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# The Dynamical Evolution of Circumbinary Planets Around Interacting Binaries

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**ABSTRACT**
This study presents a script developed to seamlessly integrate binary evolution data from the stellar evolution code `MESA` into the N-body simulation code `REBOUND`. This integration framework enables a comprehensive examination of the dynamical evolution of circumbinary planets orbiting interacting binary systems. We construct a reference binary model and introduce a recalibration method to mitigate errors from updates of binary properties during dynamical computations. Our findings reveal that, in the reference model, the nearest stable orbital separation for circumbinary planets is roughly 2.5 times the binary separation after mass transfer. We implement tidal effects within the `REBOUNDx` library, adapting parameters based on changing stellar structure. Notably, tidal effects have minimal impact on planetary dynamical evolution in our simulation. This research provides a valuable framework for exploring circumbinary planet dynamics in interacting binary systems.

**Key words:** orbital dynamics, circumbinary planets, binary stars

## 1 INTRODUCTION

The existence of circumbinary planets (CBPs) offers valuable insights into the underlying physics involved in planet formation and the dynamical evolution of planetary systems. After the discovery of the first CBP Kepler-16 b (Doyle et al. 2011), a series of CBPs have been reported from `Kepler` (Borucki et al. 2010) and `TESS` mission. About 10 of them are around binary systems containing an evolved star such as a white dwarf or a subdwarf, which are suggested to be post-common envelope binaries Pulley et al. (2022). These binaries are implied to have experienced a dramatic mass transfer episode and a subsequent unstable mass transfer triggering a common envelope (CE) phase. The binaries that survive the CE phase will eject the CE and undergo a significant orbital shrinkage. How CBPs form and evolve in such evolved binaries are still not clear. The recently suggested existence of a possible hot Jupiter around the subdwarf and M-dwarf binary Kepler 451 (Esmer et al. 2022) challenges further our understanding of planet formation and dynamics in the context of binary interactions.

Given the advancements in ongoing and forthcoming surveys and instruments that seek planetary systems across diverse host systems, we expect to discover an escalating number of CBPs around various binary systems. It is becoming increasingly urgent to explore the planetary dynamics in conjunction with interacting binaries in a more general way. How the CBPs behave amid binary interactions is a crucial point to fully understand such intricate systems. Compared with CE evolution, the process of stable mass transfer stands out as a more fundamental process in binary evolution, bolstered by a more comprehensive understanding. In light of this, it is both important and intriguing to investigate the dynamical stability of planetary systems around binaries that undergoes stable mass transfer process.

To accurately simulate the binary evolution, we adopt the state-of-the-art, open-source stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA, Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023). In `MESA`, we can calculate mass transfer self-consistently considering the rotation of the stars and adopt sophisticated stellar winds models and tidal prescriptions all along the binary evolution. For the dynamical evolution of CBPs, we use the high-performance N-body simulation code REBOUND (Rein & Liu 2012). In this study, we aim to build an integrated module coupling `MESA` and `REBOUND`, serving as a tool for the study of the dynamical evolution of CBPs involving accurate calculation of binary evolution. It is the first attempt to include detailed binary evolution in the framework of dynamical N-body simulations.

## 2 MESA BINARY MODEL

To construct the binary evolution model with `MESA`, we adopt the `MESA` setup in `POSYDON` framework (Fragos et al. 2023). This framework, a recently developed platform for binary population synthesis, is built upon extensive binary models with `MESA`, containing one of

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the latest MESA configuration for binary evolution. In the configuration, the MESA Dutch scheme is used for the stellar wind prescription with modifications related to stellar state and surface temperature (see Sec.3.2.2 of Fragos et al. 2023). Tidal effect is treated following the linear approach by calculating the synchronization timescale, distinguishing radiative and convective layers (Hut 1981; Hurley et al. 2002; Qin et al. 2018). To calculate the mass-loss rate resulting from Roche-lobe overflow mass transfer, the Kolb scheme (Kolb & Ritter 1990) within MESA is used when the donor has left the main sequence (MS) with an extended envelope. The transferred material carrying the specific angular momentum based on de Mink et al. (2013, see Appendix A.3.3) is accreted by the accretor. Then, if the accretor reaches critical rotation, the accretion is capped and the material leaves the star in the form of boosted implicit winds. In this scenario, a small amount of mass accreted can spin up the accretor significantly and the mass transfer is highly non-conservative for typical case-B mass transfer.

