Chemically homogeneous evolution in massive binaries

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Abstract. Rotation can have severe consequences for the evolution of massive stars. It is now considered as one of the main parameters, alongside mass and metallicity that determine the final fate of single stars. In massive, fast rotating stars mixing processes induced by rotation may be so efficient that helium produced in the center is mixed throughout the envelope. Such stars evolve almost chemically homogeneously. At low metallicity they remain blue and compact, while they gradually evolve into Wolf-Rayet stars and possibly into progenitors of long gamma-ray bursts.

In binaries this type of evolution may occur because of (I) tides in very close binaries, as a result of (II) spin up by mass transfer, as result of (III) a merger of the two stars and (IV) when one of the components in the binary was born with a very high initial rotation rate. As these stars stay compact, the evolutionary channels are very different from what classical binary evolutionary models predict. In this contribution we discuss examples of nearly chemically homogeneous evolution in very close tidally-locked binaries. Even in such very close massive binaries, the stars may remain compact and avoid mass transfer, while Roche lobe overflow and a merger would be inevitable in the classical picture. This type of evolution may provide an alternative path to form tight Wolf-Rayet binaries and massive black hole binaries.

Keywords: Massive stars, early type, OB type, rotation, binaries, mixing, surface abundances, Wolf-Rayet stars, high-mass black-hole binaries, long gamma-ray bursts

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INTRODUCTION

The rotation rate is considered as one of the main initial stellar parameters, along with mass and metallicity, which determine the evolution and fate of single stars. Rotation can deform the star, interplay with the mass loss and trigger instabilities in the interior leading to turbulent mixing in otherwise stable layers [e.g. 1]. As rotationally induced mixing can bring processed material from the core to the surface, it has been proposed as explanation for observed surface abundance anomalies, such as a nitrogen enrichment found in several massive main-sequence stars [e.g. 2, 3, 4]. Rotation has also been successfully invoked to explain various phenomena [5, and references therein]: the ratio between O-stars and various types of Wolf-Rayet stars at different metallicities [6], the production of nitrogen in the early universe [7], the (apparent) presence of multiple populations in intermediate-age and globular clusters [8, 9, 10], the variety of core collapse supernovae [11] and the formation of progenitors of long gamma-ray bursts [12].

In models of rapidly rotating, massive stars, rotational mixing can efficiently transport centrally produced helium throughout the stellar envelope. Instead of expanding during core H-burning as non-rotating models do, they stay compact, become more luminous and move blue-wards in the Hertzsprung-Russell diagram [13]. This type of evolution is often referred to as (quasi-)chemically homogeneous evolution and has been proposed as a pathway for the formation of long gamma-ray burst progenitors [14, 15].

High rotation rates can be achieved in binary systems due to mass and angular momentum transfer [16], by tidal interaction in close binaries [17] and, possibly, when the two stars in a binary merge. In this contribution we discuss the possibility and consequences of chemically homogenous evolution in close massive binaries, which according to classical evolutionary models would inevitably experience Roche lobe overflow.

 STELLAR EVOLUTION CODE

We model the evolution of rotating massive stars using the 1D hydrodynamic stellar evolution code described by Yoon et al. [14] and Petrovic et al. [19], which includes the effects of rotation on the stellar structure and the transport of
angular momentum and chemical species via rotationally induced hydrodynamic instabilities [20]. We refer to [18] for a full description of the code.

CHEMICALLY HOMOGENEOUS EVOLUTION IN VERY MASSIVE BINARIES (50$M_{\odot}$ + 25$M_{\odot}$)

In massive binaries, rotational mixing can be so efficient that the change in the chemical profile leads to significant structural changes. In this section we discuss models for which we adopt a primary mass of 50$M_{\odot}$, a secondary mass of 25$M_{\odot}$, orbital periods varying from 1.5 to 4 days, assuming an SMC composition. Although such massive close systems are rare, observational counterparts do exist, for example two of the four massive binaries presented by Massey et al. [21] which are located in the R136 cluster at the center of the 30 Doradus nebula in the Large Magellanic Cloud: R136-38$^1$ and R136-42$^2$. Another example with an even closer orbit is [L72] LH 54-425$^3$ located in the LH 54 OB association in the Large Magellanic Cloud [22]. All three binary systems have O-type main-sequence components, which reside well within their Roche lobes.

