Binaries at Low Metallicity: ranges for case A, B and C mass transfer

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Abstract. The evolution of single stars at low metallicity has attracted a large interest, while the effect of metallicity on binary evolution remains still relatively unexplored. We study the effect of metallicity on the number of binary systems that undergo different cases of mass transfer.

We find that binaries at low metallicity are more likely to start transferring mass after the onset of central helium burning, often referred to as case C mass transfer. In other words, the donor star in a metal poor binary is more likely to have formed a massive CO core before the onset of mass transfer. At solar metallicity the range of initial binary separations that result in case C evolution is very small for massive stars, because they do not expand much after the ignition of helium and because mass loss from the system by stellar winds causes the orbit to widen, preventing the primary star to fill its Roche lobe.

This effect is likely to have important consequences for the metallicity dependence of the formation rate of various objects through binary evolution channels, such as long GRBs, double neutron stars and double white dwarfs.

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INTRODUCTION

During their life stars can expand to a radius which is up to 1000 times bigger than their initial radius. In close binary systems, they start to transfer mass if their radius exceeds a critical radius, the Roche lobe radius. It is usually the initially most massive star, the primary star, which “fills its Roche lobe” first.

At solar metallicity binary evolution has been studied by various groups, while their evolution at low metallicity is relatively unexplored. Heavy elements, such as carbon, oxygen, nitrogen and iron, are important contributors to the opacity of stellar material in metal rich stars. Due to the lower opacity, metal poor stars are generally hotter and more compact. As it is the evolution of the radius of a star in a binary which determines if and when mass transfer occurs, we expect that the evolution of binaries in metal poor environments is significantly different from binaries in the solar neighborhood.

In this work we study the radius evolution of stars with different masses in order to infer the frequency of various cases of binary evolution as a function of metallicity. In a second contribution to this proceedings we discuss the effect of metallicity on the expansion of accreting main sequence stars and the potential consequences for binary evolution.

EVOLUTION CODE

We use the fully implicit stellar evolution code STARS, originally developed by Peter Eggleton [3, 4, 5], updated with the latest opacity tables [6, 7, 8]. For the hydrogen and helium abundance we assume a linear relation with Z: X = 0.76 − 3.0Z and Y = 0.24 + 2.0Z. The abundances of the heavier elements are assumed to scale to solar and meteoric abundance [9] so that they are consistent with the opacity tables. A mixing length ratio l/Hp = 2.0 is assumed. Convective overshooting is taken into account.
FIGURE 2. The initial orbital periods that lead to case A, B and C mass transfer are given as function of the primary mass assuming an initial mass ratio of 0.75 [inspired by 2]. Widening of the orbit due to angular momentum loss in the form of stellar winds is taken into account. The hatching indicates approximately in which cases the donor has a convective envelope.

as in Schröder et al. [10] with a free parameter $\delta_{ov} = 0.12$ calibrated against accurate stellar data from non-interacting binaries [11].

For the mass loss at solar metallicity we assume de Jager et al. [12] and [13]. We assume that the mass loss scales with metallicity of the surface layers:

$$\dot{M}(Z) = \dot{M}(Z_\odot) \times \left(\frac{Z_{ surface}}{Z_\odot}\right)^{0.8}$$

[inspired by 14]. We want to emphasize that both the overshooting parameter and the assumed mass loss, especially when the stars become red giants, are important uncertainties in the model, which can have a large effect on the radius evolution.

RESULTS

Historically binary models have been classified as Case A when primary fills its Roche Lobe during its main sequence evolution, as Case B when it happens after H exhaustion, but before the central ignition of Helium [15] and as Case C when mass transfer starts after the ignition of Helium [16].

Figure 1 shows the evolution track of a 6$M_\odot$ star in the HR diagram at different metallicity. Throughout the main sequence the low metallicity star is more compact and hotter. The circle indicates exhaustion of H in the center (which we define as the moment that the central abundance drops below $10^{-4}$). Ignition of He (when the luminosity by He burning exceeds 5% of the total luminosity) is indicated with an asterisk. The low metallicity star ignites He at a much smaller radius, while it is still in the blue part of the diagram. The solar metallicity star first expands towards the giant branch before it ignites Helium. This has implications for the occurrence of case B and C evolution as a function of metallicity.

To determine the fraction of binaries that undergo case A, B and C mass transfer, we calculated a set of stellar models with different initial masses at $Z = 0.02$ and $Z = 0.00001$ from which we determined the maximum radius before H exhaustion and before He ignition. We can convert the radii to initial orbital periods, if we assume a companion mass 0.75$M_{prim}$ and that the mass lost by stellar winds from the primary take away the specific angular momentum of the orbit of the primary, causing the system to widen, and if we neglect mass loss from the secondary star. The result is shown in Figure 2, where we plot which initial orbital periods lead to case A, B and C mass transfer for different masses of the primary. If we assume that binaries are formed with initial orbital periods distributed uniformly in the log, then the vertical width of the bands in the diagram directly represent the fraction of binaries.

The blue band corresponds to the radius increase during main sequence evolution, or to case A mass transfer. The yellow band corresponds to case B evolution, which extends up to the maximum radius reached before the onset of Helium burning. For stars more massive than 5$M_\odot$ the range for case B becomes much smaller at low metallicity compared to solar metallicity. The green band corresponds to case C evolution. Beware that the upper boundary is given by the maximum radius during our evolutionary calculations which is only a lower limit for the real maximum radius that a star would reach. The low mass stars, for example, ignite helium in a degenerate core and we stopped our evolutionary calculation. Case C evolution is likely to occur also for low mass stars although it is not plotted in the diagram.

The hatching indicates in which systems the primary
star will have a convective envelope containing more than 15% of its mass. For these systems mass transfer will occur on a dynamical timescale, causing the accreting star to expand rapidly, probably resulting in a common envelope situation.

The most striking difference is that the range for case C is much larger at low metallicity. This is partly caused by the fact that low metallicity stars ignite He at a much smaller radius. A second effect, which is most prominent at high masses, is that mass loss from solar metallicity stars causes the orbit to widen, therefore decreasing the initial periods leading to case C mass transfer. The range for case C at solar metallicity becomes almost negligible for binaries with primary masses above 30M☉.

CONCLUSION

We find that at low metallicity the donor star in a binary is more likely to have developed a massive CO core before the onset of mass transfer. For binaries with primary masses above 30M☉ Case C mass transfer may occur almost exclusively at low metallicity.

This effect potentially has important consequences for the metallicity dependence of the formation rate of various objects through binary evolution channels such as long Gamma Ray Burst progenitors [see discussion section of 17] but also double neutron stars and double white dwarfs. More work on binary evolution at low metallicity is needed.

The precise fraction of Case C binaries as function of metallicity depends on assumptions about the distribution of initial binary parameters, the description of mixing and overshooting and the (metallicity dependence) of the mass loss rate. We find that the maximum radius can vary by more than a factor of 10 when we compare calculations of the STARS code to calculations done with the code described in [18] and when we vary the amount of overshooting. In a forthcoming paper we will present the range case A, B and C mass transfer for a range of metallicities for different assumptions for the uncertain parameters [19].

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