Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
Proceedings IAU Symposium No. 343, 2019
F. Kerschbaum, M. Groenewegen & H. Olofsson, eds.

doi:10.1017/S1743921318006117

Lumpy stars and bumpy winds

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Abstract. The wind-driving process of AGB stars is thought to be a two-step process: first matter is levitated by shock waves, and then accelerated outwards by radiation pressure on newly condensed dust grains. When modelling such a wind, spherical symmetry is usually assumed. This is in stark contrast with recent observations, which shows significant non-spherical structures. Giant convection cells cover the surface of the star, and matter is being ejected into the atmosphere where it condenses into lumpy dust clouds. We try to quantify the differences between what is simulated in the 3D star-in-a-box models (CO5BOLD code) and the 1D dynamical atmosphere and wind models (DARWIN code). The impact of having a non-spherical star on the wind properties is also investigated. We find that the inherent non-spherical behaviour of AGB stars might induce a dust-driven weak wind already early on the AGB, and including that the star is anisotropic when simulating the wind leads to large time variations in the density of the outflow. Such variations might be observable as small-scale structures in the circumstellar envelope.

Keywords. Evolved stars, AGB stars, Stellar winds

1. Introduction

From both 3D models and from high-angular observations it has become increasingly obvious that AGB stars are not only highly variable, but they also have a complex non-spherical morphology. Near-IR interferometric imaging of the surface layers shows variable bright spots, and inhomogeneous distributions of molecules (Haubois *et al.* 2015), which indicates the presence of giant convection cells. As mentioned by Kamiński *et al.* (2016), the inhomogeneous distribution of molecules should influence the dust formation around AGB stars. At distances of 2-3 stellar radii ($R_\star$) dust forms intermittently in clumpy clouds, instead of in spherical shells (Khouri *et al.* 2016). Such non-spherical structures in both the surface layers and in the inner atmosphere also arise in the 3D models of AGB stars. When modelling the AGB star dust-driven wind, however, spherical symmetry is usually assumed. While there are no 3D wind models (yet), attempts to evaluate the effects of a non-spherical star on the stellar wind are outlined here. For an in detail description of the results, see Liljegren *et al.* (2018).

2. Anisotropic morphology and stellar wind

The wind-driving mechanism in AGB stars is a two-stage process; the pulsations of the star eject material into the atmosphere, and when the temperature is low enough dust will condense. This dust interacts with the radiation field through either absorption or scattering, and is accelerated outwards, which induces a wind. Here the dynamical atmosphere and wind driving are described with the DARWIN code, which features frequency-dependent (non-grey) radiation hydrodynamics and includes time-dependent non-equilibrium growth of dust (for details see Höfner *et al.* 2016). The inner boundary of

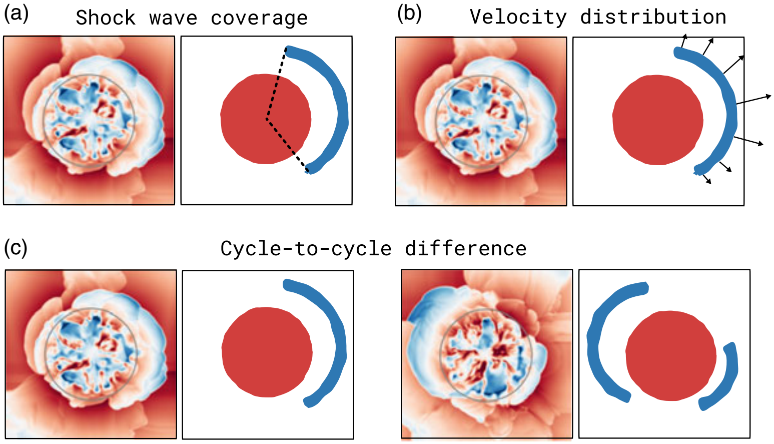

Figure 1. Plot showing three processes present in the 3D models, but not in the 1D models. The left subplot is the radial velocity (blue: outgoing gas, red: in-falling gas), while the right subplot is a schematic picture with the red circle representing the star and the blue arc representing the shockwave of a 3D model.

the DARWIN models is set just below the photosphere at $\sim 0.9\, R_\star$ and the outer boundary is typically located around $\sim 25\, R_\star$, where the wind has reached its final velocity v_∞. It is however unknown to what extent any deviation from spherical symmetry, which is a core assumption in the DARWIN models, will affect the mass-loss rate predictions.

