Triple common envelope evolution: Circumstellar triples

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ABSTRACT
The dynamical evolution of triple stellar systems could give rise to the formation of compact binaries and induce binary mergers. Common envelope (CE) evolution, which plays a major role in the evolution of compact binary systems, can similarly play a key role in the evolution of triples. Here we use hydrodynamical simulations coupled with few-body dynamics to provide the first detailed models of triple common envelope (TCE) evolution. We focus on the circumstellar case, where the envelope of an evolved giant engulfs a compact binary orbiting the giant (inner-binary), which then in-spirals into the core of the evolved star. Through our exploratory modeling we find several possible outcomes of such TCE: (1) The merger of the binary inside the third star’s envelope; (2) The binary disruption of the in-spiraling binary following its plunge, leading to a chaotic triple dynamics of the stellar-core and the two components of the former disrupted binary. The chaotic evolution typically leads to the in-spiral and merger of at least one of the former binary components with the core, and sometimes to the ejection of the second, or alternatively its further now-binary common-envelope evolution. The in-spiral in TCE leads to overall slower in-spiral, larger mass ejection and the production of more aspherical remnant, compared with a corresponding binary case of similar masses, due to the energy/momentum extraction from the inner-binary. We expect TCE to play a key role in producing various types of stellar-mergers and unique compact binary systems, and potentially induce transient electromagnetic and gravitational-wave sources.

Key words: stars: evolution – hydrodynamics – stars: mass-loss – (stars:) binaries (including multiple): close

1 INTRODUCTION
Triple systems are frequent among stellar systems, and in particular massive systems (e.g. Toonen et al. 2016; Moe & Di Stefano 2017, and references therein) and their evolution may lead to a wide variety of non-trivial and sometimes exotic outcomes. These include the formation of various types of compact stellar binaries\triples, stellar mergers, and the possible triggering of transient events (e.g. Eggleton & Verbunt 1986; Iben & Tutukov 1999; Ford et al. 2000; Soker 2004; Perets & Fabrycky 2009; Thompson 2011; Perets & Kratter 2012; Hamers et al. 2013; Naoz 2016; Di Stefano 2019). Although triple stellar systems had been extensively studied, the vast majority of the studies focused on the dynamical evolution of such systems; either through short-term dynamical evolution of unstable systems, or the longer-term secular evolution of triples (e.g. Valtonen & Karttunen 2006; Naoz 2016, and references therein). Few studies explored the implications of mass-loss and/or mass transfer in stellar triples (Iben & Tutukov 1999; Soker 2004; Perets & Kratter 2012; Shappee & Thompson 2013; de Vries et al. 2014; Michaely & Perets 2014; Stefano 2018; Portegies Zwart & Leigh 2019; see Toonen et al. 2016 for an overview), but a detailed modeling of the triple common envelope (TCE) phase, and in particular fully hydrodynamical simulations of this phase had not yet been explored, to the best of our knowledge, and are the focus of our study.

Binary common envelope (CE) results from an unstable Roche-lobe overflow in a binary system, most typically following the evolution of one of the binary components and the extension of its envelope during the red giant phase (RG). The binary components are thought to in-spiral inside the (now shared) CE, leading to the shrinkage of the orbit, on the expense of the outer envelope expansion and ejection. CE evolution (CEE) is believed to be one of the most important steps in the evolution of close binaries, providing an essential part in the formation of compact binaries and stellar mergers (Paczynski 1976; Izzard et al. 2012; Ivanova et al. 2013; Soker 2017, and references therein).

