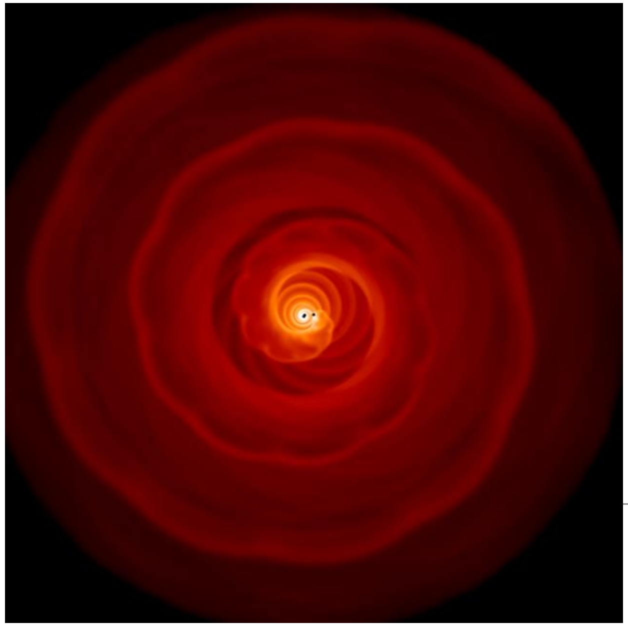
Dusty AGB stars
Science goals and modeling



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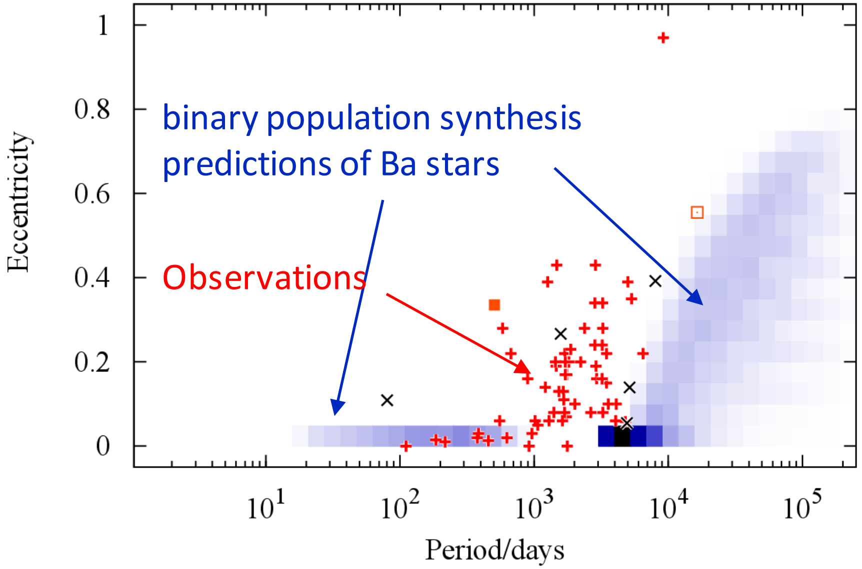
Phantom users workshop

Monash University, Melbourne, Australia
Feb 13-17, 2023

AGB stars, dust and binaries

- AGB stars are the site of a unique nucleosynthesis (e.g. fluorine, s-elements) that make them easy to identify spectroscopically
- Strong producers of dust which is the driver of strong winds
- The presence of a mass loosing AGB star in a binary can
  - Strongly impact of the morphology of the circumstellar environment
  - Affect our estimates of the mass loss rate
  - induce mass exchange leading to
    - (*dusty*) common envelope evolution for short P system
    - Formation of chemically peculiar stars (Ba stars, CEMP, …) with **puzzling orbital parameters**



AGB stars in binaries are excellent laboratories to study binary interactions but a consistent modeling of wind ejection and dust is required

