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Explaining Classical Wolf-Rayet Stars as Merger Products with MESA

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Context. Wolf Rayet (WR) stars are massive post main sequence stars characterised by broad emission lines of ionised helium with carbon or nitrogen. The formation of WR stars is mainly attributed to stellar wind or binary interaction. But in the Small Magellanic Cloud, these formation channels do not explain 7 out of 12 WR stars, where binary companions were not found.

Aims. One possible explanation is that an intermediate binary system has experienced a merger event where the primary star gets stripped of its hydrogen layer by a companion and when the secondary star is evolved enough it would produce an unstable mass transfer which would cause the merging event. Observing if this is a suitable explanation is needed.

Methods. We have simulated the evolution of a binary system with MESA to find a parameter space where this merging event could happen to explain the 7 Wolf Rayet stars in the Small Magellanic Cloud. We varied the mass of the primary star in the binary system to compare the fraction of successful merging events, that meet conditions we have set.

Results. We found that there is an upper limit for the mass of the primary star in the intermediate binary system. A suitable parameter grid with an upper and lower limit for the mass ratio and period between the two binary stars to achieve a merging event was also found. Ultimately, our results have favoured a lower mass primary star with a mass ratio closer to, but not exactly at, unity within a short period of several days.

Conclusions. While not proven, it was shown that the formation of WR stars in the SMC by our merging theory seems very plausible.

I. INTRODUCTION

Wolf Rayet (WR) stars are massive, post-main sequence stars in the most advanced stages of their life before going supernova or forming a black hole (Van Der Hucht et al. 1995). They are defined as stars whose spectra have prominent broad emission lines of ionised helium, plus highly ionised lines of nitrogen or carbon, sometimes with oxygen. WR stars are rarely observed due to the fact that only a few massive stars go through the brief WR phase. WR stars are believed to have started their lives as O-type stars that leave the main sequence. These massive stars evolve through an intermediate stage before experiencing high mass-loss during the WR phase and the outer hydrogen envelope of the star's upper atmosphere is ejected to expose the hot He-rich core. This enriches the environment around them and drives the chemical evolution of galaxies (Maeder 1983) (Dray et al. 2003) (Cherchneff et al. 2000). The two popular theories of how the hydrogen envelopes of WR stars are stripped are single star formation or through a binary interaction. The single star scenario relies on strong stellar winds that strip the hydrogen envelope (Shenar, Gilkis, et al. 2020).

These sufficiently strong winds only develop on the most massive stars (Pauli et al. 2022). The efficiency of the single star channel is dependent on the metallicity of the environment. It was found that the lower the metallicity, the harder it was for a massive star to achieve sufficiently strong stellar winds to facilitate self-stripping (Vink, Koter, and Lamers 2001) (Vink and Koter 2005) (Crowther and Hadfield 2006) (Hainich et al. 2015) (Shenar, Sablowski, et al. 2019) (Shenar, Gilkis, et al. 2020).

The majority of massive stars interact with a companion during their evolution (Weis, Duschl, and Bomans 2001) (Hugues Sana et al. 2012). The WR binary channel is a favoured WR evolution model since most O-type stars are born in close binaries or multiple systems (Sota et al. 2014). Rather than have their hydrogen-rich envelope stripped by strong stellar winds like with the single-star channel, the star experiences Roche lobe overflow (RLOF) in a binary system. This evolution path is more suited to explain the formation of WR in lower metallicity environments such as the Small Magellanic Cloud (SMC).

The SMC has a fifth of the metallicity of the Sun

(Venn 1999) and it has 12 known WR stars. While hot and massive companion stars have been found in the systems of 5 of these WR stars, the search for companions for the remaining 7 stars has not been successful (Kerr 1964) (Smith 1968) (Sanduleak 1968) (Sanduleak 1969) (Breysacher and Westerlund 1978) (Azzopardi and Breysacher 1979) (A. F. Moffat 1982) (A. F. Moffat, Jacques Breysacher, and Seggewiss 1985) (A. F. Moffat 1988) (Morgan, Vassiliadis, and Dopita 1991) (Bartzakos, A. Moffat, and Niemela 2001) (Massey and Duffy 2001) (Massey 2003) (Foellmi, A. Moffat, and Guerrero 2003) (Cedric Foellmi 2004) (Hainich et al. 2015) (Shenar, Hainich, et al. 2016) (Tomer Shenar, Rainer Hainich, et al. 2018) (Neugent, Massey, and Morrell 2018) (Schootemeijer et al. 2024). In their paper, Schootemeijer et al. (2024) present a modern radial velocity (RV) monitoring survey of the 7 WR stars in the SMC using data from the Very Large Telescope (VLT). Despite binary evolution being the more likely evolution model for lower metallicity environments, Schootemeijer et al. (2024) shows that binary evolution does not convincingly explain the evolution of the 7 remaining WR stars found in the SMC. They found that the presence of a companion for a WR star more massive than $5M_{\odot}$ and with an orbital period shorter than one year was unlikely with $\sim 95\%$ confidence.

Since the binary evolution model is considered unsuitable for the 7 remaining WR stars in the SMC, another evolution model must be proposed to explain the formation of single WR stars in a low metallicity environment. In this paper, stellar merger evolution is explored as a possible model for single WR stars in the SMC and other low metallicity environments. The scenario that will be considered is presented in Tomer Shenar, Wade, et al. (2023b), where it is proposed that the He cores of two intermediate stars merged to produce the $2M_{\odot}$ quasi-WR star HD 45166.

Two zero-age main sequence (ZAMS) stars are considered in this scenario. They form a binary system as shown in Figure 1. The more evolved and massive primary star of the binary system will begin to expand and fill its Roche lobe once

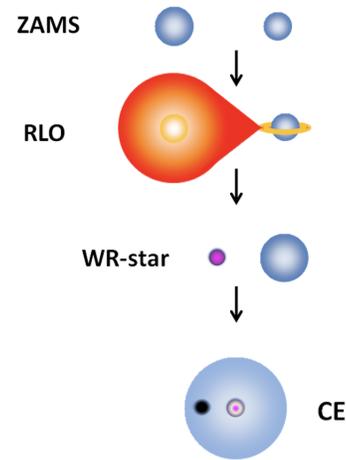


Figure 1: The evolution of a merger event in a zero age main sequence (ZAMS) binary system. Roche lobe overflow (RLOF or RLO) strips the primary star and evolves the secondary star to allow inverse mass transfer. Unstable inverse mass transfer produces a common envelope (CE), which causes the merging event. Figure adapted from Marchant et al. (2016)

it has completed burning hydrogen in its core. The Roche lobe of the binary system is the region around a star where the material of the star is still gravitationally bound. Once the primary star exceeds this region, it transfers the mass outside of its Roche lobe to the secondary star through the first Lagrange point (L1). This process is known as the Roche lobe overflow (RLOF). This strips the primary star and it begins to burn helium in its core. The mass transfer will rejuvenate the secondary star and it will begin to evolve more quickly, catching up with the evolution of the primary star. If the secondary star can finish burning hydrogen before the primary star finishes burning helium, the secondary star will begin to fill its own Roche lobe. Once again, if the secondary star exceeds the equipotential surface inside its Roche lobe, the star will then dump mass through L1 during this stage. This leads to mass transfer back to the primary star. However, if the secondary star also ejects mass in the direction opposite to the primary star known as the second Lagrange point (L2), the mass transfer is considered unstable (Linial and Sari

2017). This produces a gaseous envelope around the two stars in the system. Friction between the stars and this envelope will reduce the angular momentum of the binary system, causing the stars to spiral inwards. This is the beginning of a merger event of the two helium-burning stars (Tomer Shenar, Wade, et al. 2023), while the common envelope disperses into the interstellar medium (ISM).

Our paper is organised as follows. In section 2, we will discuss our computational method for running our binary evolution model simulations and the parameters that we varied. As well as that, we consider the conditions that must be met for a termination to be considered a successful merger event. In section 3, the results of our simulation are reviewed and how the varied parameters affected these results. We will also consider stricter conditions to what we consider a desired merging episode, in relation to the aims of this paper. Finally, in section 4, we will examine the implications of our results with reference to observational data and discuss whether stellar mergers can explain the formation of classical WR stars.

II. METHOD

Our objective is to simulate the evolution of a binary system until inverse mass transfer occurs which is the conditions we want to produce to obtain a merger event. To simulate the system we will use Modules for Experiments in Stellar Astrophysics (MESA) (Paxton, Bildsten, et al. 2011)(Paxton, Cantiello, et al. 2013)(Paxton, Marchant, et al. 2015)(Paxton, Schwab, et al. 2018)(Paxton, Smolec, et al. 2019)(Jermyn et al. 2023). We will use version 24.08.1 of MESA and particularly the module binary with no rotation (binary_norot) ¹ because models for the star rotation are often uncertain, leading to the possibility of more tricky and intricate simulations.

Using MESA, we conducted numerous simulations by varying two initial parameters around three

fixed masses for the primary star which were $4M_{\odot}$, $5M_{\odot}$ and $6M_{\odot}$. The first parameter that we varied was the q-ratio defined by

$$q = \frac{M_{s,0}}{M_{p,0}} \quad (1)$$

where $M_{s,0}$ is the mass of the secondary star and $M_{p,0}$ the mass of the primary star. Since the mass of a star is related to the evolutionary stage the star is in, the q-ratio sets how evolved we want our secondary star to be in relation to our primary star. The second parameter we varied is the orbital period which we let vary in \log_{10} -scale in unit days. The objective in varying these parameters is to see how the orbital period and the q-ratio affect the evolution of the binary system and to see the conditions required where we can expect a merger to form our WR star.

The other important parameter is the metallicity of the environment which was set to the SMC, a low metallicity environment which is our region of interest. Finally, there is the overshoot parameter for the phenomenon of the same name. It is set as 0.1, which must fit for lower masses even though it is an uncertain parameter. 0.1 is commonly accepted to model the evolution of low mass stars.

Our simulations terminate when there is no sufficient model found or when unphysical things happen. For example, L2 overflow or maximum mass transfer. Finally, the simulations terminate when there is also an inverse mass transfer rate from the secondary to the primary star. It is the later termination result that we have to look out for, though there are other conditions needed. We want to make sure that both our stars are helium stars, with the primary being of the Main Sequence for optimal conditions for merging. In the subsection 'Extra Conditions' in section 3A, we shall see based on our results which extra conditions are needed to ensure the merging.