A circumstellar TCE occurs when a more-compact binary (hereafter the inner-binary, as it is termed in the context of hierarchical triples) orbits an evolved star which fills its Roche-lobe. Then, similarly to the binary CE case, if
the mass-transfer is unstable, a shared envelope is formed. The evolution in this case will be somewhat different due to the potential additional energy input from the inner binary system and/or the more complex and potentially chaotic dynamics of the (possibly unstable) triple. Moreover, the inner-binary’s internal motion and evolution could be affected by the interaction with the gas. As we discuss in the following, the outcome of such process can be a merger of the core with one or more of the companions, a merger of the inner binary, or a tidal disruption of the binary and the possible ejection of one of the stellar components. The different evolution could also induce a different structure of the remnant planetary nebulae around the resulting system (Soker et al. 1992).

A TCE could also involve a different, circumbinary configuration. In this case a binary CE is formed in a system with a distant third companion, i.e. the evolved star is now a part of an inner binary, orbited by an outer third component. The expansion of the envelope during the binary CE may then lead to engulfment of the third companion, and its potential in-spiral onto the binary in a TCE. Here we focus on the circumstellar case; the circumbinary case will be explored elsewhere.

The paper is structured as follows. We first describe our simulation methods in the following section. We then present our results (section 3) and possible outcomes of circumstellar TCE, discuss them in section 4, and summarize.

2 METHODS

In our models we simulate the dynamical evolution of an evolved triple system in which a binary system orbits a more massive red giant (which we term the circumstellar case). The giant’s envelope engulfs the binary, leading to the binary’s in-spiral into the giant envelope and producing a triple common envelope (TCE) configuration. For this purpose, we first modeled a red-giant star using the MESA 1D stellar evolution code (Paxton et al. 2011), and then mapped its density profile into a 3D model to be used in the hydrodynamical code GADGET2 (Springel 2005). After relaxing the star in the hydrodynamical code, we coupled the star to an outer-orbiting binary (the inner-binary; modeled as two point mass stars, unlike the fully hydro-modeled giant star, and coupled the hydro model with a higher resolution dynamical code).

We use the AMUSE - Astrophysical Multi-purpose Software Environment (Portegies Zwart et al. 2009) as a platform for coupling between several external codes used for the physical processes. In particular, we used MESA (Paxton et al. 2011), the stellar evolution code, in order to produce the initial profile of the RG star. The dynamics of the inner binary stars is modeled by the dynamical code HUAYNO (Pelupessy et al. 2012) which is a N-Body code, and the affect of the inner binary on the envelope is modeled by M16 (Fujii et al. 2007). In the following we provide a more detailed description of the different parts of our model.

2.1 Modeling the giant gaseous envelope and core

2.1.1 Stellar evolution

The initial giant model is created with the stellar code MESA (Paxton et al. 2011). We create the initial model simulating the stellar evolution of a star from the zero-age main sequence stage up to the red-giant stage. Here we explored cases where the giant reached its maximal radius (if it were to evolve in isolation) when the TCE stage ensues. We run MESA within the AMUSE framework which uses MESA-SDK. This allows us to better control the stopping condition by running the evolution step by step. Furthermore, the final model can then be simply coupled with the other few-body modeling components discussed above.

2.1.2 Smoothed Particle Hydrodynamics simulation

We use the GADGET2 (Springel 2005) smoothed-particle hydrodynamics (SPH) for the hydro-dynamical modeling. The SPH method works by dividing the fluid into a set of discrete elements, referred to as particles. These particles have a spatial distance, termed the “smoothing length”, typically represented in equations by $h$, over which their properties are “smoothed” by a kernel function. This means that the physical quantity of any particle can be obtained by summing the relevant properties of all the particles which lie within the range of the kernel, and the contribution of each particle is weighted according to its distance from the particle of interest.

