Dust Formation in Common Envelopes.

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Introduction

What is a common envelope (CE) and why it matters?

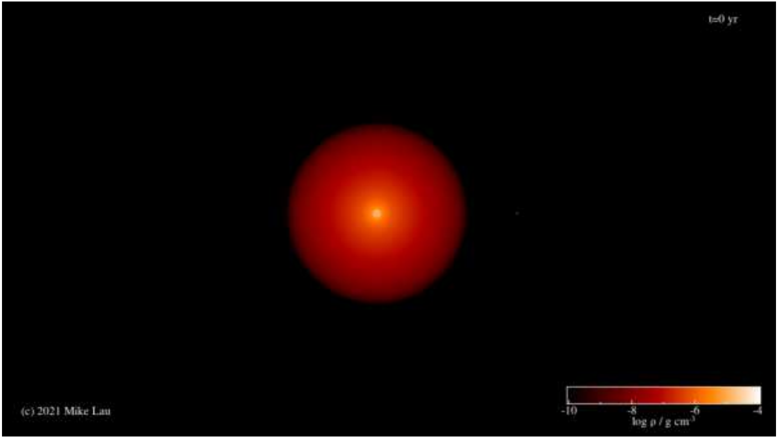

Figure: Video associated with Lau et al., (MNRAS 512, 5462–5480 (2022))

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- Dust formation may occur during the common envelope phase ($\sim$10 years).
- Increased mass loss through stellar radiation pressure on dust grains with high opacity.
- The dust can also change the appearance of the common envelope, for example by increasing its infrared brightness.

Method

How to set up and run a common envelope binary simulation? All the instructions can be found at
`https://phantomsph.readthedocs.io/en/latest/examples/CE.html`

For all simulations we use 1.37×10^6 SPH particles and consider the formation of carbon-rich dust assuming a C/O ratio of 2.5

Models	MS mass	AGB mass	AGB radius	core mass	companion mass	orbital separation
$1.7\ M_\odot$	$2\ M_\odot$	$1.7\ M_\odot$	$260\ R_\odot$	$0.56\ M_\odot$	$0.6\ M_\odot$	$550\ R_\odot$
$3.7\ M_\odot$	$4\ M_\odot$	$3.7\ M_\odot$	$343\ R_\odot$	$0.72\ M_\odot$	$0.6\ M_\odot$	$637\ R_\odot$

Table: Physical parameters of the binary systems.

For more details, please see `https://arxiv.org/abs/2401.03644` (Bermúdez-Bustamante et al., submitted)

Method

Formation of dust is a two-step process:

- Condensation of seed particles from the gas (nucleation phase).
- Aggregation of monomers onto the seed particles, which grow to macroscopic sizes (growth phase).

We use the theory of moments, developed by Gail et al. (1984), to calculate the process. The moments, $\mathcal{K}_i$, of the grain size distribution $f(N,t)$, are given given by:

$$\mathcal{K}_i = \sum_{N=N_l}^{\infty} N^{i/3} f(N,t) \tag{1}$$

$\mathcal{K}_0$ ($\mathcal{K}_3$) can be interpreted as the average number of dust grains (condensed carbon atoms) per volume.

Method

From the moments you can obtain several dust properties:

- Average radius of dust grains:

$$\langle r_d \rangle = a_0 \frac{\mathcal{K}_1}{\mathcal{K}_0} \tag{2}$$

- The Planck mean dust opacity:

$$\kappa_{\mathrm{d}} = \frac{\pi a_0^3}{\rho} Q'_{\mathrm{ext}} \mathcal{K}_3, \tag{3}$$

with $Q'_{\mathrm{ext}} = 6.7\ T_{\mathrm{d}}\ \mathrm{cm}^{-1}$

- Total mass of carbon atoms condensed into dust:

$$\mathrm{M}_{\mathrm{dust}} = \sum_{\mathrm{part.}} \frac{m_{\mathrm{SPH}}}{\rho} m_c \mathcal{K}_3 \tag{4}$$

