The Slow Merger of Massive Stars

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Abstract. We study the complete merger of two massive stars inside a common envelope and the subsequent evolution of the merger product, a rapidly rotating massive supergiant. Three qualitatively different types of mergers have been identified and investigated in detail, and the post-merger evolution has been followed to the immediate presupernova stage. The “quiet merger” case does not lead to significant changes in composition, and the star remains a red supergiant. In the case of a “moderate merger”, the star may become a blue supergiant and end its evolution as a blue supergiant, depending on the core to total mass ratio (as may be appropriate for the progenitor of SN 1987A). In the case of the most effective “explosive merger”, the merger product stays a red giant. In last two cases, the He abundance in the envelope is increased drastically, but significant s-processing is mainly expected in the “explosive merger” case.

1 Introduction

It is evident that the internal structure of the progenitor of a core-collapse supernova (SN) is one of the dominant factors that determines the characteristics of the supernova explosion, such as the light-curve and the abundances produced in the supernova (see e.g. [7]). It has also been shown that the distribution of the angular velocity can produce a strong asymmetry in the nucleosynthesis during the SN explosion and in its ejecta [3]. This makes it necessary to follow the detailed evolution of the abundances and the rotation profile at all stages of the evolution of a massive star before it explodes as a core-collapse SN. Observationally, it is well established that ∼ 40 % of all massive stars are members of binary systems with orbital periods shorter than 1 year and that at least 25 % of these will start to interact by Roche-lobe overflow (RLOF) during the advanced stages of the primary’s evolution [4,10]. This implies that a significant fraction of all core-collapse supernova progenitors will have been affected by a previous binary interaction, where one of the most important interactions is the spiral-in of the two binary components inside a common envelope (CE) [10]. The final result of the spiral-in depends on how much of the released orbital energy has been converted into driving the expansion of the envelope relative to its binding energy. Here we study the situation where the deposited energy is not sufficient to eject the common envelope. This leads to the complete merger of the secondary with the core of the primary, forming a rapidly rotating single star in the process. Since the timescale of the merger is much longer than the dynamical timescale of the CE, it cannot be treated with a purely hydrodynamical code. Mass transfer in the merging phase changes not only the chemical composition
profile and the angular velocity distribution, but can also cause the erosion of part of the core, changing the core/envelope ratio. The evolutionary path of the merger product may also differ from that of a normal single star, e.g. by making a late blue loop more probable. Since the resulting supernovae may also differ from those with single-star progenitors, these merged objects are likely to be responsible for some of the variety observed among Type II supernovae.

In this paper we present the results of the modelling of the complete slow merger of a massive binary within a common envelope. In Section 2 we briefly describe the assumptions that were used to model mergers, and in Section 3 we present some of the main results.

2 Method and Initial Models

We used a standard Henyey-type stellar evolution code [8], updated recently [11]. The nuclear reactions rates were taken from Thielemann’s library REACLIB [13] and updated as in [2]. In the code OPAL opacities [12] are used, supplemented with contributions from atomic, molecular and grain absorption in the low temperature regime [1].

To model the merger we implemented a number of modifications to the single stellar evolution code. These modifications were made mainly to treat the presence of the secondary inside the primary’s envelope, including the mass transfer from the secondary to the core and the associated nucleosynthesis and mixing. A more detailed description of the modifications in the code can be found in [5]. We determine how deep the hydrogen-rich stream penetrates into the core of the primary using the prescription developed in [6].

We considered binaries consisting of a $18 - 22 M_\odot$ primary and a $1 - 5 M_\odot$ secondary. At the start of the spiral-in, the primary had already completed core helium burning. The chemical composition was taken as typical for young stars in the LMC ($X = 0.71$ and $Z = 0.01$). We adopted the Schwarzschild criterion for convection and took a mixing-length parameter $\alpha = 2$ and a convective-overshooting parameter equal to 25% of a pressure scale height. These parameters were chosen since they are most appropriate for merger models of the progenitor of SN 1987A (see [9]).

