

A Methodology for Synthesizing Cataclysmic Variable Populations Using the Output of the MESA Stellar Evolution Code

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Abstract. This paper presents a methodology for synthesizing populations of cataclysmic variables (CVs) using the MESA stellar evolution code. We construct a grid of binary systems with varying initial white dwarf progenitor masses, companion star masses, and orbital periods, and evolve these systems through pre- and post-common envelope phases. Preliminary results reveal diverse evolutionary pathways, including standard CV formation, mergers, double white dwarf formation, and systems that bypass Roche lobe overflow. These outcomes underscore the complexity of binary evolution and the need for refined models, particularly for common envelope ejection. We discuss the implications of our findings and outline future work incorporating statistical distributions for initial binary parameters to generate synthetic CV populations that can be compared with observational data, thus aiming to improve our understanding of CV formation and evolution.

Keywords: *common envelope; MESA; population synthesis; stars: cataclysmic variables; stars: evolution*

1 Introduction

Stars are essential to understanding the universe, governing galaxy evolution, chemical distribution, and the formation of planetary systems. Their life cycles provide insight into many astrophysical phenomena, including the production of elements necessary for life. However, stars often exist in binary or multiple star systems, where interactions between the stars can significantly alter their evolutionary paths. These interactions influence mass loss, aging, and the nature of stellar remnants, such as white dwarfs, neutron stars, or black holes.

Cataclysmic variables (CVs), a type of binary system, are especially interesting. In CVs, a white dwarf (WD) accretes material from a companion star, typically a

Sun-like main-sequence star, through a process called mass transfer. CVs are key to understanding stellar evolution and explosive events like novae. Rappaport, *et al.* in [1] explains the evolution of such system. Their initial orbits, ranging from 60 minutes to 5 hours, gradually shrink over time. Once the period shortens to 2-3 hours, mass transfer temporarily halts—a phenomenon known as the "period gap"—before resuming as the period drops below 2 hours. Eventually, the companion star becomes degenerate, resulting in a minimum orbital period of around 60 minutes, after which the period begins to expand. Systems at this stage are referred to as "period bouncers."

Recent observational data on CV populations, such as those from Gänsicke, *et al.* [2], show discrepancies when compared to theoretical predictions. For example, studies predict a higher proportion of period bouncers and lower mean WD masses in CV populations than observed. Surveys report a mean WD mass of $\sim 0.8 M_{\odot}$, in contrast to theoretical models suggesting $\sim 0.6 M_{\odot}$, and fewer period bouncers than expected. These discrepancies highlight the need for more robust methodologies to synthesize CV populations and bridge the gap between observations and models.

This study proposes a methodology for binary stellar population synthesis, using data from the stellar evolution code MESA (Modules for Experiments in Stellar Astrophysics) developed by Paxton, *et al.* in [3] and [4]. By leveraging MESA's extensive stellar evolution capabilities, we aim to create a more accurate framework for synthesizing CV populations. Our goals are: (1) to investigate how MESA can be used to generate synthetic CV populations, and (2) to refine the methodologies for modeling these systems. This paper outlines our approach, including an overview of CV evolutionary pathways (Section 2), the proposed synthesis methodology (Section 3), and we present the preliminary results of our simulations (Section 4), concluding with future research directions in Section 5.

2 Stellar Evolution and Cataclysmic Variables

Creating a CV population synthesis requires simulating CV evolution based on theoretical principles. Key concepts in CV evolution include the mechanics of mass transfer, binary system evolution, and the observable effects of these interactions. Understanding how these processes shape CV characteristics—such as mass distribution, orbital periods, and evolutionary pathways—is essential for modeling CV populations.

2.1 General Stellar Evolution

Stellar evolution is driven by processes like nuclear fusion, gravity, and mass loss, with a star's life cycle primarily determined by its initial mass and

composition. According to Iben [5], stars begin as collapsing gas clouds, eventually achieving nuclear fusion, which generates outward pressure to balance gravity. As hydrogen in the core is depleted, the core contracts and heats, allowing fusion of heavier elements and causing the star to expand, entering phases like the red giant. For intermediate-mass stars ($1.0\text{--}8.0 M_{\odot}$), their final stages involve shedding outer layers and leaving behind a white dwarf remnant. Evolution rates depend on mass, with more massive stars evolving faster due to higher core temperatures and fusion rates, while lower-mass stars evolve more slowly.