The reference binary model we compute has a donor star of $M_1 = 2.21\,M_\odot$, mass ratio of $q = M_2/M_1 = 0.8$, and an initial orbital period of 6 d in a circular orbit. Figure 1 shows the evolution of the radii and the absolute values of mass change rates as a function of the time for both stars. After leaving the MS, the donor expands gradually and fills the Roche lobe at around 532.3 Myr, initiating a fast mass transfer phase. The mass transfer rate reaches the maximum of $\sim 10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$ at about 532.9 Myr. Then, the binary enters a slow mass transfer phase with a mass transfer rate of $\sim 10^{-8} - 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$, lasting about 6 Myr. At the beginning of the mass transfer phase, the accretor accepts all the material from the donor. In a short period of time, the accretor is spun up and the accretion rate drops quickly. After the mass transfer process, the donor's hydrogen envelope is stripped and it shrinks significantly, becoming a subdwarf. Figure 2 shows the evolution of the masses and the binary separation. The donor mass changes from 2.21 $M_\odot$ to $\sim 0.47\,M_\odot$ and the accretor accretes $\sim 0.04\,M_\odot$. Through the mass transfer phase, the binary separation increases from $\sim 0.10$ AU to $\sim 0.33$ AU.

## 3 COUPLING OF MESA AND REBOUND

To build up circumbinary planet systems in REBOUND, we first add two stars with the same properties as the MESA binary properties at the time we start to trace the dynamical evolution of the planets. Then, we add planets that can be described by the mass, radius, and orbital elements. We use the WHFast integrator, which is a second order symplectic Wisdom Holman integrator (Rein & Tamayo 2015), with a fixed timestep of $10^{-3}$ yr by default to calculate the dynamical evolution of the planets. Throughout the calculation process, as the properties of the central binary are determined directly by MESA including masses, radii, and orbital separation, it is imperative to synchronize and refresh these parameters for the central binary in REBOUND in a proper way. In cases where the binary exists in a stable state, it is feasible to update the binary properties at a low frequency. In contrast, when the binary is experiencing dramatic changes, such as during a rapid mass transfer phase, a reduction in the time interval for the updates becomes essential. In MESA, its adaptive timesteps are governed by multiple factors, following the trend that the timesteps decrease when the systems exhibit notable and significant changes. It is natural to adopt the time series from MESA history as the time points to update the binary properties. However, this approach is insufficient because it would introduce systematic errors in the cases where the binary state changes substantially within a single MESA timestep. Thus, we introduce an input parameter defined as the change of the quantity within one MESA timestep to further adjust the timesteps for the updates. Before modifying the timesteps, we linearly interpolate all the binary properties preparing for the generation of a new set of MESA binary history. During mass transfer, the most rapidly changing parameter is the donor mass. As a result, we monitor the change of the donor mass $\Delta M_1$ for the mass transfer phase. If $\Delta M_1$ is larger than a specific threshold, we split this particular step evenly into a greater number of smaller intervals to ensure that $\Delta M_1$ for a single new timestep is below the threshold. In this way, we generate a revised sequence of binary properties, predetermined by the interpolated MESA binary history data, along with re-calibrated time intervals, in preparation for the subsequent computation of planetary dynamics.

