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Rotational mixing in close binaries

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Abstract. Rotational mixing a very important but uncertain process in the evolution of massive stars. We propose to use close binaries to test its efficiency. Based on rotating single stellar models we predict nitrogen surface enhancements for tidally locked binaries. Furthermore we demonstrate the possibility of a new evolutionary scenario for very massive ($M > 40\mathrm{M}_\odot$) close ($P < 3$ days) binaries: Case M, in which mixing is so efficient that the stars evolve quasi-chemically homogeneously, stay compact and avoid any Roche-lobe overflow, leading to very close (double) WR binaries.

Keywords. stars: rotation, binaries: close, stars: Wolf-Rayet, stars: abundances

1. Introduction

Rotation plays an important role in the evolution of massive stars: it causes deformation of the star due to the centrifugal force, it interplays with stellar mass loss, and it can induce instabilities leading to internal mixing of the star. Mixing induced by rotation has been successful in explaining the ratio of red to blue super giants and it has been

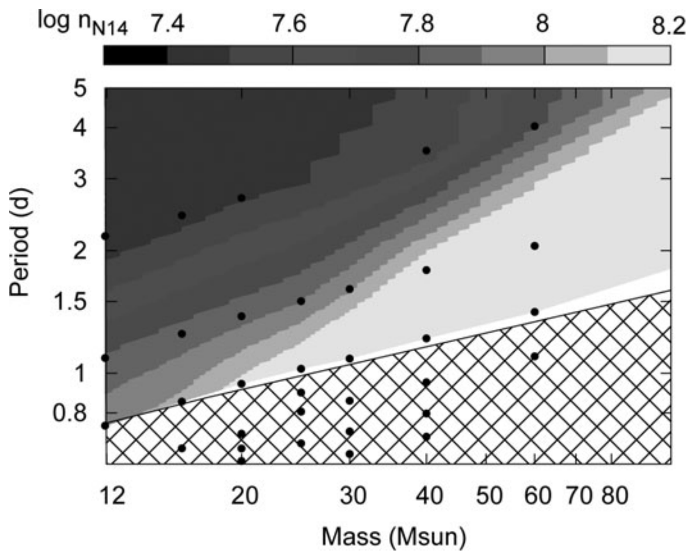

Figure 1. The nitrogen surface abundance is plotted in color shading for rotating single stellar models (black dots) at a metallicity of Z=0.004 with different masses and initial spin periods at the end of their main sequence evolution. In a tidally locked binary the spin period corresponds to the orbital period. The hashed region is excluded for binaries as the two stars are in contact at zero age.

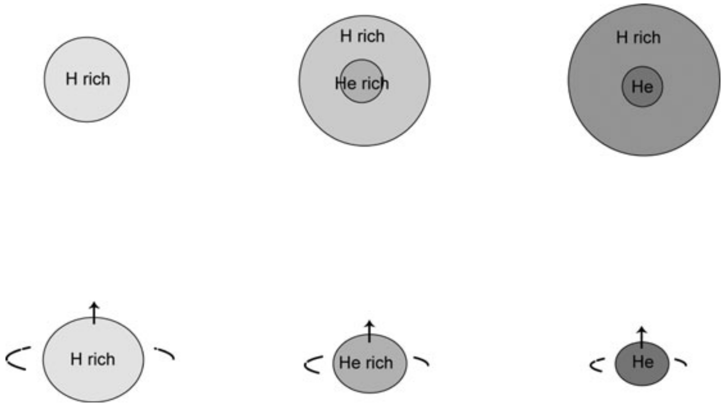

Figure 2. Cartoon representation the evolution of a core hydrogen burning star. A slow rotor will form a core-envelope structure (top row). Fast rotators will evolve quasi chemically homogeneously, and they will stay compact gradually becoming a WR star (bottom row).

invoked to explain the helium and nitrogen enhancements observed in OB stars (Heger & Langer 2000; Maeder & Meynet 2000, and references therein).

Although extensive literature exists on the subject, the efficiency of rotationally induced mixing is still very uncertain. The VLT-FLAMES survey of massive stars (Evans *et al.* 2005), which resulted in rotational velocities and surface abundances of about one thousand O and early B stars provided a major step forward. However it raised more questions than it answered regarding rotational mixing (Hunter *et al.* 2007). This motivated us to formulate potential observational tests to constrain the corresponding uncertain physical parameters. For this purpose we focus on tidally locked binaries.