Effect of dust on the hydro equations

Dust is opaque and can absorb radiation which translates into

- **radiation force**

radiation force

dust opacity

$$\frac{d\mathbf{v}}{dt} = -\frac{\nabla P}{\rho} + \Pi_{\rm shock} + \mathbf{a}_{\rm sink-gas} + \boxed{\mathbf{F}_{\rm rad}}$$

$$a_{\rm sink-gas} + F_{\rm rad} = -\frac{GM_{\rm sink}}{r^2}(1 - \boxed{\Gamma})$$

$$\Gamma = \frac{(\kappa_{\rm g} + \boxed{\kappa_{\rm dust}})L_*}{4\pi c G M}\, e^{-\tau}$$

optical depth

- **extra heating/cooling** because $T_{\rm dust} \neq T_{\rm gas}$

$$\frac{du}{dt} = -\frac{P}{\rho}(\nabla \cdot \mathbf{v}) + \Lambda_{\rm shock} - \frac{\Lambda_{\rm cool}}{\rho}$$

$$\Lambda_{\rm cool} = \frac{3R}{2\mu}\frac{(T_{\rm gas} - \boxed{T_{\rm dust}})}{C'} + \Lambda_{\rm HI}$$

$$\tau = \int_{R_*}^{r} \kappa\rho\, dr$$

gas-dust heat exchange

- **drift** terms

Determination of $T_{\rm dust}$

- Approximate solutions require calculation of optical depth
- RT codes e.g. MCFOST

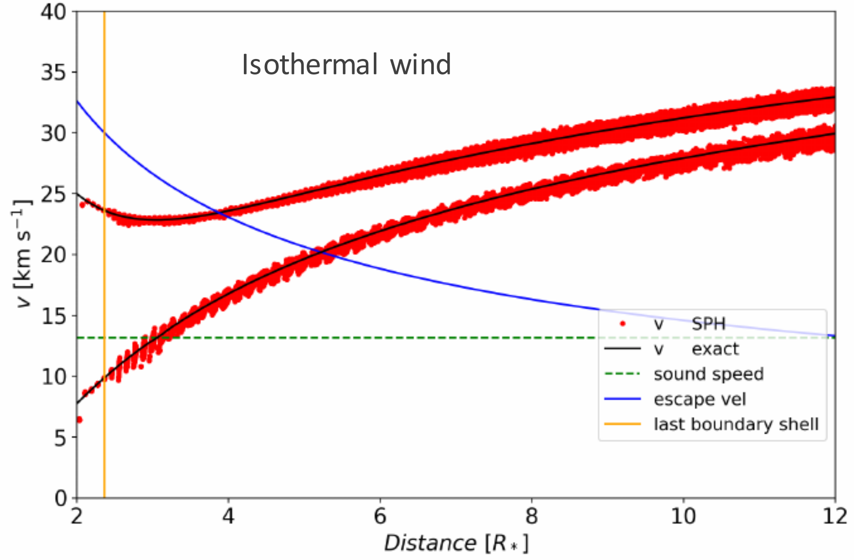
$$T_{\rm dust}^4 = \frac{1}{2}\left(1 - \sqrt{1 - \left(\frac{R_*}{r}\right)^2}\right) T_*^4\, \boxed{e^{-\tau}}$$

Implementation of mass loss

1. Given an injection radius, wind temperature and mass loss rate we calculate the *steady 1D wind profile*

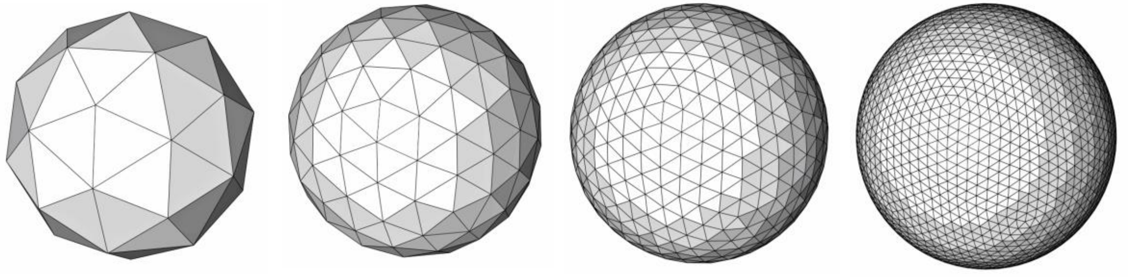
$$\frac{\mathrm{d}v}{\mathrm{d}r} = \frac{2c_\mathrm{s}^2/r - GM_*(1-\Gamma)/r^2 - (\gamma-1)\Lambda/v}{v(1-c_\mathrm{s}^2/v^2)}$$

$$\frac{\mathrm{d}T_\mathrm{g}}{\mathrm{d}r} = (1-\gamma)T_\mathrm{g}\left(\frac{2}{r}+\frac{1}{v}\frac{\mathrm{d}v}{\mathrm{d}r}\right) + \frac{(\gamma-1)\,\mu m_\mathrm{u}}{k}\frac{\Lambda}{v}$$