In order to obtain an appropriate threshold for $\Delta M_1$, a convergence test is conducted by exploring different limits of $\Delta M_1$. We consider a simplified model where the only circumbinary planet is a test particle with an initial separation of 1 AU from the center of the mass in a circular orbit. We adopt five thresholds for $\Delta M_1$, ranging from $10^{-2}\,M_\odot$ to $10^{-6}\,M_\odot$, spaced apart by one order of magnitude. We calculate the orbital evolution of the planet from about 2 Myr prior to the mass transfer phase to the end of the slow mass transfer phase. Figure 3 shows the evolution of the semi-major axis of the planets $a_\mathrm{p}$ under different thresholds for $\Delta M_1$ through the binary mass transfer phase. Above $10^{-3}\,M_\odot$, we find unexpected fluctuations and large deviations from other tracks, indicating large errors. The values of $10^{-4}\,M_\odot$ and $10^{-5}\,M_\odot$ lead to similar final $a_\mathrm{p}$. However, with a further reduction to $10^{-6}\,M_\odot$, the evolutionary track diverges, deviating from convergence. To verify our calculation and to find out a suitable threshold for $\Delta M_1$, we do an analytical calculation for the planet's orbit. In this case, the distance between the planet and the binary exceeds the binary separation by a considerable degree, which enables us to treat the binary as a single object. Consequently, the mass loss resulting from the binary mass transfer process can be seen as the wind loss from a single star. The black dotted line in Figure 3 shows the semi-major axis evolution of the planets because of the mass loss of the central object. The analytical calculation aligns most closely with the case of $10^{-5}\,M_\odot$, resulting in a comparable final $a_\mathrm{p}$. In the case of $10^{-6}\,M_\odot$, the newly determined time intervals for MESA seem too small to allow the integrator stabilizing the planet's orbit. The errors accumulate through the too frequent updates of the binary properties, leading to an excess of $a_\mathrm{p}$. As a result, we adopt $10^{-5}\,M_\odot$ as the threshold for $\Delta M_1$ through the mass transfer phase in our calculation.

## 4 EVOLUTION OF A SINGLE CIRCUMBINARY PLANET

With the binary evolution integrated in REBOUND, we are able to calculate the dynamical evolution of a single circumbinary planet through the mass transfer phase. We consider a Jupiter-like planet in a circular orbit starting from 1 Myr prior to the onset of mass transfer and progressing through the mass transfer phase. The initial separations for the planet and the center of the mass are from 0.2 AU to 0.45 AU, spacing apart by 0.05 AU, and from 0.5 AU to 1.0 AU with a step size of 0.1 AU. Figure 4 shows the evolution of $a_\mathrm{p}$ for Jupiter-like planets with different initial separations. The black dashed line indicates the separation of the central binary stars. We can see that the planets with initial $a_\mathrm{p}$ below about 0.3 AU are dominated by the gravitational forces of the central binary. In the case of 0.35 AU, the planet exhibits instability and moves inwards before the dramatic mass loss of the binary. The planet's orbit expands rapidly during the fast mass transfer phase, and then in the course of the