2.2 Cataclysmic Variables Progenitor

In binary star systems, stars are rarely isolated; their interactions can significantly alter the course of their evolution. One of the key paradigms in binary stellar evolution is Roche lobe overflow (RLOF), as described by Iben in [5]. Each star in a binary system possesses a region around it, known as the Roche lobe, within which its gravitational influence is predominant. The shape of the Roche lobe is determined by the masses of the stars and their orbital separation, expressed by Eggleton in [6] as follow:

$$R_L = \frac{0.49Q^{2/3}}{0.6Q^{2/3} + \ln(1 + Q^{2/3})} A, \quad (1)$$

where R_L is the Roche lobe radius from the center of the star, Q is the mass ratio between the star in question and its companion, A is the separation of two stellar centers. When one star in the binary system evolves and expands, its radius may reach the Roche lobe radius, resulting in mass transfer as it overflows beyond this boundary. This process can lead to significant changes in both stars' evolutionary paths, influencing phenomena such as mass transfer rates and the formation of CVs.

According to Iben in [5], Warner in [7] and Eggleton in [8], CVs are a specific class of binary star systems formed when a WD is paired with a companion star, typically a main-sequence star. Prior to this formation, the WD was originally a main-sequence star of intermediate mass. In contrast, the companion star is usually a low-mass star (below $1.0 M_{\odot}$). This implies that the progenitor of the WD evolved earlier than the companion star. As the WD progenitor expands and enters the red giant phase, its radius exceeds the Roche lobe radius, leading to RLOF exceeds a critical threshold (as discussed by Eggleton in [8] and Marchant, *et al.* in [9]), the mass transfer becomes unstable, resulting in material being

transferred from the WD progenitor enveloping both stars. This condition is known as the "common envelope" (CE) phase.

2.3 Post-CE Evolution

During the CE phase, friction within the envelope causes the stars' orbits to shrink, leading to angular momentum loss and ejection of the envelope. This leaves behind a WD while the companion remains unaffected. Warner in [7] explains that the WD-main sequence system continues to shrink due to magnetic braking and gravitational radiation, eventually triggering RLOF again. Since the WD has lost much of its mass during the CE phase, the resulting mass transfer is stable, forming a typical CV. Even though, the WD losses so much mass, the WD mass M_{WD} still remains higher than the companion mass. If it the otherwise, it will result in other forms of binary, instead of typical CVs.

Mass transfer dynamics depend on the orbital separation and the companion star's state. Stable transfer allows the system to reach quasi-equilibrium, but excessive accretion onto the WD can trigger novae as given by Warner in [1]. As the system evolves, the orbital period shrinks to the period gap (2-3 hours), after which shrinkage continues until the minimum period, typically ~80 minutes observed by McAllister, *et al.* in [10], though theory predicts ~60 minutes. At the minimum, the orbit begins to expand as the companion star becomes degenerate.

3 The Proposed Method

We begin our method of synthesizing the CV population with a series of simulations on CV evolution. In this section, we delve into our proposed methodology, which starts by constructing a grid of initial parameters based on the characteristics of CV progenitor system. We utilize MESA (Paxton, *et al.* in [3] and [4]) to run simulations using these initial parameters as input. The simulation output from MESA is then processed and refined to synthesize the CV population observed today, but we have not yet implemented it.

3.1 Initial Parameters

The initial parameters for the population synthesis of CVs are crucial in accurately modeling the evolutionary processes that lead to the formation of these systems. The main parameters we focus on include the mass of the WD progenitor star, the mass of the companion star, and the orbital period. We can also include metallicity as one of the parameters, but it will be excluded in this study, at least for now, and we will discuss it in Section 3.1.4. These parameters are chosen

based on theoretical considerations of CV evolution. Finally, we obtained a grid of 1389 models.

