AGB Atmospheres in Binary Environments: A First Step with CO^{5}BOLD

Gabriel Tomassini [1] Andrea Chiavassa [1] Bernd Freytag [2] Eric Lagadec [1]

[1]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France
[2]Theoretical Astrophysics, Department of Physics and Astronomy, Uppsala University, Box 516, 751 20 Uppsala, Sweden

Introduction

Asymptotic Giant Branch (AGB) stars play a central role in the chemical enrichment of galaxies through their intense mass loss. The morphology of their extended atmospheres shapes this process, yet the physical mechanisms driving it remain uncertain. Observations of post-AGB systems reveal strong signatures of binarity — such as disks, tidal structures, and asymmetric outflows — suggesting that companions may be key in shaping late stellar evolution. However, the impact of companions, ranging from stellar to planetary masses, on AGB atmospheres is still poorly understood.

To investigate this, we perform 3D radiative hydrodynamical simulations of AGB convection with the CO^{5}BOLD code (Freytag et al., 2012). We introduce a time-independent binary potential, including a centrifugal term, to explore how a companion-like perturbation affects the atmospheric structure and dynamics.

A binary potential

In CO^{5}BOLD, the gravitational potential is initially modelled in a Newtonian form, assuming all stellar mass is concentrated at the centre. To mimic the presence of a companion, we extend this formulation by adding (i) a **second Newtonian potential** and (ii) a **centrifugal term** accounting for the system's rotation around the barycentre of an hypothetical binary system. This results in a tidal locked configuration where the companion remains fixed in the co-rotating frame ie always facing one side of the carthesian box:

$$\Phi = -\underbrace{\frac{\mathrm{G}M_1}{r_1}}_{\text{central star}} - \underbrace{\frac{\mathrm{G}M_2}{r_2}}_{\text{companion}} - \underbrace{\frac{1}{2}\Omega^2\left|\vec{r}_\perp - \vec{l}\right|^2}_{\text{centrifugal (rotation)}} \tag{1}$$

where:

- M_1 and M_2 are the masses of the central star and the companion, respectively.
- r_1 and r_2 are the distances to the central star and to the companion, respectively.
- $\Omega = \sqrt{\frac{\mathrm{G}\,(M_1+M_2)}{a^3}}$ is the orbital angular frequency of the system, with a the separation between the two bodies.
- $\vec{r}_\perp$ is the projection of the vector from the centre of the companion to a given point onto the plane perpendicular to the rotation axis.
- $\vec{l}$ is the vector from the centre of the companion to the barycentre.

