











# Dust formation during the interaction of binary stars by common envelope

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**Abstract.** We performed numerical simulations of the common envelope (CE) interaction between two intermediate-mass asymptotic giant branch (AGB) stars and their low-mass companions. For the first time, formation and growth of dust in the envelope is calculated explicitly. We find that the first dust grains appear as early as  $\sim 1\text{--}3$  yrs after the onset of the CE, and are smaller than grains formed later. As the simulations progress, a high-opacity dusty shell forms, resulting in the CE photosphere being up to an order of magnitude larger than it would be without the inclusion of dust. At the end of the simulations, the total dust yield is  $\sim 8.2 \times 10^{-3} M_{\odot}$  ( $\sim 2.2 \times 10^{-2} M_{\odot}$ ) for a CE with a  $1.7 M_{\odot}$  ( $3.7 M_{\odot}$ ) AGB star. Dust formation does not substantially lead to more mass unbinding or substantially alter the orbital evolution.

**Keywords.** stars: AGB and post-AGB, stars: winds, outflows, (stars:) binaries (including multiple): close

## 1. Introduction

Unstable mass transfer from an expanding, more massive star to a compact star leads to a CE interaction (Ivanova et al. 2013). The envelope of the giant eventually surrounds both the donor star's core and the companion. At the end of this phase, the envelope may be ejected and a binary system with a much smaller orbital separation or a merger is left behind.

The exact source(s) of energy driving the expansion and ejection of the envelope is not fully identified, and there are problems when considering only orbital energy and angular momentum transfer from the stars to the envelope (but see [Valsan et al. 2023](#)), although the work done by recombination energy released in inner layers of the donor likely plays a major role (e.g., [Ivanova et al. 2015](#); [Reichardt et al. 2020](#); [Lau et al. 2022](#)).

The CE interaction leads to the formation of systems such as cataclysmic variables, X-ray binaries or progenitors of type Ia supernovae ([Paczynski 1971](#); [Ivanova et al. 2013](#); [De Marco & Izzard 2017](#)). It is also likely responsible for at least a fraction of intermediate luminosity transients ([Kasliwal et al. 2011](#)), such as luminous red novae (e.g., [Blagorodnova et al. 2017](#)), some of which produce dust ([Tylenda et al. 2011](#); [Nicholls et al. 2013](#)). From the above, dust might act as an additional driving mechanism, altering the appearance of transient objects by increasing their opacity.

Previous studies on dust in interacting binary stars were conducted in 1D ([Lü et al. 2013](#)), analyzed envelope thermodynamic properties without explicitly calculating dust formation ([Glanz & Perets 2018](#); [Reichardt et al. 2019](#)), calculated dust formation but in post-processing ([Iaconi & De Marco 2019](#); [Iaconi et al. 2020](#)), or focused on the phase before the common envelope ([Bermudez et al. 2020](#)).

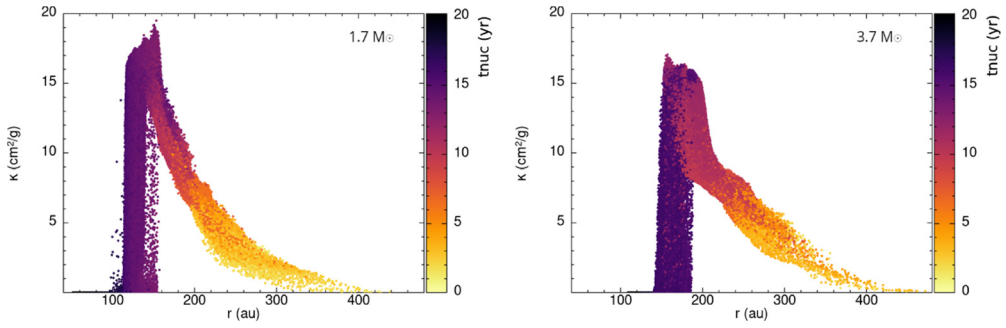
In [González-Bolívar et al. \(2023, hereafter paper I\)](#) we performed CE simulations with intermediate-mass AGB stars, using a simplified formulation by [Bowen \(1988\)](#) to calculate the dust opacity. We find that dust does not significantly increase the mass loss, but it does increase the envelope opacity. Unfortunately, the Bowen formulation does not provide us with information about the properties of the dust, such as its mass or grains size. For this reason, we perform CE simulations with an explicit calculation of the dust formation process.