3.1.1 Masses of the WD Progenitor Star

The WD progenitor star must be a star capable of forming a degenerate core during the red giant branch (RGB) phase of its evolution. This limits the mass range of the progenitor star to between 1 and 10 $M_{\odot}$. Stars with masses below 1 $M_{\odot}$ will generate a very low core mass, and stars above 10 $M_{\odot}$ end their lives as supernovae, leaving behind either neutron stars or black holes as given by Iben in [5]. Thus, the grid of initial WD progenitor masses M_1 for our simulations includes a set of discrete values from 1 $M_{\odot}$ to 10 $M_{\odot}$. For the WD progenitor star, we selected the following values:

$$M_1 = \{1.0, 1.3, 1.7, 2.0, 2.3, 2.7, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10\} M_{\odot}. \quad (2)$$

3.1.2 Orbital Periods and Roche Lobe Considerations

The orbital period P in binary star systems is directly related to the size of the Roche lobe (see Eq. (1)), which dictates the onset of mass transfer through RLOF. In order to initiate a common envelope (CE) phase, the Roche lobe radius must be smaller than or comparable to the maximum radius of the star at the end of the asymptotic giant branch (AGB) phase, when the star's envelope expands to its largest size. Using Kepler's laws, we can relate the Roche lobe radius to the orbital period:

$$P = 2\pi \sqrt{\frac{A^3}{G(M_1 + M_2)}}, \quad (3)$$

where G is the gravitational constant. The maximum orbital period is therefore constrained by the maximum radius of the progenitor star at the AGB phase. If the orbital period exceeds this limit, the system will not enter the CE phase, preventing the formation of a close WD + main-sequence binary. Based on this, we set the grid of initial orbital periods (P) to have 10 logarithmically spaced values.

3.1.3 Masses of the Companion Star

The mass of the companion star M_2 must not exceed the maximum core mass of the WD progenitor star. If M_2 is larger than the core mass, it would result in a

system where the WD is less massive than its companion, a configuration that is rare in the observed CV population as given by Zorotovic, *et al.* in [11]. To determine the maximum core mass for each progenitor star mass, we conducted a series of single-star evolution simulations using MESA. The simulations follow the evolution of stars from the main sequence through the AGB phase, and the core mass is measured at the end of the AGB phase. The results of these simulations are shown in Figure 1, which lists the maximum core mass as a function of progenitor mass. The companion star mass M_2 is set in multiples of $0.05 M_\odot$, ranging from $0.1 M_\odot$ to the maximum core mass of the WD progenitor star. It also agrees with mass-core mass relations given by Iben in [5].

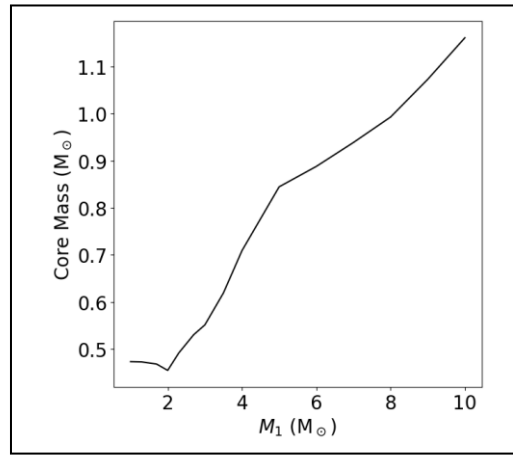


Figure 1 Maximum Core Masses of WD Progenitor Stars at the End of the AGB Phase as resulted from our MESA simulation.

3.1.4 Metallicity Assumptions

In this study, we do not include metallicity Z as a variable parameter in our grid, assuming instead that the metallicity of the stars in the observed CV population is approximately solar, with $Z = 0.02$. This assumption simplifies the population synthesis by focusing on other key parameters (e.g., mass and orbital period), and lower computational consumption. However, it is important to note that metallicity varies across both space and time. According to Chiappini, *et al.* in [12], galactic chemical evolution models and observations of stellar populations across the Milky Way show that metallicity has increased over cosmic time, with older populations typically having lower metallicities. Recent studies, such as by Lian, *et al.* in [13], have profiled metallicity across space of the Milky Way.