In Figure 2 we can see the composition of our stars, where certain inner cores are neglected in our image. In our project, we will often refer to the M_{CO} , the mass of the carbon-oxygen (CO) core, and M_{He} , the mass of the helium core, of our stars. The helium

¹ https://github.com/orlox/mesa_input_data/tree/mesa-24.03.1-update/2016_binary_models/mesa-24.08.1-update

core is defined in this report as the region in the star where hydrogen burning has stopped, while the CO core is defined as the region where helium fusion has ended. Note that based on these definitions, the helium core also includes the CO core and all other inner cores.

III. RESULTS

A. Mass primary star is $5M_{\odot}$

1. The first results

The first results can be found in Figure 3, where we have additional information on our primary star, to analyse if it is of the Main Sequence or already a helium star. The yellow grids with the "HE primary off MS" are the ones we want to delve deeper into, as these follow our pre-defined conditions. These yellow grids are known as our 'hits' or the simulations we consider a success in relation to the objective of this paper. One can already observe that we do not see hits if the period is too large, starting from around $\log(P) \approx 1.667$ or equivalent $P \approx 46.5$ days, our binary system instead reaches maximum transfer rate when terminating. One could assume this mostly has to do with a high orbit implying a longer time before RLOF happens. When RLOF happens, the primary star is already far more developed than the secondary star which can lead to the mass transfer rate being too high. This causes the binary system to undergo the CE evolution before the secondary star can start to transfer mass to the primary star. Due to the conditions not being met, this merger would not lead to a WR star.

We also see a region where the period is too low for the merging to happen. In Figure 3, we see this happen for mostly $P \approx 1$ day. The termination results we have at a low period, next to our hits, are "Primary in MS". It seems the small period is the cause of mass transfer happening too fast so that when the inverse mass transfer rate happens, the primary star has not gotten enough time to develop being of the Main Sequence. Thus we can already observe that the period is indeed an important parameter, which needs to be low (less

than 50 days), but can not be exceedingly low.

Another important factor is the mass ratio, it can not be too low. When a binary system has a lower mass ratio, we do not see the conditions being met for a hit because it causes the primary to be of the Main Sequence while not being a helium star. It seems due to this low mass ratio that the primary star is already too developed and is thus no longer a helium star.

2. Extra conditions

While not obvious at first, looking at Figure 3, the mass ratio can not be too high. If one in the secondary star also observes the abundance of He4 in its core in Figure 4 (defined as the mass fraction of He4 in the stellar core) or observes the mass fraction of the CO core in Figure 5, defined in equation (2) with M_{CO} the mass of the CO core and M the mass of the secondary star, then one sees that in these simulations where the mass ratio is close to unity, our secondary star is already too far developed and has already passed its helium-burning phase as it already has a CO core.

$$\frac{M_{CO}}{M} \quad (2)$$

So for further conditions and based on our earlier definitions, we need to take into account that a massive helium core is not enough and that the carbon-oxygen core of the stars also needs to be small. Thus it can indeed be concluded that we need additional conditions.

Based on Figure 4 and Figure 5, we assign the condition that the abundance of He4 in the secondary star needs to exceed 0.1, while the mass fraction of the CO core needs to remain under 0.1. We can compare Figure 3 with Figure 6, where we look at the abundance of He4 in the primary star, or we can also compare it with Figure 7, where we again show the mass fraction of CO core but now for the primary star. Notice that on the diagonal of our possible WR merger products, the primary star is close to ending its helium-burning phase and starts being a CO-star. We also want to exclude these results because our primary helium star needs to be at the beginning

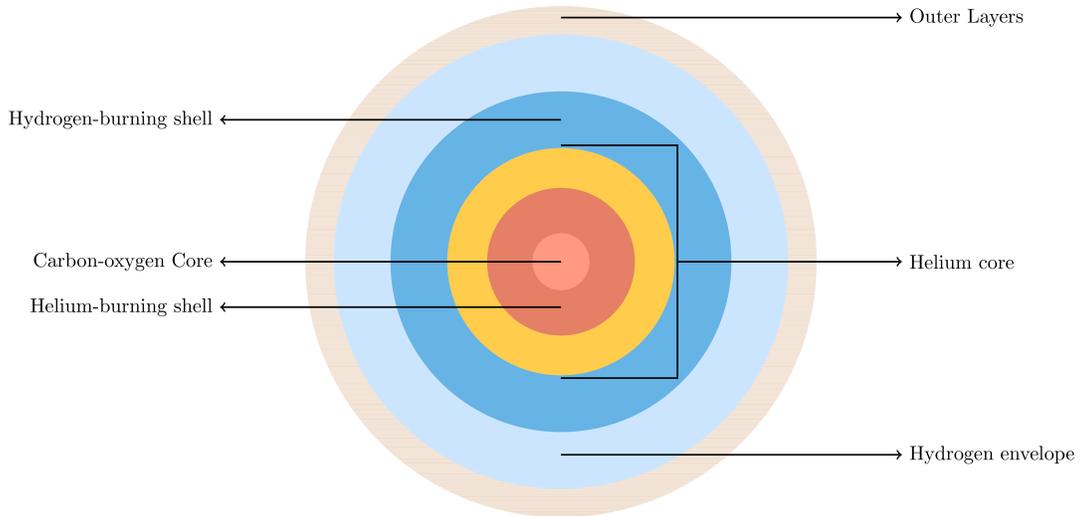


Figure 2: The different layers of our star neglecting inner cores as inspired by Fraknoi, Morrison, and Wolff (2016).

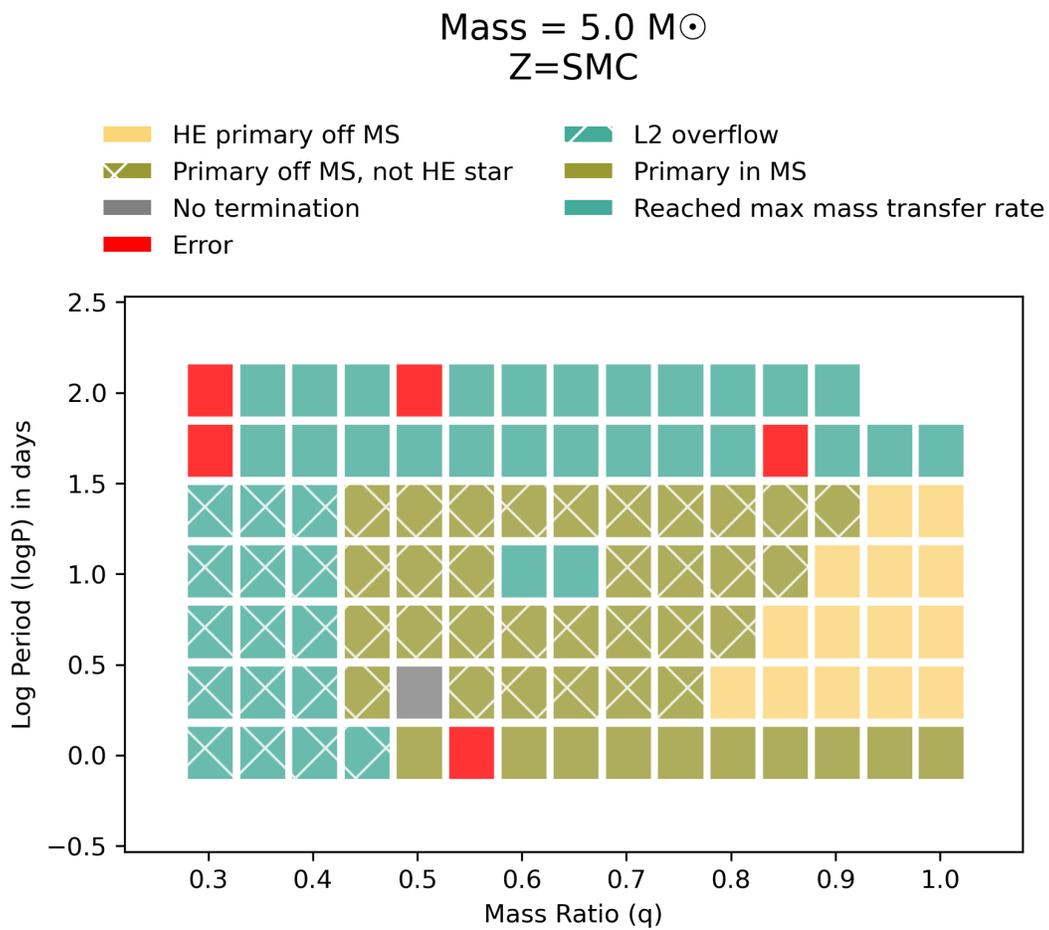


Figure 3: Termination results from simulations using the binary model for MESA with no rotation for a primary star of mass $5M_{\odot}$ in SMC.

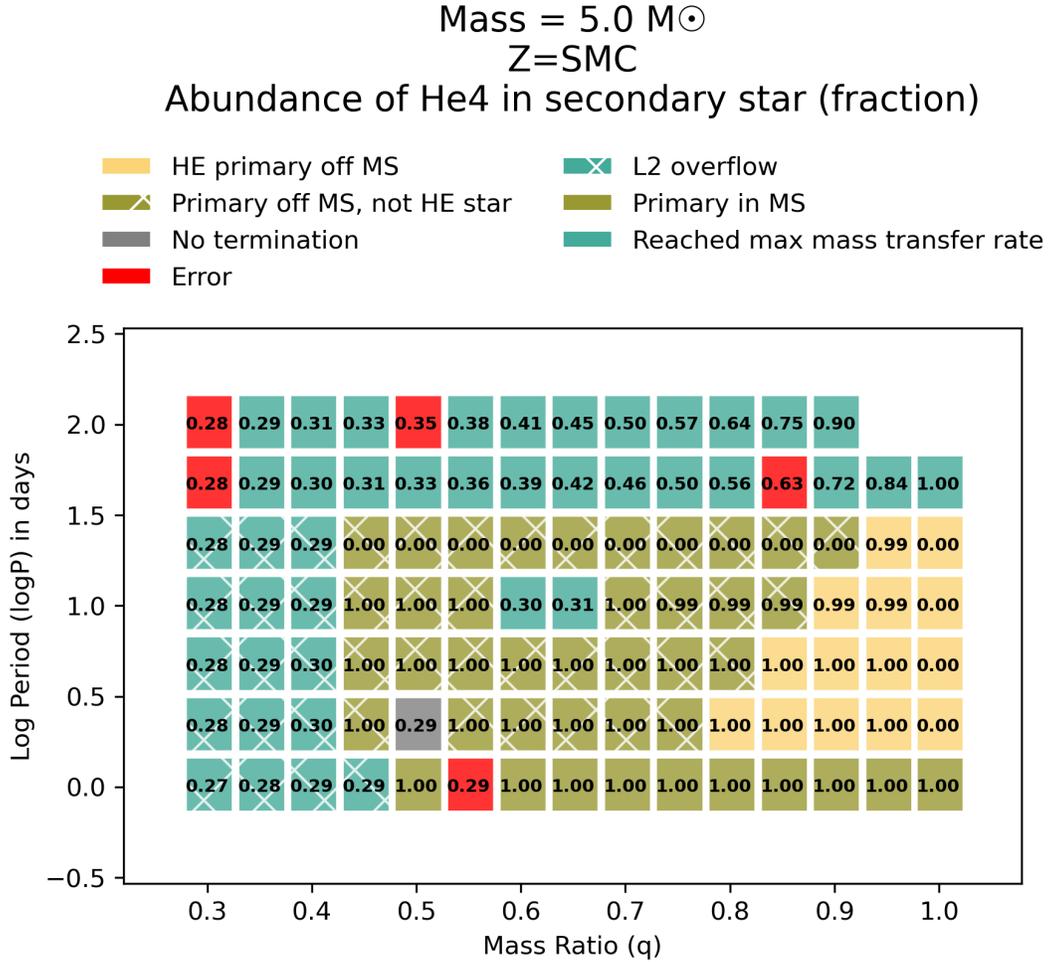


Figure 4: Termination results from simulations using the binary model for MESA with no rotation for a primary star of mass 5M_⊙ in SMC together with the abundance of He4 in the secondary star at the end of the simulation written in text.