## 2. Numerical Setup

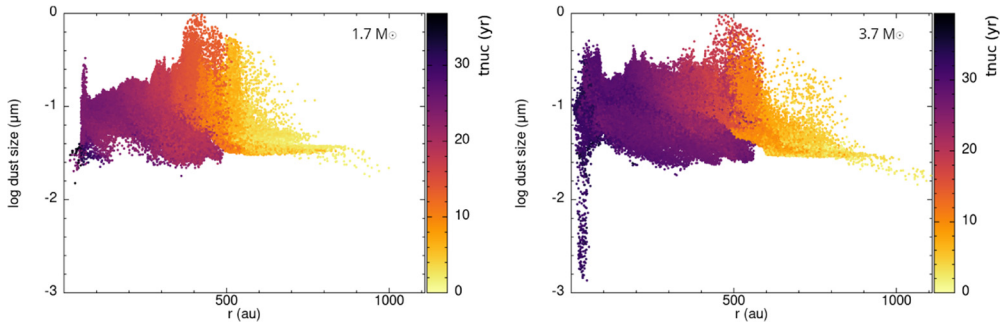
We use the same stellar models as in [Paper I](#), calculated with the 1D stellar evolution code of MESA (e.g., [Paxton et al. 2011](#)). The first model is an AGB star, evolved from the main sequence, with a total mass of  $1.7 M_{\odot}$  ( $0.56 M_{\odot}$  in the core), a radius of  $260 R_{\odot}$ , undergoing its seventh thermal pulse. The second model is an AGB star with a total mass of  $3.7 M_{\odot}$  ( $0.72 M_{\odot}$  in the core), a radius of  $343 R_{\odot}$ , experiencing its fourth thermal pulse. Both models feature a  $0.6 M_{\odot}$  companion star initially positioned at the critical distance for triggering Roche lobe overflow, i.e., at a distance of  $550 R_{\odot}$  ( $637 R_{\odot}$ ) from the  $1.7 M_{\odot}$  ( $3.7 M_{\odot}$ ) AGB star.

We use the smoothed particle hydrodynamics (SPH) code PHANTOM ([Price et al. 2018](#)) with  $1.37 \times 10^6$  SPH particles as was done by [González-Bolívar et al. \(2022\)](#). We also use PHANTOM's implementation of MESA's OPAL/SCVH equation of state tables (as done by [Reichardt et al. 2020](#)) to account for recombination energy. We assume the formation of carbon-rich dust with a C/O ratio of 2.5, despite both AGB stars having a C/O ratio of 0.32 when our MESA models ceased. The C/O ratio is not anticipated to impact the AGB convective structure.

We use the treatment described in [Siess et al. \(2022\)](#) for carbon dust nucleation and growth, which takes place in two steps: i) the formation of seed particles from the gas phase in the so-called nucleation stage, followed by ii) a growth phase where monomers (dust building blocks) accumulate on the seed particles to reach macroscopic dimensions. The treatment is based on the theory of moments presented by [Gail et al. \(1984, and subsequent papers\)](#).



**Figure 1.** Dust opacity versus distance from the centre of mass for the  $1.7 M_{\odot}$  (left) and  $3.7 M_{\odot}$  (right) models after 20 years of simulation. The color bar indicates  $t_{\text{nuc}}$ , the time in years after the start of the simulations, when dust nucleation occurred for each SPH particle.



**Figure 2.** Average dust grains size versus distance for the  $1.7 M_{\odot}$  (top) and  $3.7 M_{\odot}$  (bottom) model, after 44 years of simulations. Same color bar as in Figure 1.