3.2 Simulation

The simulations were performed using the MESA code driven by Python code. We divide the simulation into two phases, namely the pre-CE phase and the post-CE phase. Both simulation phases are performed separately. Simulation of one evolutionary track is performed repeatedly with different M_1 , P , and M_2 , following the grid obtained in Section 3.1.

3.2.1 Pre-CE Simulation

We assume that both stars in the system are born at the same time, so we begin the simulation with a zero-age main-sequence (ZAMS) binary star using the MESA binary module (Paxton, *et al.* in [4]). The simulation reaches a stopping condition near CE. The stopping condition is defined as the radius of the WD progenitor star has expanded to approach the Roche lobe radius and mass transfer begins to increase significantly.

3.2.2 Getting Around the CE Phase

As stated by Paxton, *et al.* in [5], MESA binary cannot simulate the common envelope phase. An analytical approach is used to pass through this phase. The parameters that change significantly in this phase are the separation distance or period due to the loss of angular momentum carried by the ejected envelope material. These changes are calculated in a formalism called “the α formalism” by Webbink in [14] as follows:

$$\frac{A_f}{A_i} = \frac{M_c/M_1}{1 + 2M_e/(M_2\alpha_{CE}\lambda r_L)}, \quad (4)$$

where A_i and A_f are respectively the orbital separation distances at the end of the pre-CE phase and at the beginning of the post-CE phase, M_c and M_e are respectively the core and envelope masses of the primary star, α_{CE} and λ are respectively the common envelope ejection efficiency and the nondimensional binding energy parameter, and r_L is the Roche radius of the lobe in A_i .

The value of α_{CE} is usually 1 in binary star evolution simulation works (e.g. Davis in [15]). which means that the gravitational potential resulting from the orbital contraction process in the CE is used entirely to eject envelope material. De Kool in [16] also argued that $\alpha_{CE} = 1$ is in a good agreement with the observed population. However, several recent studies have shown evidence that α_{CE} is suggested to be smaller. For example, Toonen and Nelemans in [17] present the

effects of common envelope parameters on the post-CE binary star population and show that smaller α_{CE} gives a longer period population on average. For our simulation in this study, the value of $\alpha_{\text{CE}} = 0.5$ was used. Meanwhile, the value of λ used was assumed to be 0.5, a common value used in binary star evolution. Other parameters were obtained from the results of pre-CE phase simulation.

3.2.3 Post-CE Simulation

The simulation is continued by reloading the secondary star model from the last model of the pre-CE phase simulation. The secondary star is paired with a point mass assumed to be the WD. The initial separation distance of this simulation is the value of A_f obtained from the calculation of Eq. (4). The mass of the WD is obtained from the core mass of the primary star at the end of the pre-CE phase. The simulation runs until the mass of the secondary star is too small ($0.1 M_{\odot}$).

3.2.4 Mass Loss in WDs

WDs in CVs do not simply gain mass due to mass transfer from secondary stars. McAllister, *et al.* in [10] found no evidence of significant WD mass gain due to mass transfer. According to Prialnik & Kovetz in [18], mass loss in CVs is due to many factors such as strong wind and novae explosion cycles. With MESA binary by Paxton, *et al.* in [4], we can get around this with the transfer efficiency parameters. Suppose that the efficiency of 1 means that every materials being tranfered to the WD. It can be subtracted by a fraction of mass lost from the vicinity of the WD as β . In our study, we use $\beta = 0.9$ which means materials that tranfered to the WD will loss 90% of it.

