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The role of convection and magnetic field in mass loss of evolved cool stars

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Abstract. Red supergiants (RSG) and asymptotic giant branch (AGB) stars produce strong stellar winds, which are not well understood. These winds have a key role in the enrichment of the interstellar medium with chemical elements, which are the building blocks for the next generation of stars. The magnetic field in such stars coupled with the atmospheric dynamics may also affect the stellar wind, since it increases atmospheric velocities and higher temperatures in the chromosphere. The understanding of the stellar wind dynamics is crucial for unveiling the unknown mass-loss mechanism, their chemical composition, and their stellar parameters. The radiative-hydrodynamics code, CO5BOLD, solves the equations of compressible hydrodynamics and non-local radiation transport. It is used to produce 3D grids of global "star-in-a-box" models. In this ongoing study, we used CO5BOLD to perform simulations of RSG and AGB so we analyze and better understand the mechanisms and rate of mass-loss of such stars related to convection and magnetic field. We could compare the differences between our AGB and RSG models regarding density, velocity, pressure and B field, and found that magnetic fields could be part of the mass-loss mechanism in RSGs.

Resumo. Estrelas supergigantes vermelhas (RSG) e do ramo das gigantes assintóticas (AGB) produzem fortes ventos estelares, que não são bem compreendidos. Esses ventos têm um papel fundamental no enriquecimento do meio interestelar com elementos químicos, que são os blocos de construção para a próxima geração de estrelas. O campo magnético nessas estrelas aliado à dinâmica atmosférica também pode afetar o vento estelar, uma vez que aumenta as velocidades atmosféricas e temperaturas mais altas na cromosfera. O entendimento da dinâmica do vento estelar é crucial para desvendar o mecanismo desconhecido de perda de massa, sua composição química e seus parâmetros estelares. O código de hidrodinâmica radiativa, CO5BOLD, resolve as equações de hidrodinâmica compressível e transporte de radiação não local. Ele é usado para produzir grades 3D de modelos globais "star-in-a-box". Neste estudo, ainda em andamento, usamos CO5BOLD para realizar simulações de RSG e AGB para analisar e entender melhor os mecanismos e a taxa de perda de massa dessas estrelas relacionadas à convecção e ao campo magnético. Pudemos comparar as diferenças entre nossos modelos AGB e RSG em relação à densidade, velocidade, pressão e campo B, e descobrimos que os campos magnéticos podem ser parte do mecanismo de perda de massa em RSGs.

Keywords. Stars: AGB and post-AGB – Stars: supergiants – Stars: mass-loss – Magnetohydrodynamics (MHD)

1. Introduction

Evolved cool stars, such as red supergiants (RSG) and asymptotic giant branch (AGB) stars, are major cosmic engines. They enrich their environment with chemical elements, which are the building blocks of the planets and life. RSG stars are late-type stars which luminosities place them among the brightest stars, and they are visible up to very large distances (Chiavassa et al. , 2011). Detailed simulations of RSGs (Freytag et al. , 2002; Freytag & Höfner , 2008; Chiavassa et al. , 2009, 2010) show that these stars are characterized by vigorous convection, which imprints a pronounced granulation pattern on the stellar surface. AGB stars are very bright, have a strong influence on integrated-light properties (Bruzual & Charlot, 2003), and are associated with characteristic phenomena such as pulsation, dust formation, and mass loss through massive stellar winds (Freytag & Höfner , 2008). These processes play an important role in the evolution and for observable properties of both individual cool giants and stellar systems since AGB stars are major contributors to the chemical enrichment of the interstellar medium and to the integrated light of galaxies.

The energy produced in the solar core is transported outward by radiation, then further out primarily by convection, and finally most of this energy is emitted in the form of radiation in the photosphere. However, a small part of the energy is carried by waves and by magnetic fields, driving stellar activity phenomena in the solar chromosphere and corona (Freytag et al. , 2002; Wedemeyer-Böhm et al. , 2012). In RSGs and AGBs the internal structure is more complex, with several shells of nuclear fusion and multiple convection zones. To access the physical processes from the inner shells to the outer layers of stellar atmosphere, physical models of stars with a realistic treatment of both radiation and convection are essential.