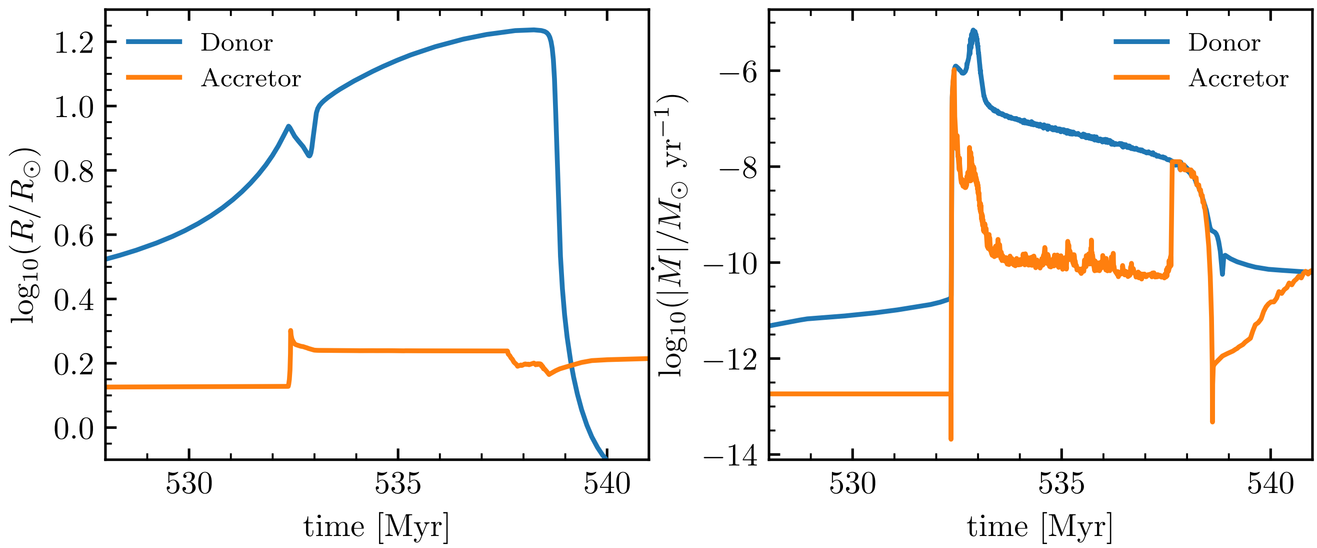


**Figure 1.** Evolution of binary stars' radii and the absolute values of mass change rates during the mass transfer phase. The blue and orange lines indicate the donor and the accretor, respectively.

