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Towards a complete picture of the evolution of planetary systems around evolved stars

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Abstract. Solar-like stars evolve through the Asymptotic Giant Branch (AGB) phase. This phase is characterized by increased radii, high luminosities, and significant mass loss. In order to understand the survival of companions during this phase, and explain the presence of planets orbiting white dwarfs, it is essential to examine the orbital evolution of these systems. Several physical mechanisms come into play for AGB stars, such as stellar mass-loss and tidal interactions between the star and its companion. On the one hand, evaluating mass-loss rates and accretion to the companion requires complex radiation-hydro-chemical simulations. On the other hand, the full history of tidal dissipation in low-mass stars during their late stages of evolution, which strongly depends on internal structure and boundary conditions, still requires dedicated studies. Finally a simultaneous treatment of winds and tides is required to predict a planet's orbital evolution.

Keywords. AGB stars, stellar winds and mass-loss, tides, star-planet interactions

1. Introduction

About 95% of all stars in the galaxy have an initial mass lower than 8 $M_\odot$. When these stars evolve off the main sequence, they will go through the Asymptotic Giant Branch (AGB) phase, just before turning into a white dwarf. This phase is characterized by increased radii, high luminosities, intense pulsations, and significant mass loss (Höfner & Olofsson 2018). In order to get a complete picture of the evolution of planetary systems from the birth to the final state of their host stars, as well as to understand the survival of planetary or stellar companions during this phase and explain the presence of planets orbiting white dwarfs, it is essential to examine the orbital evolution of these systems (Mustill & Villaver 2012; Madappatt *et al.* 2016). Several key physical mechanisms come into play for studying orbital evolution around AGB stars, such as the stars significant mass-loss rate, the efficiency of mass accretion onto the companion, and the tidal interactions between the star and its companion.

2. 3D radiation-hydro-chemical simulations of AGB stellar outflows

AGB stars lose a significant amount of mass through a pulsation-enhanced dust-driven wind. Pulsations at the surface of AGB stars push material into sufficiently high layers where it is cool enough for molecules to condensate into dust. These dust particles can be caught by radiation pressure and pushed outwards. Finally, the dust particles collide with the remaining gas particles and create a steady outflow of material (Höfner & Olofsson 2018). Their outflows exhibit complex structures, such as arcs, spirals, disks, and bipolarity where the current theory suggests that they are caused by an unseen companion (Decin *et al.* 2020). To understand this phenomenon, complex 3D radiation-hydro-chemical simulations (see e.g. Fig. 1) are necessary to understand the influence a companion can have on the morphological structures of AGB outflows. These simulations will also allow us to investigate the impact of the companion on the star's mass-loss rate and the efficiency of accretion onto the companion. However, existing simulations are computationally demanding, and ongoing efforts are focused on enhancing the computational speed (Siess *et al.* 2022; Esseldeurs *et al.* 2023).

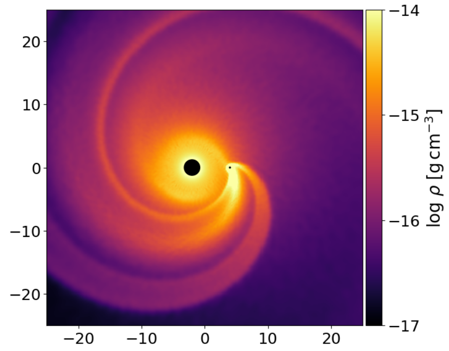

Figure 1: Density profile of a companion-perturbed AGB outflow in a slice through the orbital plane, simulation from Esseldeurs *et al.* (2023).

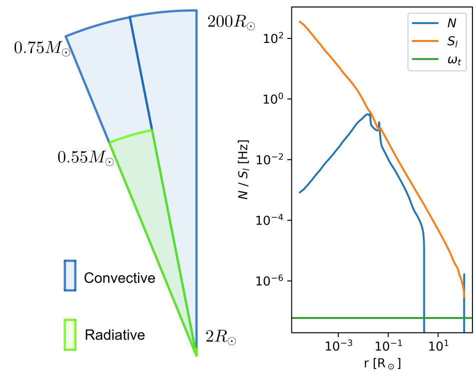

Figure 2: Internal structure (left) and important frequencies for tidal waves; Brunt–Väisälä, Lamb, and tidal frequencies (right) of a 0.75 $M_\odot$ AGB star, computed using MESA (Paxton *et al.* 2011).

3. Identifying tidal dissipation mechanisms around evolved stars

Tidal dissipation encompasses two components: the equilibrium and dynamical tides. The former occurs due to hydrostatic displacement induced by the ellipsoidal deformation triggered by the companion. Its energy is dissipated because of turbulent friction in convective layers, generating transfer of angular momentum between the spin and the orbit (e.g. Zahn 2012; Remus *et al.* 2012). The latter involves stellar oscillation modes excited by the tidal potential. Their dissipation is function of the star's internal structure, depicted on the left of Fig. 2 for AGB stars. On the right, Fig. 2 shows important frequencies for tidally-excited-oscillations: the Brunt–Väisälä and Lamb frequencies, and the tidal frequency our Earth would induce if it were to orbit an AGB star. AGB stars possess a deep convective envelope where inertial modes can be excited (only for stellar companions, as planetary companions don't spin up the star sufficiently) and a radiative core where low-frequency gravity waves are triggered by tides (similar to RGB stars; Ahuir *et al.* 2021). The dissipation of these waves varies depending on the boundary conditions chosen. While for main-sequence stars static boundary conditions are adequate, the substantial mass loss of AGB stars will necessitate the exploration of more suitable boundary conditions, like a dynamical (mass losing) outer boundary.

4. The interplay between winds, pulsations, and tides

Tidal dissipation and mass loss are not problems that can be treated separately. On the one hand, the AGB's dust-driven winds are initiated by pulsations, while the presence of tides may induce additional pulsations. Hence tides can result in an increased mass-loss rate. On the other hand, mass loss may dissipate energy stored in tidal waves moving through the surface of the star. Hence, mass-loss may induce additional dissipation of tidal energy. Finally, both stellar mass-loss and tides induce an orbital evolution of the companion.

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