In Gadget2, which we use, the kernel function is (Monaghan 1992):

$$W(r,h) = \frac{8}{\pi h^3} \begin{cases} 1 - 6 \left( \frac{r}{h} \right)^2 + 6 \left( \frac{r}{h} \right)^3 & 0 \leq r \leq \frac{h}{2} \\ 2 \left( 1 - \frac{r}{h} \right)^3 & \frac{h}{2} \leq r \leq h \\ 0 & h < r \end{cases}$$

where one should note that the smaller is the smoothing length, the smaller is the number of neighbors that should be taken into account for the calculation of each particle. Another important parameter is the softening length, which keeps the simulation from non-physical behavior at very small separations between particles. The gravitational potential is then

$$\phi = \frac{GM}{(\Delta r^2 + \epsilon^2)^{1/2}},$$

and in cases (like ours), where the simulation uses the softening length to smoothing the kernel, $\epsilon$ is effectively the radius of the point-mass particle.

2.1.3 Conversion of the stellar model into a SPH model

2.1.3.1 Mapping: The core of a giant star is much denser than its outer envelope, and is not resolved in our simulations. Our focus here is not on modeling physical mergers and interactions with the small and unresolved dense core, but rather exploring the interactions with the stellar envelope. We therefore represent the core in our simulations as a point mass particle without considering changes in its internal structure. We chose the softening length such that the potential of the core declines to 0 in $h = 2.8 \epsilon \approx 10 r_c$, where $r_c$ is the radius of the hydrogen exhausted core.
To convert the stellar model created by MESA into a 3D SPH model, we used AMUSE’s function Star_to_sph (Portegies Zwart & McMillan 2018). This function converts the core region into a point mass particle, and divides the gaseous envelope to our desired number of particles, with equal masses and different sizes. Each gas particle has its own gravitational potential and can interact with its surrounding, i.e. we use the Lagrangian form of the fluid equations of motion.

2.1.3.2 Relaxation: Following the mapping of the 1D model from MESA to 3D, and the use of somewhat different equation of state between the codes, a relaxation stage is required as to initiate a stable stellar configuration for the SPH model. In order to produce a stable configuration we first include the gravitational potential of the compact binary, but do not allow the binary to evolve (i.e. it is considered as a constant potential at this stage), where we follow the same approach as de Vries et al. (2014). During this stage, we keep the center of mass (COM) position and COM velocity constant; we adiabatically adjust the position and velocity of each SPH particle at each time step:

\[ r_{i,j} = (r_{i,j} - v_{COM,i}) + v_{COM,0} \]

\[ v_{i,j} = (v_{i,j} - v_{COM,i}) \cdot \text{step/steps} + v_{COM,0}. \]

until the particles positions and velocities converge, after a few dynamical times (we evolved the system up to 130 days).

Note that while taking the companion into account during the relaxation stage we shall place it far enough from the giant such that it won’t affect the giant’s shape too much, but still close enough so that the system will eventually enter the CE stage during the simulation time.

2.2 Coupling of the red-giant with the inner (point masses) binary

The motion of the system of the inner binary is a classical 2-body problem, which is perturbed by the gravitational potential of the core and the envelope of the giant star. In order to improve the model accuracy of the binary orbital evolution of our binary common envelope evolution effects on systems of similar masses and outer binary separations. In Fig. 1, we show the orbital evolution of binary common envelope evolution where the inner binary component in the TCE was replaced by a single star of the same total mass, as to compare, to some level, triple and binary common envelope evolution effects on systems of similar masses and outer binary separations. In Fig. 1, we show the orbital evolution of our binary common envelope evolution for two possible masses for the stars and the evolved companion at initial separation of 1 AU. The orange line corresponds the orbit of a binary system consisting of 2M\(_\odot\)giant with 1M\(_\odot\) companion at initial separation of 0.227 AU.

Finally, we also compared the results of a TCE with a binary common envelope evolution where the inner binary component in the TCE was replaced by a single star of the same total mass, mass-transfer dynamics in triple systems (but not a TCE phase).

2.3 Code bench-marking and resolution

In order to test our code, we first successfully reproduced the simulated evolution of previously studied binary common envelope and triple mass-transfer systems (Passy et al. 2012 and de Vries et al. 2014, respectively). We then ran several TCE models, at progressively higher resolution. We found that the use 250K SPH particles produced similar results compared with higher resolution simulations (500K) and we use this resolution throughout the models discussed below.

