we present the binding energy of the envelope above radius \( r \) as a function of that radius. Considering the virial theorem, we take the binding energy to be \( E_{\text{bind}}(r) = -0.5 E_{\text{orb}}(r) \), where \( E_{\text{orb}}(r) \) is the gravitational energy of the envelope mass above that radius. We also plot the gravitational energy that the companion of mass \( M_2 = 0.5 M_\odot \) releases to envelope removal as it inspirals to a radius \( r, E_2 = \alpha_{\text{CE}} G M(r) M_2 / (2r) \), where \( \alpha_{\text{CE}} \) is the common envelope parameter and \( M(r) \) is the mass of the primary star (giant) inner to radius \( r \). From Fig. 2 we learn that the companion can remove the envelope gas residue above radius \( r_T \approx 1.5 R_\odot \) for \( \alpha_{\text{CE}} M_2 \geq 0.2 M_\odot \). We therefore remove the entire envelope mass above the mass coordinate \( M = 4.8 M_\odot \).

The orbital period of the companion on the surface of the giant star is about two years. We expect the spiralling-in process of the secondary star down to the core to last for approximately tens of years. Due to numerical reasons though, we remove the envelope of the giant star, of \( 10.5 M_\odot \), within a time of about 2000 years at a constant rate.

At the end of the envelope removal phase, before we add the mass of the secondary star, the giant in our simulation with rotation has a hydrogen mass of \( 0.11 M_\odot \), while in the simulation without rotation the hydrogen mass is \( 0.10 M_\odot \).

**Figure 1.** The profiles of some quantities of the \( M_\text{ZAMS} = 16 M_\odot \) stellar model with rotation, when we start to remove the envelope. In the upper panel we present the composition of the main elements and in the lower panel we present the radius (blue-thin line) and density profile (orange-thick line) as a function of mass.

**Figure 2.** Some relevant quantities to envelope mass removal at the onset of the CEE for the \( M_\text{ZAMS} = 16 M_\odot \) stellar model with rotation (Fig. 1). In the solid orange line we present the radius as a function of mass, and in the solid black line we present the binding energy of mass residing above radius \( r \). We also plot the gravitational energy that the spiralling-in secondary star of mass \( M_2 = 0.5 M_\odot \) deposits to the envelope for two values of the \( \alpha_{\text{CE}} \) common envelope parameter as indicated in the inset.

### 4 MERGER TO EXPLOSION

After most of the hydrogen-rich envelope is removed (section 3) we accrete the companion to the (almost) bare core, namely, we add a mass of \( M_{\text{add}} = M_2 = 0.5 M_\odot \) and the same composition as the initial composition of the primary star. Including the leftover hydrogen, the merger product has a new hydrogen-rich envelope with a hydrogen mass of \( \approx 0.44 M_\odot \).

The destruction of the companion occurs over several times the dynamical time of the core-companion binary system, amounting to about few days and less. But, again, due to strong numerical limitations we add the mass at a slow rate over a time of \( t_{\text{add}} = 5 \times 10^3 \) yr. Although much longer than the dynamical time, it is much shorter than the rest of the evolutionary time until explosion (about \( 10^8 \) yr). Due to this long time the merger product is thermally relaxed at the end of the numerical mass addition phase.

In the simulation with rotation that we present here, we set the equatorial rotation velocity at the end of mass addition to be \( v_{\text{rot,merg}} = 4.8 \) km s\(^{-1}\), which is about 10% the break up rotation velocity at the end of the mass addition phase. As with young stellar objects that accrete mass, the merger product can lose a large amount of angular momentum by magnetic activity that blows off a small amount of mass. Namely, the merger product might have a slow rotation. We simulated therefore a case with no rotation, and also two cases with faster rotations (that we do not present here).

In Fig. 3 we present the structure of the star (merger product) in the rotating simulation at the end of the mass addition phase.

We now follow the star until core collapse. The final mass of the envelope, in particular the final hydrogen mass, strongly depends on the mass-loss rate. Because the envelope spins-down with mass loss, the final hydrogen mass at
explosion only weakly depends on whether we simulate with or without rotation. Therefore in this study we present in detail only the simulation which starts with rotation on the MS and after merger reaches a rotation of 10 per cent of the break up rotation. We simulated cases with faster initial rotation, up to 90 per cent of the break up velocity, and found only small differences in the final hydrogen mass.

We find that the hydrogen mass at core collapse is $M_{H, \text{exp}, \text{rot}} = 0.085M_\odot$ for the evolution with rotation, and $M_{H, \text{exp}} = 0.089M_\odot$ in the case without rotation. These values fall in the range of SNe IIb (section 1).

In Fig. 4 we present the radius, luminosity, and mass of the two models we describe here, with and without rotation, from the end of the mass addition phase to core collapse. Note that the two models do not start this phase at the same time due to different evolution times until mass removal (the model without rotation evolves faster). Besides the age, the differences between the two models are very small.

In Fig. 5 we present the evolution of the $M_{\text{ZAMS}} = 16M_\odot$ star on the HR diagram. Because our phases of mass removal and then mass addition are set by numerical limitations we do not show them. We show two phases of evolution, from ZAMS to the beginning of mass removal (black line), namely the onset of the CEE, and from the end of mass addition to core collapse (orange).