3.3 Building the Population Synthesis

In this section, we outline a proposed methodology for generating a synthetic cataclysmic variable (CV) population based on an initial set of parameters generated through statistical distributions of stellar masses, orbital periods, and mass ratios. Although we have not yet implemented this stage of the project, the methodology provides a framework for synthesizing a population that can be calibrated to observational data. The main steps involve generating distributions for M_1 , P , and mass ratio $q = M_1/M_2$ based on recent initial mass function (IMF) and binary population studies, and then using these distributions in conjunction with a stellar formation rate over time to create a synthetic population.

3.3.1 Initial Mass Function

To create a distribution of M_1 we propose using the IMF developed by Kirkpatrick, *et al.* in [19], which shows strong agreement with previous well-established IMFs, such as by Salpeter in [20]. The IMF $\xi(M_1)$ is as follow:

$$\begin{aligned}\xi(M_1) &= 0.0150(M_1)^{-2.30}, \text{ for } 0.55 < M_1 < 8.00 \text{ M}_\odot \\ &= 0.0273(M_1)^{-1.30}, \text{ for } 0.22 < M_1 < 0.55 \text{ M}_\odot \\ &= 0.1340(M_1)^{-0.25}, \text{ for } 0.05 < M_1 < 0.22 \text{ M}_\odot \\ &= 0.0469(M_1)^{-0.60}, \text{ for } 0.01 < M_1 < 0.05 \text{ M}_\odot.\end{aligned}\tag{5}$$

We can extrapolate the IMF beyond 8 and 0.01 $\text{M}_\odot$. The IMF accurately reflects the distribution of stellar masses across the mass range relevant to CV progenitors. To generate a random set of parameters, we can sample from this distribution using inverse transform sampling method. Given that the IMF shapes the number of stars formed at different masses, the mass distribution plays a critical role in determining the fraction of stars that evolve into CVs.

3.3.2 Orbital Period and Mass Ratio Distributions

For the distributions of orbital period P and mass ratio $q = M_2/M_1$, we adopt the statistical analysis conducted by Moe and Di Stefano in [21] (see their Figure 2, Figure 35, Figure 37, and Table 13), who provide a comprehensive distribution for binary star properties. Moe, *et al.* derived empirical distributions for the periods and mass ratios of binary systems, which we use to generate a random set of P and q parameters in the synthetic CV population. The orbital period distribution is crucial for determining the likelihood of mass transfer and interaction phases (e.g. CE phase) in binary evolution.

3.3.3 Stellar Formation Rate and Age Distribution

The stellar formation rate (SFR), which represents the total mass of stars formed per unit time, is incorporated to account for the evolving star formation history of the Milky Way. We adopt the SFR over ten time intervals spanning the galaxy's history (~ 14 billion years), based on the findings of Fantin, *et al.* in [22] (see their Figure 9). The total stellar mass per time window is allocated to the IMF established in Section 3.3.1 to ensure consistency with the observed stellar mass distribution in the Milky Way over time. To filter out single stars, we apply the total multiplicity frequency from Moe and Di Stefano in [21] (see their Figure 38 and Table 13) and retain only the stars that form binaries. Each binary receives an age based on its formation time within the 10 time windows, enabling us to track the age distribution of CV progenitors across the galaxy's history.

3.3.4 Parameter Assembly and Interpolation with Simulation Output

Once the M_1 and age parameters are established, we combine them with the P and q distributions to generate a complete parameter set of synthetic CV progenitor systems. This parameter set represents a grid of initial conditions that map directly onto the MESA simulation outputs generated in Section 3.2. Finally, we will interpolate the MESA simulation data based on this parameter set to construct a synthetic population of CVs. This interpolation step involves matching the generated grid with the evolutionary tracks from MESA to simulate how each progenitor system evolves under its specific initial conditions. This approach allows us to give synthetic observable properties of the CV population today, facilitating a meaningful comparison with observational data.