The duration of the relaxation stage and the CE stage were chosen to be larger than a dynamical time. After a few simulations using sink particles, accretion on the companion and core was found to be negligible compare to their mass, in an agreement with Passy et al. (2012). For that reason, we neglect any accretion effects. Some studies suggest feedback from accretion outflows/jet may affect the evolution (e.g. Sabach et al. 2017; Schreier et al. 2019; Soker 2020, and references therein); the potential importance of such effects, is still debated and are beyond the scope of the current study.

Finally, we also compared the results of a TCE with a binary common envelope evolution where the inner binary component in the TCE was replaced by a single star of the same total mass, mass-transfer dynamics in triple systems (but not a TCE phase).
The chaotic evolution can then lead to the merger of any two of the components, and the possible ejection of one of them from the system.

In Fig. 2 we compare the separations between the center of mass of the inner binary and the giant’s core for the configurations initialized with 0° orbital phase. All of our simulations of such initial zero-phase cases resulted in a core merger with one of the inner-binary components. This suggests that the evolution is sensitively dependent on the initial closest approach of the binary closer component. The phase, and hence the initial separation of the closest binary component to the giant determine the evolution of the in-spiral, its duration and timing of both the entrance to the rapid plunge-in phase as well as the initiation of the self regulating stage before merger. For binaries initialized with 90° inclination in respect to the orbit (orbital phase), both the stellar components are effectively initially at larger separations from the giant, and therefore show far weaker interaction at first, and required the extension of our simulation run times. Therefore, in such cases, we re-initialized these models and placed the inner binary closer to the edge of the envelope, at ~ 0.6AU. The results of this configuration can be seen in figure 3, where, similar to the low-inclination cases, the evolution of inner binaries with smaller separations lead to their mutual merger before the binary approached the core.

For the two different inclinations we considered, the in-spiral process lasts much longer for the more compact inner-binary. This is due to additional energy/momentum imparted to envelope by the inner-binary as its two components mutually in-spiral through their coupling to envelope (on top of the in-spiral of the inner-binary center of mass onto the RG core). In other words, the in-spiral of the inner binary provides an additional energy/momentum source term. The expansion of the CE is accelerated and its density decreases, consequently decreasing the dissipation and in-spiral of the inner-binary COM onto the RG core. Wider binaries show slower in-spiral thereby prove less efficient in exchanging the binary potential energy to the CE. In both inclinations, the shorter period inner binary resulted in an inner merger just shortly before merging with the core. In contrast, binaries with larger separation were eventually disrupted as they inspired close to the core.

In order to consider the sensitivity to the initial separation between the inner-binary and the giant we studied the differences between the simulations where the inner binaries where positioned at 1AU, and those initialized at 0.6AU. Figure 4 presents the results. We find that the inner binary significantly evolves in the 1 AU models before they even reach separations of 0.6 AU, and can even merge before reaching that point. In other words, it is critical to initialize the binaries sufficiently far from the giant core as to correctly follow their evolution, as significant evolution can happen even in the early in-spiral phases.

### 3 RESULTS

#### 3.1 TCE outcomes

We studied a limited grid (given the computational cost) of possible configurations, and considered two different mass ratios. The first grid is for a 8$M_\odot$ RG with two 1$M_\odot$ companions, where we varied the following parameters with two possible values for each parameter, and considered all the possible combinations for a total of 8 modeled configurations. These parameters include (1) the initial separations; (2) the relative inclination; and (3) the orbital phases (combined with additional an 90° orbital inclination); the models parameters are listed in table 1. In addition, we simulated 3 different inner separations for the second mass ratio of 2$M_\odot$ (RG) and 0.6$M_\odot + 0.4M_\odot$ companions. Overall we simulated 11 configurations for triple systems. As mentioned above we consider only circumstellar configurations where a more compact point-masses binary orbits an evolved star and in-spirals in its envelope. The summarized results of the evolutionary outcomes can be found in tables 3, 4, and 5.

