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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, including stellar mass loss and tidal interactions between the star and its companion. Assessing mass-loss rates and accretion to the companion requires complex radiation-hydro-chemical simulations. Furthermore, comprehending the full history of tidal dissipation in low-mass stars during their late evolutionary stages, which strongly depends on their internal structure, requires dedicated analytical and numerical studies.

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 (WD). 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 evolutionary state of their host star, to understand the survival of planetary or stellar companions during the AGB phase and to explain the presence of planets orbiting WDs, 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 captured by the star's radiation pressure and pushed outwards. Finally, the dust particles collide with the remaining gas particles and create an outflow of material (Höfner & Olofsson 2018). AGB outflows exhibit complex structures, such as arcs, spirals, disks, and bipolarity where the current theory suggests that these 3D structures are caused by an unseen companion (Decin *et al.* 2020). To understand this phenomenon, complex 3D radiation-hydro-chemical simulations (see for example Fig. 1; depicting the density structure of a companion-perturbed AGB outflow with the AGB star on the left and the companion on the right) are necessary to understand the influence a companion on the morphological structures of AGB outflows. However, existing simulations are computationally demanding and ongoing efforts are focused on enhancing computational speed (Siess *et al.* 2022; Esseldeurs *et al.* 2023). These simulations will allow us to investigate the impact of the companion on the star's mass-loss rate and the efficiency of accretion onto the companion, currently unaccounted for.

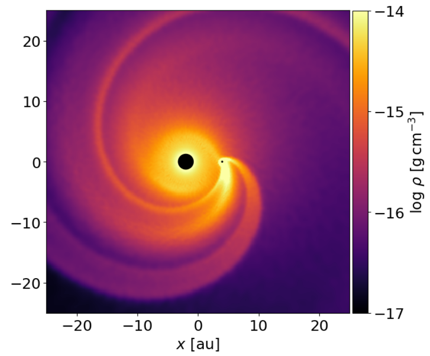

Figure 1: Density structure of a companion-perturbed AGB outflow, shown in a slice through the orbital plane with the AGB star on the left and the companion on the right; simulation from Esseldeurs *et al.* (2023).

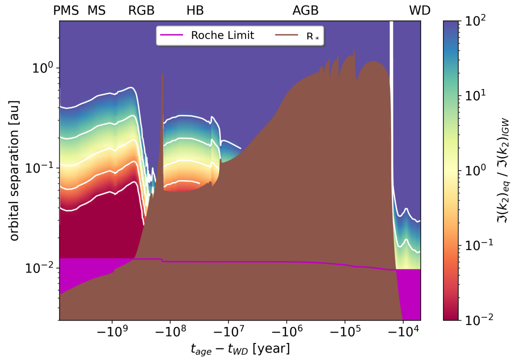

Figure 2: Competing dissipation strengths of the equilibrium ($\Im(k_2)_{eq}$) and dynamical ($\Im(k_2)_{IGW}$) tide as a function of the orbital separation and stellar age (t_{age} upto the age where the star becomes a white dwarf t_{WD}), for a 1.2 $M_\odot$ host star; simulation from Esseldeurs *et al.* (in prep.).

3. Identifying tidal dissipation mechanisms around evolved stars

Tidal dissipation encompasses two components: the equilibrium and dynamical tides. The former occurs due to the 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 1966; Remus *et al.* 2012). This equilibrium tide has been used in studies of AGB stars (e.g. Mustill & Villaver 2012; Madappatt *et al.* 2016), but the dynamical tide has never been formally evaluated during this phase despite its importance for subgiants and RGB stars (Weinberg *et al.* 2017; Ahuir *et al.* 2021). This dynamical tide involves stellar oscillation modes excited by the tidal potential. Depending on the internal structure of the star, as well as the Brunt–Väisälä and Lamb frequency compared to the tidal frequency, different oscillation modes can be exited. In the deep convective envelope of an AGB star, inertial modes in the convective layer can be excited only for stellar companions, as planetary companions don't spin up the star sufficiently. In the radiative core low-frequency progressive gravity waves are triggered by tides, both for stellar and planetary companions (Esseldeurs *et al.* in prep.). Fig. 2 shows how tidal gravity waves compete with the equilibrium tide as a function of the orbital distance of a planetary companion and stellar age for a 1.2 $M_\odot$ host star. In this model, the equilibrium tide is the dominant dissipation mechanism during the AGB phase, while both are important at the white dwarf stage.

4. The interplay between winds, pulsations, and tides

Tidal dissipation and mass loss in AGB stars is currently always treated separately, but these problems are inherently coupled. On the one hand, the AGB's dust-driven winds are initiated by pulsations, which can be enhanced by additional tidally induced pulsations. On the other hand, tidal energy stored in the form of waves can be transported through the stellar wind, enhancing the dissipation. Therefore, it will be necessary to simultaneously treat mass loss and tidal dissipation.

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