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Introduction and Background

Asymptotic giant branch (AGB) stars are low- and intermediate mass stars which have gone through the phases of hydrogen burning and core helium burning, and are now producing their energy by alternate burning of hydrogen and helium in shells surrounding a degenerate core consisting of carbon and oxygen. The coolest and most luminous of these AGB stars are undergoing heavy mass loss due to slow winds, a phenomenon which dramatically influences their evolution. Eventually, mass loss becomes the dominant factor, transporting material away from the stellar surface faster than nuclear reactions change the stellar interior. The material expelled from the stars through stellar winds contributes to the enrichment of the interstellar medium with newly formed elements and thus to the chemical evolution of galaxies.

The most widely accepted scenario for the formation of these winds is based on a two-step process: stellar pulsation causes propagating shock waves which lead to a levitation of the outer atmospheric layers. The dense, cool environment of these layers makes the formation of molecules and dust grains much more efficient than in a static atmosphere. Subsequently, radiation pressure accelerates the newly formed dust grains and the gas in the levitated zones away from the star. In this context, molecules play a key role both for the formation of these winds, and for determining their properties from observations.

Wind Models

We have developed a new generation of models describing dynamical atmospheres and winds of cool giant stars (Höfner et al. 2003, A&A 399, 589). These models combine time-dependent dynamics with both, frequency-dependent radiative transfer and non-equilibrium dust formation. They bridge the gap between classic hydrostatic model atmospheres which put the emphasis on detailed radiative transfer but neglect the effects of stellar pulsations and winds, and previous generations of time-dependent wind models which only include crude (grey) radiative transfer, resulting in unrealistic atmospheric structures. All three ingredients, dynamics, non-grey radiative transfer (including molecular opacities) and a detailed description of dust formation, are crucial for consistent models stretching from the atmospheric layers into the circumstellar envelope, and, consequently, for a reliable interpretation of observations.

The models span a region starting just below the stellar photosphere and reaching out to typically 20 to 30 stellar radii. At this distance from the star the outflows have usually reached their asymptotic behavior in terms of wind velocity and dust-to-gas ratio. The stellar pulsation is simulated by a variable inner boundary (oscillating membrane, variable luminosity) which can either be specified as a simple function or be taken from pulsation/convection models of the stellar interior (see also *Current Projects*).

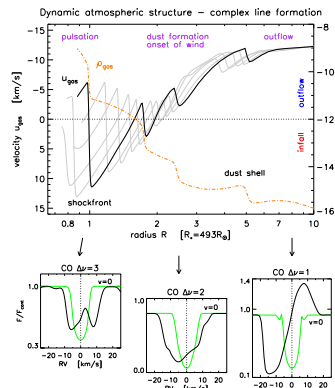
Observable Properties

We have tested these models against various types of observations that give different types of constraints on the models. Low-resolution spectra covering a wide wavelength range and molecular features formed at various depths in the atmospheres and winds (e.g. ISO data) give good indications for the overall structure of the models. Gautschi-Loidl et al. (2004, A&A 422, 289) have performed a systematic comparison of spectra resulting from our models with observations of C-rich AGB stars. In the wavelength range between 0.5 and 5 micron, we find good agreement between observations at different phases and a single model for each star. Furthermore, the models offer the first self-consistent explanation for the observed absence of a feature around 14 micron due to C₂H₂ and HCN in certain stars while clear features of the same molecules are seen at shorter wavelengths.

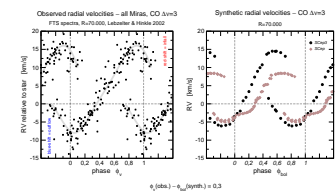
The Role of Molecules

We have investigated the time-dependent behaviour of individual spectral lines of molecules, and in particular of CO, resulting from our models. Depending on the location of line formation in the atmosphere and/or wind, vibration-rotation lines of CO and other molecules are known to show complex, variable line profiles due to Doppler shifts caused by pulsation and outflow. Previous models could only reproduce the behaviour of spectral lines formed either in the pulsating layers of the atmospheres, or in the wind.

As demonstrated in two papers by Nowotny et al. (2005, A&A 437, 273; A&A 437, 285), our latest generation of models gives - for the first time - qualitatively correct results in both regimes, i.e. throughout the atmosphere and wind. This opens new possibilities for quantitative studies of the dynamics of the atmospheres and winds, and in particular to address questions like the connection between pulsation and mass loss.



The figure above shows a typical density structure and velocities at several phases, indicating the regions where different types of CO vibration-rotation lines are formed in the atmosphere or wind. The figure below compares the temporal variation of radial velocities (Doppler shifts) of CO lines in observations and models, including the characteristic line doubling around light maximum.

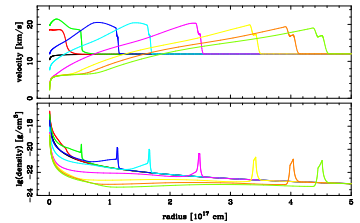


Current Projects

At present, we are working on several major projects to further improve or apply our detailed models for atmospheres and winds of AGB stars: (i) implementation of a description of dust formation in environments with C/O < 1, (ii) application of the wind models to stellar evolution (mass loss rates), and (iii) 3D radiation-hydrodynamical models of the convective stellar interior to study the effects of giant convection cells on dust formation. Below we present some preliminary results illustrating points (ii) and (iii).

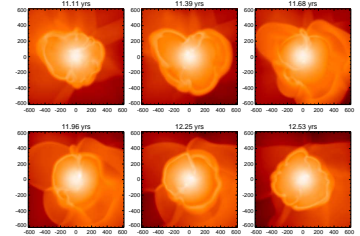
Formation of detached shells

In AGB stars the burning of hydrogen in a shell surrounding the stellar core is periodically interrupted by brief phases of runaway burning of the accumulated helium. During these phases, the stellar parameters change drastically, which may result in a strong variation of the wind properties. In this context, a geometrically thin but dense shell of material is expelled and later becomes visible in, e.g., molecular rotation lines. Picking a sequence of stellar parameters from an evolution model, we have calculated the evolution of mass loss during such a He-shell flash, and followed the dynamical evolution of the detached shell (Mattsson et al., in prep.). The figure below shows a time sequence of snapshots of the corresponding velocity and density structures.



Effects of Convection Cells

We have performed three-dimensional radiation hydrodynamics simulations of the outer stellar convection zone and the inner atmosphere of an AGB star ($T_{\text{eff}}=2800$ K, $M=1 M_{\text{Sun}}$, $R=350 R_{\text{Sun}}$) with *COSBOLD*.



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.

The dust grains which play a key role for the formation of the winds condense under non-equilibrium conditions with temperature acting as a threshold, prevailing densities and abundances determining the efficiency of grain growth, and propagating shock waves setting the time scales. Therefore, it can be expected that the spatial patterns of density and temperature are to some degree imprinted on the dusty envelopes. Preliminary results of 3D models which include a detailed description of dust formation seem to confirm this expectation (Freytag & Höfner, in prep.).