or the middle of its phase for optimal conditions. Finally, we will also add the condition that the mass fraction of the helium core of our primary star is higher than 0.9 to have optimal conditions. We will summarize all these conditions below.

The conditions for a hit are:

- Termination result is "HE primary off MS"
- Abundance of He4 for both primary and secondary star is higher than 0.1
- $\frac{M_{\text{He},p}}{M_p} > 0.9$

$$\bullet \frac{M_{\text{CO},p}}{M_p}, \frac{M_{\text{CO},s}}{M_s} < 0.1$$

Where M_p and M_s refer to the mass of the primary and the second star respectively. M_{He} and M_{CO} refer to the mass of the helium and the carbon-oxygen core respectively.

Table 1: Stricter requirements imposed on a hit region to avoid false positives.

Using these conditions, we find our desired results in Figure 8. We see that our hit region has shrunk, but the previous conclusion still holds, we have an area where our period needs to be low, while the mass ratio needs to be high, though both can not be

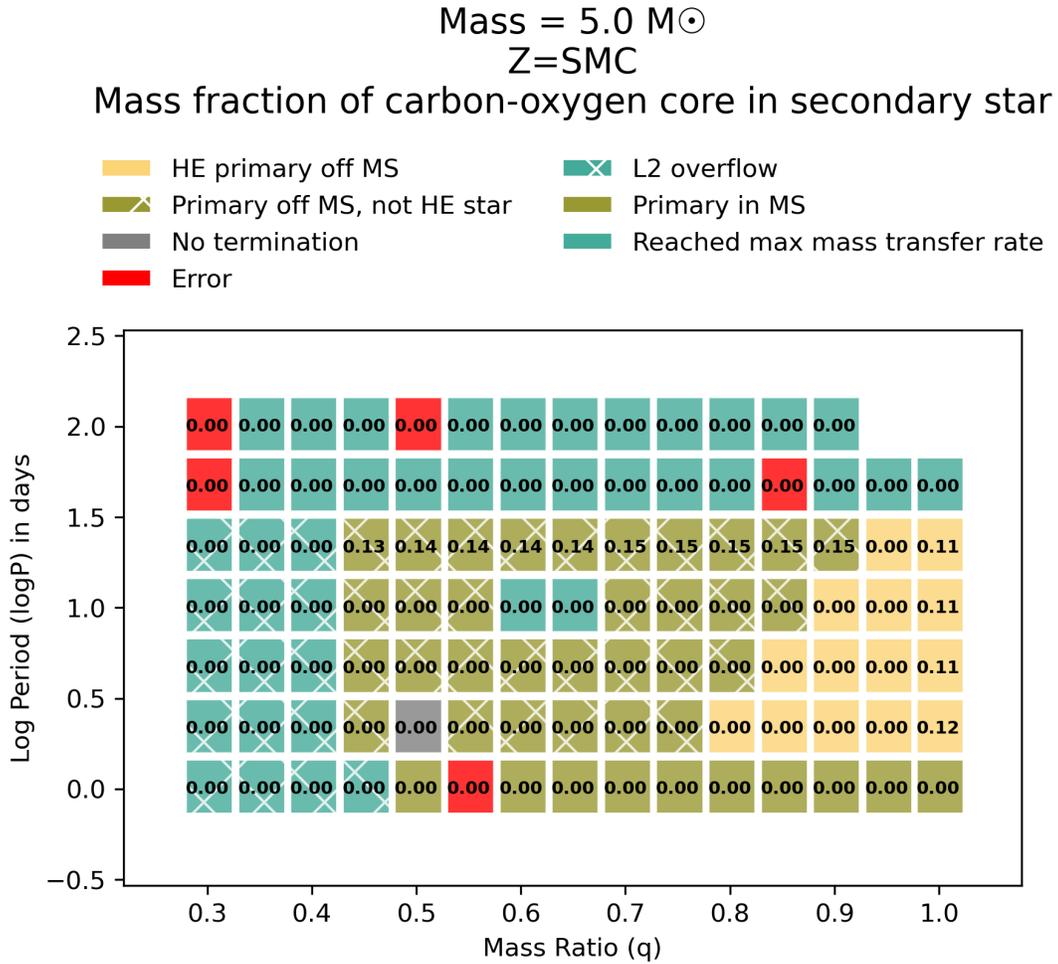


Figure 5: Termination results from simulations using the binary model for MESA with no rotation for a primary star of mass $5M_{\odot}$ in SMC together with the mass fraction of CO core in the secondary star at the end of the simulation written in text.

too high or too low.

3. Refinements

We have refined to see the borders of Figure 8 more accurately as in the initial simulations, we increased the mass ratio in increments of 0.05 and the log period in increments of $1/3$ days. Now we let the mass ratio vary from 0.65 to 0.99 with increments of 0.02 and the period varies from 0.08 to 1.20 by increments of 0.04. In Figure 9, we see that it is a peculiar plot. This mostly has to do with our grey spots, which were spots with data corruption. Remarkably, we can see the boundaries of the triangular hit region and one can notice that a good lower limit for our orbital period is $\log_{10}(P) \geq 0.16$ or

equivalently, $P \geq 10^{0.16} \text{ days} \approx 1.45$ days. A good lower limit for the mass ratio is $q \geq 0.83$ but we see that our mass ratio can go as low as 0.65 if the period is also sufficiently low. Then as another boundary in our triangle, one has an undefined, seemingly linear relation wherefore further research is needed. The more peculiar aspect of Figure 9 is the bottom left corner, where hits are observed. This is not a region we would expect to have sufficient conditions for a hit but it still returned hits. As it is rather unphysical to have systems with such a low period and such low mass ratios, we will not delve into it, but it can be an interesting region for further research.

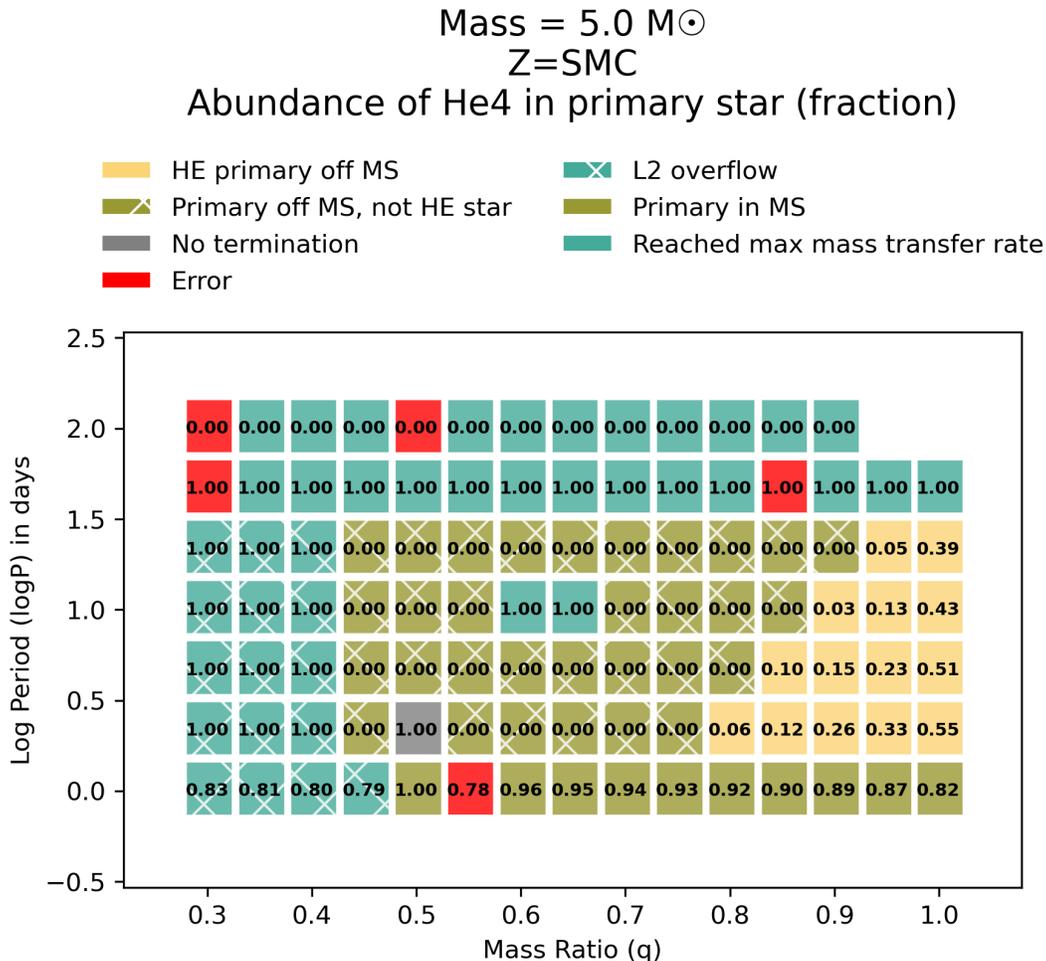


Figure 6: Termination results from simulations using the binary model for MESA with no rotation for a primary star of mass $5M_{\odot}$ in SMC and the abundance of He4 in the primary star at the end of the simulation.