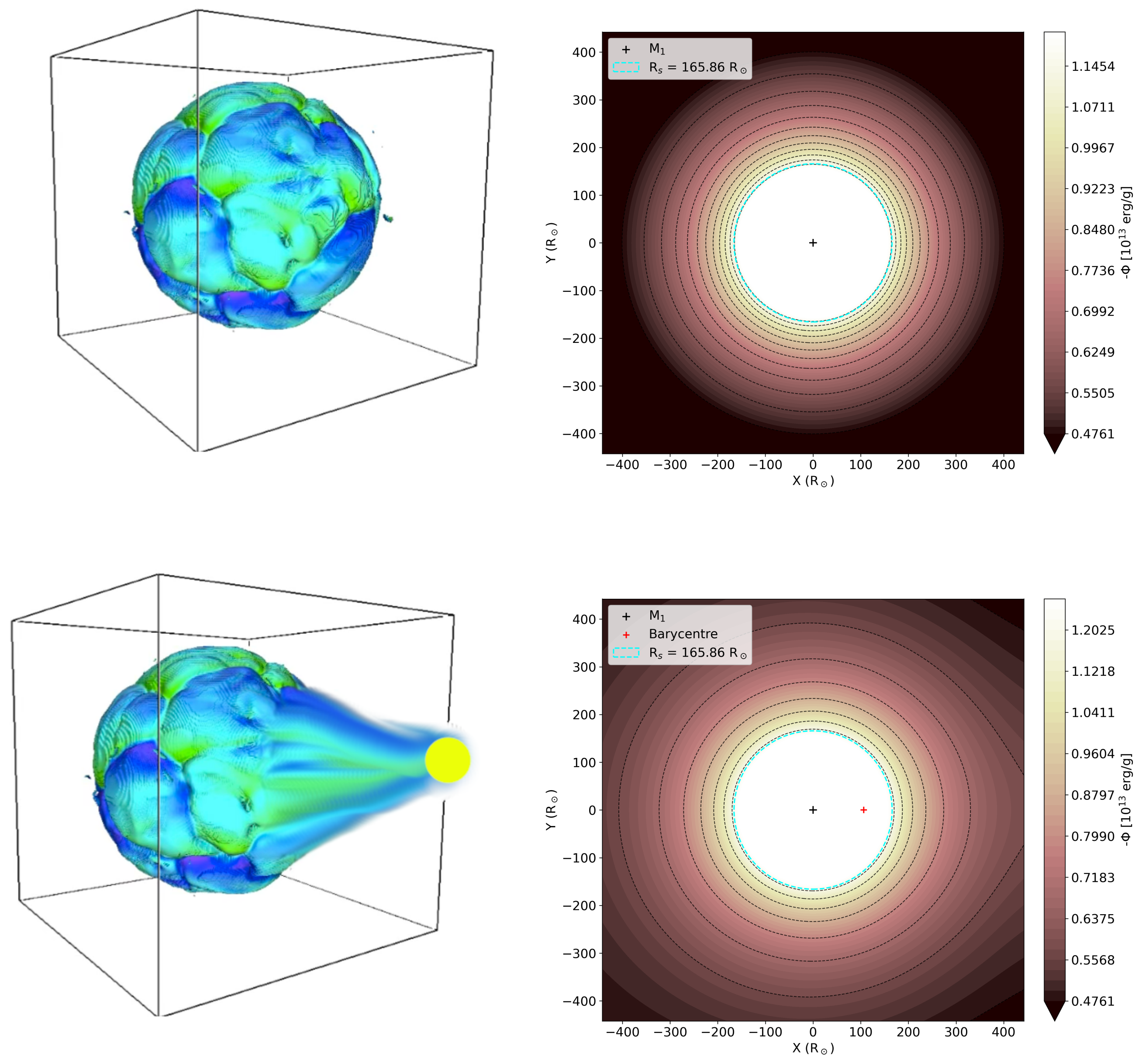

Figure 1. Gravitational equipotential (right) and schematic representation (left): only one star (top) and two stars (bottom) in the orbital plane for $M_1 = 1\ M_\odot$, mass ratio q = 0.17 and separation a = 718 $R_\odot$. Model Parameters: T = 3177 K, $\log g$ = 0.01 [cgs], R = 165 $R_\odot$.

Methodology

To assess the effect of the binary potential, we analyze the density distribution in the box by dividing it into 15° cone and taking the mean in the 6 principal directions (x_+, y_+, z_+ and their opposites). We can then construct an anisotropic ratio α to quantify the degree of anisotropy in the density distribution:

$$\alpha = \rho_x / \langle \rho_y, \rho_z \rangle \tag{2}$$

where $\rho_i = \frac{1}{2}(\rho_{i+} + \rho_{i-})$ (i = x, y, z) is the density in the direction of the companion and $\langle \rho_y, \rho_z \rangle$ is the average density in the perpendicular directions. This ratio allows us to identify potential anisiotropies in the density distribution toward the companion that may arise due to the change in the potential.

Another ratio β is defined to quantify the degree of anisotropy in the orbital plane (X,Y) and is given by:

$$\beta = \rho_x / \rho_y \tag{3}$$

where ρ_x and ρ_y are the densities in the direction of the companion and perpendicular to it, respectively. This ratio allows us to identify potential anisotropies in the density distribution in the orbital plane itself.

Results

For each model we compute these two ratios as a function of the radius. To minimize the influence of convection, we average the ratios over time. We also divided α and β by a reference value for the case of no companion. The results are shown in Fig. 2.

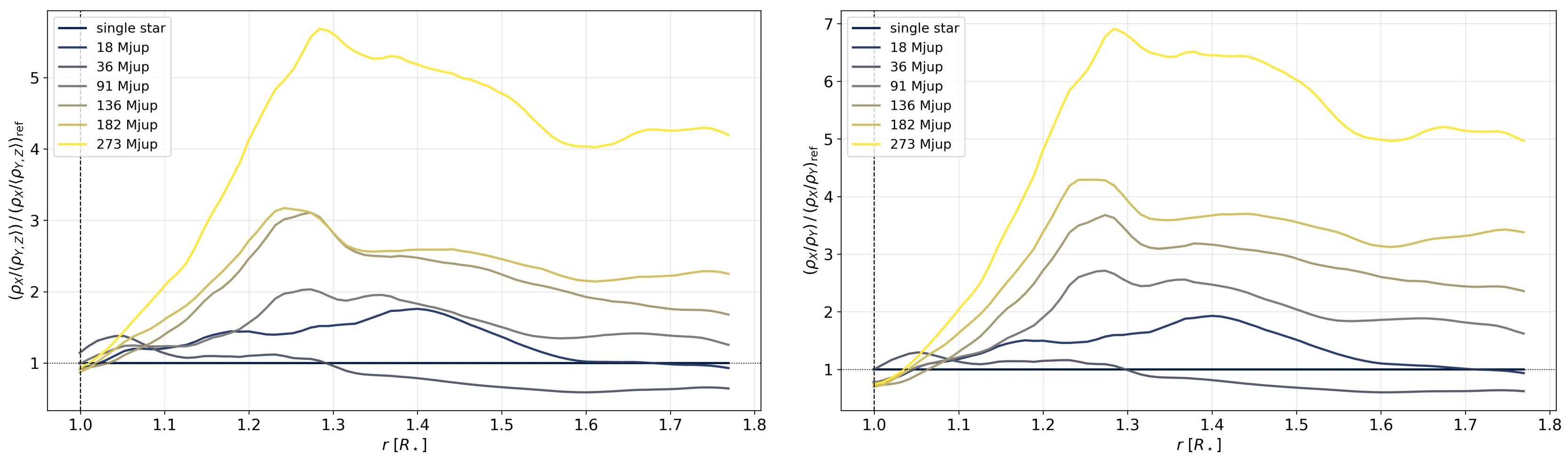

Figure 2. Left: alpha ratio as a function a radius Right: beta ratio as a function of radius.