While the extended atmosphere and the wind driving cannot yet be modelled in 3D, there are 3D models of the interior and the inner atmosphere. The CO^{5}BOLD radiation hydrodynamical code has been used in e.g. Freytag *et al.* (2017) to simulate the AGB stars. These are 3D star-in-a-box models where the full star is described. While some parts of the atmosphere are covered as the models reach as far as $\sim 2\, R_\star$, no dust-gas interaction is included in the code.

These two modelling methods describe vastly different parts of an AGB star. However, they have a region above the stellar photosphere, but below the dust condensation distance at $\sim 1 - 2\, R_\star$, where they overlap. In this region the pulsations and the ballistic motions of the gas dominate the dynamics. In the DARWIN models the behaviour at these distances is very much a consequence of the choice of inner boundary conditions. The atmospheric dynamics of the CO^{5}BOLD models, however, depend on shock waves triggered by pulsations that emerge in the simulations.

This overlap region can be used to compare the gas dynamics in the two model approaches, to try to deduce what impact the 3D effects present in the CO^{5}BOLD models might have on the wind driving. There are three major differences;

(*a*) **Shock wave coverage.** The anisotropy present in the 3D models also means that while the shock waves are of global scale they do not cover the full surface, which is clearly seen in Fig. 1, panel a).

(*b*) **Velocity distribution in the shock.** In contrast to the 1D models, the shock fronts in the 3D models display non-spherical structures. In the DARWIN models the velocity in the shockwave at a certain time and distance is always the same, while this is not the case in the 3D models (Fig. 1, panel b)).

(*c*) **Cycle-to-cycle variations.** In the 3D models there are also large cycle-to-cycle variations in both the direction and size of the shockwave. This can be seen in panel c) of Fig. 1.

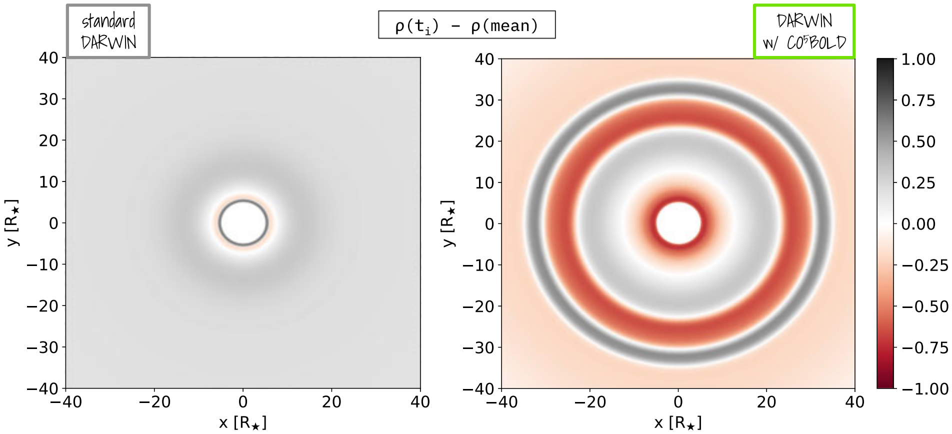

Figure 2. The density fluctuation in the wind of a snapshot of a standard DARWIN model (left), and a DARWIN model with CO^{5}BOLD input (right).