Figure 1 shows the evolution of our models in the Hertzsprung-Russell diagram. The tracks are plotted until one of the stars in the binary fills its Roche lobe (not necessarily the primary, see below). At the onset of hydrogen burning their location in the diagram is very similar, although the stars in tighter binaries, which rotate faster, are slightly cooler and bigger. This is a direct consequence of the centrifugal acceleration. As they evolve their tracks start to deviate. The wider systems ($P_{\text{orb}} > 2.0d$) evolve similarly to non-rotating stars: they expand during core hydrogen burning, evolving towards cooler temperatures until they fill their Roche lobe. Their evolutionary tracks overlap in the Hertzsprung-Russell diagram.

The primaries in the tighter systems ($P_{\text{orb}} < 2.0d$) behave very differently: they evolve left- and upward in the HR-diagram, becoming hotter and more luminous while they stay relatively compact. The transition in the morphology of the tracks around $P_{\text{orb}} = 2$ days is analogous to the bifurcation found for fast rotating single stars [13, 12].

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1. $M_1 = 56.9 \pm 0.6$ $M_{\odot}$, $M_2 = 23.4 \pm 0.2$ $M_{\odot}$, and $P_{\text{orb}} = 3.39d$
2. $M_1 = 40.3 \pm 0.1$ $M_{\odot}$, $M_2 = 32.6 \pm 0.1$ $M_{\odot}$, and $P_{\text{orb}} = 2.89d$
3. $M_1 = 47 \pm 2$ $M_{\odot}$, $M_2 = 28 \pm 1$ $M_{\odot}$, and $P_{\text{orb}} = 2.25d$
FIGURE 2. **First row:** Nitrogen abundance as a function of age at the surface for the primary and secondary star of the same systems as plotted in Figure 1. Note the different scales. **Second row:** Radius as fraction of the Roche-lobe radius for the primary (left panel) and secondary star (right panel).

**Surface abundances**

Rotational mixing is so efficient in these systems that even a large amount of helium can be transported to the surface. Figure 1 depicts the helium mass fraction at the surface as a function of the helium mass fraction in the center. In the hypothetical case that mixing would be extremely efficient throughout the whole star, the surface helium abundance would be equal to the central helium abundance at all time. This is indicated by the dotted line. For the widest systems, the surface helium mass fraction is not affected by rotational mixing, while for the tighter systems $X_{\text{He}}$ reaches up to 65%. They follow the evolution of chemically homogeneous stars. Figure 1 also shows that for each system, mass transfer starts before all hydrogen is converted into helium in the center. Note that the highest central He mass fraction when mass transfer starts is reached in the 1.7 day system (more than 80%), whereas on the basis of standard binary evolution theory [e.g. 23] one would expect this to occur in the widest system. This anomalous behavior is connected to the evolution of the radius, as discussed below.

All systems show large enhancements of nitrogen at the surface of the primary, see Fig. 2. The wider systems are enhanced by up to 0.9 dex. In the tight systems the enhancement reaches almost 2 dex. This extreme increase is partly due to the fact that abundance is measured relative to hydrogen, which is significantly depleted at the surface of the primaries in the tightest systems. In fact, due to rotational mixing, H is transported from the envelope to the core as well, where it is burned to He. Also the secondary stars show nitrogen surface enhancements, of up to 0.5 dex.
Evolution of the radius

The increase of helium in the envelopes of the primary stars in the tightest binaries leads to a decrease of the opacity and an increase in mean molecular weight in the outer layers, resulting in more luminous and more compact stars. In Fig. 2 we plot the stellar radii as a fraction of their Roche-lobe radii. The primary stars in the wider systems expand and fill their Roche lobe after about 2.5-3 Myr. Contrary to what one might expect, we find that Roche-lobe overflow is delayed in tighter binaries. Whereas classical binary evolution theory predicts that the primary star is the first to fill its Roche lobe, we find instead that for systems with \( P_{\text{orb}} \leq 1.7 \) days it is the less massive secondary star that starts to transfer mass towards the primary. This is because the efficiency of rotational mixing increases with increasing stellar mass [e.g. 14], making the effect on the stellar structure more significant in the primary star. During this phase of reverse mass transfer from the less massive to the more massive star, the orbit widens. Nevertheless we find that, if we continue our calculations, the two stars come into contact shortly after the onset of mass transfer and the stars are likely to merge.