It is crucial to have a detailed understanding of wind physics across the life cycle of these stars as well as in relation to their cosmic environment. Strong mass-loss may be related to the interplay of convective motions, acoustic waves, magnetic field, and radiation pressure on molecular lines and/or dust. Therefore, the main topics we investigate are: how the winds are launched and which physical processes determine their properties, and how do the mass-loss rate and other wind properties depend on fundamental stellar parameters. In this work-in-progress study, part of the ANR funded project PEPPER, we perform global simulations of evolved cool stars, including the magnetic field, and analysis of mechanisms related to winds and mass-loss of such stars, in to understand and characterize the link between convection and magnetic field in the stratification of stellar atmosphere.

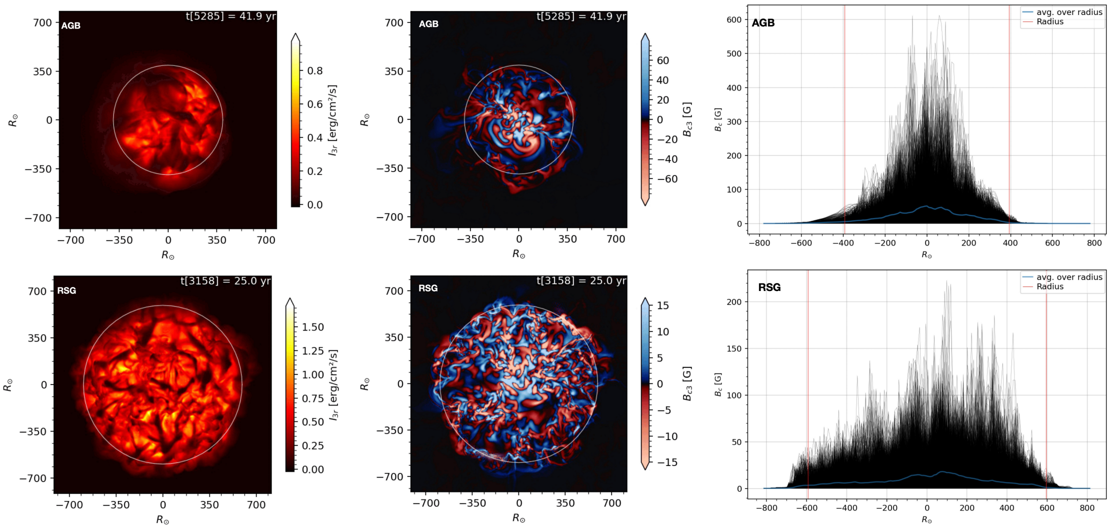

Figure 1. Bolometric intensity (left panels) and magnetic field (center and right panels). The upper panels are for the AGB model and the lower panels are for the RSG model. *Left panels:* the white circle represents the apparent radius of the stars, which is an average over time, and it was defined where optical depth, $\tau = 1$, by the Rosseland approximation. Above the circles, there are the atmosphere and outer layers of the stars. *Center panels:* observer's line of sight component of the magnetic field, B_z. The white circle represents the apparent radius of the stars. *Right panels:* distribution of B field intensity, $|B| = \sqrt{B_x + B_y + B_z}$. Zero in x-axis is the center of the star, the red lines are the stellar radius, and the blue lines are the $|B|$ average over radius..

2. Methodology

We performed global simulations (star-in-a-box setup) of a RSG and an AGB star. For that we use the COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions (CO^{5}BOLD; Freytag et al. , 2002; Freytag & Höfner , 2008; Freytag et al. , 2012; Riva & Steiner , 2022). This is a radiation magnetohydrodynamics (RMHD) code for the computation of compressible convection in a 3D box, that reproduces convective effects of the star, uses detailed microphysics under the conditions in stellar surface layers, and the equations of ideal magneto-hydrodynamics, including gravity and radiative energy exchange. The computational domain is a cubic grid, and the same open boundary condition is employed for all sides of the computational box.

