Hidden extra dimensions in dusty stellar winds

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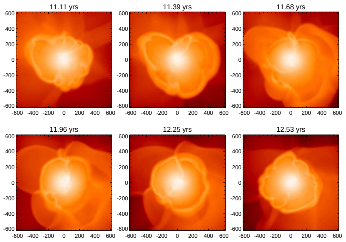
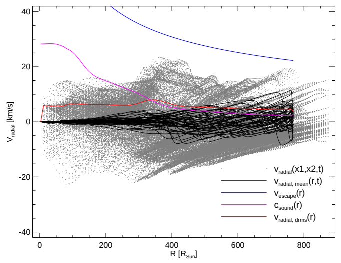
3D star-in-a-box model

Three-dimensional radiation hydrodynamics simulations of the outer stellar convection zone and the inner atmosphere of an AGB star ($T_{\rm eff}$=2800 K, M=1 $M_{\rm Sun}$, R=350 $R_{\rm Sun}$) were performed with *CO5BOLD* (see table).



The figure above displays a time series of cuts through the center of the computational box, showing the gas density. The models exhibit huge convection cells, pulsations, and shock waves running into the outer atmosphere.

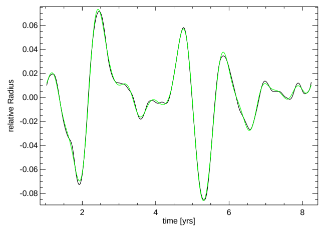


Typical radial velocities are of the order of 10 km/s. Maximum values lie around 20 km/s. Averages over spherical shells give the radial part of the velocities (black lines in the figure above). They account for a considerable part of the motions (grey points) in the outer atmosphere, but only for a small fraction inside the convective envelope (R<350 $R_{\rm Sun}$).

3D → 1D: Extraction of piston movement

The 3D models cover only the inner part of the atmosphere and do not span long enough time intervals to study the formation of a wind, yet. However, the restriction to spherically symmetric models allows this and the inclusion of more detailed micro-physics (see table).

To couple both types of simulations we first average the density of the 3D models over spherical shells. Integration over radius gives the mass contained within a certain radius at a given time step. It also gives the radial coordinate of a mass shell over time.



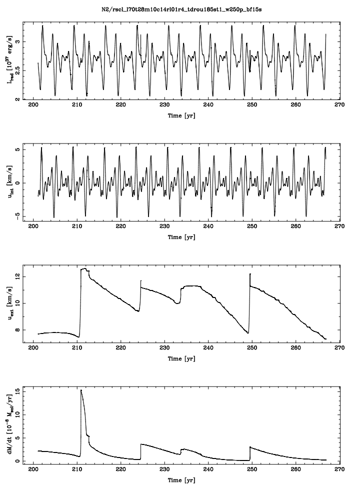
The relative radial variations of a mass shell close to the stellar surface are plotted here (black curve) for an interval where the first and last point fit nicely together. Retaining the first 14 components of a Fourier decomposition gives a smooth, perfectly periodic curve (green), which is then fed into the 1D models to describe the variable location of the inner boundary (piston).

Abstract

Pulsation, dust formation, and mass loss through massive stellar winds are characteristic phenomena associated with Asymptotic Giant Branch (AGB) stars. These processes influence both the observable properties and the further evolution of these objects. During the past decade, major progress has been made regarding modelling of dynamical atmospheres and winds of cool giants, and the models are reaching a stage where they can be used for quantitative interpretation of spectra and prediction of mass loss rates. Such models, however, rely on stellar pulsation properties as external input, typically in the form of variable inner boundary conditions ('piston models'), while realistic modelling of pulsations of AGB stars is a notorious problem. In this contribution, we report ongoing work combining spherically symmetric dynamical models for atmospheres and winds (including detailed microphysics) with 3D 'star-in-a-box' radiation hydrodynamical models for interiors of AGB stars (based on simpler input physics). In particular, we focus on how variable boundary conditions for the spherical models can be extracted from the 3D models, and we show first results obtained by applying these more complex boundary conditions to our atmosphere and wind models.

Feature	3D RHD (CO5BOLD)	1D RHD
Region	outer convection zone and photosphere	photosphere and wind formation region
Hydrodynamics	compressible, incl. ionization	compressible
Radiation	non-local short characteristics	non-local long characteristics + Eddington tensors
Rad. pressure	no	yes
Opacity	grey	sampling (50 wavelength points)
Gravity	prescribed potential	via Poisson equation
Dust	–	4-moment formalism
Inner boundary	constant heating	piston (variable membrane)
Outer boundary	open	open

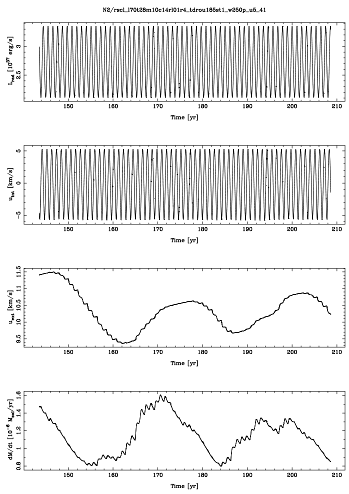
1D wind model: piston from 3D model



The figure above shows first results obtained with the detailed spherical RHD code using a boundary condition derived from the 3D model described earlier. The two top panels show the resulting luminosity variations and the velocity in the innermost shell of the model (close to the piston). The remaining quantities in the lower panels are the outflow velocity of the stellar wind and the mass loss rate (in units of 10^{-6} $M_\odot$/yr). Note that the time scales for the variations in the wind are much longer than the variation due to the inner boundary (piston), and that the variations of wind velocity and mass loss rate are considerable during the time interval of 70 years plotted here.

It should be noted, that we have increased the relative variations of the inner boundary by a factor of 1.5 compared to the values derived form the 3D model since the original amplitude was not sufficient to produce a stellar wind for a star with the given parameters (and C/O = 1.4). This, however, is not unreasonable: as discussed above, the spherical mean of the radial velocities is rather small compared to the actual local values encountered in the 3D model at the location of the piston

1D wind model: sinusoidal piston



For comparison, we also show a wind model with a sinusoidally moving piston and a corresponding velocity amplitude of 5 km/s. This amplitude is comparable to the maximal variations seen in the wind model with the boundary condition taken from the 3D model. The sinusoidal model with the 5 km/s amplitude produces a mean mass loss rate and outflow velocity comparable to the non-sinusoidal wind model (but with smaller temporal variations). A sinusoidal model with a piston of 3.5 km/s (which is probably closer to the average piston velocity in the non-sinusoidal case), however, is found to have a much lower mass loss rate and wind velocity.

Conclusions

- The 3D convection models give reasonable radial velocities.
- In the wind models, the mass loss rates are mainly determined by the maximum velocities of the piston.
- The two extra dimensions hidden in the piston influence the temporal behaviour of the wind.