The advantage of using binaries is that the major stellar parameters, such as the masses, radii and effective temperatures, can be accurately determined (e.g. Hilditch *et al.* 2005) and also, if high resolution spectra are available, the surface abundances. This enables us to test our stellar models directly against well understood systems (see also de Mink *et al.* 2007). A second advantage of using close binaries is that the tidal forces synchronize the spin period of the stars with the orbital period, such that $P_{\rm spin} = P_{\rm orbit}$. This enables us to determine the rotation rate of the stars much more accurately than in the case of single stars, where it can only be estimated from $v \sin i$, derived from spectral fitting. The inclination i of th rotation axis is generally not known for a particular single star.

In this contribution we use of rotating single stellar models (as published by Yoon *et al.* (2006), to which we refer for details) to demonstrate two predictions for detached tidally locked binaries. In Section 2 we discuss the surface enhancement which can be expected in close binaries. In Section 3 we discuss a new evolutionary binary scenario for the most massive close binaries, case M, in which rotational mixing is so efficient that the stars stay compact and avoid any Roche lobe overflow.

2. Surface abundances

The faster the initial rotation of a star of a given mass, the more efficient is rotational mixing. For example a 20 solar mass single star rotating with an initial equatorial rotational velocity of 180 km/s (corresponding to a spin period of about 1.5 days) enhances

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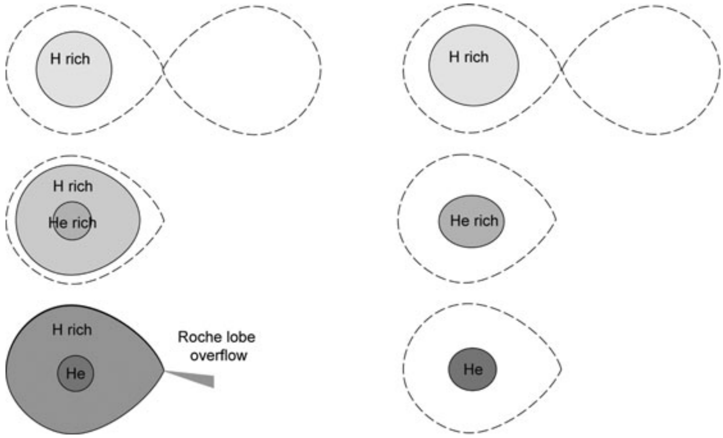

Figure 3. Cartoon of the evolution of normal star inside a Roche lobe (left column) and a quasi-chemically homogeneous evolving star which avoids Roche-lobe overflow: *Case M* (right column).

its surface nitrogen abundance by about 0.5 dex over the course of its main sequence evolution.

Figure 1 shows the surface N abundance at the end of core H burning for the grid of single stellar models published by Yoon *et al.* (2006). In a tidally locked binary the spin period corresponds to the orbital period. The figure therefore shows the maximum surface abundances which we can expect for close detached binaries. For example the sample of OB type binaries with orbital periods ranging from 1-5 days by Hilditch *et al.* (2005) should show enhanced N abundances by up to 0.4 dex. Currently no spectra are available of these systems with high enough resolution to determine the surface abundances. In more massive systems the enhancements will be even larger. In principle even one well-determined binary systems could serve as a strong test case for rotational mixing. In fact, even if in close binaries mixing is enhanced by processes such as tides or irradiation, these observations can be used to set an upper limit to the efficiency of rotational mixing.

3. Chemically homogeneous evolution in binaries

In rapidly rotating stars mixing can be so efficient that the stars fail to form the usual core/envelope structure. These stars stay compact during core H burning and gradually become WR stars (Maeder 1987; Yoon & Langer 2005), illustrated by the cartoon in Figure 2. This type of evolution has been suggested to lead to the formation of long GRB progenitors (e.g. Yoon & Langer 2005; Cantiello *et al.* 2007).

Figure 4 shows that for tidally locked binary systems there is a small range in the parameter space where chemically homogeneous evolution can occur in synchronously rotating binaries. This implies that in such close massive binaries the stars will stay compact and avoid Roche-lobe overflow completely (see the cartoon in Figure 3).

To demonstrate that this situation, predicted on the basis of single stellar models, can actually occur in binary evolution models we performed some preliminary calculations. Figure 5 shows the evolutionary track of a non-rotating 100 $M_\odot$ star at a metallicity of $Z = 10^{-5}$ together with four tracks corresponding to the evolution of a 100 $M_\odot$ star in a close binary with an equal mass companion, in orbits with initial periods of 1.7, 1.4, 1.2 and 1.15 days, respectively.