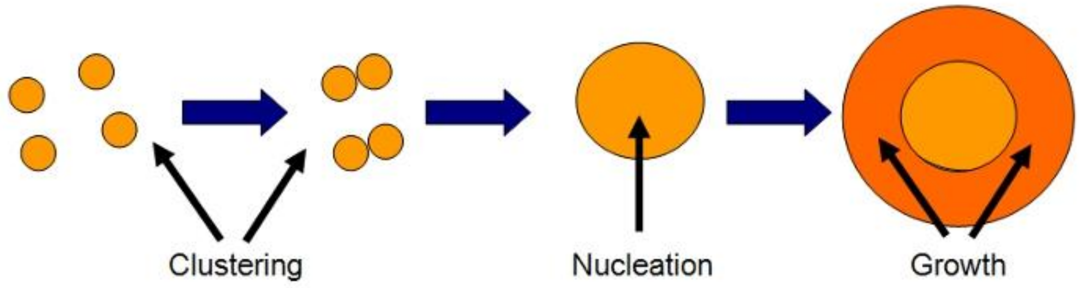


2. When particles are released, they are assigned the properties of the 1D wind solution (v, u)

3. The ejected particles are distributed on an isocahedron surface
    - The number of particles N is quantisized
    - Spheres are rotated between injections to remove artifacts



Dust formation



A two step process

1. Nucleus formation

- Process operates at the molecular scale
- seeds contain 100 to 1000 atoms
- To compute the nucleation rate, we need abundances of *monomers* (dust building blocks)

→ chemical network including 7 atoms : H, C, O, N, Si, S, Ti and 25 molecules (C_2, H_2, OH, H_2O, CO, CO_2, CH_4, C_2H, C_2H_2 , TiO, SiO ….)

→ we assume chemical equilibrium : no need to store individual abundances, only that of atomic carbon

2. Grain growth

- Gas molecules stick to the grain surface and make it grow
- The growth proceeds via

$$\begin{array}{lcl} C_N + & \begin{array}{|l|} \hline C \\ C_2 \\ C_2H_2 \\ C_2H \\ \hline \end{array} & \begin{array}{l} \rightarrow\ C_{N+1} \\ \rightarrow\ C_{N+2} \\ \rightarrow\ C_{N+2} + H_2 \\ \rightarrow\ C_{N+2} + H \end{array} \end{array}$$

Dust evolution : Moment equations

This theory does not calculate the grain size distribution $f\,(N,\,t)$ but uses its moments $\mathcal{K}_i$ to describe the global dust properties:

- Average grain radius $\langle a\rangle \propto \mathcal{K}_1/\mathcal{K}_0$
- Average grain surface $\langle S\rangle \propto \mathcal{K}_2/\mathcal{K}_0$
- Number monomers condensed in grains $\boxed{\mathcal{K}_3 \propto \text{opacity}}$

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

N is the number of monomers in the grain

The evolution of the moments is given by

$$\frac{d\widehat{J_*}}{dt} = \frac{\widehat{J_*^s} - \widehat{J_*}}{\tau_*}$$

$$\frac{d\widehat{\mathcal{K}_0}}{dt} = \widehat{J_*}$$

$$\frac{d\widehat{\mathcal{K}_i}}{dt} = \frac{i\,\widehat{\mathcal{K}_{i-1}}}{3\tau} + N_l^{i/3}\widehat{J_*},$$