B. Primary star has masses $4M_{\odot}$ and $6M_{\odot}$

To investigate how the merger channel would be affected by different primary star masses, simulations for $4M_{\odot}$ and $6M_{\odot}$ primary stars were also run using the binary model for MESA in the SMC.

1. $4M_{\odot}$ simulations

Figure 10 shows the result obtained with MESA using the module `binary_norot` with the SMC metallicity for a $4M_{\odot}$ primary star. The plot shows that we initially, without applying the strict conditions, have some hits between 0.65 and 1.0 mass ratio for a $\log_{10}(P)$ above 0.33 and below 1.33 days which is shifted to the left compared to the $5M_{\odot}$ primary star simulations in the previous section. Initially, a

single spot for $P = 1$ day at 0.5 mass ratio can also be seen, which is unexpected. We can also see that there are no hits for periods above $\log_{10}(P) \approx 1.33$ days and for mass ratios below 0.6 except for the single spot at 0.5. The simulation shows that it is easier for a binary system with a primary star of $4M_{\odot}$ to achieve a hit compared to the $5M_{\odot}$ with an extended set of mass ratios. This result is expected, indeed if the primary star has a lower mass, the helium core which is only a fraction of that total mass will also have a lower mass. Given that for low mass stars, the primary star will evolve more slowly because of its low helium core mass, the secondary star will have an easier time after the mass transfer to catch up with the evolution of the primary star than for the $5M_{\odot}$ primary mass systems as explained in detail

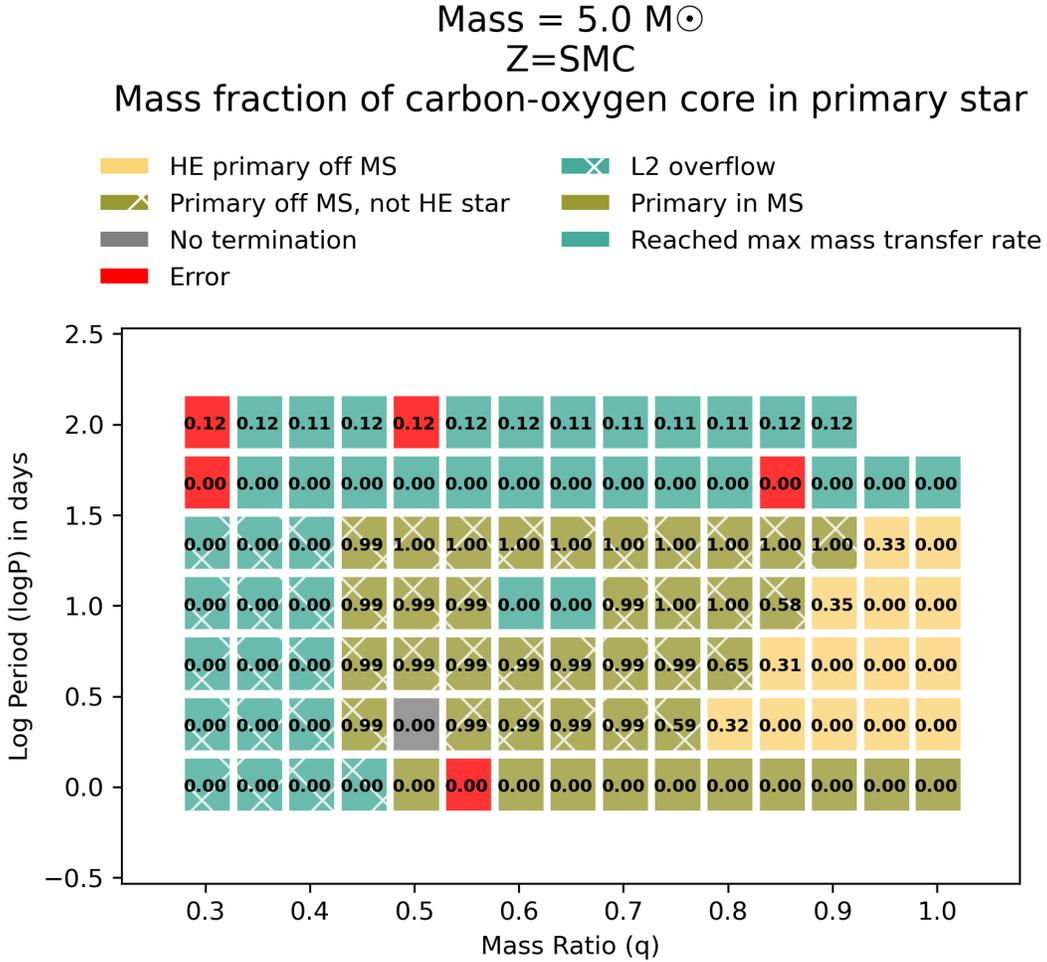


Figure 7: Termination results from simulations using the binary model with no rotation for MESA for a primary star of mass $5M_{\odot}$ in SMC and the mass fraction of the CO core in the primary star at the end of the simulation written in text.

in the introduction. Because this happens faster, we conclude that we have a higher chance of a successful simulation.

When applying the stricter conditions of Table 1, we can see in Figure 11 some of the simulations were not real hits but very close and like we expected, the hit at $P \approx 1$ day disappears. However, we can still see the triangle shape we already observed without the stricter condition and in the $5M_{\odot}$ systems. The hits seen at longer periods and lower mass ratio became 'no hit' because the abundance of He4 in the primary star was lower than needed as shown in Figure 16 (as shown in Appendix A). We also see that some simulations with $\log_{10}(P) \geq 1.0$ were not successful, due to the secondary already being too far developed with a CO core or the He core mass not

being big enough. The detailed figures (Figure 15 and Figure 16), showing the mass fraction of the CO core in the secondary star and the mass fraction of He4 in the primary star, respectively, can be found in Appendix A.

2. $6M_{\odot}$ simulations

Figure 12 shows the termination results from the simulations using the binary model for MESA for a primary star of mass $6M_{\odot}$ in the SMC. This plot shows that initially, the simulations returned a 'hit' region shifted to the right in comparison to the $5M_{\odot}$ primary star simulations (mentioned in the previous section) but similar to that of the $5M_{\odot}$ primary star simulations in terms of the period. Hits are not

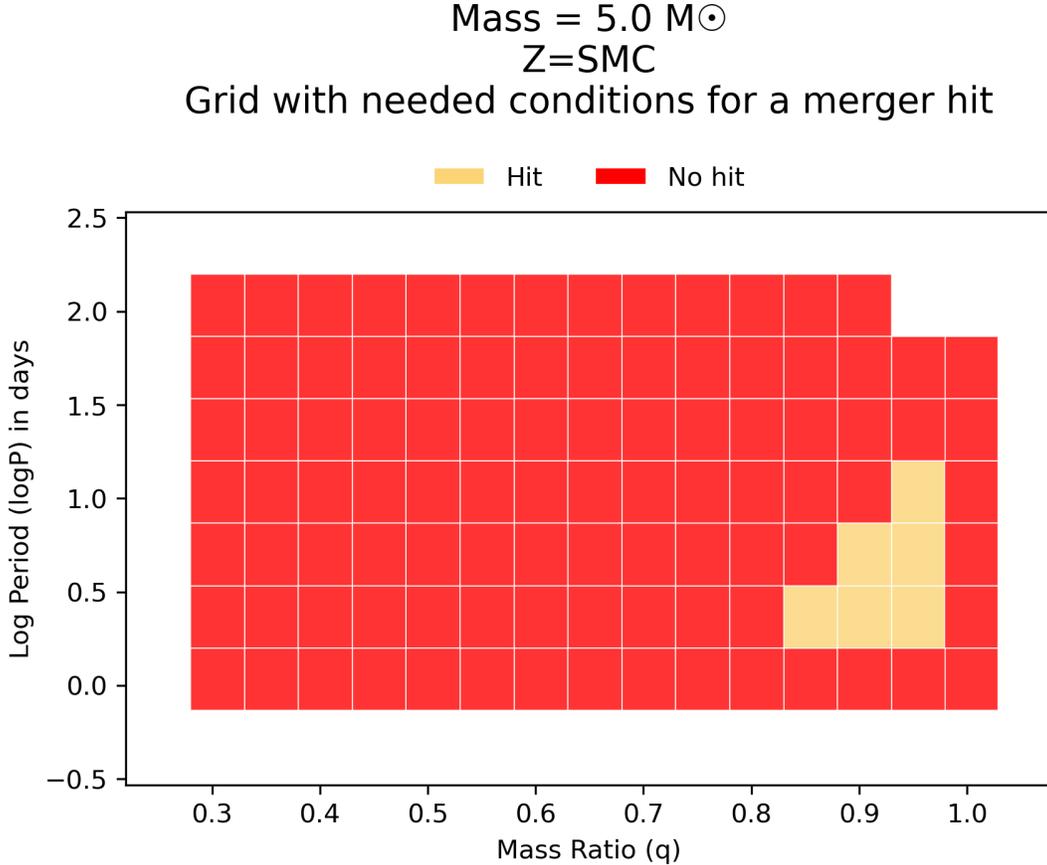


Figure 8: Results from simulations using the binary model with no rotation for MESA for a primary star of mass $5M_{\odot}$ in the SMC with stricter requirements for grids containing hits, illustrated in Table 1.

observed at very low periods of $P \approx 1$ day or at high periods of $P \approx 100$ days. As mentioned in the previous section, at high periods the binary system reaches the max transfer rate when terminating, meaning the RLOF process is delayed and the primary becomes too evolved. The mass transfer rate is therefore too high and the secondary does not fulfil the requirement of mass transferring back onto the primary star. At very low periods, the RLOF process is too fast and we do not see the primary star becoming a helium star, thus not fulfilling one of the requirements of a merging event.