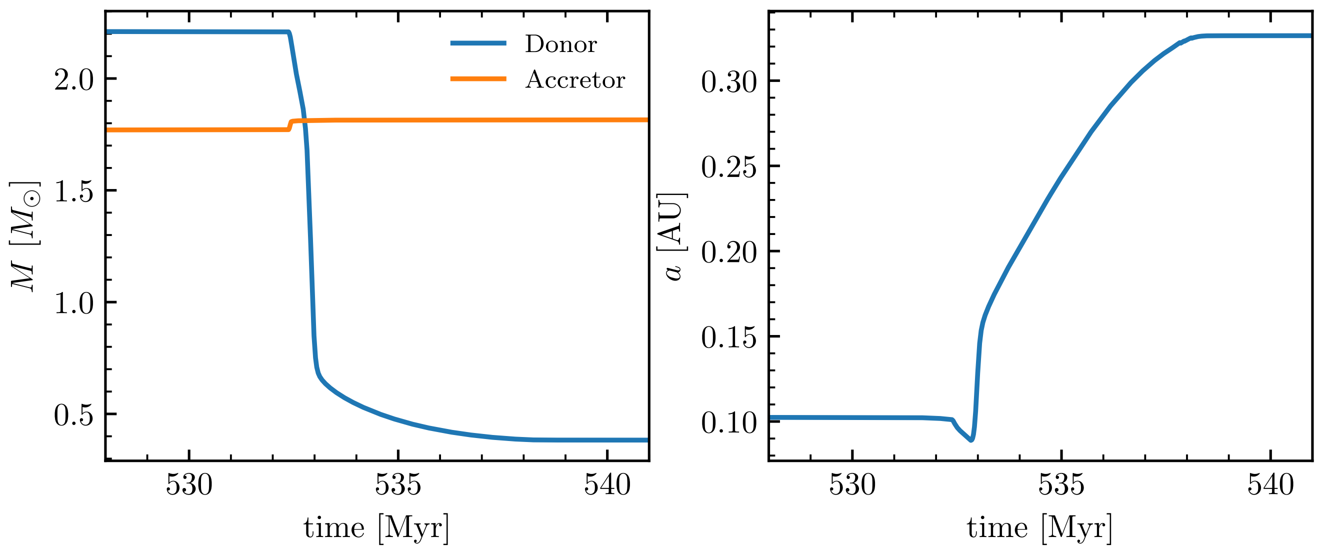


**Figure 2.** Evolution of binary stars' masses and the binary separation.

slow mass transfer phase, the orbit of the planet displays intensified oscillations as the binary separation gradually increases. Eventually, in the midst of the slow mass transfer phase, the planet is engulfed by the binary. The planet with initial separation of 0.4 AU also survives the fast mass transfer phase and got engulfed in the subsequent slow mass transfer phase due to an escalation in orbital instability. The rest of the planets originally situated at a separation above 0.4 AU survive the whole mass transfer process. They all experience an rapidly accelerating orbital expansion as the mass transfer rate attains its maximum, followed by a decelerated expansion during the subsequent phase of slow mass transfer. The nearest stable orbit locates at around 0.85 AU, 2.5 times the binary separation after the mass transfer phase. As the planets being farther away from the central binary, the oscillations of the orbit gradually diminish in intensity in the late slow mass transfer phase.

## 5 TIDES

In the region where the planets' semi-major axis is not significantly larger than the binary separation, it is essential to consider the tidal effects on the planets. We apply the prescription in Lu et al. (2023), where they implement self-consistent spin, tidal, and dynamical equations of motion in the `REBOUNDx` framework (Tamayo et al. 2020). The tidal prescription is based on the approach in Eggleton et al. (1998), considering the acceleration from the quadrupolar distortion:

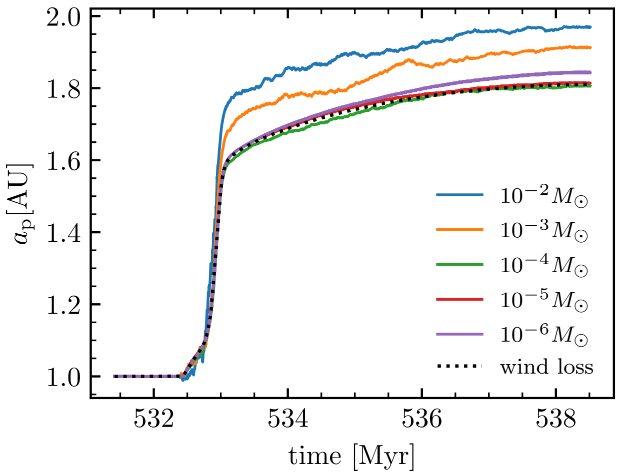


**Figure 3.** Evolution of the semi-major axis of the planets with different thresholds for the donor mass change within a single MESA timestep. The dotted line indicates the orbital evolution due to mass loss from the central object.

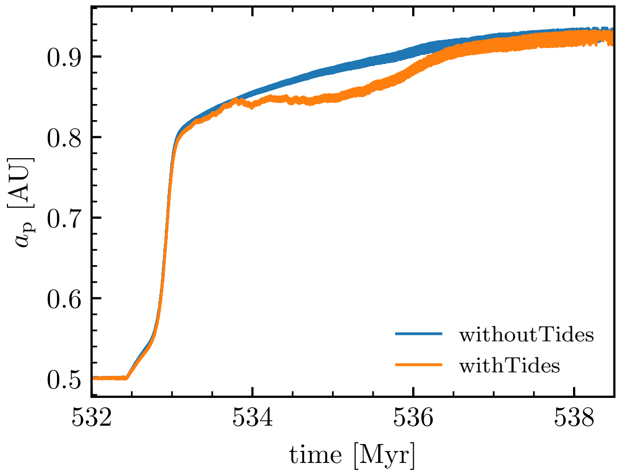


**Figure 5.** Evolution of the semi-major axis for a Jupiter-like planet, initially initially situated at a separation 0.5 AU, both with and without the inclusion of tidal effects.

