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Applying Wind Roche-Lobe Overflow in Binary Evolution using MESA and POSYDON

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ABSTRACT

Wind Roche-Lobe Overflow (WRLOF) is a mechanism of mass transfer in a binary system where the wind acceleration zone radius of the donor exceeds the Roche lobe radius and the stellar wind transfers mass to the accretor. The observed population of carbon-enhanced metal-poor (CEMP) stars has been shown to be explained by WRLOF. Apart from fast population synthesis code, WRLOF has not yet been applied to detailed binary evolution with a large parameter range. We implement WRLOF in MESA and POSYDON for donor star mass range 0.7 to $8.0 M_\odot$, accretor star mass range 0.1 to $0.9 M_\odot$, and orbital period range 10^2 to 10^6 days. We found that when using WRLOF, the accretor gained $\sim 0.05 M_\odot$ from wind accretion and evolved off the main sequence earlier. The mass loss rate of the accretor is enhanced because it evolves off the main-sequence evolution after gaining mass from the donor's wind.

Keywords: binaries: general — stars: mass loss — Astrophysics - Solar and Stellar Astrophysics

INTRODUCTION

Mass transfer in a binary system affects the evolution of the stars (Sana et al. 2012, De Marco & Izzard 2017). Material can be transferred from the donor (primary) star to the accretor (secondary) star when the donor expands to fill its Roche lobe radius $R_{\mathrm{L},1}$ (Roche-lobe overflow) or when some of the material which escapes from the donor into its stellar wind is captured by the accretor (wind mass transfer) (Bondi & Hoyle 1944). The process may be stable, caused by the nuclear evolution of the donor which remains in thermal equilibrium, or unstable, where the mass transfer rate undergoes runaway increase resulting in a common-envelope of material around the system (Pols 2012).

Wind Roche-Lobe Overflow (WRLOF) is a mechanism of mass transfer in which the stellar wind of the donor is contained within the wind acceleration zone radius R_d. When $R_\mathrm{d} \geq R_{\mathrm{L},1}$, the wind becomes focused in the direction of the secondary star, and mass is accreted onto the secondary star through the inner Lagrangian point where the Roche lobes of the two stars meet (Mohamed & Podsiadlowski 2007). This occurs in the case of slow and dense winds, which are characteristic of asymptotic giant branch (AGB) stars (Abate et al. 2013).

Abate et al. (2013) showed that WRLOF mass transfer in a binary system consisting of an AGB primary and a low-mass MS secondary is able to account for the discrepancy between the observed fraction of carbon-enhanced metal-poor (CEMP) stars to very metal-poor stars of 9-25% (Beers et al. 1992, Christlieb et al. 2001) and the predictions of standard stellar models. Models were able to reproduce the lower end of 9%, but did not match the expected abundance of elements (Lucatello et al. 2005a, Izzard et al. 2009, Komiya et al. 2007). CEMP stars are found in the Galactic halo and have an abundance of s-process elements (Aoki et al. 2007). S-process elements are formed in AGB stars and the helium shell burns into carbon, so mass transfer from an AGB star could explain the composition of CEMP stars (Lucatello et al. 2005b). Abate et al. (2013) found that WRLOF allows systems with higher initial orbital periods and lower secondary masses to become progenitors of CEMP stars.

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In this paper, we follow the analysis from Abate et al. (2013) using Modules for Experiments in Stellar Astrophysics code (MESA, version 11701; Paxton et al. 2011, 2013, 2015, 2018, 2019) and POpulation SYnthesis with Detailed binary-evolution simulatiONs (POSYDON, Fragos et al. 2022), by implementing WRLOF into MESA and then using POSYDON to simulate and evolve a grid of binaries. We apply WRLOF to detailed binary evolution with a large parameter range to explore the parameter space of binaries which may be progenitors of CEMP stars. We will compare our results to Abate et al. (2013) to provide a better understanding of the discrepancy between the observed population of CEMP stars and the population predicted by models.

METHODS

We used the MESA binary module to evolve two stars simultaneously in a binary system. MESA performs 1-dimensional simulations of stars, including rotation, mass transfer, loss of mass and angular momentum, among other characteristics and evolutionary processes present in a binary system (Paxton et al. 2015).

