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PHOTOCENTRE DISPLACEMENT OF RHD SIMULATIONS OF AGB STARS AND CORRELATION WITH STELLAR PARAMETERS

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Abstract.
The evolution of stars with low to intermediate masses culminates in the Asymptotic Giant Branch (AGB) phase. During this phase, these stars undergo intricate dynamics marked by several processes, including convection, pulsation, and shockwaves. These processes give rise to strong stellar winds that significantly enhance the interstellar medium with various chemical elements. Over time, this enrichment has implications for astronomical measurements, amplifying uncertainties in the determination of essential stellar parameters. Furthermore, the development of convection-related structures on the surfaces of evolved stars leads to temporal fluctuations in the position of the photocentre. This variability influences Gaia measurements, where it contributes substantially to the uncertainties associated with parallax. In this work, we used 3D radiative-hydrodynamics simulations of stellar surface convection, computed with CO^5BOLD, to study the photocentre displacement and possible correlations with stellar parameters. This is done for 31 AGB simulations. Ultimately, our objective is to develop a systematic approach, a roadmap, for quantitatively determining the surface gravities of AGB stars from Gaia data, taking into account the inherent uncertainties, and leveraging tailored radiative-hydrodynamics simulations to enhance precision.

Keywords: stars: atmospheres, stars: AGB and post-AGB, astrometry, parallaxes, hydrodynamics

1 Introduction

After the main sequence, low- to intermediate-mass stars evolved into the Asymptotic Giant Branch (AGB). Their effective temperature is around $3300K$ and their luminosity ranges from 2000 to $10000L_{\odot}$ (Decin 2021). They are characterized by dynamics encompassing convective motions, pulsation, shockwaves... which induce strong winds, at a $10^{-8} - 10^{-5}M_{\odot}/yr$ mass-loss rate (De Beck et al. 2010) that enrich massively the interstellar medium in gas and dust (Höfner & Olofsson 2018).

Mira stars are peculiar AGB stars whose envelope is pulsating over a period from 100 to 1000 days, resulting in large-amplitude variations in radius, brightness and temperature of the star, above 2.5 magnitude in the V band for example (Decin 2021). As a consequence, it is difficult to accurately measure their stellar parameters and astrometric properties (Gaia Collaboration et al. 2019).

Chiavassa et al. (2018, 2022) used three-dimensional (3D) radiative hydrodynamic simulations of convection with CO^5BOLD and determined the impact of temporal variability of convection-related surface structures on the position of the photocentre. Its position does not coincide with the barycentre of the star as the surface pattern changes with time. These movements are up to $5 - 10\%$ of the stellar radius, depending on the stellar parameters, in particular the surface gravity. Moreover, Chiavassa et al. argued that this variability accounts for a substantial part of the Gaia parallax uncertainty.

These earlier works demonstrated the principle but were limited by the number of 3D simulations used. In this paper, we provide an extension of their works based on a larger grid of simulations with stellar parameters covering a larger portion of the Hertzsprung-Russell diagram. The objective is to obtain analytical laws allowing the extraction of the surface gravity from Gaia parallax uncertainty.

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2 Methods

We used radiative-hydrodynamics (RHD) simulations of AGB stars (from Freytag et al. 2017; Chiavassa et al. 2018; Ahmad et al. 2023, and private communication) computed with CO^5BOLD code (Freytag 2012). The code solves the coupled non-linear equations of compressible hydrodynamics and non-local radiative energy transfer, assuming solar abundances. The configuration is a "star-in-a-box" which describes the dynamics of the convective envelope and the inner atmosphere. Additionally, the simulations covers the range 2500 to $3300K$ in effective temperature, $\log(g)$ (surface gravity) spans values between -0.85 and 0.16, $2000-10000L_\odot$ in luminosity, 130 to $440R_\odot$ in stellar radius and 100 to 600 days in pulsation period (see details for computation of stellar parameters in Ahmad et al. 2023).

We post-processed a set of temporal snapshots using the radiative transfer code Optim3D (Chiavassa et al. 2009), which takes into account the Doppler shifts, partly due to convection, in order to compute intensity maps (Figure 1) integrated over the Gaia G band [320-1050 nm].

For each map, we then calculated the position of the photocentre as the intensity-weighted mean of the x-y positions of all emitting points tiling the visible stellar surface according to :

$$P_x = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} I(i,j) * x(i,j)}{\sum_{i=1}^{N}\sum_{j=1}^{N} I(i,j)} \tag{2.1}$$

$$P_y = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} I(i,j) * y(i,j)}{\sum_{i=1}^{N}\sum_{j=1}^{N} I(i,j)} \tag{2.2}$$

where $I(i,j)$ is the emerging intensity for the grid point (i,j), with coordinates $x(i,j)$, $y(i,j)$ of the intensity map in solar radii, and N the total number of grid points in the simulated box (from 281 to 637). The position of the photocentre doesn't coincide with the barycentre of the star as large convective cells result in intensity asymmetries.