In this work we are focused on the magnetic field influence on the models, since the presence of magnetic fields results in a wide range of additional complex 3D phenomena (Freytag et al. , 2012). Small-scale concentrations of magnetic flux lead to enhanced radiative losses, both in the photosphere and in the chromosphere (Freytag et al. , 2012). The interaction of convection and magnetic fields can be modeled in the framework of (ideal) MHD.

We use hydrodynamical (without magnetic fields) models that are already relaxed, *i.e.* simulations which the stellar parameters fluctuations are stable. Then we add an initial torus-shaped magnetic field close to the center of the star of 0.5 G and run the simulations until the magnetic energy saturates. The AGB model refers to a star of 1 $M_\odot$, 7000 $L_\odot$, 393 $R_\odot$, $T_{\rm eff}$ of 2660 K, log g of −0.75, and spatial resolution of 317^3 grid points. The RSG model has the following parameters: 5 $M_\odot$, 41,200 $L_\odot$, 594 $R_\odot$, $T_{\rm eff}$ of 3370 K, log g of −0.41, and spatial resolution of 315^3 grid points. The simulated time were respectively 42 and 25 years, which were the necessary period for the simulation to get stable stellar parameters. The bolometric intensities and radii of both models are shown in the left panels in Figure 1.

3. Preliminary Results and Discussion

The convection cells of the AGB model are larger than those of the RSG model, due to a lower mass and also the radius (left panels in Figure 1). The size of the convective surface cells relative to the stellar radius scales well with $R_\star$ / $M_\star$. Temperature, energy and log g are lower, as pressure scale height is higher, which makes the AGB to have a more diluted atmosphere. The magnetic field is higher and more concentrated in the center of the AGB model (center and right panels in Figure 1).

Figure 2 shows the logarithm of density, log $|\rho|$, logarithm of gas pressure, $|P_{\rm G}|$, logarithm of magnetic field intensity, log $|B|$,for both the AGB (left panels) and the RSG model (right panels). These 2D representations are the parameters averages taken from 20 central slices over the z-axis. One may observe that shock waves happens where the log ρ and log $P_{\rm G}$ decreases. Similar patterns can be seen in log $|B|$, due to the convection-magnetic connection.

Regarding the $P_{\rm T}$ / $P_{\rm G}$ ratio (center panels in Figure 3) the AGB model shows higher increase above the radius than the RSG model, however it is lower in the outer layers of the stellar atmosphere. Radial velocity decreases right above the radius and increase in the outer layers, steeper in the RSG model (left panels in Figure 3). In the non-magnetic AGB model (cyan line) radial velocity has a lower increase in the outer layers compared to the model with magnetic field. That may indicate the magnetic fields play a significant role for the wind-formation process.Also, above the radius in the AGB model the Alfvén velocities are higher than in the RSG model (right panels in Figure 3). However, in the AGB's outer layers it decreases whereas it increases in the RSG.

4. Final Considerations

This is a work in progress and we are running different models with different initial magnetic fields. The next stjpg of our work are (a) to improve the grid of simulated models regarding different magnetic fields intensity and directions, and different boundary conditions, (b) to create a grid of models to provide