J_* : nucleation rate $f(T,P_i)$

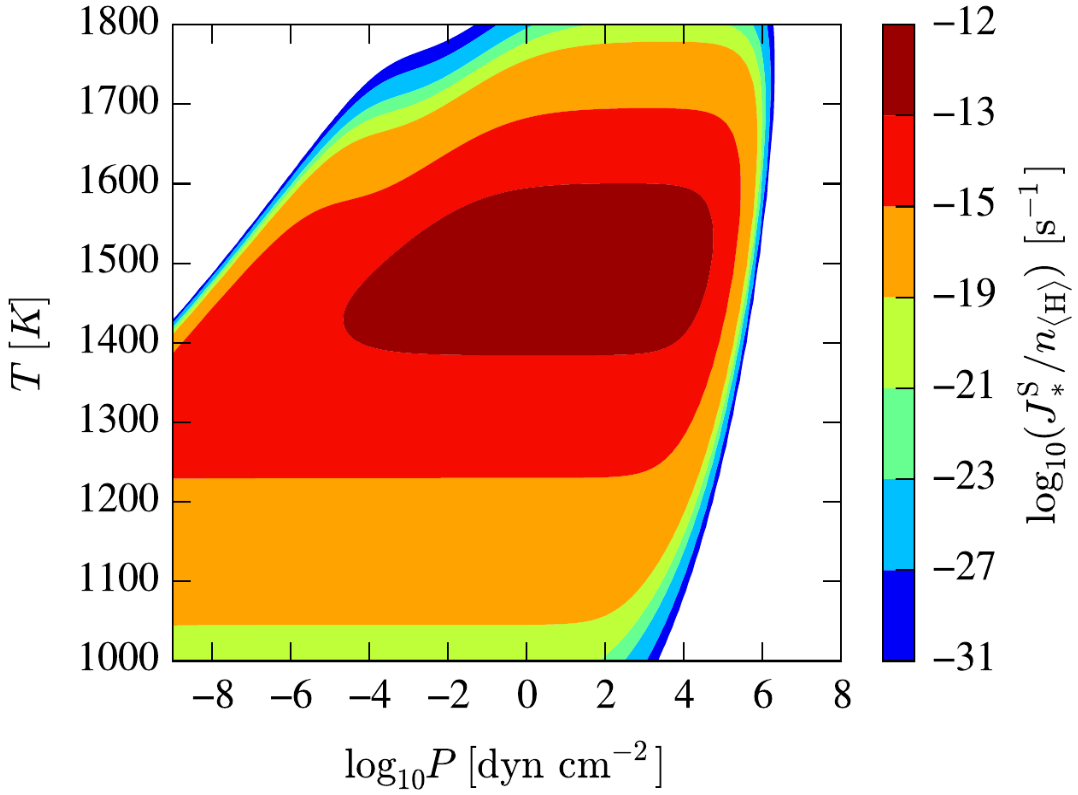
τ^{-1} : rate of growth/destruction of the grains

J_*^s : rate of formation of critical clusters

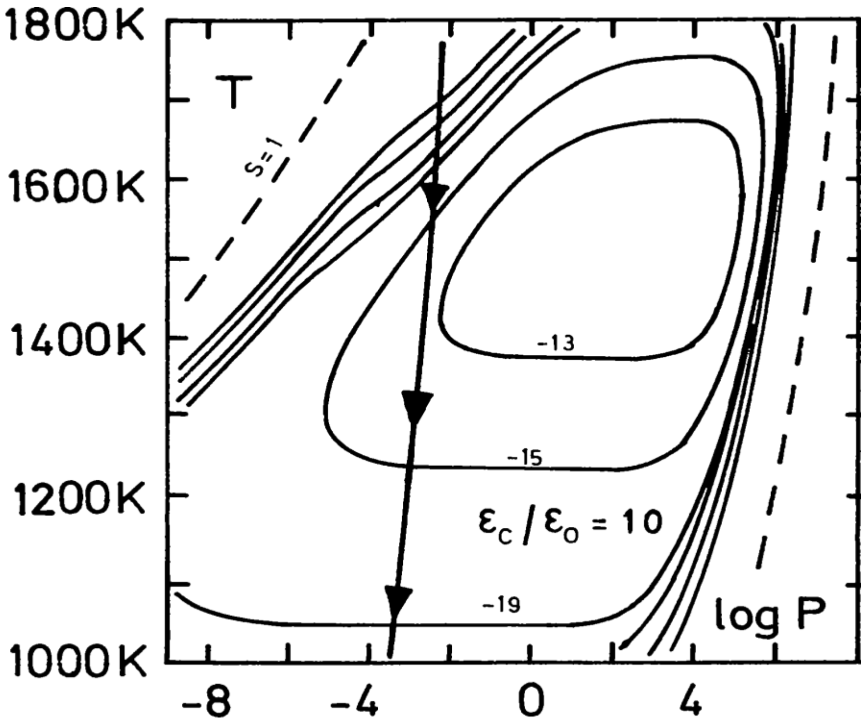
τ_* : relaxation time to equilibrium

Each SPH particle now carries the information about the moments $\mathcal{K}_i$ and J_*