Method

The equations governing the evolution of the moments are given by

$$\frac{\mathrm{d}\widehat{J_*}}{\mathrm{d}t} = \frac{\widehat{J^s_*} - \widehat{J_*}}{\tau_*}, \quad (5)$$

$$\frac{\mathrm{d}\widehat{\mathcal{K}_0}}{\mathrm{d}t} = \widehat{J_*}, \quad (6)$$

$$\frac{\mathrm{d}\widehat{\mathcal{K}_i}}{\mathrm{d}t} = \frac{i\,\widehat{\mathcal{K}_{i-1}}}{3\tau} + N_l^{i/3}\widehat{J_*}, \quad (7)$$

$\widehat{\mathcal{K}_i} = \mathcal{K}_i / n_{\langle\mathrm{H}\rangle}$, with $n_{\langle\mathrm{H}\rangle}$ the number of H atoms per unit volume, $\widehat{J_*}$ is the formation rate of seed nuclei per H-atom, $\widehat{J^S_*}$ is its quasi-stationary value, and τ_* is the nucleation relaxation time towards equilibrium.

For more details, please see Siess et al., (A&A 667, A75 (2022))

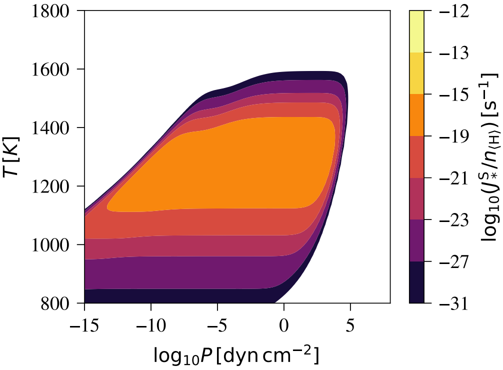


Figure: Color map of $(\widehat{J_*^S} = J_*^S / n_{\langle H \rangle})$ as a function of temperature and pressure for a C/O ratio of 2.5.

Results

1.7 $M_\odot$ and 3.7 $M_\odot$ models

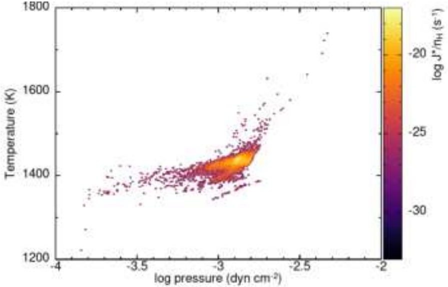
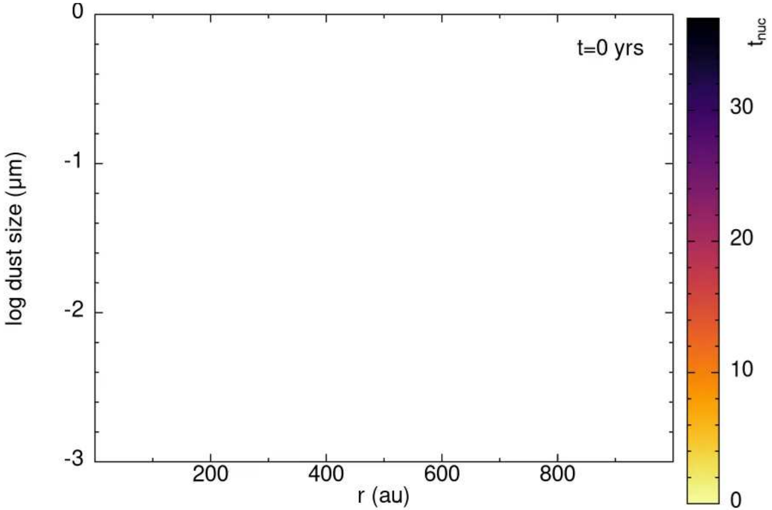


Figure: Normalized nucleation rate as a function of temperature and pressure for a collection of SPH particles at all times during the CE. The left (right) panel is for the 1.7 $M_\odot$ (3.7 $M_\odot$) model.