Initially, the inner binary is located outside the stellar envelope of the red-giant. It then progressively in-spirals due to the interaction with the stellar envelope. Table 2 shows different snapshots of the density profile during the evolution of the CE of the first simulated scenario (8$M_\odot + 1M_\odot + 1M_\odot$ with 0° phase, inclination of 5° and inner distance of 26$R_\odot$). When the binary spirals into the envelope and forms a TCE, the spiral-in becomes more rapid, the envelope expands, and mass-loss ensues mostly through the second Lagrangian point. If we compare the last snapshots with the one of corresponding (same mass) binary system, the shape of the surrounding gas differs significantly between the two cases. The TCE case is far less symmetric than the binary CE case (see also Soker et al. 1992; Bear & Soker 2017 in this regard).

When comparing cases of inner-binaries with initially shorter and long periods we find that the more compact binaries we considered in-spiral more slowly than the corresponding models with longer periods (see figures 23). The former are more strongly bound, and are not disrupted as they in-spiral close to the giant core; rather we find that in such cases the inner binary components in-spiral and merge with each other before approaching the core. Conversely, the latter, wider inner binaries in-spiral into the giant core more rapidly, and are disrupted due to the interaction with the central potential, leading to a chaotic triple dynamics of the two (former) inner-binary components and the giant’s core.

### 3.2 Binaries vs. triples

The general differences between TCEs and binary CEs can be studied by comparing simulations of triple systems and...
Table 2. Common envelope evolution of an $8M_\odot$ giant with an envelope size of 0.5AU, orbited by an inner-binary composed of two $1M_\odot$ Main-Sequence stars initially positioned at 1AU. The left and right panels correspond to a face-on view (the inner binary moves on an anti-clock-wise orbit) and an edge-on view (the binary moves towards us), respectively. The components of the inner-binary are marked with white 'X' symbols, and the giant core is marked by a red 'X' symbol. The symbol sizes do not correspond to the stellar sizes and are just shown for clarity.

Figure 2. Evolution of the distance between the center of mass of the inner binary and the giant core for different initial conditions. The plunge-in phase begins earlier in low inclination cases, due to the effective closer initial distance of one of the companions to the giant core. A shorter inner separation extends the duration of the self regulating phase, because of the potential energy stored in the orbit, part of which is extracted by the gaseous envelope during the in-spiral, leading to further envelope extension and mass ejection, and thereby slowing the in-spiral onto the giant core.

Figure 3. Evolution of the distance between the inner binary and the core for systems with initial 90° phase-angle (moving towards the reader and both companions are initially at the same distance form the giant’s core).

Figure 4. The separations between the inner binary and the core for systems with a 90° phase, for both initial positions - at 1AU, and 0.6AU.

their corresponding binary systems, in which the inner binary is replaced by single star having the summed mass of the binary components, initially positioned at the COM of the original binary. Fig. 6 shows the comparison of the evolution of the separation between the giant core and the companion star/binary-COM. As can be seen, the TCE evolution extends longer than the binary CE evolution, although it appears that the evolution following the fast plunge-in
Figure 5. Comparison of the orbital evolution in a common envelope for triples with mass components $2M_{\odot} + 0.6M_{\odot} + 0.4M_{\odot}$ of different inner separations, and the CE evolution of the corresponding binaries of equivalent masses. The first companion is $0.6M_{\odot}$ compact object, whereas the second is $0.4M_{\odot}$.