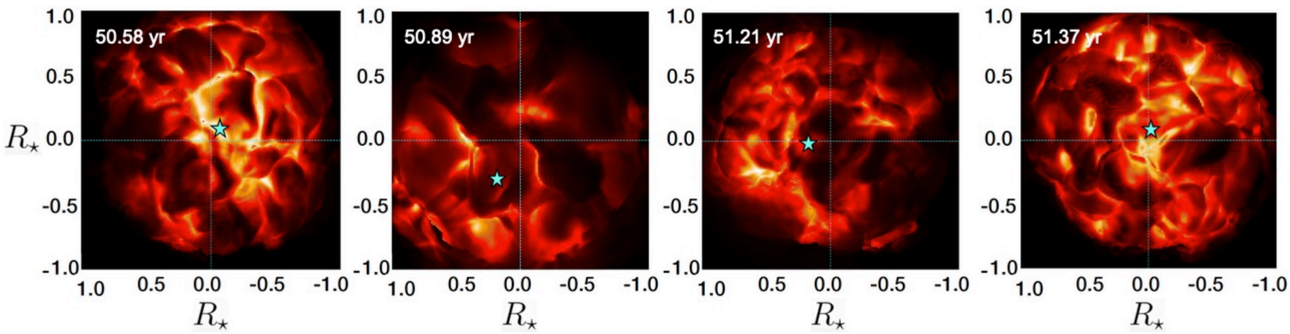

Fig. 1. Intensity maps of an AGB simulation in $erg.s^{-1}.\AA^{-1}$. The dashed lines intersect at the geometric center of the image. The star indicates the position of the photocentre at the given time.

Each snapshot of the simulation is spaced by ~ 60 days, for the simulations we used. We use ~ 100 snapshots for each simulation which gives the temporal variability of the photocentre moving across the stellar surface. We also computed the mean position of the photocentre and its standard deviation σ_P. Figure 2 displays an example of how the photocentre changes its position, the red dot indicates the mean position and the red circle the standard deviation. Figure 2 also displays how the photocentre displacement is correlated with the surface gravity. The displacements are larger when $\log(g)$ is lower ($\log(g)$=-0.36, left panel) with respect to a more compact behaviour with larger gravity ($\log(g) = 0.16$, right panel).

3 Correlation between the photocentre displacement and stellar parameters

From the study of the 31 simulations, the standard deviation of the photocentre displacement ranges from ~ 4 to 13% of the corresponding stellar radius, consistent with Chiavassa et al. (2018).

Figure 3 (left panel) displays that the logarithm of the pulsation period is decreasing with the logarithm of the surface gravity. Moreover, a correlation between the logarithm of the pulsation period and σ_P is visible in

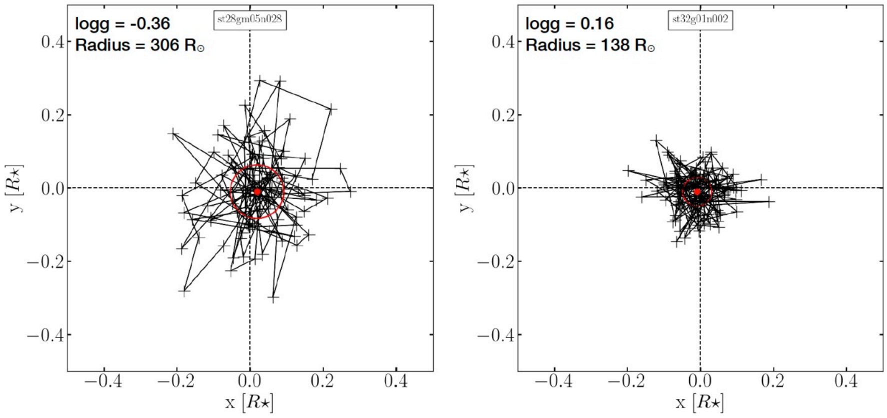

Fig. 2. Photocenter displacement of two different simulations: the red dot corresponds to its mean position and the red circle to its standard deviation. **Left:** Low surface gravity. **Right:** High surface gravity.

Figure 3 (right panel). The pulsation period gives important information about stellar interior (density) with hints on global shocks induced by large-amplitude, radial, and fundamental-mode pulsations.