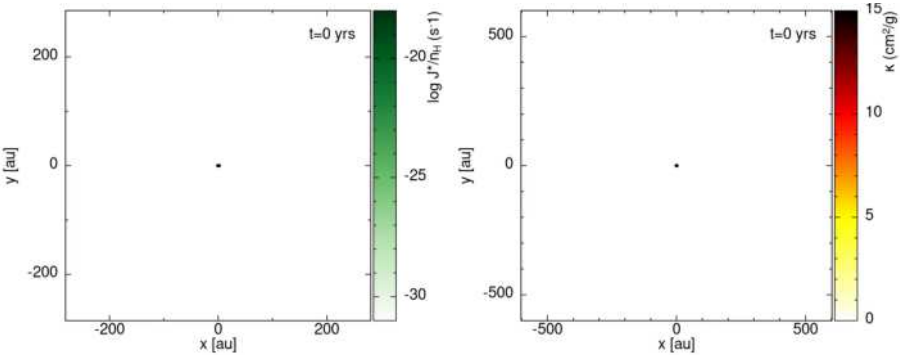
Results

1.7 $M_\odot$ model



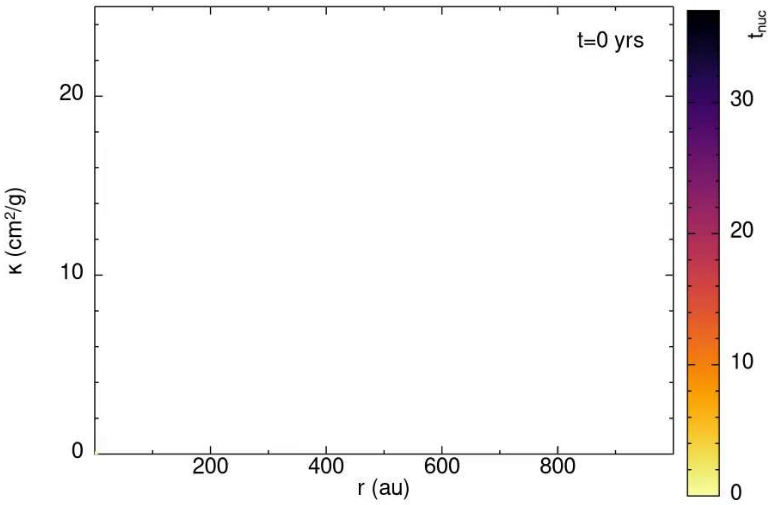
Results

1.7 $M_\odot$ model



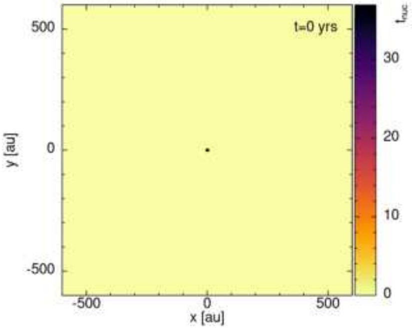
Results

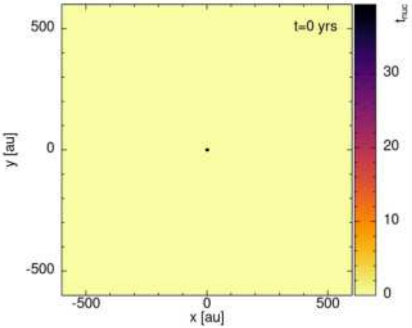
1.7 $M_\odot$ model



Results

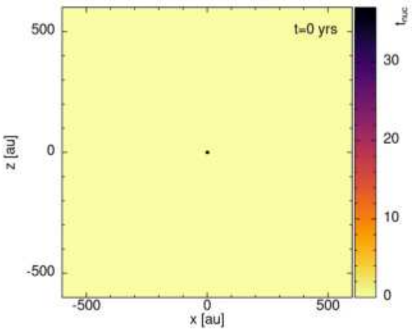
1.7 $M_\odot$ and 3.7 $M_\odot$ models

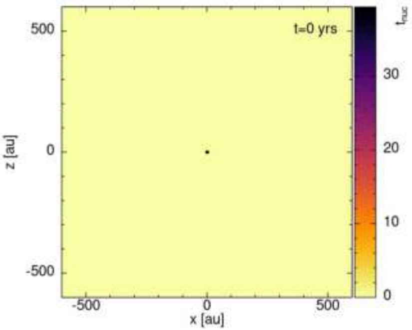




Results

1.7 $M_\odot$ and 3.7 $M_\odot$ models





Total dust mass

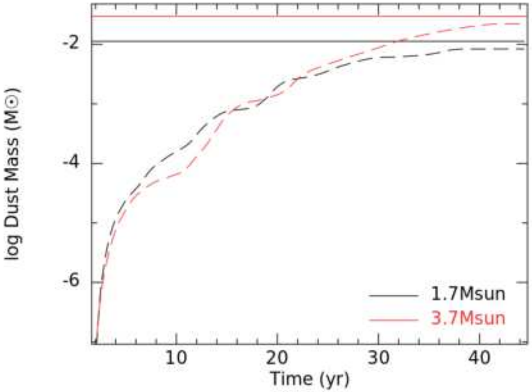


Figure: Total dust mass as a function of time for the 1.7 $M_{\odot}$ (black dashed line) and 3.7 $M_{\odot}$ (red dashed line) models.

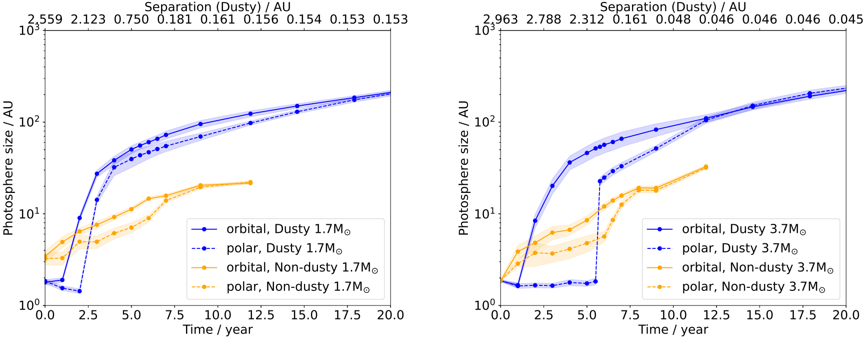


Figure: Photosphere evolution in the orbital plane (solid line) and polar direction (dashed line) for 1.7 $M_\odot$ (left panel) and 3.7 $M_\odot$ simulations (right panel) with dust (Blue) and without dust (Orange).

Summary

- Dust grains are formed in the inner layers of the ejected envelope (limited range in temperature).
- These grains are transported outward by the expansion of the envelope, new dust is formed and the cycle repeats.
- Dust formed in the early stages of the CE is smaller than the dust formed later.
- Time lag between dust formation and the increase of opacity.
- The amount of dust formed in the CE ($\sim 10^{-3} - 10^{-2}\ M_{\odot}$) impacts the optical properties of the star (change in the effective radius).

Future prospects

- What if radiative cooling (or radiation transport) is present?
- What happens with more massive companion stars?
- What about O-rich dust?

Thanks!

Introduction

What is a common envelope (CE) and why it matters?

- It is an evolutionary phase in which there are two stellar cores, immersed in a CE, revolving around their center of mass.
- The transfer of angular momentum and orbital energy from the stars to the envelope causes a shrinking in the orbital separation and the ejection of the envelope (Details of energy transport not fully understood.)
- The CE interaction is the gateway to the formation of a number of compact evolved binaries such as: Cataclysmic variables, X-ray binaries or the progenitors of type Ia supernovae.