### 3. Dust properties and its impact on orbital and thermodynamics properties

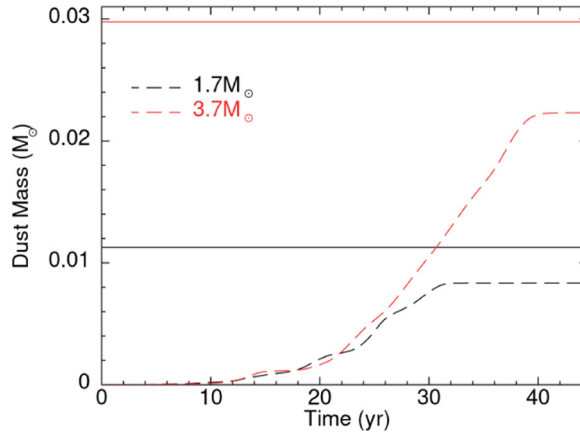
#### 3.1. Opacity of dust grains

Figure 1 shows a snapshot† of the dust opacity as a function of distance from the center of mass (the color bar depicts nucleation time  $t_{\text{nuc}}$  as explained in the caption) at 20 years from the start of the simulation. In the inner regions where there is no dust, the opacity is constant, at a user-defined value of  $2 \times 10^{-4} \text{ cm}^2 \text{ g}^{-1}$ . This value is appropriate for recombined gas, but too low for the ionised regions where electron scattering opacities are of the order of  $0.5 \text{ cm}^2 \text{ g}^{-1}$ . However, this is not important for now as these inner hot regions do not experience dust formation, which happens  $\sim 1\text{--}3$  yrs from the start of the simulation, in a shell with radii of  $\sim 10\text{--}20$  au. When dust forms, the opacity rapidly increases to values of  $\sim 17\text{--}20 \text{ cm}^2 \text{ g}^{-1}$  and decreases to almost zero again at larger radii. The dust forming shell radius expands over time and at 20 years it is  $\sim 130$  au ( $160$  au) from the  $1.7 M_{\odot}$  ( $3.7 M_{\odot}$ ) model. The dust forming shell thickness is also variable.

#### 3.2. Dust size

Figure 2 shows a snapshot of dust grains size as a function of distance (same color bar as in Figure 1). Early dust grains (yellow colour in Figure 2) have a narrow range in size around  $\sim 0.02\text{--}0.04 \mu\text{m}$ , and late dust grains (darker colours) have a larger size between  $\sim 0.03$  and  $1 \mu\text{m}$ . In the  $1.7 M_{\odot}$  ( $3.7 M_{\odot}$ ) model, the largest dust grains are formed at

† Movies corresponding to the figures are available at: <https://tinyurl.com/y455avdj>.



**Figure 3.** Dashed lines show the total dust mass over time in CE simulations. Horizontal lines represent the maximum carbon available in the envelope for  $1.7 M_{\odot}$  (black solid) and  $3.7 M_{\odot}$  (red solid) AGB stars.

$\sim 12$  yrs ( $\sim 15$  yrs). Interestingly, at the very end of the  $3.7 M_{\odot}$  simulation ( $\sim 44$  years), dust formation resumes in a thin shell near the centre, but at a low rate.

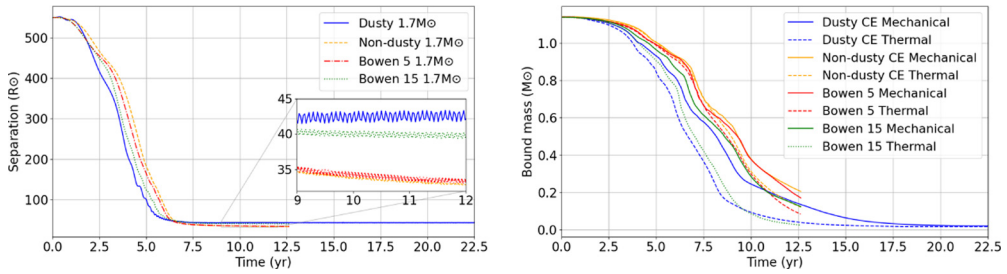
Depending on  $t_{\text{nuc}}$ , dust grains grew to different maximum sizes. Our formalism does not include dust destruction, so once a grain stops growing, its size remains constant. However, what is plotted in Figure 2 is the average grain size in a given SPH particle, which can contain many dust grains because it has a set total mass, e.g.,  $1.7 \times 10^{27}$  g or  $8.3 \times 10^{-7} M_{\odot}$  in the  $1.7 M_{\odot}$  simulation. As such, the average dust grain size in an SPH particle can decrease if new small grains are formed, even after previously-formed grains have become large.