3 Results

The qualitative behaviour of the merger and the temporal evolution of the structure of the primary within the secondary’s orbit depend on the interaction of the hydrogen-rich material with the surrounding ambient matter. In particular, it depends on how deep and how fast the hydrogen-rich material penetrates into the primary’s core and its placement with respect to the hot and/or convective zones within the secondary’s orbit. According to our prescription for determining the stream penetration depth, the most effective penetration should occur near the end of the merger phase, when the mass-loss rate is high and the exposed material from the secondary has low entropy. However, at this time the
structure of the primary has changed, and a dense hydrogen-enriched region may already have been built up around the helium core, preventing the stream from penetrating deeper. All these effects combined create a very non-linear picture of the primary’s response to mass transfer. In general, as a result of the merger, the primary’s core expands, and the central temperature of the core drops (the degree of core cooling depends on the core expansion, i.e. the merger efficiency). This increases the total evolutionary time before core carbon ignition.

Based on our systematic study, we can distinguish three qualitatively different types of merger, where the classification of the mergers can be well explained by considering the temporal evolution of the convective zones during the merger.

- **The quiet merger.** All of the He affected by the penetrating stream is mixed with the outer envelope during the merger by convection, but since most of the He shell is not disturbed, there is only a moderate change in the surface abundances (He at the surface increases only by $4 \pm 8\%$). The merger product remains a red supergiant, although the progenitor might be significantly spun up compared to a single supergiant evolved in isolation.

  This type of merger may happen in systems where the primary is close to carbon ignition at the start of the merger. This implies high pressure and temperature gradients and a correspondingly high entropy dissipation coefficient $\tilde{\Lambda}$. In addition, the secondary has to have a mass larger than $\sim 2 M_\odot$ (due to the larger entropy).

- **The moderate merger.** Here the He core expands significantly, but an extensive He-rich shell remains. During the penetration, the stream creates a hydrogen-rich zone around the core. This zone becomes convective at some point and suppresses the bottom helium convective zone (see Fig. 1). During the merger, the primary core expands more drastically than in the case of the
quiet merger. The merger product appears as a red supergiant, rotating rapidly and contracting immediately after the merger. Significant rotationally enhanced mass loss in the equatorial direction during the contraction phase is expected. Depending on the core/envelope ratio, the merger product may then perform a blue loop (if the hydrogen shell source becomes temporarily dominant) or continues its evolution as a red supergiant. In the first case, some dredge-up of helium takes place during the merger, and it can be expected that rotationally induced mixing will cause further significant enhancement of the surface helium abundance. In the second case, a delayed dredge-up phase (a few thousand years after the merger, see Fig. 1) takes place, resulting in a large overabundance of He in the envelope (20 – 80%).

At the start of the merger, the primary can be either already close to core carbon ignition and has a companion of $\sim 1 \, M_\odot$, or the primary is at the start of He shell burning and has a companion of $2 \, M_\odot$ or larger. A moderate merger is most appropriate for the progenitor of SN 1987A.

- **The explosive merger.** During the stream-core interaction, the hydrogen-rich material accumulates between two initially convective zones and slowly creates an intermediate zone, which at some point connects to the He burning shell. This leads to a dramatic nuclear flash, resulting in a drastic expansion of the He shell and complete mixing. The duration of this He shell explosion is about 0.25 year. In the case of a strong He shell explosion, even the carbon core may be disturbed. In all cases, there is an immediate significant increase of helium in the envelope, often accompanied by an increase in the carbon abundance. The stripped-off naked carbon core connects with the hydrogen-rich convective envelope and provides the site for efficient s-processing. The merger product continues its evolution as a red supergiant.

This type of the merger can take place in binaries with low-mass secondaries, not very close to core carbon ignition. The anomalous carbon star V Hydrae may provide an example for this merger channel.

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