Nucleation rate



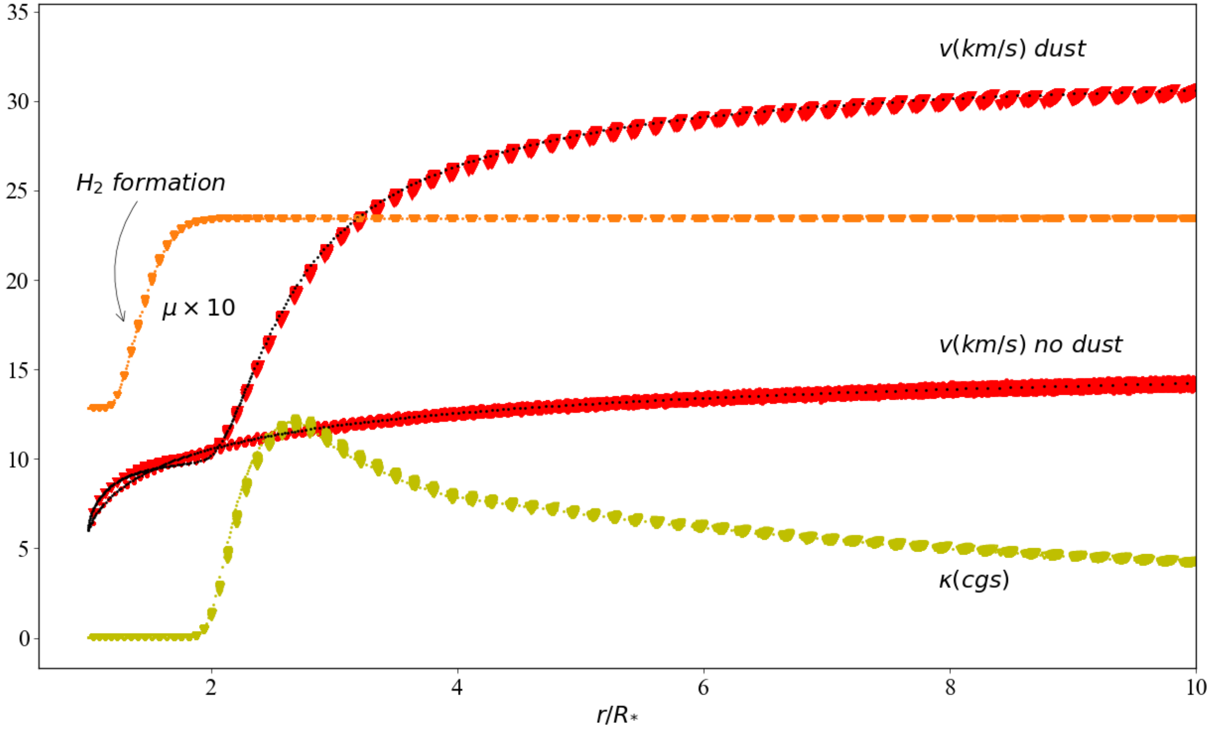
Siess+ (2022)   for C/O = 10



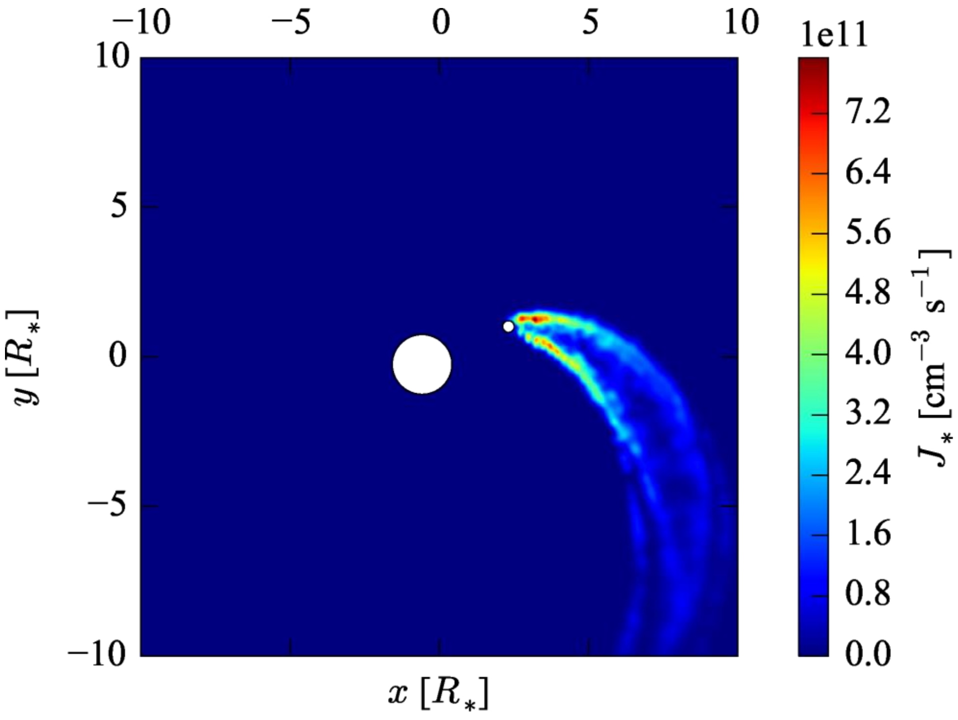
Gail & Sedlmayr (1984)