In comparison to the simulations of the $5 M_{\odot}$ primary star, the hit region (yellow grids) is shifted to the right and is not as triangular in shape (as seen in figure 12). This shifted, irregular shape is due to the mass ratio (q), defined in equation (1). For a primary star of $6M_{\odot}$, the mass ratio of successful

hits is shifted closer to unity for the binary system. In this scenario, the core of the more massive star is a larger fraction of its total mass. This means that the star has less mass in its shell to transfer to the secondary star when the RLOF process begins. In order for the requirements of a merging event to be met, the evolution of the secondary star needs to be accelerated by the first mass transfer so that it finishes burning hydrogen before the primary finishes burning helium. This would allow the merging of two He stars to form the desired WR star. With less mass to transfer from the primary star to the secondary star, the secondary star must be almost as massive as the primary star in order for it to be able to 'catch up' with the primary star with its evolution. This is why we see this shift to the right of the hits region. The three blank grids in the upper right corner are due to simulations that simply ran out of time and thus never produced a

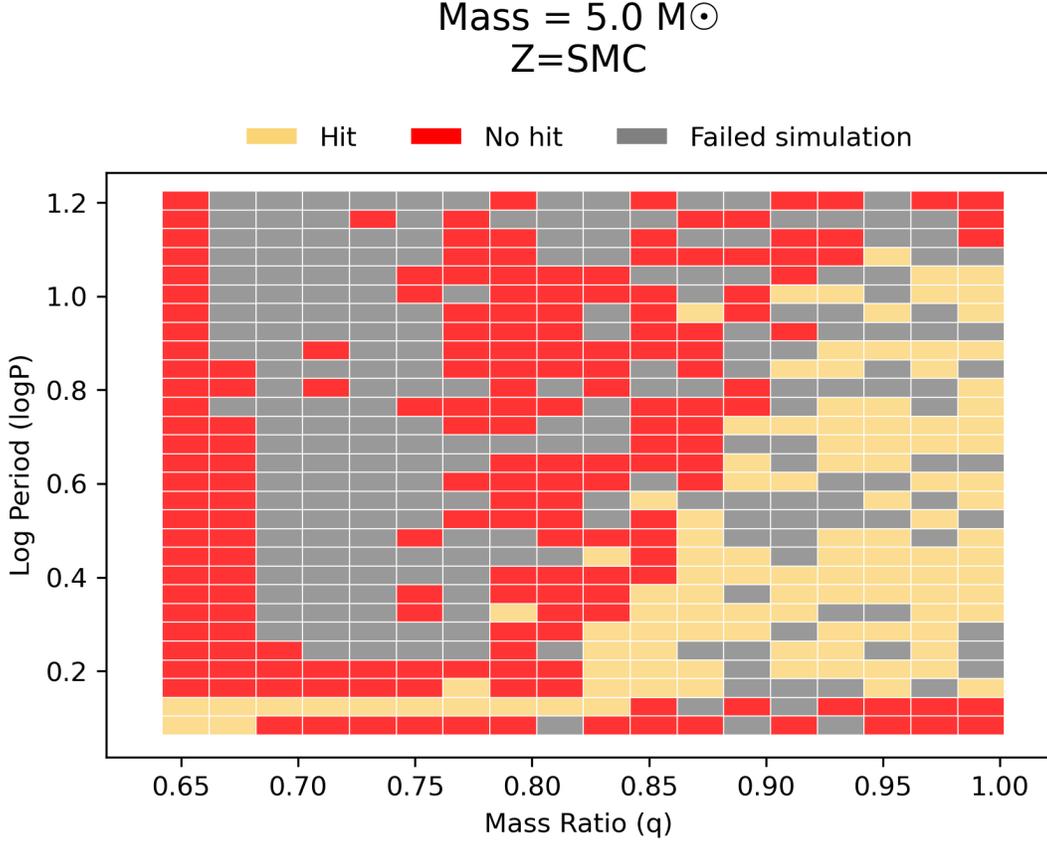


Figure 9: Refined hits from simulations using the binary model with no rotation for MESA for a primary star of mass $5M_{\odot}$ in SMC.

result or error. Some simulations get stuck in a loop and never complete, thus we take these three missing grids as an error.

When applying the stricter conditions of Table 1 to the simulations of the $6M_{\odot}$ primary star, we see that the original figure 12 was misleading in terms of the hits region. In the new figure 13, one can see that for a primary star of $6M_{\odot}$, the mass is too high to produce the type of merging event that we are interested in. To explain why this is the case, the abundances of He4 in the primary and secondary stars must be analysed.

Detailed figures (figure 17 and figure 18) can be found in Appendix B. These figures show the abundances of He4 in the original hit region of the initial results. In order for a grid to be considered a hit, the abundance of He4 must be > 0.1 , as outlined in Table 1. As we can see in Figure 17, the inner

yellow grids do not meet this condition and in Figure 18, the outer yellow grids also do not meet this condition. Thus Figure 13 has displayed no hits for a binary system with a primary star of $6M_{\odot}$. This means that the merger channel producing a classical WR star is more suited for lower mass binary stars.

3. Comparisons

We can compare the simulations of the $4M_{\odot}$ and $6M_{\odot}$ primary star systems. An obvious difference is the demonstration that the prospect of a hit is far higher for the lower mass system than the higher mass system. This is due to the fact that less massive stars have smaller cores relative to their total mass. This means that the less massive primary stars of the binary system have more mass in their envelope to transfer to the secondary stars. This is vital for the inverse mass transfer process that produces the merger event we are interested in.

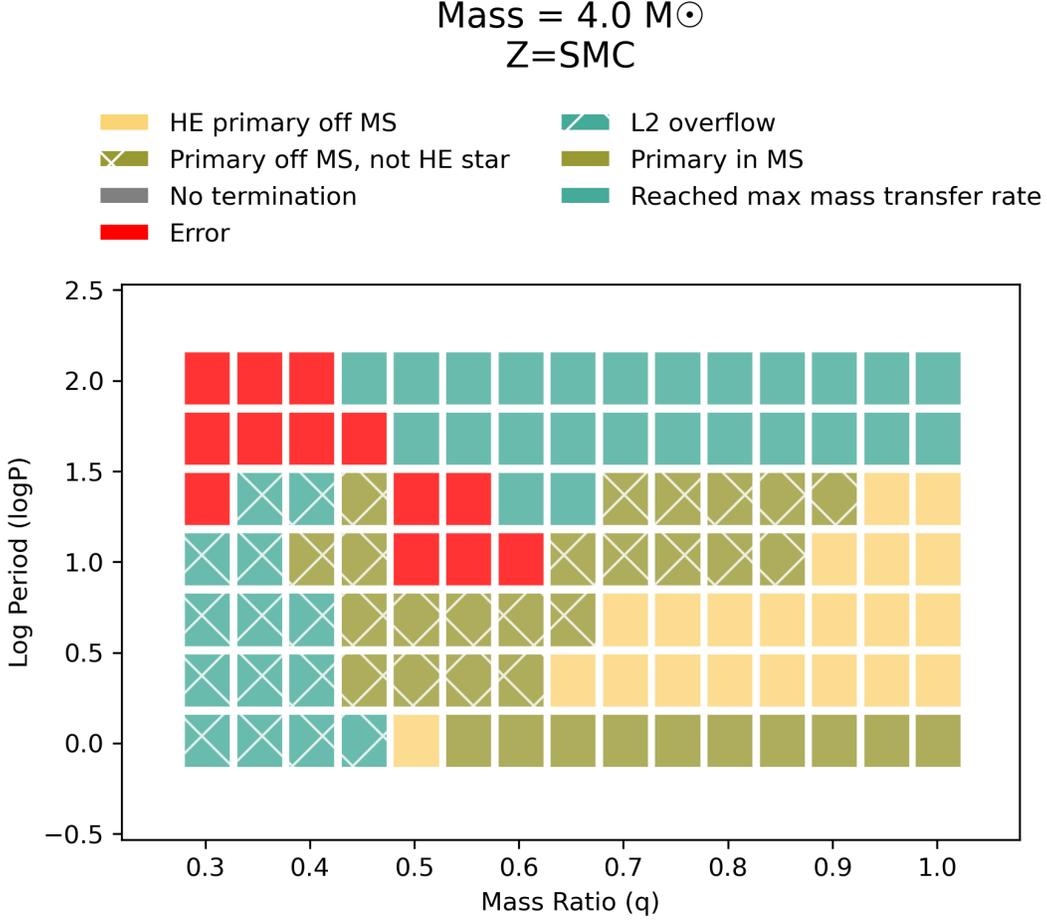


Figure 10: Termination results from simulations using the binary model with no rotation for MESA for a primary star of mass $4M_{\odot}$ in the SMC.

C. Comparison other models

As inspired by Marchant and Bodensteiner (2023), in Figure 14 a plot was recreated with the HR diagram of the start of the ZAMS until mass transfer happens for both the primary and secondary star of a $4M_{\odot}$ and $5 M_{\odot}$ primary star system. Only one system was chosen for both masses as the HR diagrams looked very similar. In the plot, possible products of a binary evolution model were shown, like binary stripped stars of intermediate mass as discussed in Götberg et al.(2023) which are proposed to be a consequence of common envelope ejection but could also be explained by a binary merging. The quasi-WR star HD 45166 (Tomer Shenar, Wade, et al. 2023) is also included, while

this star is not in the SMC, it still is possible to compare it with our simulations to see if our model seems physically suited and if our model could explain the creation of WR stars in low metallicity.

To be able to compare our simulations, we approximated the mass of our merger product for the hits we observed in the data by the following definition:

$$M_{\text{merger}} = M_p + M_{s,\text{He}} \quad (3)$$

Where M_p is the mass of the primary star and $M_{s,\text{He}}$ is the mass of the helium core mass of the secondary star at the end of the simulation. For the secondary star, we measured the helium core mass as when the common envelope gets ejected, its hydrogen will also be ejected. For the primary star, its hydrogen is already ejected.