Expected trends with system mass and mass ratio

In more massive systems the effect of rotational mixing becomes stronger in both components. This may allow for chemically homogeneous evolution to occur in binary systems with wider orbits. If the mass ratio is closer to one, \( M_2 \approx M_1 \), the effect of rotational mixing becomes comparable in both stars, and they may both evolve along an almost chemically homogeneous evolution track. In that case both stars can stay within their Roche lobe and gradually become two compact WR stars in a tight orbit. In a system with a more extreme mass ratio, \( M_2 \ll M_1 \), the secondary star will hardly evolve or expand during the core hydrogen-burning lifetime of the primary. Also in this case Roche-lobe overflow may be avoided during the core hydrogen-burning lifetime of the primary component, leading to the formation of a Wolf-Rayet star with a main-sequence companion in a tight orbit.

DISCUSSION

We have shown that rotational mixing, if it is as efficient as assumed in our models, can lead to chemically homogeneous evolution for tight binaries with a 50M\(_\odot\) primary. In these models the primary star stays so compact that the secondary star is the first to fill its Roche lobe.

This peculiar behavior of the radius of stars, which are efficiently mixed, has been noted in models of rapidly rotating massive single stars [13] and has been suggested as an evolutionary channel for the progenitors of long gamma-ray bursts [14, 15] in the collapsar scenario [24]. In single stars this type of evolution only occurs at low metallicity, because at solar metallicity mass and angular momentum loss in the form of a stellar wind spins down the stars and prevents initially rapidly rotating stars from evolving chemically homogeneously [14, 25]. In a close binary tides can replenish the angular momentum, opening the possibility for chemically homogeneous evolution in the solar neighborhood.

The binary models presented here all evolve into contact, but Roche-lobe overflow may be avoided altogether in systems in which the secondary stays compact, either because it also evolves chemically homogeneously, which may occur if \( M_1 \approx M_2 \), or because it evolves on a much longer timescale than the primary, when \( M_2 \ll M_1 \). Whereas standard binary evolution theory predicts that the shorter the orbital period, the earlier mass transfer sets in, we find that binaries with the lowest orbital periods may avoid the onset of mass transfer altogether. This evolutionary scenario does not fit in the traditional classification of interacting binaries into Case A, B and C, based on the evolutionary stage of the primary component at the onset of mass transfer [23, 26]. In the remainder of this contribution we will refer to this new case of binary evolution, in which mass transfer is delayed or avoided altogether as a result of very efficient internal mixing, as Case M.

The massive and tight systems in which Case M can occur are rare. Additional mixing processes induced by the presence of the companion star, which may be important in such systems, will widen the parameter space in which Case M can occur: it would lower the minimum mass for the primary star and increase the orbital period below which this type of evolution occurs. The massive LMC binary [L72] LH 54-425, with an orbital period of 2.25 d [22] may be a candidate for this type of evolution. Another interesting case is the galactic binary WR20a, which consists of two core hydrogen burning stars of \( 82.7 \pm 5.5 \text{M}_\odot \) and \( 81.9 \pm 5.5 \text{M}_\odot \) in an orbit of 3.69 d. Both stars are so compact that they are detached. The surface abundances show evidence of rotational mixing: a nitrogen abundance of six times solar is observed and carbon is depleted [27, 28].
Short-period Wolf-Rayet and black-hole binaries

If Roche-lobe overflow is avoided throughout the core hydrogen-burning phase of the primary star, both stars will stay compact while the primary gradually becomes a helium star and can be observed as a Wolf-Rayet star. Initially the Wolf-Rayet star will be more massive than its main sequence companion, but mass loss due to the strong stellar wind may reverse the mass ratio, especially in systems which started with nearly equal masses. Examples of observed short-period Wolf-Rayet binaries with a main-sequence companion are CQ Cep, CX Cep, HD 193576 and the very massive system HD 311884[29]. Such systems are thought to be the result of very non-conservative mass transfer or a common envelope phase [e.g. 30]. Case M is an alternative formation scenario which does not involve mass transfer.