Dust in the wind

Dust can provide a strong wind acceleration



Siess+ (2022)



Nucleation rate high in the wake of the binary companion where density is higher

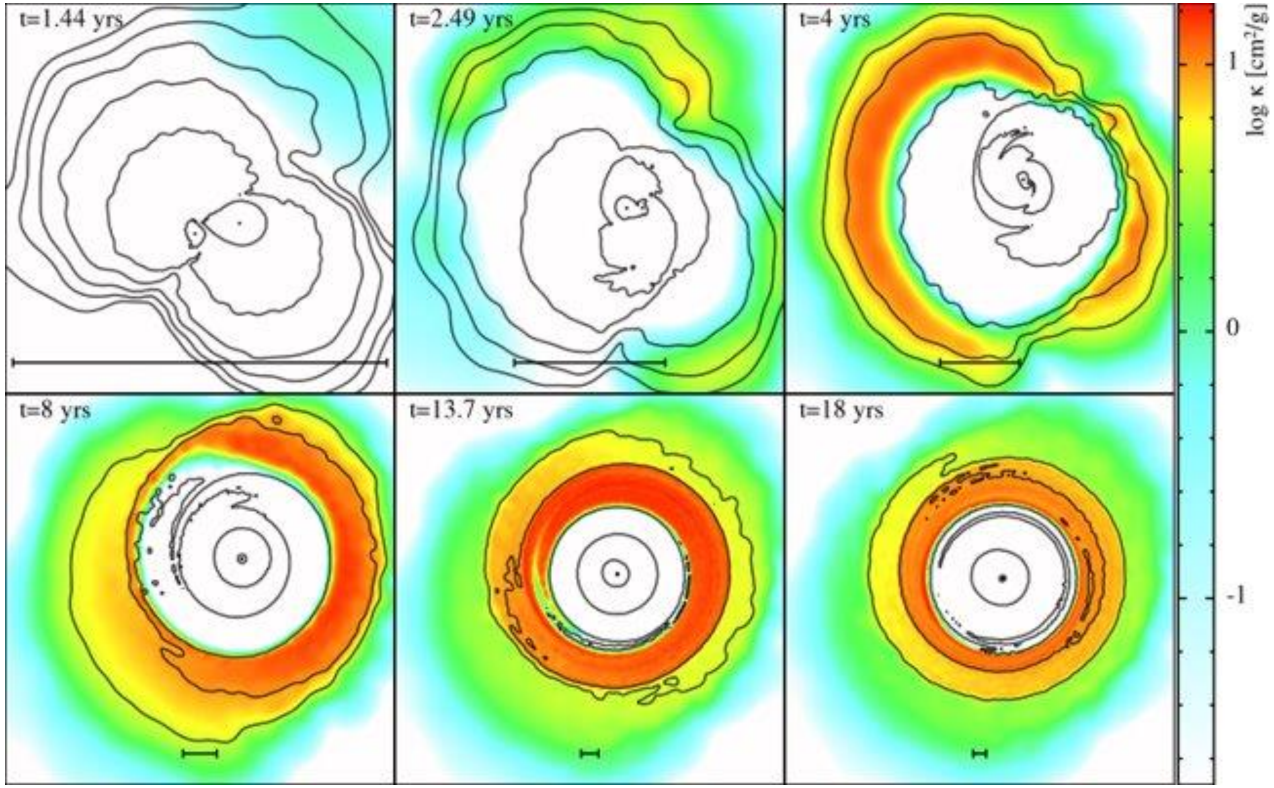
Dust in common envelopes

Dust forms in the expanding common evolution

Could have a significant impact on the observables

(Bolivar+ 2023, Bermudez+ 2023, in prep)