4 Preliminary Result and Discussion

Our preliminary MESA binary grid simulations yielded a range of evolutionary outcomes for different M_1 as shown in Figure 2. These outcomes underscore the diversity of binary evolution pathways and highlight some of the limitations in generating CVs across a broad parameter space. The primary outcomes observed include standard CV evolution, systems avoiding RLOF, merged binaries, systems with a larger companion mass than the WD, double WD systems, and cases where MESA failed to converge. We designate these outcomes as follows:

1. **Standard:** In systems with $M_1 = 1 - 1.3 M_\odot$ a significant fraction of binaries followed the standard CV evolutionary path. These systems entered RLOF and CE phases, thus resulting in WDs with masses larger than their companions.
2. **No RLOF:** Some models ended as long-period WD + main-sequence binaries. This outcome occurred when the evolutionary expansion of the WD progenitor star did not reach its Roche lobe radius R_L due to initially long orbital periods, thus preventing the model from entering the RLOF and CE phases.
3. **Merge:** A large fraction of models merged following the CE phase. According to Eq. (4), a higher M_1 leads to a smaller post-CE orbital separation A_f , thus resulting in mergers for models with larger M_1 .
4. **Very Low WD:** A small subset of models produced WD progenitors with core masses less than $0.1 M_\odot$, thus leading to the formation of very low-mass WDs.
5. **Comp. Larger:** In some models, the companion star ended with a mass $M_2 > M_{WD}$. As discussed in Section 2, such a configuration often results in non-CV binaries.

6. **Double WD:** Some models had A_f that remained relatively large. This prevented the maximum evolutionary expansion of the companion star from reaching the post-CE R_L , thus resulting in a second WD forming from the companion.
7. **MESA Failure:** MESA encountered difficulties in forming certain models at the pre-main-sequence stage. In particular, models with $M_1 = 1.7 M_\odot$ failed to form within the MESA simulation.

To extend these simulation results into a population synthesis model, we will incorporate statistical distributions representing the properties of stellar populations. Specifically, we plan to apply method in the Section 3.2. However, as we only find a small fraction of models that followed the standard CV evolutionary path, we haven't taken it to the next stage yet.

The results provide a large portion of the "Merge" model at $M_1 > 1.3 M_\odot$. If we look at Figure 1, a WD progenitor star with a mass of about $1-2 M_\odot$ will only produce a WD with a mass of $<0.5 M_\odot$. This is in contrast to the mean value of the WD mass in the CV derived through observations of $\sim 0.8 M_\odot$ by McAllister, *et al.* in [10]. These results also suggest a small A_f . In Eq. (4), A_f could be larger if M_c and α_{CE} were larger. In the previous simulation, we used the default definition of the core from MESA (Paxton, *et al.* in [3]), which states that the core boundary is where the hydrogen mass fraction is 0.01. If this value is enlarged, we can get a larger core mass. This is still in the object of various studies (e.g. Hall and Tout in [23]). Meanwhile, the value of α_{CE} could possibly use a larger number. However, as mentioned in Section 3.2.2, the smaller α_{CE} value actually gives results that are closer to observations.