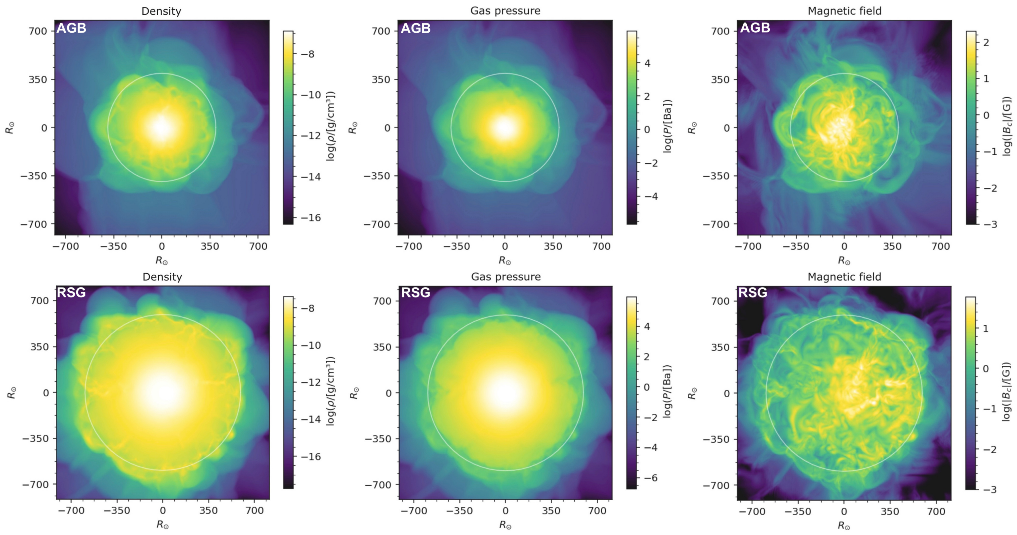

Figure 2. 2D representations of the parameters averages taken from 20 central slices over the z-axis: logarithm of density, log $|\rho|$, logarithm of gas pressure, $|P_\mathrm{G}|$, and logarithm of magnetic field intensity, log $|B|$ for both the AGB (upper panels) and the RSG model (lower panels).

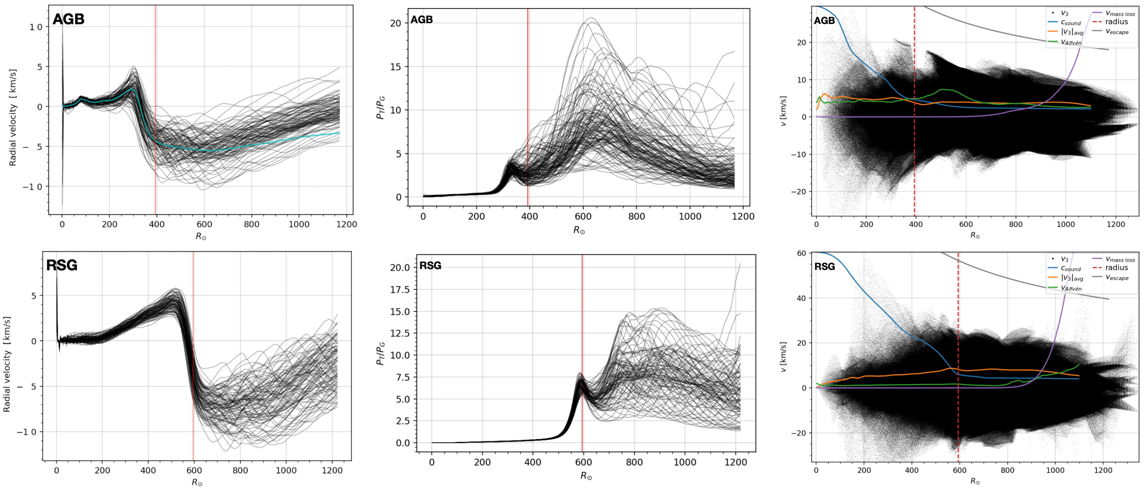

Figure 3. Radial velocity over radius (left panels), ratio of turbulent pressure and gas pressure, P_T / P_G, over radius (center panels), and Velocities over radius (right panels). The upper panels are for the AGB model and the lower panels are for the RSG model. *Left panels:* each line corresponds to a snapshot over the last 20 years (AGB) and 10 years (RSG) of the simulations. The cyan line corresponds to the no-B-field model, and the red lines are the stellar radius. *Center panels:* each line corresponds to a snapshot over the last 20 years (AGB) and 10 years (RSG) of the simulations. The red lines are the stellar radius. *Right panels:* velocities over radius (last snapshot). Black dots are radial velocity distribution, blue lines are sound speed, orange lines are radial velocity averages, green lines are Alfvén velocity, gray lines are escape velocity, and dashed red lines are stellar radius.

spectropolarimetric observables in the framework of PEPPER, and (c) to investigate how magnetic field impacts the outer layers stratification: velocity, density, mass-loss.

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