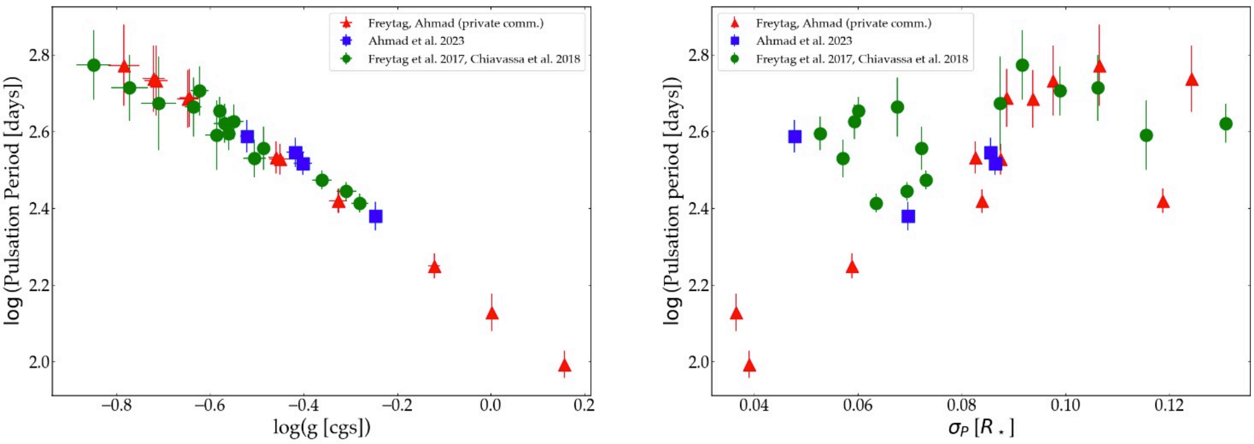

Fig. 3. Left: Log-log plot of pulsation period against surface gravity. We observe a correlation between the two parameters. **Right:** The pulsation period in logarithmic scale against σ_P. We suggest a fit with a power law whose parameters still need to be properly determined.

Figure 4 (left panel) displays a mild correlation between σ_P and stellar luminosity that further analysis will help characterise. Finally, we see a mild correlation between σ_P and the surface gravity (see Figure 4 right panel and Figure 2) as it is expected from the relations inferred in Figure 3. Interplay between large-scale convection and radial pulsations results in the formation of giant and bright convective cells at the surface. Freytag et al. (2017), and references therein, argue the size of the cells is governed by the pressure scale height. Thus, lower surface gravity means larger cells. Then, large convective cells result in intensity asymmetries, directly causing temporal fluctuations of the photocentre.

4 Followings project : exploitation of Gaia data

The next steps in our project concern the comparison of the 3D simulation predictions to Gaia data, aiming at characterising the photocentre variability hidden in Gaia uncertainty on parallax measurements of AGB stars, where convection-related variability accounts for a substantial part of it (Chiavassa et al. 2018, 2022). The final idea is to quantitatively extract the fundamental properties of AGB stars, such as surface gravity and pulsation, directly from Gaia parallax uncertainty thanks to appropriate RHD simulations. We will proceed as follows:

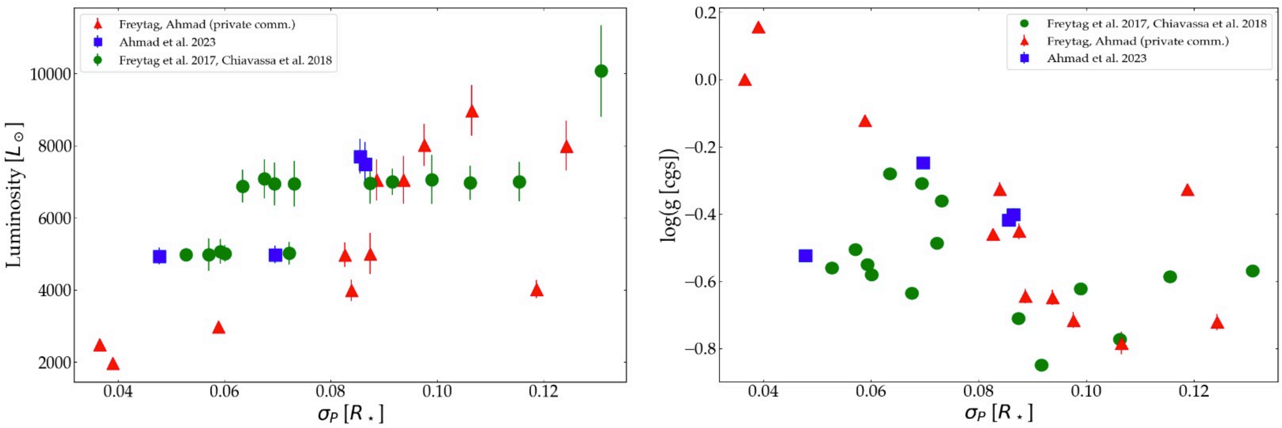

Fig. 4. Left: Luminosity against σ_P. We might find a mild correlation. **Right:** Surface gravity in logarithmic scale against σ_P. We can observe some correlation as it is expected.

- Starting from the simulations, we will provide analytical laws based on the photocentre displacement (σ_P) versus surface gravity and pulsation period ;
- Secondly, we will provide a comparison of the measured Gaia DR3 (Gaia Collaboration et al. 2016, 2023) uncertainty on parallax measurements of a sample of Mira stars (Uttenthaler et al. 2019) to our predictions of photocentre displacement ;
- Eventually, thanks to the analytical laws based on the RHD simulations, we will provide the log(g) of the observed stars.

In the end, combining our global 3D simulations with Gaia data will make it possible to systematically provide stellar parameters (surface gravity and pulsation) of AGB stars in an unique way. This work is on-going (Béguin et al., in prep.).

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