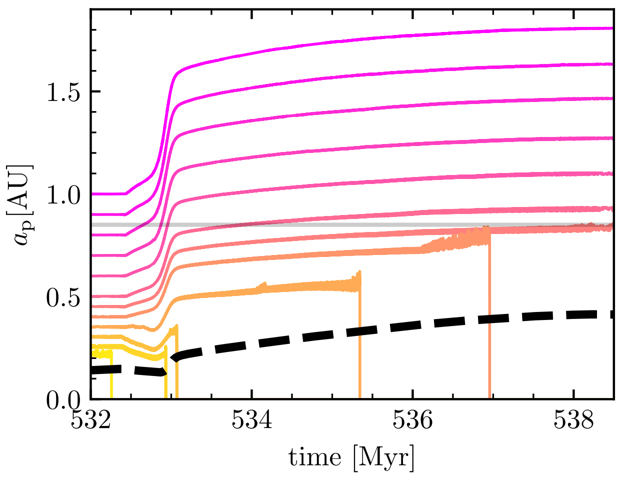


**Figure 4.** Evolution of the semi-major axis for the Jupiter-like planets with different initial separations.

$$\boldsymbol{f}_{\rm QD,1} = r_1^5 k_{\rm L,1}(1+\frac{m_2}{m_1})\cdot[\frac{5(\boldsymbol{\Omega}_1\cdot\boldsymbol{d})^2\boldsymbol{d}}{2d^7} - \frac{\Omega_1^2\boldsymbol{d}}{2d^5} - \frac{(\boldsymbol{\Omega}_1\cdot\boldsymbol{d})\boldsymbol{\Omega}_1}{d^5} - \frac{6Gm_2\boldsymbol{d}}{d^8}], \tag{1}$$

and the acceleration from tidal damping:

$$\boldsymbol{f}_{\rm TF,1} = -\frac{9\sigma_1 k_{\rm L,1}^2 r_1^{10}}{2d^{10}}(m_2+\frac{m_2^2}{m_1})\cdot[3\boldsymbol{d}(\boldsymbol{d}\cdot\dot{\boldsymbol{d}})+(\boldsymbol{d}\times\dot{\boldsymbol{d}}-\boldsymbol{\Omega}_1 d^2)\times\boldsymbol{d}], \tag{2}$$

where $r_1$ is the radius of object 1, $k_{\rm L,1}$ denotes the Love number of object 1 , while $m_1$ and $m_2$ are the masses of object 1 and object 2, respectively. $\Omega_1$ represents the angular velocity of object 1, assuming uniform rotation, and $\sigma_1$ is the dissipation constant of object 1. The parameter $d$ denotes the distance between the two objects, and $G$ is the gravitational constant. In our calculation, the binary stars experience a mass transfer process that can significantly alter the properties of the stars, especially for the donor. As a result, it is imperative to get the correct parameters in the equation above at different stages. For the stars, we have the stellar profiles provided by MESA, allowing us to calculate all the parameters self-consistently. The Love number is two times the apsidal motion constant $k$, which can be calculated with the relation (Sterne 1939):

$$k = \frac{3-\eta_2}{4+2\eta_2}. \tag{3}$$

$\eta_2$ is a function of the radius $r$ that can be obtained from the equation (Sterne 1939):

$$r\frac{d\eta_2}{dr} + \eta_2(1-\eta_2) + 6\frac{\rho}{\overline{\rho}}(\eta_2+1) - 6 = 0, \tag{4}$$

where $\rho$ is the density at $r$ and $\overline{\rho}$ is the mean density interior to $r$. We save the density profiles of the stars every ten steps in MESA to calculate $\eta_2$ and then the Love numbers. Afterwards, we perform linear interpolation to find the evolution of the Love number for both stars. As for the dissipation constant, it is connected with the Love number and the lag time $\tau$ Lu et al. (2023):

$$\sigma_1 = \frac{3r_1^5 k_{L,1}}{4G\tau_1}. \tag{5}$$

The lag time is related to the typical tidal timescale $T$, defined in Hut (1981):