In order to evolve a binary, we first initiate two individual zero-age main sequence (ZAMS) stars of some specified mass and metallicity, then place them in a binary system by setting the initial orbital period assuming a circular orbit, and then evolve simultaneously until a termination condition is met. Termination conditions include: a star's age exceeds 13.8 Gyr, a star evolves into a white dwarf (WD) or reaches end of core C-burning, a common envelope (CE) forms around the binary, or a star enters the thermally-pulsating asymptotic giant branch (TP-ABG) phase (Fragos et al. 2022).

We use POSYDON to run a grid of MESA binaries with a range of initial donor and accretor masses and orbital periods. We use a 30x10x30 grid of $M_1, M_2, P_{\rm orbital}$, respectively, where M_1 ranges $[0.7, 8.0] M_\odot$, M_2 ranges $[0.1, 0.9] M_\odot$, and $P_{\rm orbital}$ ranges $[10^2, 10^6]$ days. We assume solar metallicity.

To implement WRLOF in the AGB phase, the radius of the wind acceleration zone is defined by Höfner (2007) as

$$R_{\rm d} = \frac{1}{2} R_* \left(\frac{T_{\rm eff}}{T_{\rm cond}} \right)^{2.5}, \tag{1}$$

where $T_{\rm eff}$ is its effective temperature and $T_{\rm cond}$ is the condensation temperature of the dust in the wind, where $T_{\rm cond} = 1500$K for carbon-rich dust and $T_{\rm cond} = 1000$K for oxygen-rich dust.

We model the WRLOF accretion efficiency $\beta_{\rm acc,max}$ using the results of Abate et al. (2013), which is the ratio between the mass accreted and the mass lost from the system:

$$\beta_{\rm acc} = c_1 \left(\frac{R_{\rm d}}{R_{\rm L,1}} \right)^2 + c_2 \left(\frac{R_{\rm d}}{R_{\rm L,1}} \right) + c_3, \tag{2}$$

where $c_1 = -0.284$, $c_2 = 0.918$, and $c_3 = -0.234$. Adhering to their methods, we implement a dependency on the mass-ratio $q = M_2/M_1$ and set a limit on $\beta_{\rm acc}$ where $\beta_{\rm acc,max} = 0.5$ according to calculations by Mohamed (2010). This gives:

$$\beta_{\rm acc} = \min \left\{ \frac{25}{9} q^2 \left[c_1 x^2 + c_2 x + c_3 \right], \beta_{\rm acc,max} \right\}. \tag{3}$$

RESULTS

Figure 1 displays a comparison between the final accretor mass for a slice of the grid at initial $M_2 = 0.9 M_\odot$, for a grid without (left) and with (right) WRLOF, showing the final accretor mass and the termination condition for each binary. The left panel shows that without the implementation of WRLOF, the mass of the accretor remains approximately constant and RLO mass transfer only occurred in systems with initial $M_1 \lesssim 1.5 M_\odot$ and $P_{\rm orbital} \lesssim 1000$ days. The right panel demonstrates that when WRLOF is applied, the accretor gained approximately $\sim 0.05 M_\odot$ through wind accretion in systems with initial $M_1 \lesssim 5.6 M_\odot$ and $1500 \lesssim P_{\rm orbital} \lesssim 10^5$ days. The amount of mass accreted increased with initial M_1.

Comparisons of individual binaries with identical initial parameters indicate that WRLOF causes the mass of the accretor to increase, resulting in strong winds around the accretor when the accretor expands as it begins to evolve and is unable to gravitationally retain the material at its surface which escapes as wind. In the example of initial $M_1 = 3.2 M_\odot, M_2 = 0.9 M_\odot$, and $P_{\rm orbital} = 6200$ days, we observed an increase in the mass loss rate of the accretor due to wind. HR diagrams also show that the mass gained by the accretor due to WRLOF causes the star to start evolving off the main sequence whereas without WRLOF, the star remains on the main sequence.

