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Towards abundance determination from dynamic atmospheres

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Abstract. We summarize our efforts to determine element abundances (e. g. for the elements C and O) and isotopic ratios (e. g. $^{12}C/^{13}C$) along the Asymptotic Giant Branch (AGB). For the modelling of AGB star spectra for stars on the lower part of the AGB, hydrostatic model atmospheres have been shown to reproduce observations quite well. Stars climbing up the AGB get more and more dynamic. For these strongly pulsating stars dynamic model atmospheres have to be used in order to reproduce the observed spectra which are dominated by dynamical effects. Both the developments of hydrostatic and dynamic model atmospheres are considered, referring to the problems encountered in the synthesis of cool star spectra. We emphasize the importance of AGB stars in globular clusters, which provide a method to get a homogenous sample of stars well-defined in mass, metallicity, and luminosity. Finally, we point out the relevance of our investigations for stellar evolutionary models.

Key words. Stars: AGB and post-AGB – Stars: abundances – Stars: atmospheres – globular clusters – Nuclear reactions, nucleosynthesis, abundances

1. Introduction

Stars on the Asymptotic Giant Branch (AGB) are interesting objects in many respects. They provide an instant look into the sun's future, their high luminosity makes them attractive targets for (extra)galactic studies, and via nucleosynthesis in their interior and the subsequent processes of dredge-up and mass loss, they influence the chemical evolution of the interstellar medium (ISM) and their host galaxies to a yet quantitatively uncertain extent. The determination of chemical element abundances (e. g. Smith & Lambert 1990) in the stellar atmosphere represents a link between physical mechanisms happening in the interior of these stars and the consequences for their environment.

Extracting accurate abundances from the spectra of AGB stars requires reliable modelling of the stellar atmosphere (for an

Send offprint requests to: M. T. Lederer overview see Gustafsson & Höfner 2004). This, however, remains a challenging task as several difficulties arise which do not play a role in hotter stars. The low temperatures in AGB atmospheres lead to the formation of a variety of molecules whose opacities have a decisive influence on the pressure-temperature structure of the atmosphere. Several million molecular lines have to be included in the calculation to reproduce observed spectra (Gustafsson & Jørgensen 1994). Correct and complete data of molecular as well as atomic transitions are of crucial importance for the calculation of the atmospheric structure and the synthetic spectra.

Another prominent feature characterising AGB star atmospheres is the effect of sphericity. The photospheres are so extended that the assumption of plane parallel radiative transfer is not valid anymore (Aringer 2005). A further degree of complexity is added in the case of stars with large amplitude pulsations (e. g. Miras). When the stars are strongly pulsating, hydrostatic model atmospheres are not applicable any more for the generation of synthetic spectra. Dynamic model atmospheres have to be used instead as only these provide the possibility to reproduce observed spectral features consistently (e. g. Aringer et al. 1999, 2002; Nowotny et al. 2005a,c).

In the next sections we briefly recapitulate the basics of our hydrostatic and dynamic model atmospheres before we give a short outline on how to use them with a homogenous sample of stars for an investigation on physical processes – focussing on the Third Dredge-Up (TDU) – going on in AGB stars.

2. Hydrostatic model atmospheres

We compute hydrostatic model atmospheres using a modified version (Jørgensen et al. 1992; Aringer et al. 1997) of the MARCS code (Gustafsson et al. 1975). The opacities used for the model calculations and spectral synthesis are delivered by the COMA code (Aringer et al. 1999), while the model spectra are generated with the help of a spherical radiative transfer program described by Windsteig et al. (1997). The atomic line data are taken from VALD[1] (Kupka et al. 2000), whereas the molecular data are compiled from several sources which are constantly checked for updated values. Currently, line lists for CO, TiO, SiO, VO, OH, CH, C_2, CN, H_2O, CO_2, SO_2 and others are included.

Model atmospheres that were calculated following the method described above have been shown to describe the spectra of cool giant stars appropriately (e. g. Loidl et al. 2001; Aringer et al. 2002). In Fig. 1 we show an example for a spectral fit done for the mildly pulsating AGB star V18 in the globular cluster 47 Tuc. The strong features shown in this plot are mainly from the CO molecule bearing either the ^{12}C- or the ^{13}C-isotope. Synthetic spectra reproduce the observed spectrum quite well and we find a strongly reduced ^{12}C/^{13}C-ratio compared to the solar value.

Talking about model atmospheres, it is important to mention that an intuitive approach to the prediction of the behaviour of spectral features may lead into wrong directions. The atmospheric structure responds very sensitively to a change in molecular absorption, that may vary due to the competition of different molecular species. An astonishing fact due to this strong interplay is, that molecular and atomic lines could decrease while the metallicity is increased, although one would expect the opposite (Fig. 2). This effect is not proprietary to AGB stars, Cottrell (1978) found the same behaviour for subdwarfs with $T_{\rm eff} \leq 5500K$.