### 3.3. Dust mass

Figure 3 shows that for the  $1.7 M_{\odot}$  ( $3.7 M_{\odot}$ ) model, the total dust mass increases steadily until it plateaus at  $\sim 32$  yrs ( $\sim 38$  yrs) with a value of  $\sim 8.2 \times 10^{-3} M_{\odot}$  ( $\sim 2.2 \times 10^{-2} M_{\odot}$ ). Although it is difficult to establish a pattern with only two stars, we see that the more massive the donor star, the longer it takes for the total amount of dust to plateau.

After  $\sim 40$  yrs, the  $1.7 M_{\odot}$  ( $3.7 M_{\odot}$ ) model has produced roughly four (ten) times more dust than during the first  $\sim 20$  yrs. The drastic increase and subsequent plateauing of dust mass is a consequence of a large fraction of the expanding envelope reaching temperatures below the condensation threshold. Because of that, nucleation is efficient (i.e., there is a large number of dust seeds) and the addition of monomers contribute to dust growth, producing the increase in the dust mass. However, with further gas expansion the nucleation rate decreases, fewer monomers are available and dust production is consequently reduced.

Compared to simulations by Iaconi *et al.* (2020) for carbon grains, the amount of dust formed in our  $1.7 M_{\odot}$  ( $3.7 M_{\odot}$ ) model is four (ten) times larger for a star twice (four times) as massive. In Iaconi *et al.* (2020), the total dust mass plateaus at  $\sim 2.2 \times 10^{-3} M_{\odot}$  after  $\sim 14$  yrs for a  $0.88 M_{\odot}$  RGB star, which started off with a radius of  $83 R_{\odot}$ . It is difficult to comment on whether these differences are due to the different type of stars, to the fact that Iaconi *et al.* (2020) post-processed the dust formation in their star, or to the nucleation formalism used.



**Figure 4.** Left panel: orbital separation over time in CE simulations with a  $1.7 M_{\odot}$  AGB star. Dust formation is explicitly calculated (blue lines), or assumed with a maximum dust opacity of  $5 \text{ cm}^2 \text{ g}^{-1}$  (red lines) or  $15 \text{ cm}^2 \text{ g}^{-1}$  (green lines) as in Paper I. Also shown is a CE simulation without dust (yellow lines). The inset displays the orbital separation at the end of the in-spiral phase. Right panel: Mechanical bound mass (solid lines) and thermal bound mass (dashed lines) over time.

### 3.4. Orbital evolution, unbound mass and comparison with non-dusty simulations

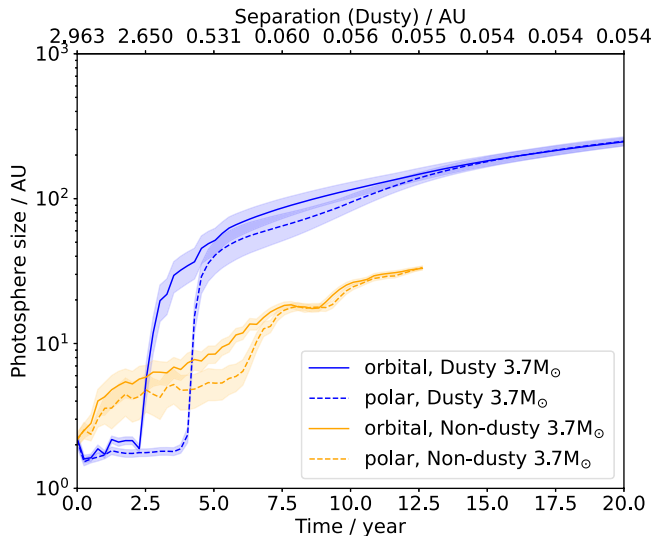
For all simulations, the dynamic in-spiral phase ends after  $\sim 7.5$  yr (Figure 4, left panel). The orbital separation decreases faster in models where dust opacity is calculated either explicitly (blue line), or using the Bowen opacity approximation (green and red lines), than in the model with no dust (yellow line). Radiative forces have a significant impact on accelerating the envelope, which interact through gravitational friction with the stars. On the other hand, the final (plateau) separation is similar, being  $\sim 42 R_{\odot}$  (blue line) and  $\sim 33 R_{\odot}$  (yellow line), although the latter is still decreasing somewhat.