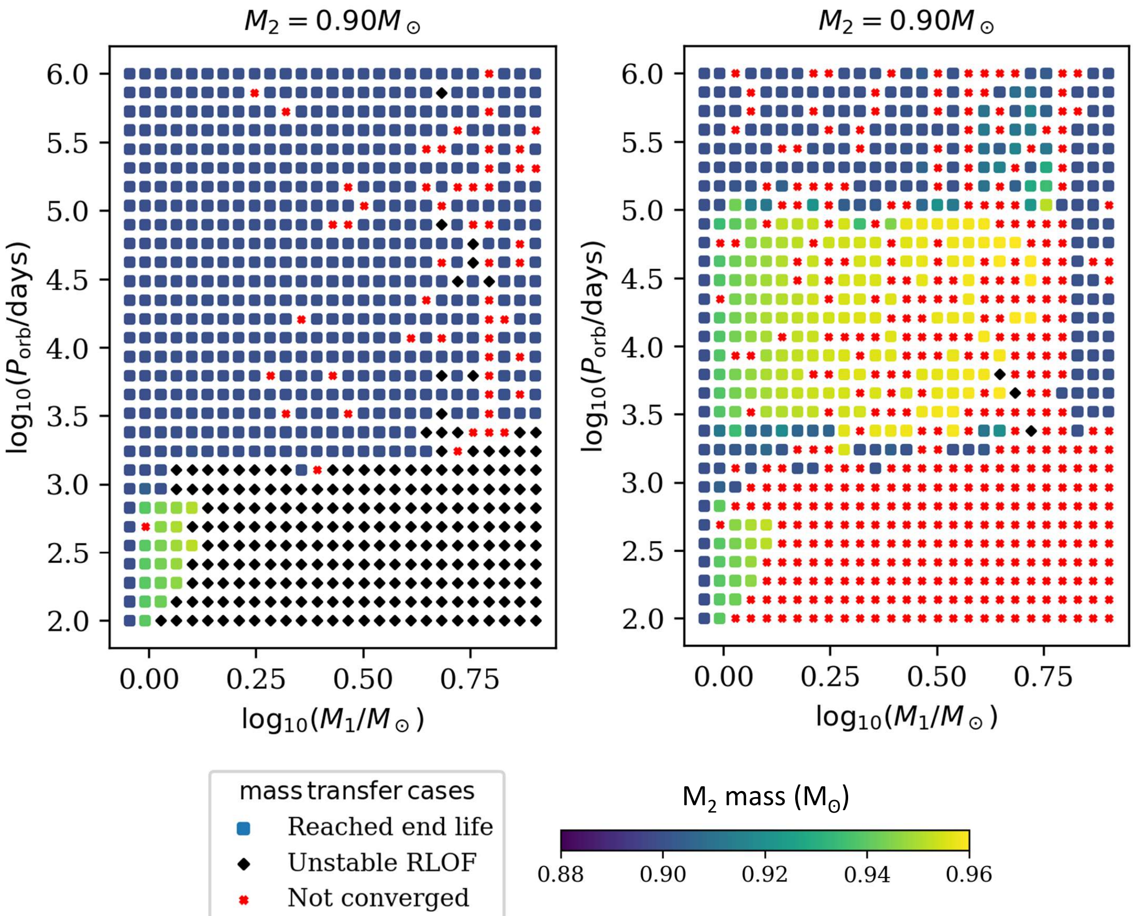

Figure 1. Slice of the POSYDON grid with initial $M_2 = 0.9M_\odot$. The marker shape indicates the termination condition for each binary and the color shows the final accretor mass. The axes are the initial parameters for M_1 and $P_{\rm orbital}$ on a log scale. The left panel uses no WRLOF and the right panel includes WRLOF.

CONCLUSIONS AND FUTURE WORK

We found that the application of WRLOF to low-mass binary systems causes the accretor to gain sufficient mass to evolve off the main sequence earlier than without WRLOF. The accretor also begins to lose mass to its wind which was enhanced by its evolution after gaining mass from the donor's wind. As these may affect the evolution of the binary system, WRLOF should be accounted for when modeling binary populations in this mass range.

To address the not-converged runs in the WRLOF grid, we will rerun the not-converged binaries with modified POSYDON defaults. We will gradually lower the mass loss rate at which a binary is marked as unstable to a level that is more appropriate for lower mass stars and then turn off hydrogen flashes in the WD cooling stage to address any remaining not-converged binaries, as some of the models crash in the WD hydrogen flash phase. Skipping this process will not impact our result.

In order to conduct a more direct comparison with the results of Abate et al. (2013), we will then repeat the grids with $Z = 0.01Z_\odot$ to match the metal-poor condition for CEMP stars. We will also investigate the effects of allowing the donor star to accrete mass from the wind of the accretor star. The additional grids will allow us to more accurately explore the parameter space which has the potential to produce CEMP stars. We will compare our results to the conclusions of Abate et al. (2013), which will provide a better understanding of the discrepancy between the observed population of CEMP stars and the population predicted by models with detailed binary evolution.

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