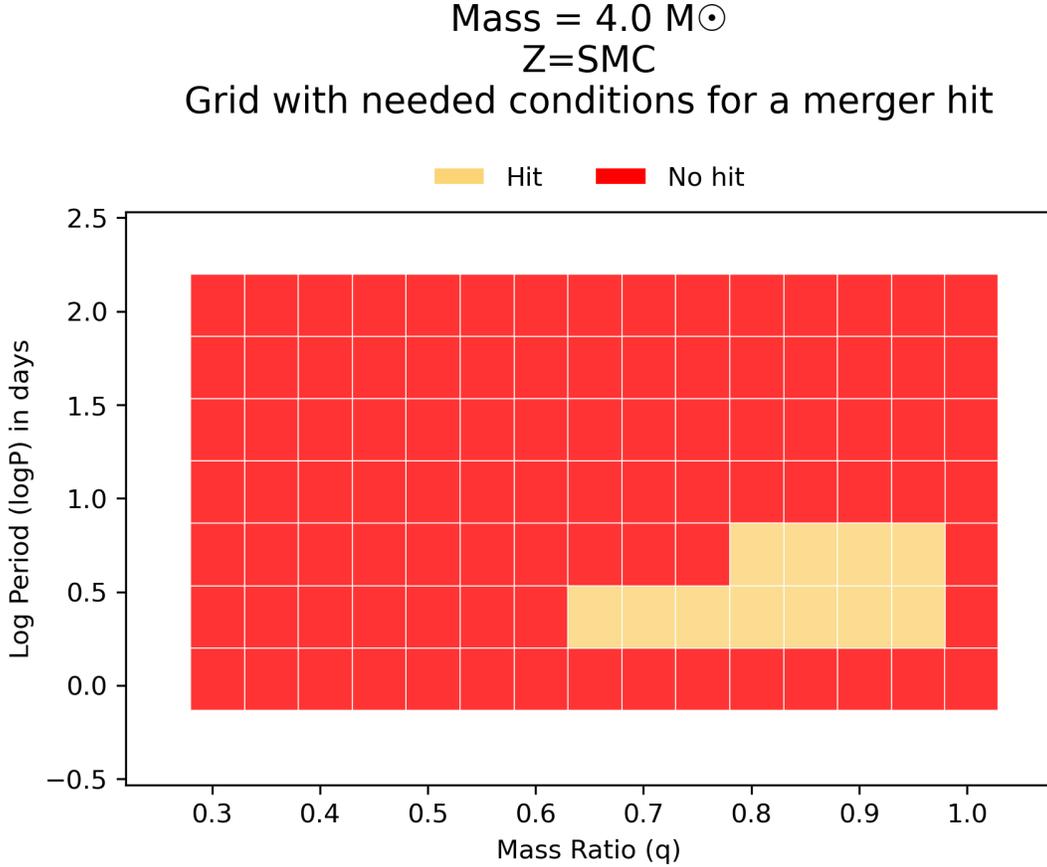


Figure 11: Results from simulations using the binary model with no rotation for MESA for a primary star of mass $4M_{\odot}$ in the SMC with stricter requirements for grids containing hits, illustrated in Table 1.

We also want to have the luminosity and effective temperature of our merger product to be able to compare it with the products. For this, simulations of stars of masses from 1.5 to $4 M_{\odot}$ were computed with a composition of 70% hydrogen and 28% helium, which terminated when the star was 9×10^7 years old. This is to reassure you that we have a helium star at the Zero Age Helium Main Sequence (ZAHMS), just like how our merger product would normally be a helium star in the ZAHMS. Afterwards, we linearly interpolated $\log_{10}(T_{\text{eff}})$ and $\log_{10}(L/L_{\odot})$ in function of $\log_{10}(M_{\text{merger}})$. Using the interpolated properties, we added the properties of our hits and also the ZAHMS for masses from 1.5 to $4 M_{\odot}$ in Figure 14.

Notice on Figure 14 the gap between the hits for our $4M_{\odot}$ and $5M_{\odot}$ primary star systems, this is due to the fact that we have not done a study for

any masses in between, which could be interesting for future research. Remember that for the $6M_{\odot}$ primary star systems, no hits were found. So on the ZAHMS there will be a boundary somewhere between $5M_{\odot}$ and $6M_{\odot}$ where the merging with the needed conditions from Table 1. will not happen, though as of now, it remains a topic for further research. Note that the rather high luminosity and effective temperature of the mergers can also be explained by looking at the HR diagrams.

The most important factor might be how all our possible products come close to our hits, with some of the error bars including the ZAHMS. It seems most stars have lower effective temperatures and higher luminosity than our merging hits, but only on a small scale. Our merger products have mostly $\log_{10}(T_{\text{eff}}) \approx 4.8 - 4.9\text{K}$ and $\log_{10}(L/L_{\odot}) \approx 3.0 - 3.8$ while the possible prod-

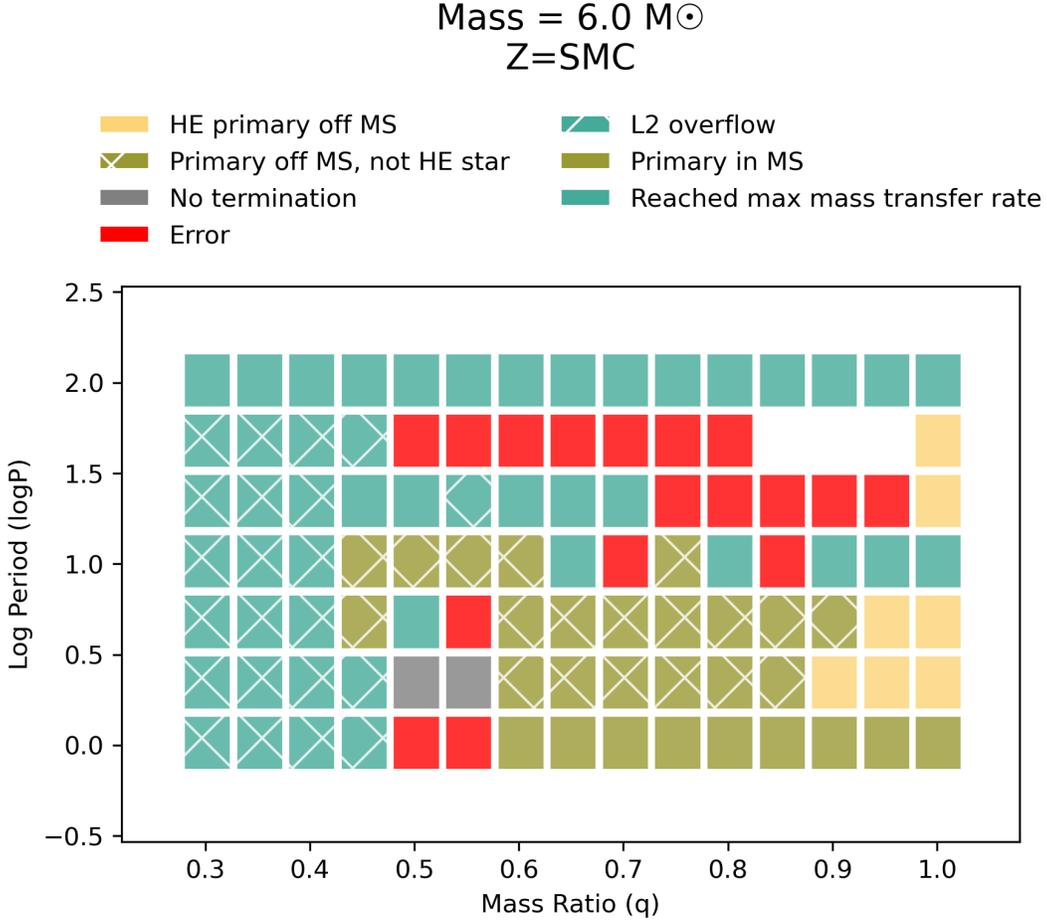


Figure 12: Termination results from simulations using the binary model with no rotation for MESA for a primary star of mass $6M_{\odot}$ in the SMC.

ucts mostly have $\log_{10}(T_{\text{eff}}) \approx 4.7 - 4.9\text{K}$ and $\log_{10}(L/L_{\odot}) \approx 3.7 - 4.3$. These numbers make it seem very possible that these binary stripped stars are products of our model, which increased their luminosity by an unaccounted physical process. Knowing that we included a quasi-WR star and stars from the SMC, it seems very plausible that WR stars in the SMC can be formed by our model.

IV. CONCLUSION AND DISCUSSION

It was our aim to research if it was possible that WR stars could originate from the mergers of two ZAMS stars which start in a binary system. The possibility to form the quasi-WR star HD 45166 as a final product of a merger event was also examined. This was achieved by using the binary evolution model of

MESA and simulating primary ZAMS stars of mass $4M_{\odot}$, $5M_{\odot}$ and $6M_{\odot}$ in the SMC. We used additional conditions on the terminations, He4 abundance and the mass fraction of the cores to ensure that the physical conditions of the simulations were met. As a parameter study, we observed the period and the mass ratio of the second ZAMS star as a function of the primary star at the beginning of our simulations.

A. Period

In all of our simulations, we noticed that our period needs to be rather small. For all of the masses, comparing the refined grid for the $5 M_{\odot}$ systems and the other mass systems, when our period was higher than $\log_{10}(P) > 10^{1.08}$ days or equivalently $P > 12.5$ days, maximal mass transfer rate was reached. This implies that for a long period, one

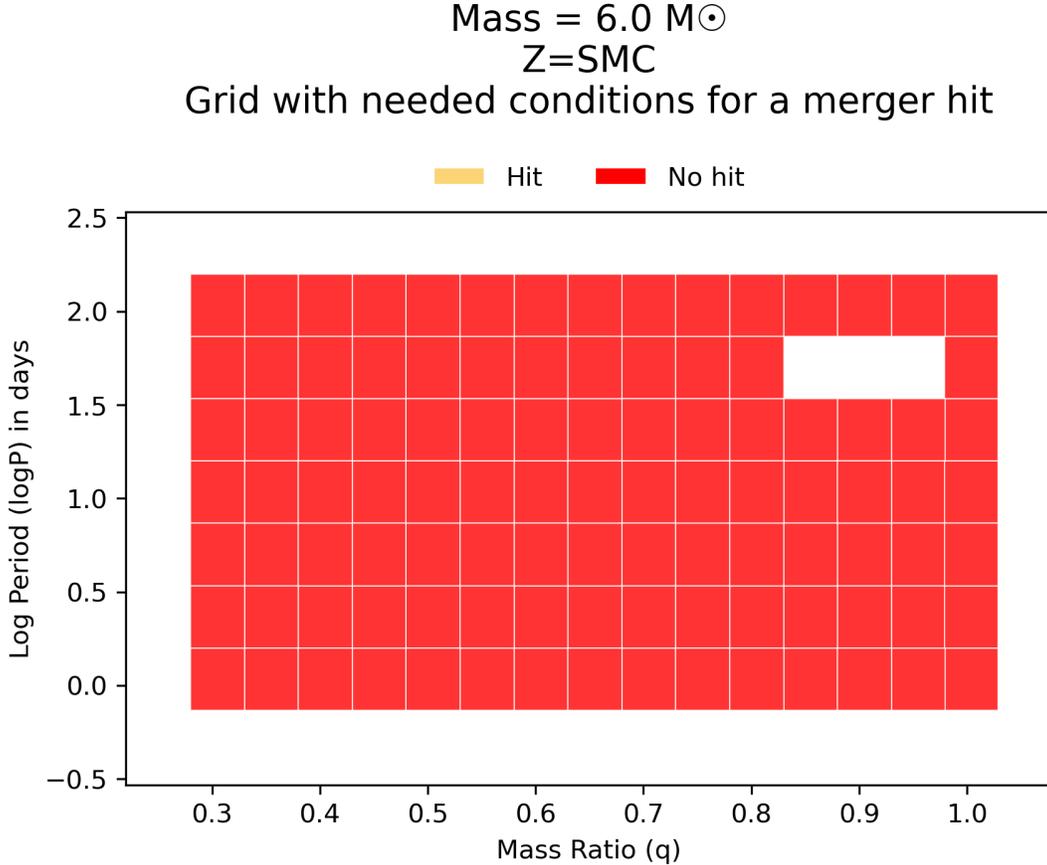


Figure 13: Results from simulations using the binary model with no rotation for MESA for a primary star of mass $6M_{\odot}$ in the SMC with stricter requirements for grids containing hits, illustrated in Table 1.

has the problem of the primary being far too developed before starting RLOF, causing the binary system to start common envelope evolution before inverse mass transfer.