Therefore we (González-Bolívar et al. 2023, submitted) carried out two CE simulations, where dust opacities are calculated using the simplified approximation of Bowen (1988):

$$\kappa_{dust} = \frac{\kappa_{max}}{1 + exp((T - T_{cond})/\delta T)} \quad (8)$$

- However, with the Bowen approximation we know nothing about the dust properties (such as opacity or size distribution) or its mass.
- For those reasons, **we present, for the first time, 3D hydrodynamics simulations of dusty CEs**, where the formation, growing and properties of the dust are calculated self-consistently.

With the dust opacity is possible to calculate the radiative acceleration on the particles:

$$\frac{d\mathbf{v}_{\mathbf{rad}}}{dt} = \frac{(\kappa_g + \kappa_{\rm d})L}{4\pi r^2 c}\ \hat{\mathbf{r}} \tag{9}$$

- Another important parameter is the supersaturation ratio S:

$$S = \frac{P_{\rm C}(T_{\rm g})}{P_{\rm sat}}, \tag{10}$$

where $P_{\rm C}(T_{\rm g})$ is the partial pressure of carbon in the gas phase and $P_{\rm sat}$ is the vapor saturation pressure of carbon in the solid phase.

- In the absence of a proper treatment of radiative transfer in our simulations, we will assume that gas and dust are thermally coupled, i.e. $T_{\rm g} = T_{\rm d} = T$.

Results

Evolution of orbital separation and of unbound mass

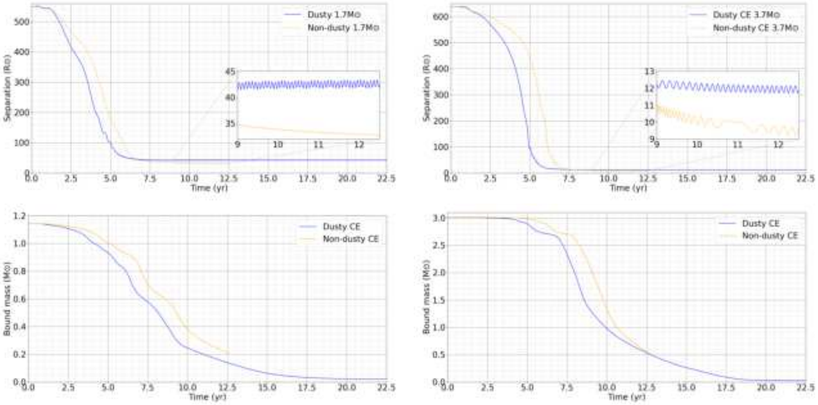


Figure: Orbital separation (top row) and bound mass (bottom row) as a function of time for the CE simulations with a 1.7 $M_{\odot}$ and a 3.7 $M_{\odot}$ AGB primary star.

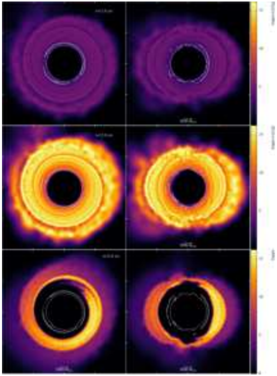


Figure: Opacity slices in the XY (left) and XZ plane (right) at 12.6 years for the Bowen simulations. $\kappa_{\rm max}$=5 cm^2 g^{-1} (top row), $\kappa_{\rm max}$=15 cm^2 g^{-1} (middle) and dust nucleation (bottom).

Results

Orbital evolution, unbound mass and comparison with non-dusty and Bowen simulations

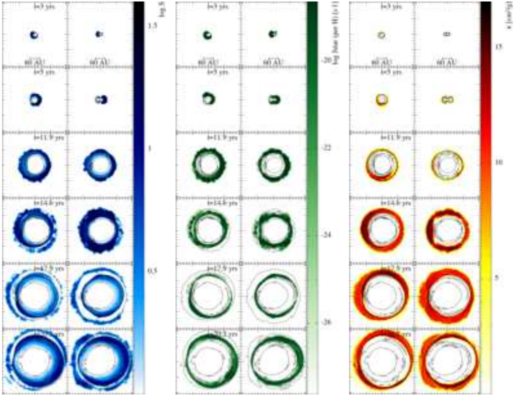


Figure: Slices in the XY (columns 1, 3 and 5) and XZ (columns 2, 4 and 6) planes of supersaturation ratio, S, nucleation rate per hydrogen atom, $\hat{J}_\star$ and opacity, κ at 6 different times for the 3.7 $M_\odot$ model.