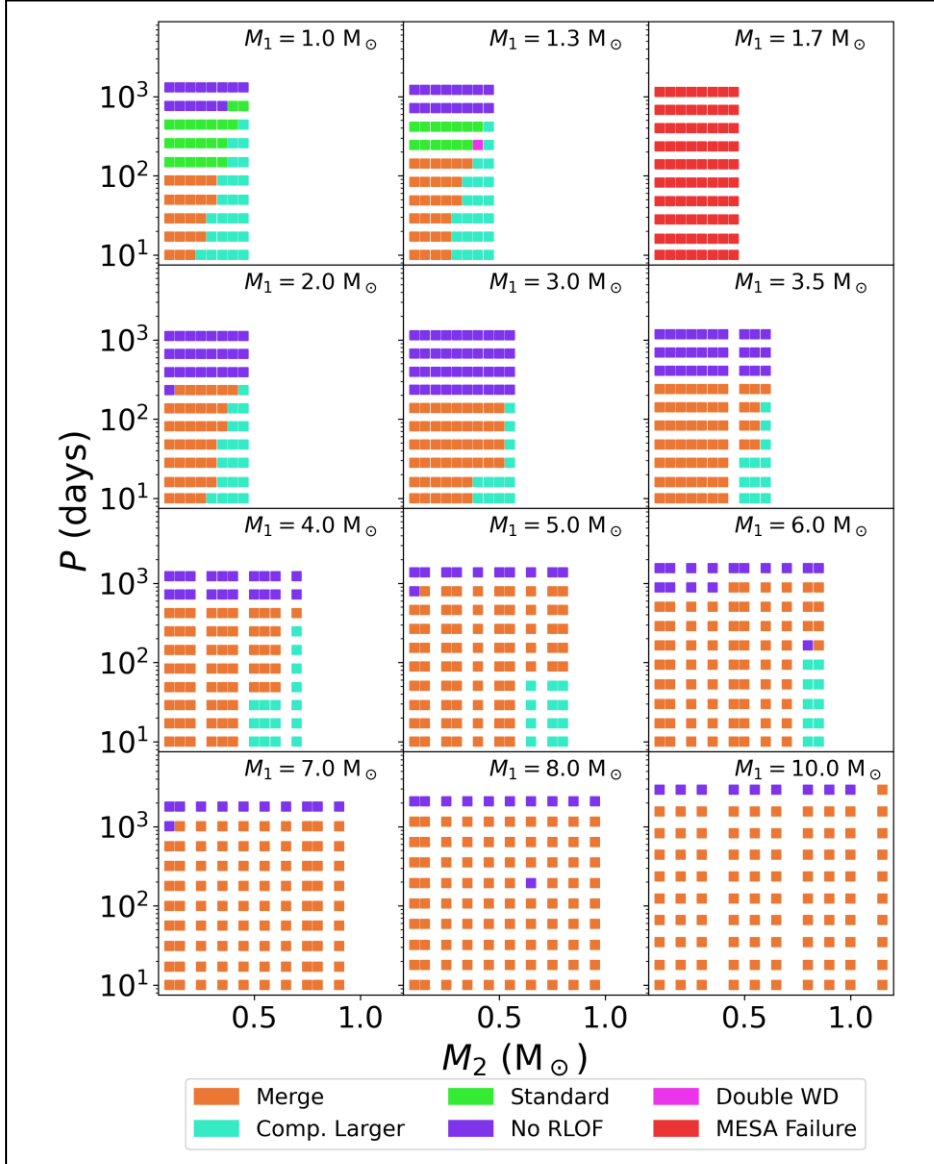


Figure 2 Evolutionary outcomes of binary systems with varying M_1 . The grid displays distinct evolutionary paths, including mergers, standard CV evolution, non-RLOF binaries, double WD systems, and MESA failures.

5 Conclusion

This study presents a methodology for synthesizing CV populations using the MESA stellar evolution code. By constructing a grid of initial binary parameters and simulating their evolution through pre- and post-CE phases, we aim to gather insights in creating a realistic model of CV formation. Our preliminary results highlight the diverse evolutionary pathways of binary systems, revealing outcomes such as mergers, double WD, and systems that bypass RLOF entirely, in addition to the standard CV evolutionary path. While a significant fraction of our simulated systems with lower-mass WD progenitors ($1.0\text{--}1.3\text{ M}_{\odot}$) follow the expected CV evolutionary track, higher-mass progenitors frequently lead to mergers. This emphasizes the importance of accurate common envelope modeling and the need for further investigation into the parameters governing this phase, especially the common envelope efficiency parameter α_{CE} . Furthermore, the discrepancy between the predicted WD masses from our simulations and those observed necessitates a re-evaluation of the core mass definition used within MESA and further investigation into mass loss mechanisms in the CE phase. Future work will focus on incorporating statistical distributions for initial binary parameters, such as the initial mass function, orbital period distribution, and mass ratio distribution, to generate a synthetic population that can be directly compared with observations. This refined population synthesis model, informed by detailed MESA simulations, promises a more comprehensive understanding of CV evolution and will contribute to resolving the existing discrepancies between theoretical predictions and observational data, and also exploring a wider range of α_{CE} and a refined core boundary definition in the CE phase.

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