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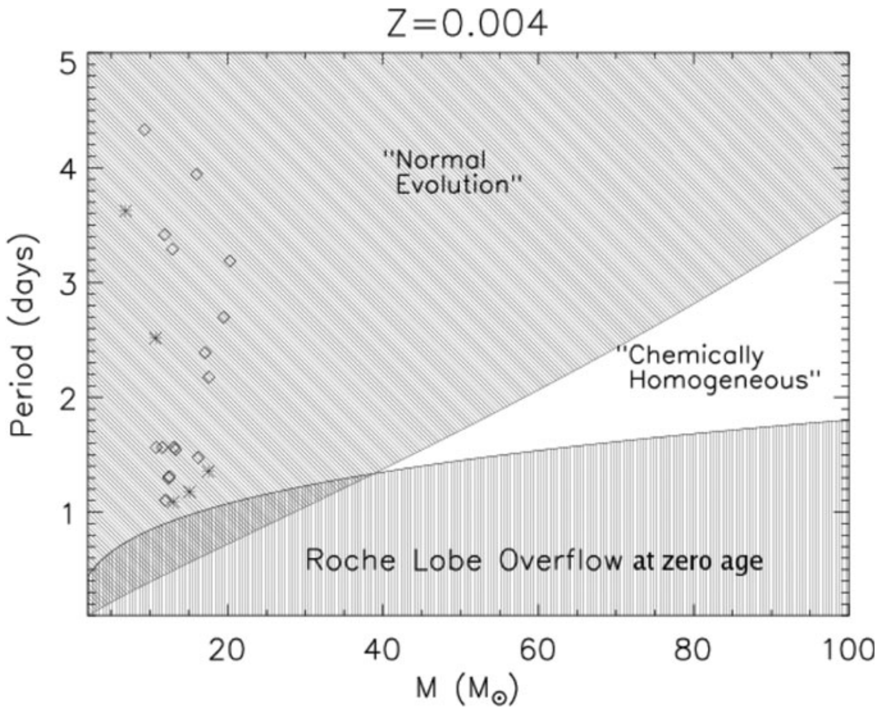

Figure 4. Parameter space for binary systems in which chemically homogeneous evolution can occur. The black hashed region is excluded as binaries do not fit in such close orbits at zero age. The symbols show observed systems in the Small Magellanic Cloud (Hilditch *et al.* 2005).

According to non-rotating models such close systems would fill their Roche lobe during their core hydrogen burning and start so called Case A mass transfer (Kippenhahn & Weigert 1967). The stars in the 1.7 day and the 1.4 day systems stay more compact than the corresponding non-rotating star, due to efficient rotational mixing. However, they cannot avoid Roche lobe overflow before the end of their main sequence evolution.

Although one may intuitively expect that an even closer system would fill its Roche lobe earlier, the primary in the 1.2 day orbit system stays compact enough to avoid mass transfer during the main sequence. It becomes brighter at almost constant radius until central hydrogen exhaustion. Then it contracts until the small amount of H that is still left in the outer layers ignites. The star expands during H shell burning and fills its Roche lobe. In the slightly more compact system with an initial orbital period of 1.15 days, mixing is so efficient that at the end of hydrogen burning both stars are basically pure helium stars, and Roche lobe overflow is completely avoided.

4. Conclusion

Close detached binaries are potentially strong test cases to constrain the uncertain physics of rotational mixing. Furthermore, we show that, contrary to expectation, the very closest massive binaries could avoid mass transfer altogether. In addition to the classic binary cases A, B and C (Kippenhahn & Weigert 1967; Lauterborn 1970), we find a new evolutionary scenario for very close massive binaries, which we named Case M, where the letter M refers to the importance of mixing. In this case both stars are so efficiently mixed, that they remain compact and avoid Roche-lobe overflow during the main sequence, and probably beyond.