$$T_1 = \frac{r_1^3}{Gm_1\tau_1}. \tag{6}$$

Then, we follow the same method in POSYDON configuration to calculate the quantity $k/T$ (see Sec.4.1 in Fragos et al. 2023) to get access to all the parameters involved in the calculation of tides for the stars. For the Jupiter-like planet, we adopt a typical $k_L$ of 0.565. As for the dissipation constant , we use the simplified assumption $Q^{-1} \sim 2n\tau$ (Lu et al. 2023) and set $Q = 10^4$ to calculate $\tau$ and hence $\sigma$, where $Q$ is the specific dissipation function (Goldreich 1963) and $n$ is the orbital mean motion.

The tidal forces between the planet and two stars are performed separately. We update the stellar properties involved in the calculation of tidal effects with the newly generated MESA time series. We ignore the tidal influence of the planet on the stars' spins as the effects between the stars themselves are predominant, which are accounted for in the `MESA` simulation. In Figure 5, we show the evolution of the semi-major axis of a Jupiter-like planet with an initial $a_{\rm p}$ of 0.5 AU, both with and without accounting for tides during the mass transfer phase. At the beginning of the simulation, although the planet is close to the stars, the Love number, dissipation constant and radius of the stars are at a low level, leading to a not noticeable impact on the planet's orbit. Then, the donor keeps expanding and the Love number increases to a high level. During the fast mass transfer phase, the mass loss from the binary system dominates the dynamical evolution of the planet. After entering slow mass transfer phase, despite the Love number initiates a decline, the donor continues to expand resulting in an amplification in the significance of tidal effects within the system. Then, as the donor being stripped, the tidal effects become less pronounced. Compared with the evolution without tides, the implementation of tides does not lead to a markedly different final position for the planet in this particular case.

## 6 SUMMARY AND DISCUSSION

In this project, we have developed a script designed to incorporate binary evolution data from the stellar evolution code `MESA` into the N-body simulation code `REBOUND`, which enables us to study the dynamical evolution of the circumbinary planets around interacting binaries. We construct a reference binary model using the `MESA` configuration in the binary population synthesis platform `POSYDON`. To mitigate the systematic errors originated from the alteration of binary parameters during the computation of planetary dynamical evolution, we introduce a method for re-calibrating the time sequence for updating `MESA` binary properties in REBOUND. We consider single Jupiter-like planets around the binary and calculate their dynamical evolution through the mass transfer phase. We find that the nearest stable orbital separation of the circumbinary planets is about 2.5 times the binary separation after the mass transfer phase in the reference model. To include tides, we apply the implementation of Lu et al. (2023) in the extended library `REBOUNDx`, adopting adaptive parameters for tidal effects based on the structure of the stars. The significance of tidal effects highly depends on the stellar structure, which undergoes substantial changes during the mass transfer phase. In the case of our simulation, tides lead to no significant differences in the planetary dynamical evolution.

In our reference model, the highest mass transfer rate is $\sim 10^{-5}\,M_\odot\,{\rm yr}^{-1}$. With the limit $\Delta M_1 = 10^{-5}\,M_\odot$, the minimal timestep for `MESA` is about 1 yr, which is still much larger than the timestep of the integrator for the dynamical evolution. The binary evolution can be seen as adiabatic in this case. As a result, the updates of binary data wound not lead to a loss of accuracy. If the change is too rapid, a finer time resolution or a more suitable integrator is required. For a different binary model, it is necessary to conduct a new test for the threshold of the changing parameter. In addition, we ignore the interaction between the planet and the lost material from the binary. It becomes more important when the mass loss occurs rapidly, such as when a common envelope evolution is initiated. This is beyond the scope of this study, which requires further investigation.

## ACKNOWLEDGMENTS

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## DATA AVAILABILITY

The scripts used to generate the data for this work can be requested to the author Zepei.Xing@unige.ch.

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