The period of the simulation can also not be too low, this caused our stars to be not developed enough to meet the conditions before inverse mass transfer happens.

B. Mass ratio

The mass ratio needs to be rather high, but not at unity. Unity would imply that a long time has lapsed before the inverse mass transfer occurs, leading to our secondary star being too developed when inverse mass transfer begins. Though for mass ratios too small, our primary was too far developed, being mostly a CO-star.

C. Mass

The lower the mass, the more extreme the mass ratios could be. This is probably due to less mass being transferred and thus even with a low mass ratio we could still have a stable system to start the merging process. Based on our earlier findings, note that the systems with successful hits are mostly triangular shaped, with the lower the mass, the more area and extreme surface.

D. qWR HD45166 and other products

Compared in an HR diagram, the quasi WR star HD45166 seemed to have comparable conditions as our approximated merger products starting from masses $5M_{\odot}$ and lower. Though we can not conclude it in this paper, it seems very plausible that the quasi WR star HD45166 could be a merger product. This paired with the fact that other observed

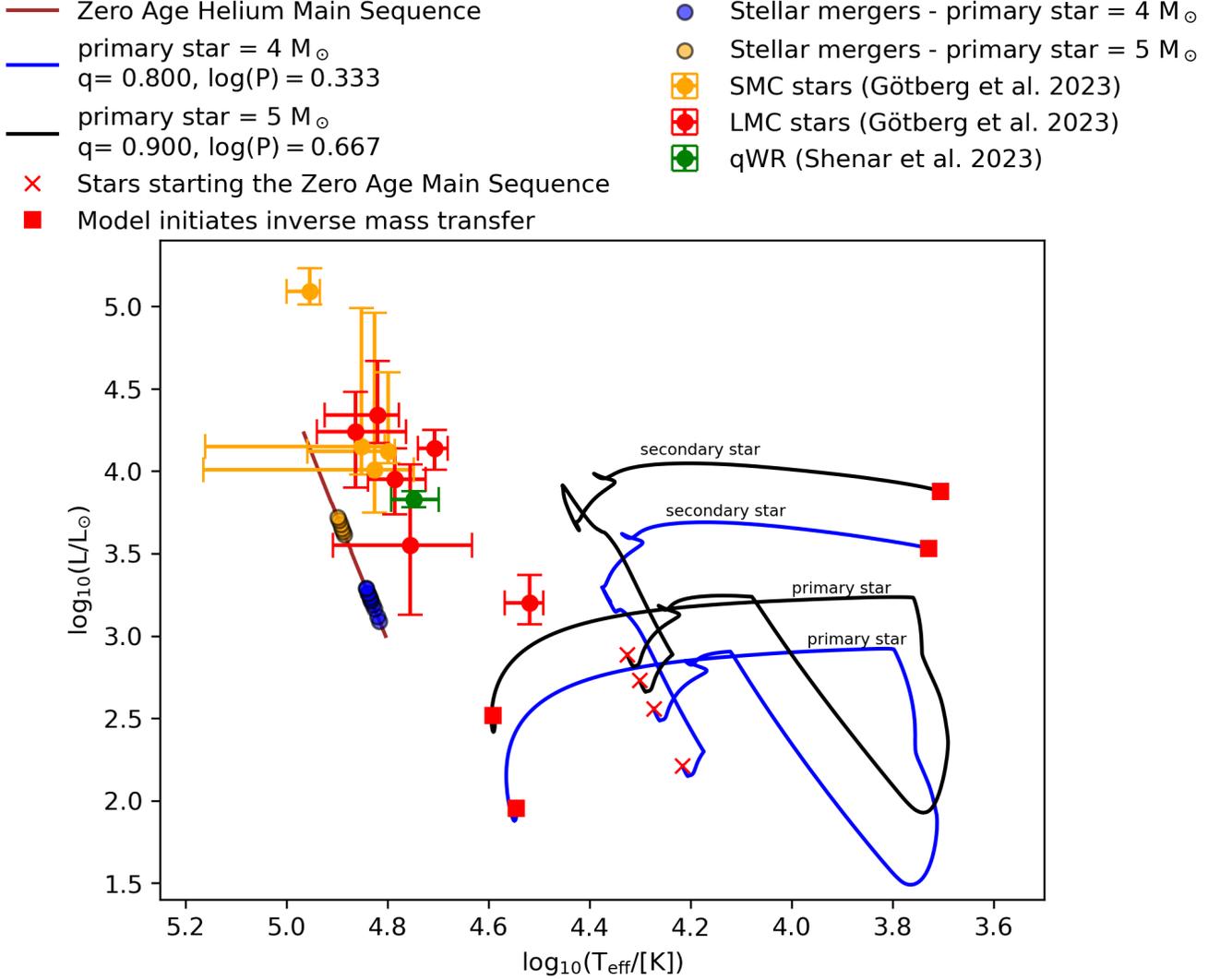


Figure 14: The HR diagram of two primary and two secondary stars, one of a $4M_{\odot}$ primary mass system, the other of a $5M_{\odot}$ primary mass system. The ZAHMS is also shown, with some merger hits from our systems denoted on it, together with binary stripped stars and the qWR HD45166 as possible merger products.

binary stripped stars in both LMC and SMC had comparable properties with our mergers, it could be very possible for also the low-intermediate mass WR stars in the SMC to be formed by merger products of intermediate He stars. Higher mass WR stars were not explored, but for these stars being stripped by strong stellar winds seems more credible. The $6M_{\odot}$ already showed that a suitable merger product for this mass would be unphysical. We thus propose that under the right physical conditions, merger products are a real probable theory.

E. Further research

Refining the hit region could be a good way to start further research, while also trying to refine the right masses to see if we could simulate HD45166 as a merger product more accurately and to investigate what the maximal mass is that leads to a hit. We also would propose trying to simulate beyond the inverse mass transfer to see how this merger would evolve. Refining could also be necessary to explain in more detail the physical reasons why the boundary is at a certain place in the parameter space. We also

think it would be beneficial to do this study in other metallicities to research whether this model could explain other astronomical products. A population synthesis also seems needed for further research, to know if our merger products can have any physical significance and if their lifetime would support the theories of our possible products.

V. APPENDIX

A. $4M_{\odot}$ primary star binary system

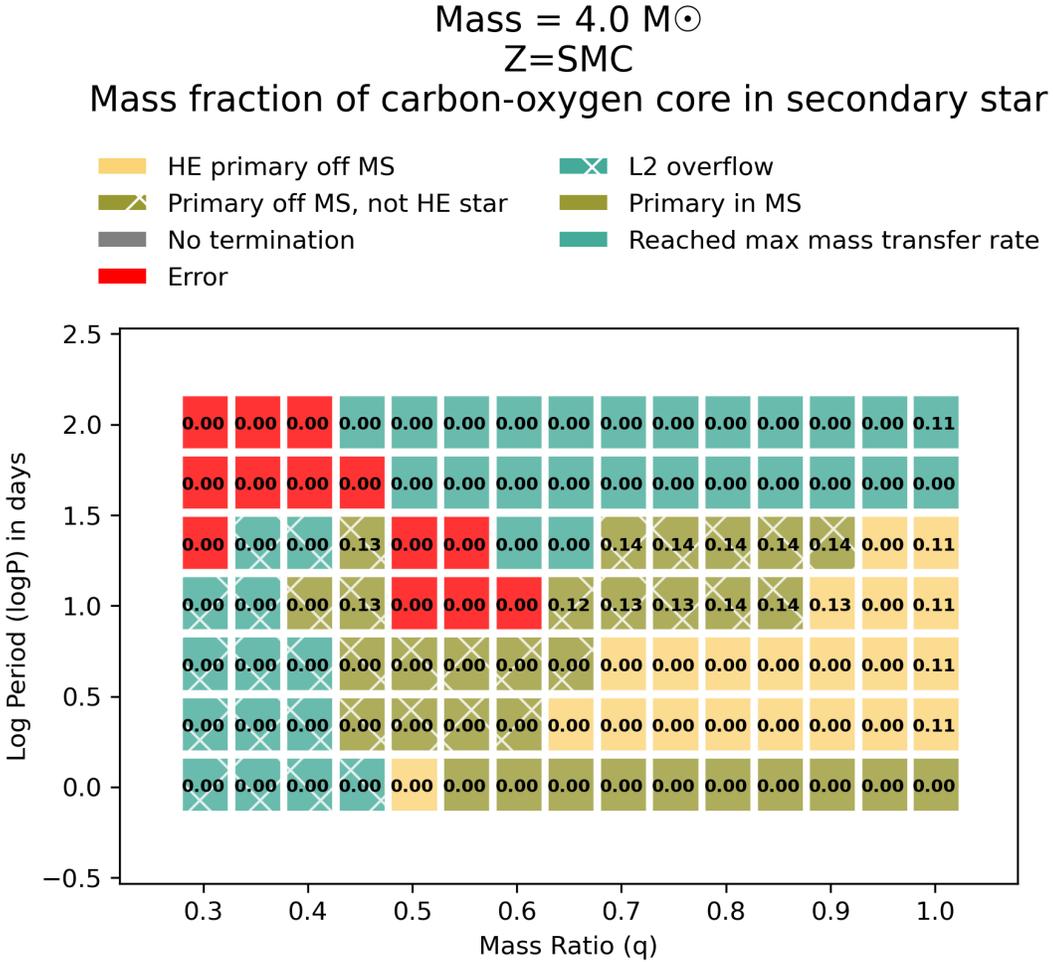


Figure 15: Termination results from simulations using the binary model with no rotation for MESA for a primary star of mass $4M_{\odot}$ in the SMC together with the mass fraction of the CO core in the secondary star at the end of the simulation written in text.