3. Wind models with 3D input

As there are no 3D wind models available (yet) we try to imitate reality by constructing 1D DARWIN models with 3D CO^{5}BOLD model input, to estimate the effect of non-spherical morphology. By using the light curves from the CO^{5}BOLD models combined with derived radial motions, the impact of the anisotropic structures and irregular behaviour on the wind properties can be studied. The inner boundary condition is then also derived from independent modelling of the pulsations, in contrast to the parameterised standard boundary condition.

When comparing the standard DARWIN models with DARWIN models with 3D input, we find that there are no large differences in the averaged wind properties. Rather, the models with boundary conditions derived from the CO^{5}BOLD models have both similar mass-loss rates and wind velocities to the standard case. There is however a large difference when looking at the time evolution of the wind properties. For the standard DARWIN models the mass-loss rates typically vary little with time, indicating a steady wind. However models based on CO^{5}BOLD input can have drastic variations in both wind velocity and mass-loss rates over the simulation period, with the mass-loss rate varying up to an order of magnitude on time scales of 10-20 years. It seems like the anisotropy of the stellar interior and the atmosphere, present in the CO^{5}BOLD-derived model, is imprinted on the outgoing wind. Fig. 2 shows the density fluctuation ($\rho(t_i) - \overline{\rho}$) of a standard DARWIN model and a DARWIN model modified with CO^{5}BOLD input. As seen, there are significant density variation in the DARWIN model with CO^{5}BOLD input, which might be large enough to create observable structures further out in the circumstellar envelope. Wind-wind interaction models with larger distance range than the standard DARWIN models are however needed for any decisive conclusions.

4. Dust-driven wind of less evolved AGB stars

A shock front moving through the atmosphere in a DARWIN model will have the same velocity at a certain time. In the 3D models, however, the anisotropy means that the velocities in the shock front depend on direction. The shock front velocity will then be a distribution, which could have consequences when trying to model the wind for less evolved AGB stars (Fig. 3). While the mean of such a distribution, which is essentially what the DARWIN models try to emulate, might be too low to induce a dust-driven wind, the velocity can locally be larger. It is then possible that some material is levitated to

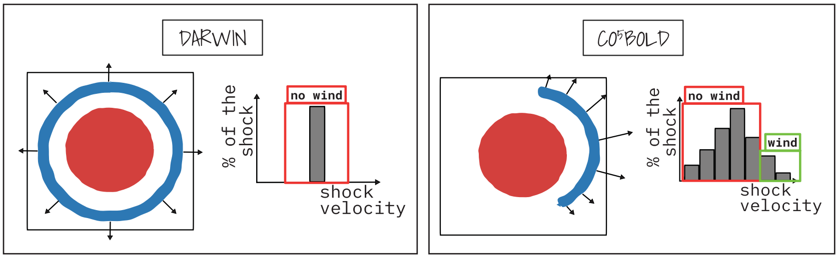

Figure 3. The shock front in the 1D case (left) and in the 3D case (left), with the associated velocity distribution in the shock.

distances where dust can form, creating a weak and maybe intermittent dust-driven wind earlier on the AGB than indicated by the standard DARWIN models. This is, however, still speculative, and both CO^{5}BOLD models and DARWIN models in this parameter space are needed to investigate this further.

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Discussion

Lançon: The 3D models predict large variations in $\dot{M}$. Do you have enough models to see if there is a correlation between dust extinction along a line of sight to the star, and either phase or the presence/strength of shocks.

Liljegren: We have not yet produced synthetic observables for these models, so we don't know. Such investigation are however in future plans.

Sahai: How do your results compare to those by an older work by V. Icke which also created density variations/$\dot{M}$ variations, which I proposed could be an explanation for the shells in the AGB envelope of the Egg Nebula as seen in HST imaging (Sahai et al. 1998,1999). The time scale for variations there is ≈ 100–200 yr.

Liljegren: We don't yet know what happens with the density variations further out in the circumstellar envelope, but we are very interested to try to model these structures.