Table 3. Results summary of $8M_{\odot} + 1M_{\odot} + 1M_{\odot}$ with $0^\circ$ phase. All models here are initialized with the inner binary located at a distance of 1AU from the giant core.

| Inclination | $a_{in}$ ($R_{\odot}$) | Merged components | Merger time (days) |
|-------------|------------------------|-------------------|-------------------|
| $5^\circ$   | 3                      | inner binary      | 706               |
| $5^\circ$   | 26                     | companion + core  | 289               |
| $45^\circ$  | 3                      | inner binary      | 760               |
| $45^\circ$  | 26                     | companion + core  | 475               |

Table 4. Results summary of $8M_{\odot} + 1M_{\odot} + 1M_{\odot}$ with $90^\circ$ phase. All models here are initialized with the inner binary located at a distance of 0.6AU from the giant core.

| Inclination | $a_{in}$ ($R_{\odot}$) | Merged components | Merger time (days) |
|-------------|------------------------|-------------------|-------------------|
| $5^\circ$   | 3                      | inner binary      | 75                |
| $5^\circ$   | 26                     | companion + core  | 544               |
| $45^\circ$  | 3                      | inner binary      | 5                 |
| $45^\circ$  | 26                     | companion + core  | 85                |

Table 5. Results summary of the models with $2M_{\odot} + 0.6M_{\odot} + 0.4M_{\odot}$ components, all with $0^\circ$ inclination and orbital phase. In both separations considered, no merger between any of the components occurs during the simulation. In the case of the small separation of $3R_{\odot}$ the inner binary merged very rapidly.

| $a_{in}$ ($R_{\odot}$) | Ejected component | Ejection velocity (km s$^{-1}$) |
|------------------------|-------------------|---------------------|
| 13                     | $0.6M_{\odot}$    | $\sim 82$          |
| 26                     | $0.4M_{\odot}$    | $\sim 120$         |

Figure 6. Comparison between the evolution of a triple system with $8M_{\odot}$ giant with $1M_{\odot} + 1M_{\odot}$ companions and a corresponding binary system, consisting of a companion which is the sum of the inner binary, the upper plot shows the complete orbit of the triple system, compared with the binary case (until both in-spiral down to the giant’s core). The bottom plot shows the separation between the binary companions and the center of mass of the inner giant. After the inner-binary breakup, the plot only follows the separation of the closer-in companion (yellow line).

is not significantly different. Similar conclusions can be obtained from Fig. 5.

4 DISCUSSION

Our results suggest TCE evolution in circumstellar configurations typically lead to either the merger of the inner binary before it approaches the core; or the excitation of the inner-binary orbit and eventually its disruption as it in-spirals closer to the core, leading to a chaotic triple dynamics involving all three components (the inner-binary components and the giant core), which are still embedded in the gaseous envelope. Following the chaotic evolution, the components of the disrupted binary can either mutually merge, one or both can merge with the core, or one of them may be ejected from the system. We briefly discuss each of these possibilities in the following.

As discussed above, the specific evolution of the TCE strongly depends on the triple configuration, including the inner and outer binary separations, the mutual inclination between the inner binary and its orbit around the giant, and masses of the components. We see that all of the parameters we investigated affected the triple common envelope process; its duration, the final result and even its observed shape. The results may have important implications for the formation and evolution of various types of compact binaries, their mergers and the possible electromagnetic and gravitational-wave transients they might produce.
4.1 Mergers

In our simulations, the exact nature of the inner-binary components was not prescribed, and they could potentially be either MS stars or compact objects. We briefly discuss some of the more unique outcomes that may potentially arise from such evolutionary scenarios.

The merger of two MS stars could leave behind a blue straggler. Formation of blue-stragglers in triples were explored by us and others before (Perets & Fabrycky 2009; Perets & Kratter 2012; Naoz & Fabrycky 2014), but following very different evolutionary scenarios, and giving rise to different outcomes. In particular, if the merged star does not merge with the core during the CE, the post-CE binary (formerly triple) would become a unique binary - a potentially short-period blue-straggler binary, with a likely He-WD companion (or He-CO hybrid WD; Zenati et al. 2019), a configuration which is difficult to explain through other evolutionary scenarios. Interestingly, a binary He/hybrid-WD - blue-stragglers might have already been observed (Gosnell et al. 2014).