See Miguel's talk to follow

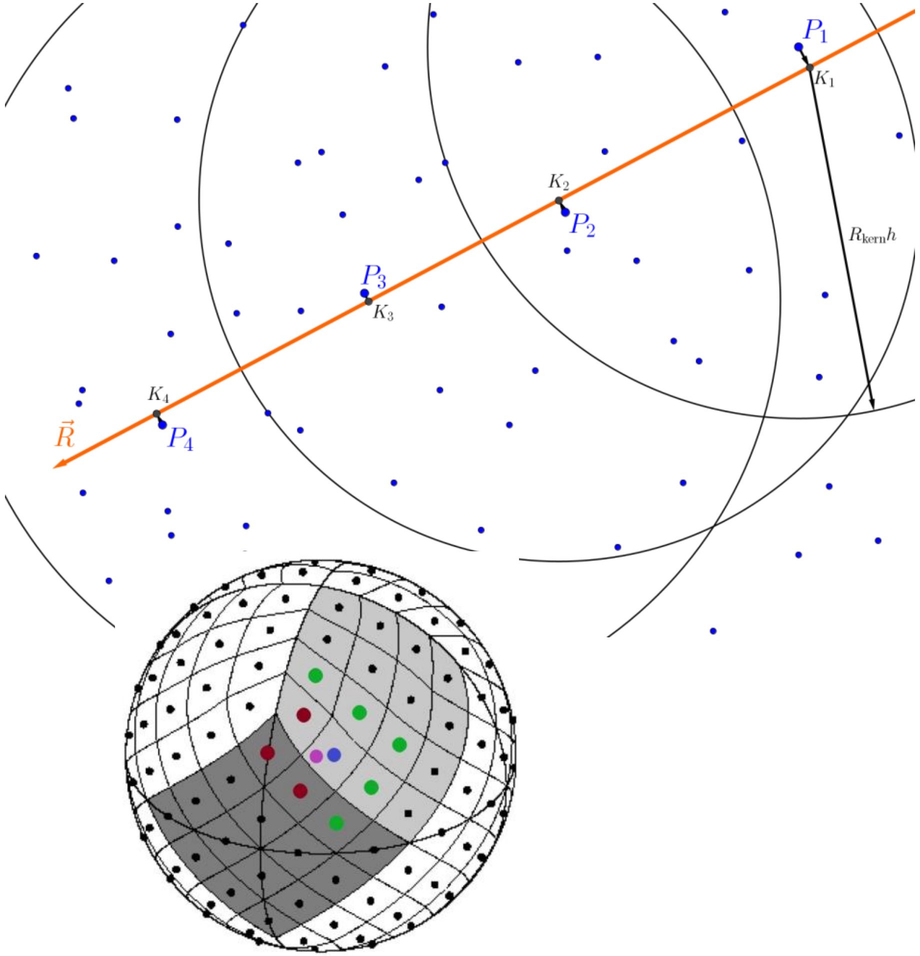


Bermudez+ (2023)

Ray tracer implementation

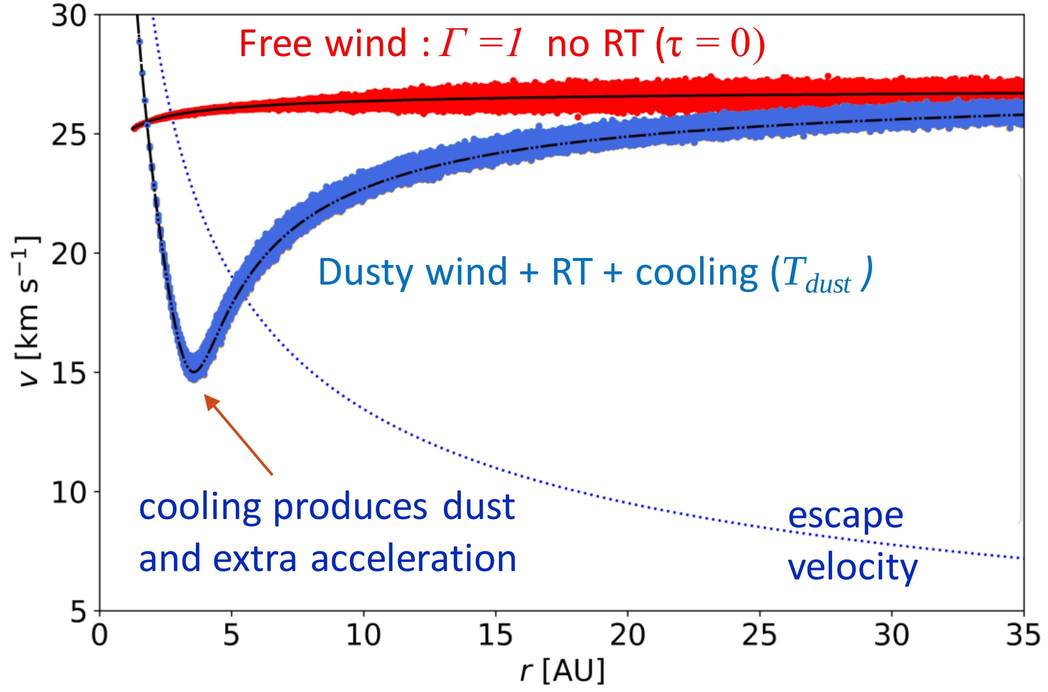
Algorithm adapted from the Magritte code (de Ceuster)