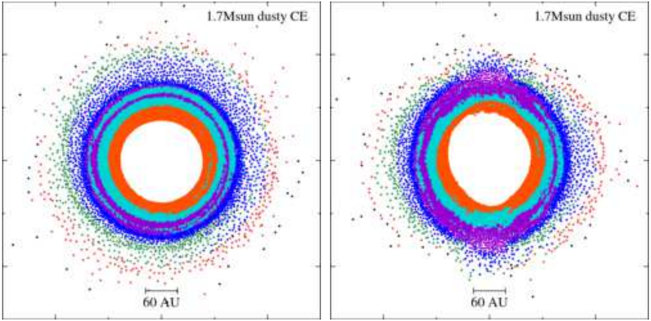


Figure: Dusty SPH particles distribution in the XY (left) and XZ plane (right), for the CE simulations. The colors indicate the time when dust was formed.

Results

Orbital evolution, unbound mass and comparison with non-dusty and Bowen simulations

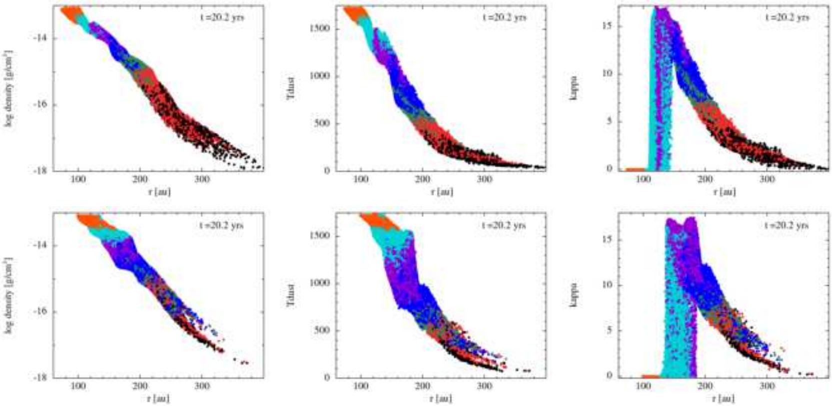


Figure: Density (left column), temperature (middle column) and dust opacity (right column) versus distance from the center of mass, for the 1.7 $M_\odot$ (top row) and 3.7 $M_\odot$ (bottom row) AGB stars at 20.2 years.

Results

Dust grains size evolution.

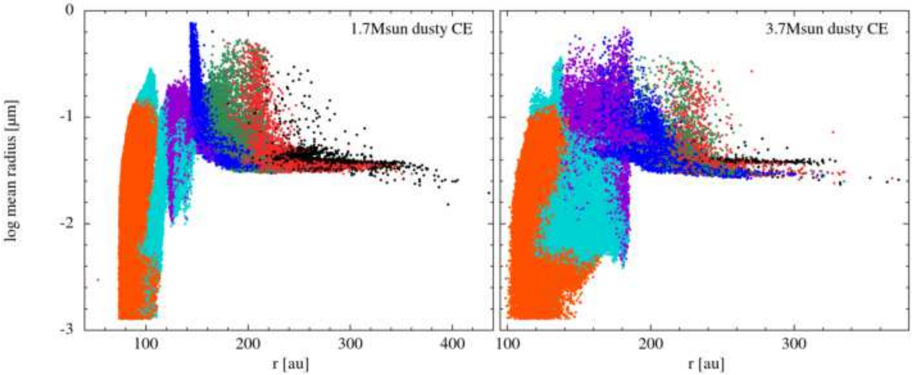


Figure: Dust grain radius as a function of distance to the center of mass at 20.2 years from the start of the simulations.