If the inner-binary components are two white-dwarfs, the merger may leave behind a massive WD, that may later merge with the RG core during the CE, or survive and then potentially merge with the remnant of the RG core, likely a He-WD or hybrid He-CO WD (if they in-spiral through gravitational-wave emission). Such evolution might give rise to a type Ia supernova (Perets et al. 2019). Alternatively, the merger of the inner-binary WD might result in type Ia supernova - (see also Di Stefano 2019) or form a different type of star (e.g. Stefano 2018). In such cases, the supernova would occur while still embedded in the CE. The strong shock interaction with the envelope might produce a long-lasting and more luminous supernova, possibly also related to the recently suggested origin of superluminous supernovae from thermonuclear explosions inside a common envelope (Jerkstrand et al. 2020).

We note on passing, that in cases where the inner-binary is composed of neutron stars or black holes, a TCE could induce their merger, leading the production of gravitational-waves sources with unique signatures (e.g. somewhat similar to the cases of CE-induced gravitational-waves sources explored by us; Ginat et al. (2019)). However, the evolution of such massive components is not explored by our current models, and the study of whether a realistic evolutionary scenario can produce such cases is beyond the scope of the current work.

The result of a merger between one of the inner-binary components and the RG core, leaves behind the second component, which can then continue to a second CE phase. Such evolution will form a new star with a larger mass than the original core, but smaller than the initial evolved giant. The exact nature of such rejuvenated red-giant (or possibly a Thorne-Zytkow, Thorne & Zytkow 1977; in case a neutron-star in-spirals to the core) is yet to be explored.

We should also note that in a somewhat different scenario of a resulting binary system, a further accretion could occur from the inner gas with its new formed core, on the other companion, suggested to form an X-Ray binary by Eggleton & Verbunt (1986).

4.2 Ejections, runaway stars and single SdB stars

Due to the chaotic triple interaction between the inner-binary components and the RG core, one of the components might be ejected. Its typical velocity would be comparable to the orbital velocities at the point of the inner-binary disruption, which can be as high as a few tens or even 100 km s$^{-1}$. The TCE could therefore give rise to a novel channel for the production of runaway stars, albeit likely only in relative rare cases. If the RG core is ejected, it might be observed as a single sdB star. Interestingly, single sdB stars are difficult to explain as such stars are typically expected (and observed; e.g. Geier et al. 2008) to have a close-by companion which took part in their formation through stripping their envelope. Though TCEs are unlikely to explain a high frequency of single sdBs, the finding of runaway single sdBs could provide a potential smoking gun signatures for such processes.

4.3 Planetary nebulae

Shortly after the end of the self regulating phase, any of the observed system will consist of one or more compact objects, surrounded by the unbounded gas as a planetary nebula. As discussed above TCE could give rise to highly aspherical planetary nebulae, where the produced shape is not ellipsoidal as in post-CE binary cases (see also Soker et al. 1992; Bear & Soker 2017).