Both ratios show a clear trend of increasing **anisotropy with companion mass**, particularly in the outer layers of the atmosphere and in the ejected material. This indicates that the presence of a companion significantly alters the density distribution, leading to a more pronounced asymmetry in the stellar envelope. These also show a **maximum anisotropy at a radius between $\sim$ 1.2 $R_\star$ and $\sim$ 1.4 $R_\star$**, which corresponds to the region where the companion's gravitational influence is strongest.

To further investigate the relationship between companion mass and anisotropy, we compute the radial average of the ratios α and β over the range of radii where the maximum anisotropy is observed. The results are shown in Fig. 3. **We find that both ratios increase with companion mass**, indicating that more massive companions induce stronger anisotropies in the density distribution. This suggests that the presence of a companion can significantly influence the structure and dynamics of AGB star atmospheres, potentially affecting their mass-loss processes and shaping their circumstellar environments.

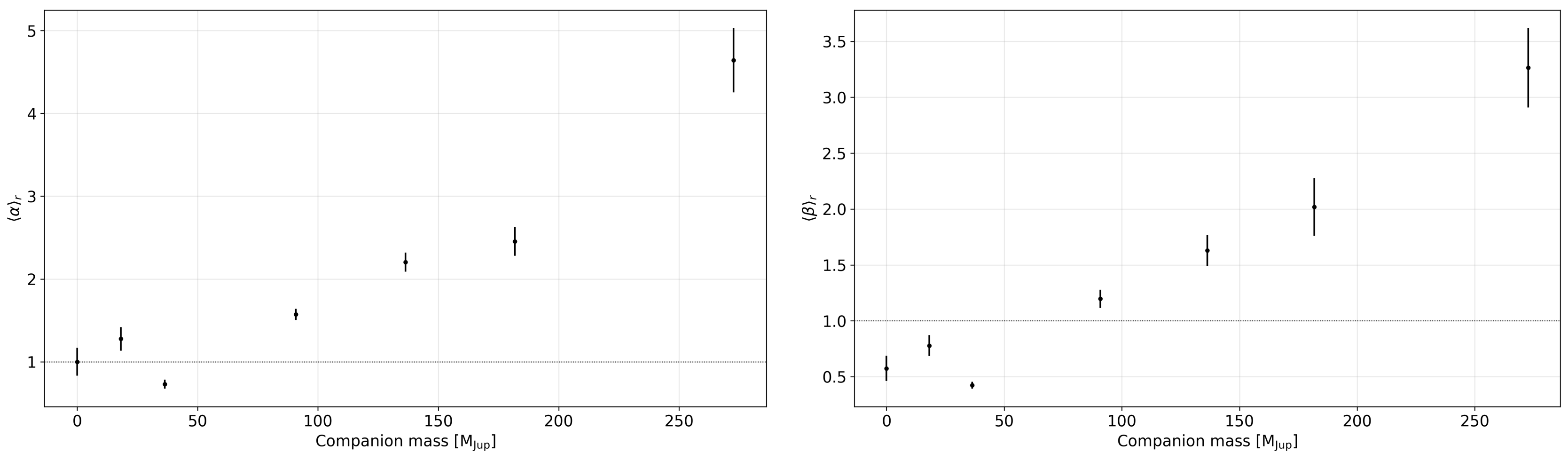

Figure 3. Left: Radial average of the alpha ratio as a function of companion mass. Right: Radial average of the beta ratio as a function of companion mass.

Conclusion and Perspectives

The implementation of a binary gravitational potential in the CO5BOLD code highlights the substantial influence of binarity on AGB star atmospheres. **Our initial results show that the presence of a companion significantly modifies the density distribution around the star**. These findings indicate that binary companions can play a crucial role in driving the dynamical behaviour and mass-loss processes of AGB stars, with important consequences for their late evolutionary stages.

Future developments of this work will aim to:

- Extend the parameter space by varying orbital separation and mass ratio to investigate a broader range of binary configurations.
- Examine the influence of orbital eccentricity on atmospheric structure and pulsation dynamics.
- Confront the numerical results with observational diagnostics to assess the realism of the simulated stellar behaviour.

References

Freytag, B., Liljegren, S., and Höfner, S. (2017). Global 3D radiation-hydrodynamics models of AGB stars. Effects of convection and radial pulsations on atmospheric structures. *A&A*, 600:A137.

Freytag, B., Steffen, M., Ludwig, H. G., Wedemeyer-Böhm, S., Schaffenberger, W., and Steiner, O. (2012). Simulations of stellar convection with CO5BOLD. *Journal of Computational Physics*, 231(3):919–959.

Note: Paper to be submitted on this study

https://github.com/gtomass
gabriel.tomassini@oca.eu