1. A series of rays are emitted and evenly distributed on a sphere (HEALPix). Number of rays = 12 x 4^{order}
2. For each ray, do outward integration :
   1. Start from a point P_i
   2. Take all the nearest neighbors in the sphere of influence
   3. Find the particle closest to the ray $\longrightarrow P_{i+1}$
   4. Calculate the optical depth increment $\mathrm{d}\tau_i = <\kappa\rho>\, ds_i$ along the segment $ds_i = P_i P_{i+1}$ using all $part. \in R_{kern}$
3. For each particle, find the closest rays (HEALPix) and do the inward optical depth integration, averaging the $\mathrm{d}\tau_i$ contribution from the closest 4 rays

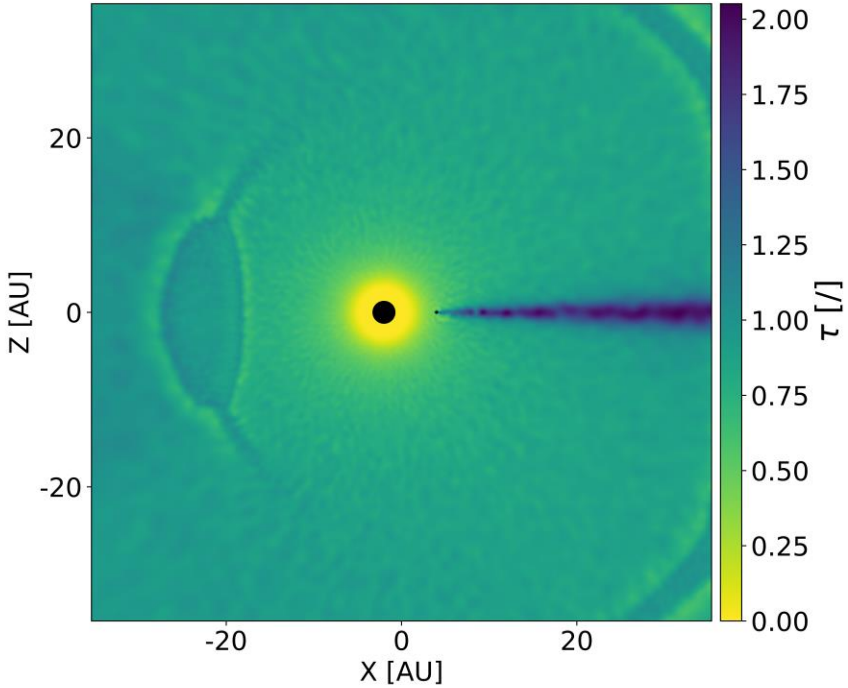


Preliminary results

Effective wind launching



Shadow cone generated
by the AGB companion



Esseldeurs+ 2023 (in prep)

Future prospects

- **Radiative transfer** - coupling with MCFOST (started). Aim is to recover grain size distribution from moments so MCFOST can estimate T_{dust}, optical depth (τ), radiation force (Γ)
- **Cooling** - test numerical scheme + implement more accurate prescriptions (CO, H_2O line cooling, ...)
- **Pulsations** - improve wind launching mechanism. May need to solve the energy transport in the STAR
- **Chemistry**
  - Adapt dust formation to C-poor stars (C/O<1)
  - Chemistry in AGB outflows is complex --> chemical network emulator to get cooling rates and molecular abundances (Jolien's talk)
- **Dust-gas coupling**

With the goals to better understand

- ALMA observations, mass loss rates, binary interactions with an AGB primary
- Common envelope evolution and its optical counterpart (transients) ...
- Try it ! `writemake.sh wind > Makefile`