Case M is also interesting in the light of massive black-hole binaries. Orosz et al. [31] recently published the stellar parameters of M33 X-7. This system is located in the nearby galaxy Messier 33 and harbors one of the most massive stellar black holes known to date, $M_{bh} = 15.7 \pm 1.5M_\odot$, orbiting a massive O star, $M_O = 70 \pm 7M_\odot$, which resides inside its Roche lobe in spite of the fact that the orbit is very tight, $P_{orb} = 3.45$ d. The explanation for the formation of this system with standard binary evolutionary models involves a common-envelope phase that sets in after the end of core helium burning (Case C). This is because the progenitor of the black hole must have had a radius much greater than the current orbital separation. This scenario is problematic as it requires that the black-hole progenitor lost roughly ten times less mass before the onset of Roche-lobe overflow than what is currently predicted by stellar evolution models [31]. An additional problem is that the most likely outcome of the common envelope phase would be a merger, as the envelopes of massive stars are tightly bound [32]. However, see Valsecchi et al. these proceedings and [33]. In the Case M scenario the black-hole progenitor can stay compact and avoid Roche-lobe overflow, at least until the end of core helium burning. This way the star retains its envelope. Whether this scenario can explain all the system parameters, remains to be investigated [see also 34, 35, and references therein]. Homogeneous evolution helps to explain the high mass of the black hole, but the short orbital period poses a difficulty also for Case M. This is because strong mass loss during the Wolf-Rayet life time will widen the orbit.

The subsequent evolution of tight, rapidly rotating Wolf-Rayet binaries remains to be investigated. If one or both members of the system can retain enough angular momentum to fulfill the collapsar scenario [24], which may be hard as the tides can slow down the stars [e.g. 17], it may lead to the production of one or even two long gamma-ray bursts.

CONCLUSION

We investigated the effect of rotational mixing on the evolution of detached short-period massive binaries using a state of the art stellar evolution code. These systems often show eclipses and big radial velocity variations, such that their stellar parameters, the rotation rate and possibly their surface abundances can be determined with high accuracy. This enables a direct comparison between an observed system and models computed with the appropriate stellar and binary parameters. Therefore we proposed in De Mink et al. [18] to use such systems as test cases for rotational mixing. An additional major advantage of using detached main-sequence binaries is the constraint on the evolutionary history. For a fast spinning apparently single star we do not know whether it was born as a fast rotator or whether its rotation rate is the result of mass transfer or merger event. In a detached main-sequence binary we can exclude the occurrence of any mass transfer phase since the onset of core-hydrogen burning.

In the most massive binaries we find that rotational instabilities can efficiently mix centrally produced helium throughout the stellar envelope of the primary. They follow the evolutionary path of chemically homogeneous stars: they stay within their Roche lobe, being over-luminous and blue compared to normal stars. Due to large amount of nitrogen and helium at the surface these stars can be observed as Wolf-Rayet stars with hydrogen in their spectra. In contrast to standard binary evolution, we find that it is the less massive star in these systems that fills its Roche lobe first.

There may be regions in the binary parameter space in which Roche-lobe overflow can be avoided completely during the core hydrogen-burning phase of the primary. The parameter space for this new evolutionary scheme, which we denote Case M to emphasize the important role of mixing, increases if additional mixing processes play a role in such massive systems. It may provide an alternative channel for the formation of tight Wolf-Rayet binaries with a main-sequence companion, without the need for a mass transfer and common envelope phase to bring the stars close together. This scenario is also potentially interesting for tight massive black hole binaries, such as the intriguing system M33 X-7 [31].
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