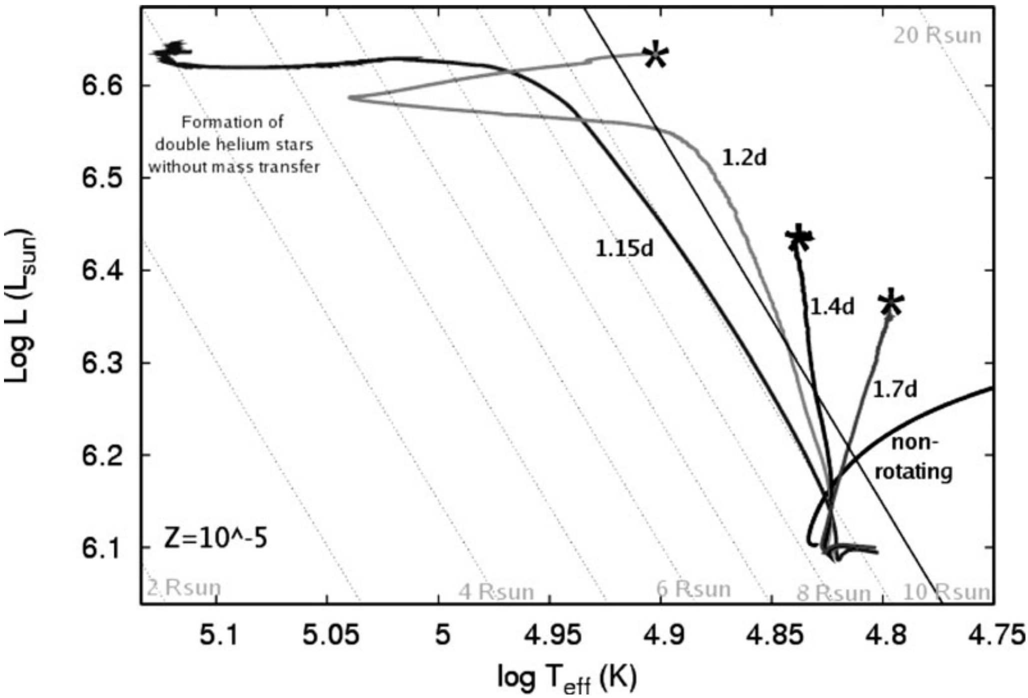

Figure 5. Evolution of stars of 100 $M_{\odot}$in the HR diagram, showing the effects of rotational mixing in binaries. The diagonal lines are lines of constant radii. The black line shows a non-rotating 100$M_{\odot}$ single star for reference. The colored lines show the evolution of 100$M_{\odot}$ stars which orbit around a 98 $M_{\odot}$mass companion with an initial orbital period of 1.7d (purple), 1.4d (blue), 1.2d (green), until the onset of Roche-lobe overflow (asterisk symbol). The red curve corresponds to an initial period of 1.15d. This system ends as two massive helium star in a close orbit.

According to this evolutionary scenario, double helium star systems in very close orbits can be made. Perhaps WR20a, a binary consisting of two detached core hydrogen burning stars of about 80 solar masses in a 3.6 day orbit (Bonanos *et al.* 2004), is an example of this type of evolution. It remains to be investigated whether this evolutionary scenario can lead to the formation of two long GRB progenitors.

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Discussion

Deng: I am very interested in your case M, as they are always blue and bright. Can we call them "super-blue-stragglers"? Is there any observational evidence for that?

de Mink: Good point. Probably WR20a belongs to the cluster Westerlund 2. Its components could be "super-blue-stragglers" with respect to the cluster. However, the cluster is so young that it may be hard to see whether the stars of WR20a are significantly bluer than the other cluster members. We are currently investigating which other observed systems are potential case M in candidates.

Han: Is there any observational evidence for close BH/NS binaries with low-mass companions? Such binaries would be difficult to form from other channels, such as common-envelope evolution.

de Mink: That is a good idea and could be an interesting application. I think it deserves further investigation.

Belczynski: (1) For an example if you take a ($80M_\odot + 60M_\odot$ binary) – do you know if these stars are synchronized? Any observations? (2) Is it possible that these stars overfill their Roche Lobes, before they get synchronized? (i.e., they evolve very rapidly and may expand rather fast.)

de Mink: (1) The time scale for synchronization is very short compared to the main sequence life time, even for these vary massive stars, so we assume it is tidally locked. High resolution spectra of this system are available, but to my knowledge they have not been used to determine the rotational velocity of the stars directly. It would be interesting as a test for the efficiency of the tides in such an extreme system like WR20a. (2) Apart from there pre-main sequence evolution, which is very uncertain, I would expect that, if the stars filled their Roche Lobes before, they would still fill their Roche Lobes today, which they don't.

Herwig: Could this also work in low-mass binaries to lead to close double-degenerate systems – maybe at very low Z?

de Mink: I do not think so. Rotational mixing becomes less efficient in lower mass stars. Therefore, the window in the binary parameter space, in which we expect case M to occur, closes for masses below 40 $M_\odot$. If mixing is more efficient in binaries we might be able to go to lower masses. Using the models by Yoon *et al.* (2006), which span a metallicity range from $Z=10^{-5}$ to 0.004, we find that the "window" for homogeneous evolution shifts to smaller periods but not to smaller masses.

Meynet: Are there results obtained with models including magnetic fields, i.e., with the dynamo theory proposed by H. Spruit?

de Mink: Yes. We plan to investigate the effects of magnetic fields in more detail, but qualitatively we find the following: if we "switch off" transport of angular momentum and chemical species by magnetic fields, the star will rotate more differentially and shear mixing becomes more important. It would be interesting to see under what conditions chemically homogeneous evolution occurs in your models and what this implies for tidally locked binaries.