Overall, the evolution on the HR diagram is similar, but not identical, to that of stars that start on the ZAMS with a mass of $\approx 10 – 20M_\odot$ (e.g., fig. 2 of Georgy et al. 2013). Before mass removal our model is not different from other models (e.g., the 9$M_\odot$ model of Georgy et al. 2013). However, after we remove most of the envelope and add only 0.5$M_\odot$, the star becomes bluer than single stars that suffer no rapid mass loss. As the star here keeps some hydrogen-rich envelope, at its final evolutionary stage before core collapse it expands and becomes redder (e.g., the 20$M_\odot$ model of Georgy et al. 2013).

We repeat our treatment as described in the previous sections for a 12$M_\odot$ primary star the with rotation. In Fig. 6 we present the $M_{\text{ZAMS}} = 12M_\odot$ star on the HR diagram, similar to Fig. 5. We find the hydrogen mass at core collapse to be $M_{H, \text{exp}, \text{rot}} = 0.084M_\odot$.

5 DISCUSSION AND SUMMARY

We studied the fatal CEE channel for the formation of SN IIb progenitors. In this channel a low mass, $M_2 \approx 0.5 – 1M_\odot$, main sequence (MS) secondary star spirals-in inside the giant envelope of the primary star and removes most of the giant envelope before it merges with the giant.
core. The core tidally destroys the MS companion. The gas of the destroyed secondary star forms a new giant envelope that contains little mass of hydrogen at core collapse (explosion).

Nomoto et al. (1995) and Young et al. (2006) already considered the fatal common envelope evolution (CEE) channel to form SNe IIb. Our addition is the consideration of the formation of a new envelope from the destroyed secondary star. We followed the evolution of the merger product until core collapse (explosion). Our study is complementary to these earlier studies, and strengthens the merit of this scenario.

We studied in detail the case of a primary star with a ZAMS mass of $M_{\text{ZAMS}} = 16M_\odot$. In Fig. 1 we present some stellar properties after the rapid expansion of the star to become a giant. We showed (Fig. 2) that a secondary stars can remove most of the envelope if $\alpha_{\text{CE}} M_2 \gtrsim 0.2M_\odot$, where $\alpha_{\text{CE}}$ is the common envelope parameter. We then removed the mass above the mass coordinate $M = 4.8M_\odot$ which corresponds to a radius of $r \simeq 1.5R_\odot$ (Fig. 1) at the beginning of the CEE. At that radius the core tidally destroys a low mass MS companion. We mimicked the merger process by adding the companion mass of $M_2 = 0.5M_\odot$ to the almost bare core of the primary star. Due to numerical difficulties, we added the companion mass over a long time period of about $5 \times 10^4$ yr.

We present the structure of the merger product at the end of the mass addition phase in Fig. 3, and its evolution in Fig. 4. We found little differences in the final hydrogen mass between models with and without rotation. In Figs. 5 and 6 we present the evolution of the star before the CEE and after the merger in the HR diagram, for the $M_{\text{ZAMS}} = 16M_\odot$ and $M_{\text{ZAMS}} = 12M_\odot$ models, respectively.

For the $M_{\text{ZAMS}} = 16M_\odot$ model we found that the hydrogen mass at core collapse is $M_{\text{H,exp,rot}} = 0.085M_\odot$ for the evolution with rotation, and $M_{\text{H,exp,rot}} = 0.089M_\odot$ in the case without rotation. For the $M_{\text{ZAMS}} = 12M_\odot$ model we run the case with rotation only, and found $M_{\text{H,exp,rot}} = 0.084M_\odot$.

Despite some uncertainties in our calculations, we conclude that the fatal CEE scenario can account for some SNe IIb.

The main uncertainties in our calculations are as follows.

1. The outcome of the CEE. The first uncertainty concerns the envelope ejection before and during the CEE. We incorporated the CEE uncertainties in the commonly used $\alpha_{\text{CE}}$ parameter. However, the CEE is not fully solved, and recent studies have raised questions and found difficulties in removing the common envelope and in explaining the final orbital separation (e.g., Glanz & Perets 2018; Ivanova 2018; MacLeod et al. 2018; Soker et al. 2018; Reichardt et al. 2019; Iaconi & De Marco 2019, for a sample of papers just from the last year). The outcome depends on several factors, such as on the evolution just before the CEE (e.g., Bear & Soker 2010; Iaconi & De Marco 2019), and on the question of whether the companion launches jets that help in removing the common envelope (e.g., Shiber et al. 2019).

2. The merger process. The second uncertainty involves the core-companion merger process, as we do not know how much mass might be lost during the process. If a large fraction of the mass is lost, e.g., in jets and disk outflow from the merging core-companion system, then we can allow for a more massive companion. But we cannot allow for a too massive companion, as such a companion can remove the entire envelope before it merges with the core.

3. Wind mass-loss rate. The third uncertainty involves the mass-loss rate of the merger product (section 2). The uncertainty in mass loss rate is common also to single star evolution.

These uncertainties do not preclude the fatal CEE scenario, but they make it difficult to estimate the exact ranges of secondary masses and initial orbital separations that lead binary systems to form SNe IIb through the fatal CEE scenario. This in turn implies that we have a hard time in estimating the fraction of SNe IIb that comes from the fatal CEE scenario. Soker (2019) estimates that the fatal CEE scenario accounts for $\approx 10 - 30\%$ of SNe IIb, or $1 - 3\%$ of all CCSNe (as SNe IIb amount to $\approx 10\%$ of all CCSNe, e.g., Shivers et al. 2017). Other channels, like single-star evolution, the Roche-lobe overflow scenario (e.g., S. garn & et al. 2019), the grazing envelope evolution scenario (Soker 2017), and a scenario of a CEE where the companion survives, account for the rest.

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