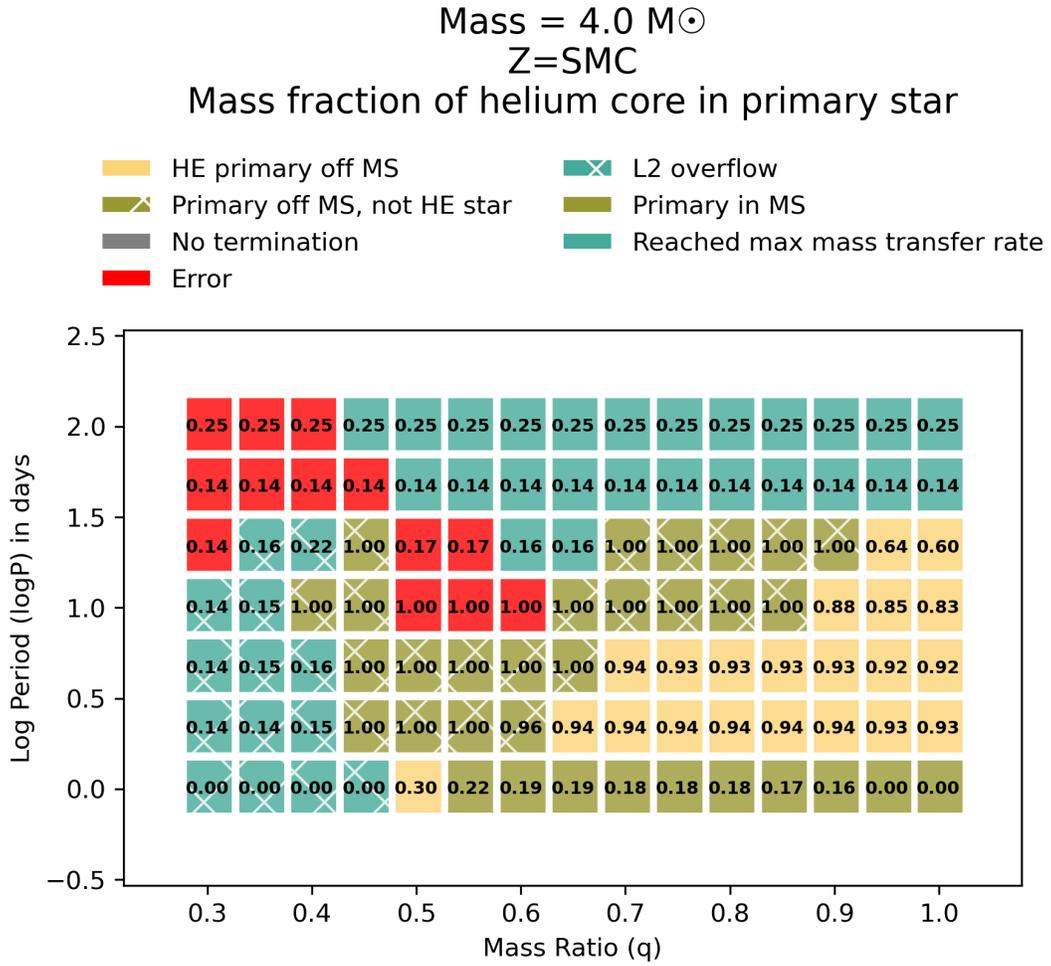


Figure 16: Termination results from simulations using the binary model with no rotation for MESA for a primary star of mass 4M_⊙ in the SMC together with the mass fraction of the He core in the secondary star at the end of the simulation written in text.

B. $6M_{\odot}$ primary star binary system

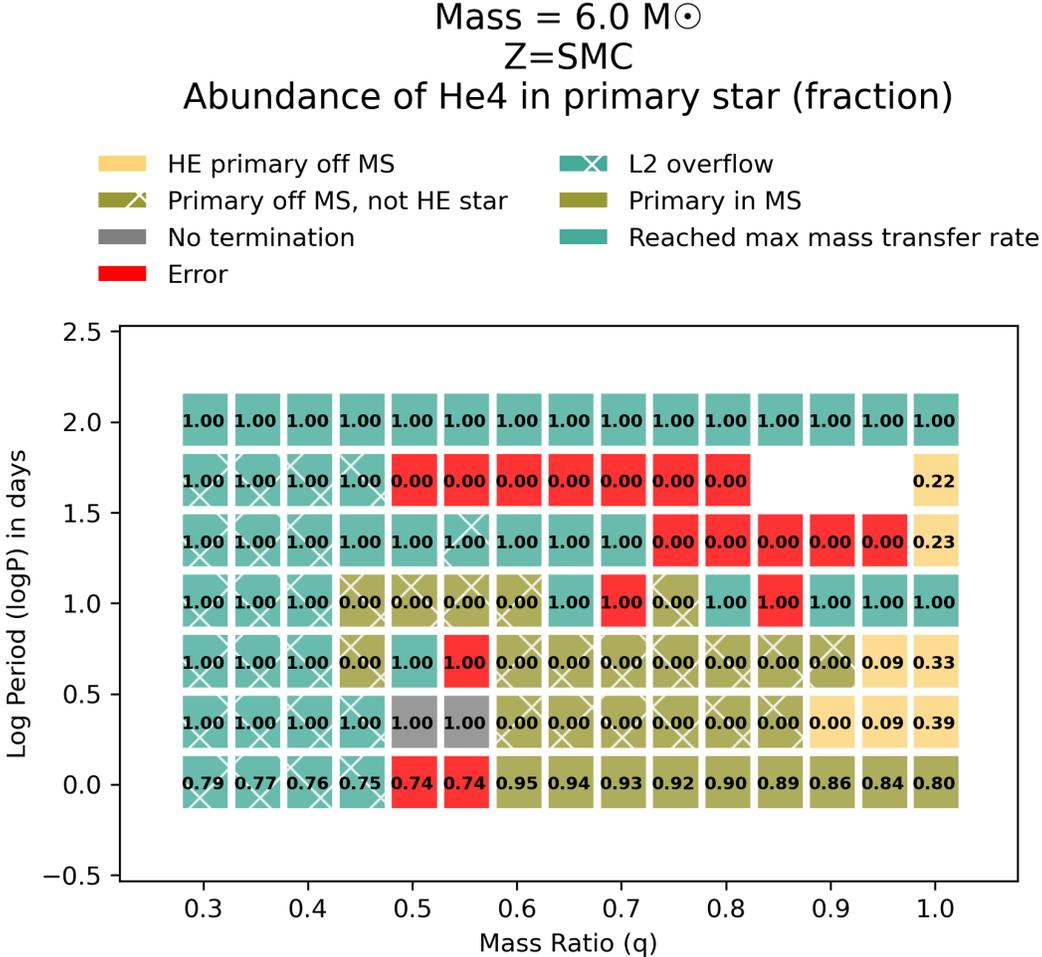


Figure 17: Termination results from simulations using the binary model with no rotation for MESA for a primary star of mass $6M_{\odot}$ in SMC and the abundance of He4 in the primary star at the end of the simulation written in text.

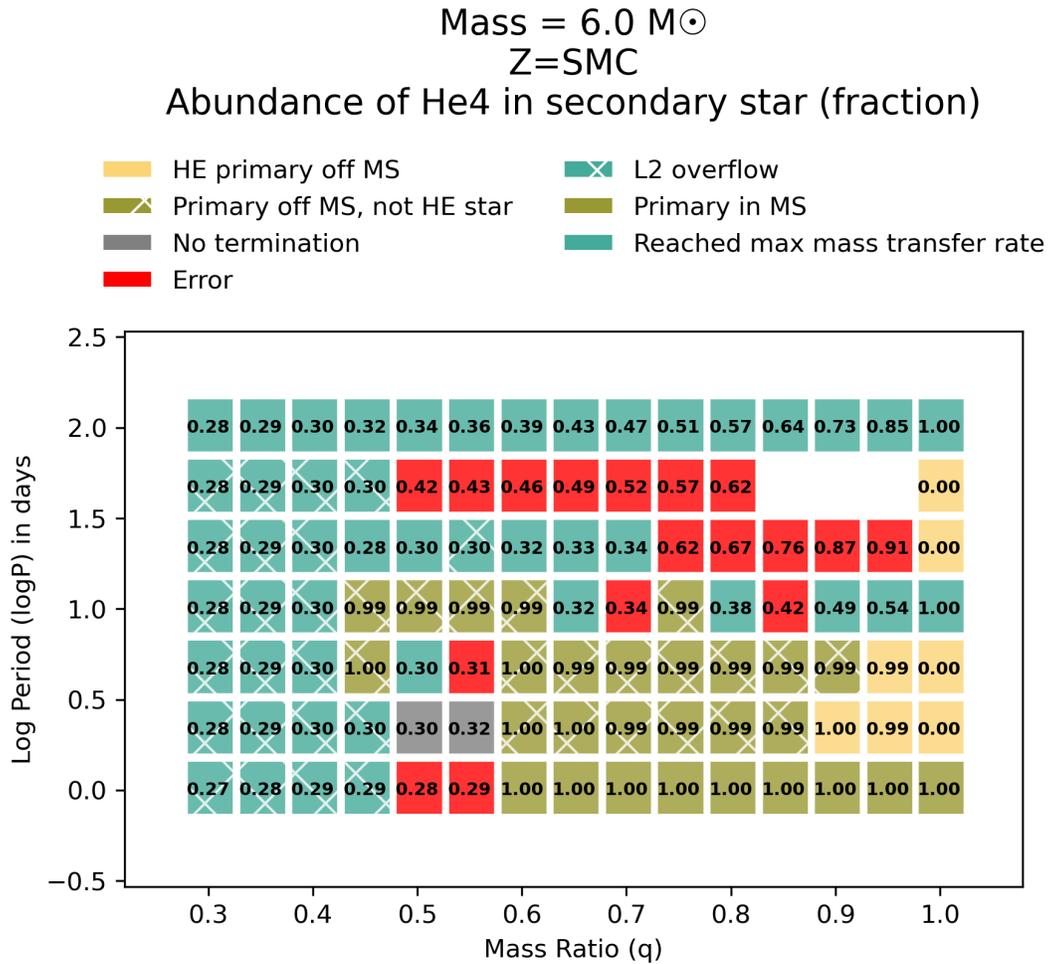


Figure 18: Termination results from simulations using the binary model with no rotation for MESA for a primary star of mass $6M_{\odot}$ in SMC and the abundance of He4 in the secondary star at the end of the simulation written in text.

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