4.4 Mass loss

Hydrodynamical simulations of binary CEE show that only a fraction of the envelope mass is ejected, while the majority (typically 90-80%) remains bound; (e.g. Passy et al. 2012; Ricker & Taam 2012; Ivanova et al. 2013, 2015; Kurwuata et al. 2016; Ohlmann et al. 2016; Iaconi et al. 2017), posing a potential problem, given that post-CE binaries show no remnant ejecta. It was suggested that recombination energy can provide an additional energy source to drive the ejection of the envelope (Ivanova et al. 2015, and references therein). However, the fraction of the recombination energy lost to radiation is still debated (Soker & Harpaz 2003; Ivanova 2011; Clayton et al. 2017; Sabach et al. 2017; Grichener et al. 2018). Furthermore, it is unclear whether it can explain wide post-CE orbits (Ivanova et al. 2015). Others suggested that accretion energy mediated by jet/outflows may play a role (e.g. Shiber et al. 2019; Schreier et al. 2019, and references therein) or that dust formation inside the CE could drive winds and help to eject more material (Glanz & Perets 2018, and references therein) on longer timescales, with possible observational evidence for such long-term mass-loss (Michaely & Perets 2019; Igoshev et al. 2019). Our hydrodynamical simulations of a TCE evolution show that TCE also gives rise to inefficient mass-loss. However, as discussed above, the coupling of the binding energy of the inner-binary to the envelope provides and additional energy/momentum source and leads to a longer in-spiral timescale, and a much larger mass-loss from the TCE, compared with the corresponding binary CEE cases. In the longest-lasting in-spiral we find a mass loss of $\sim 27\%$, compared with only $\sim 8\%$ in the equivalent binary case. Moreover, our simulations terminate once two of the components merge, while the CE may
proceed afterwards, and therefore the TCE mas–loss fractions cited are only a lower-limit. Since only a fraction of CE cases involve triples, the more efficient TCE mass-losses can not generally solve the envelope-ejection problem, but the more significant mass-loss do show an additional qualitative difference in the TCE evolution compared to binary CEE.

5 SUMMARY

In this study we have made the first hydrodynamical modeling of a triple common envelope evolution in a circumstellar configuration, where a more compact binary (termed the inner-binary) orbits an evolved giant and eventually in-spirals into its envelope producing a TCE. We made use of the Gadget2 SPH code coupled to few-body codes using the AMUSE environment to combine the hydrodynamical aspects with the few-body dynamics involved. Given the computational expense we studied only a limited grid of models, serving as initial exploration of the sensitivity of the evolution to the initial orbital configurations, and the possible different outcomes of TCEs. We studied a total of 11 TCE models with different masses, inner-binary separations, orbital, relative inclinations and orbital phases. We also compared our models with corresponding binaries, where the inner-binary was replaced with a single component of the same total binary mass. We terminated the simulations once any two components merged during the simulation (the inner-binary components and/or the RG-core).

We find that the TCE evolution leads to both the mutual in-spiral of the inner-binary components, and their possible merger, as well as the in-spiral of the inner-binary towards the red-giant core. We find that the more compact inner-binary configurations result in the mutual merger of the inner-binary components before they approach the RG-core, while wider inner-binaries do not merge, but in-spiral to the core and are then disrupted by the RG inner-potential. In the latter case the (now unbound) inner-binary components and the RG-core evolve through a chaotic triple dynamics, while still embedded in the envelope, leading to the merger of at least two of these components, and the possible ejection of the third.

The inner-binary provides an additional energy/momentum source, and its coupling to the envelope gives rise to stronger expansion of the envelope and significantly larger mass-loss. Consequently, the envelope density decreases more rapidly, and the timescale for the in-spiral towards the core is extended in comparison to the binary models. In addition, this evolution lives behind a significantly more aspherical remnant than the binary case. We find that the specific evolution is sensitive to the initial configurations; but our models provide only a limited sample of the large phase space of triples, while a full characterization of the dependence is yet to be explored.

Our findings suggest that TCE can give rise to unique outcomes, and the possible production of peculiar blue-straggler binaries; unique gravitational-wave sources with gas-coupling dominated evolution (see also Ginat et al. 2019); potentially superluminous peculiar thermonuclear supernovae (due to explosions following WD mergers inside the TCE); short-GRBs from neutron-stars mergers inside a TCE and the production of gravitational-wave sources; runaway stars (and possibly runaway SdBs); and other exotic mergers and their potential transient outcomes. Predicting the rates and branching ratios for the rich phase space of TCEs is beyond the scope of our exploratory study; and should be explored in the future.

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