In the right panel of Figure 4, “mechanical” bound mass (solid lines) is the mass of SPH particles whose sum of kinetic and gravitational potential energy is negative, while “thermal” bound mass (dashed lines) is the mass of SPH particles whose sum of kinetic, gravitational and thermal energy (not including recombination energy) is less than zero. The bound mass decreases faster in models with explicit dust formation (blue lines) than in models (i) without dust (yellow lines) or (ii) with a maximum Bowen opacity of  $5 \text{ cm}^2 \text{ g}^{-1}$  (red lines); however, when the latter increases to  $15 \text{ cm}^2 \text{ g}^{-1}$  (green lines), the evolution of the bound mass is similar. High-opacity dust is located too far in the wind<sup>†</sup> to generate effective driving on a dynamical timescale required to aid with envelope ejection, because at those distances, the radiative flux is greatly diluted and the material is mostly unbound already. We conclude that dust formation does not lead to substantially more mass unbinding, although  $\sim 10^{-2} M_{\odot}$  of dust is produced.

## 4. The photospheric size

Figure 5 shows the average radius, in the polar and orbital directions, of the stellar surface where the optical depth, calculated using the Planck-mean opacity, becomes 1 (i.e. the photosphere). We note that after  $\sim 5$  yrs the size of the photosphere is an order of magnitude larger when dust is included. This is expected, since dust opacity will be high enough for the expanding envelope to become optically thick. We also note that in the dusty model, the equatorial photosphere grows approximately one year before the polar photosphere, effectively indicating that there is a “hole” at the poles where an observer would see deeper into the object. However, this hole is filled rapidly and the size of the photosphere in the two orthogonal directions becomes very comparable, indicating an approximately spherical object.

<sup>†</sup> See movies of dust opacity versus distance at <https://tinyurl.com/y455avdj>.



**Figure 5.** Photosphere size over time in the orbital (solid lines) and the “polar” plane (dashed lines) for the  $3.7 M_{\odot}$  model with and without dust (blue and orange, respectively). Shaded areas depict uncertainty.

## 5. Summary

We have carried out simulations of CE interactions of two intermediate-mass AGB stars ( $1.7$  and  $3.7 M_{\odot}$ ) with a  $0.6 M_{\odot}$  companion. To test the dust grains properties, simulations include a self-consistent treatment of dust formation with a C/O ratio of 2.5 (by number). Our main conclusions are:

- (1) Dust formation starts  $\sim 1$ – $3$  yrs after the onset of the CE and leads to the formation of a dusty shell that moves outward. At  $\sim 20$  yrs the shell has a thickness of  $\sim 40$  au and it is located at  $\sim 130$  au ( $\sim 160$  au) in the  $1.7 M_{\odot}$  ( $3.7 M_{\odot}$ ) model.
- (2) Dust begins as tiny seeds and grows via monomer addition. The growth halts once the dust moves away along with the expanding envelope. Dust grains formed at  $\sim 1$ – $3$  yrs are smaller ( $\sim 0.02$ – $0.04 \mu\text{m}$ ) than dust grains formed after  $\sim 10$  yrs ( $\sim 0.03$ – $1 \mu\text{m}$ ).
- (3) The amount of dust rises and plateaus just below the theoretical maximum, yielding  $\sim 8.2 \times 10^{-3} M_{\odot}$  ( $\sim 2.2 \times 10^{-2} M_{\odot}$ ) for the  $1.7 M_{\odot}$  ( $3.7 M_{\odot}$ ) model.
- (4) High-opacity dust is located too far in the wind to generate effective driving on a dynamical timescale required to aid with envelope ejection. Because of that, although  $\sim 10^{-2} M_{\odot}$  of dust is produced, it does not lead to substantially more mass unbinding.
- (5) Dust greatly impacts the optical appearance of the CE. At  $\sim 12$  yrs, the photosphere is an order of magnitude larger if dust is included.

Movies corresponding to the figures are available at: <https://tinyurl.com/y455avdj>.

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