In the discussion of model atmosphere calculations and spectral synthesis, the question of consistency is stressed frequently. The ideal case is achieved when both model atmosphere and spectrum computations are based upon the same physical principles formulated in the same geometry using the same approximations, methods, and sets of input data. The only difference should actually be the spectral resolution (Höfner et al. 2005). In practice, however, some aspects (such as lines which do not influence the overall atmospheric structure) are

[1] Note that wavelengths from VALD are vacuum wavelengths below 2000 Å, otherwise they are quoted for air!

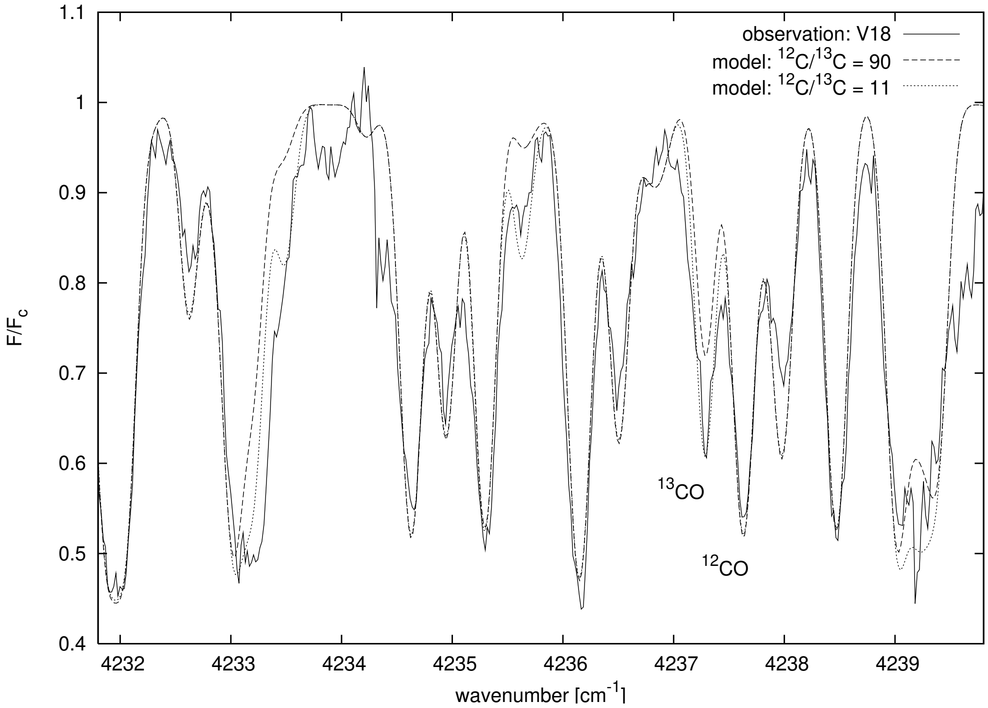

Fig. 1. Comparison of synthetic spectra with the observed spectrum of an AGB star (V18, following the nomenclature of Clement et al. 2001) in the globular cluster 47 Tuc. The spectral region shown (located around 2.3 μm) is dominated by CO lines. Stellar parameters were determined to be $T_{\rm eff}$= 3400 K, L = 2000 $L_\odot$, and M = 0.8 $M_\odot$. A solar C/O-ratio was assumed in the model calculations, the $^{12}C/^{13}C$-ratio (where $^{12}C/^{13}C$ = 90 is the solar value) has been adjusted in order to reproduce the ^{13}CO-features (examples are labeled).

omitted in model atmosphere computations for the sake of simplicity.

Nevertheless, it is important to have a look at the consequences arising from inconsistencies. Examples can be found in Aringer (2005) who showed the effect of an inconsistent treatment of sphericity, and in Uttenthaler et al. (2004) where the consequences of a different metallicity in model atmosphere and spectral synthesis calculations are demonstrated.

Recently, further efforts have been made to improve consistency issues. Fig. 3 shows improvements made to MARCS models compared to the version of Aringer et al. (1997). In a first step, opacity data had to be revised in order to overcome difficulties due to a considerably underestimated absorption at wavelengths longward from 12.5 μm. Furthermore, atomic opacities as well as opacities for VO and OH have been included into model atmosphere computations.

3. Dynamic model atmospheres

For the modelling of stars on the upper part of the AGB, frequently showing large amplitude pulsations, we use dynamic models from Höfner et al. (2003). These are based on a time-dependent description of radiation hydrodynamics with frequency-dependent radiative transfer including dust formation for C-rich chemistry. The work on the more challenging O-rich case is still in progress. Pulsation is introduced as a variable inner boundary condition (sinusoidally moving piston). As a consequence, these models show shock waves run-

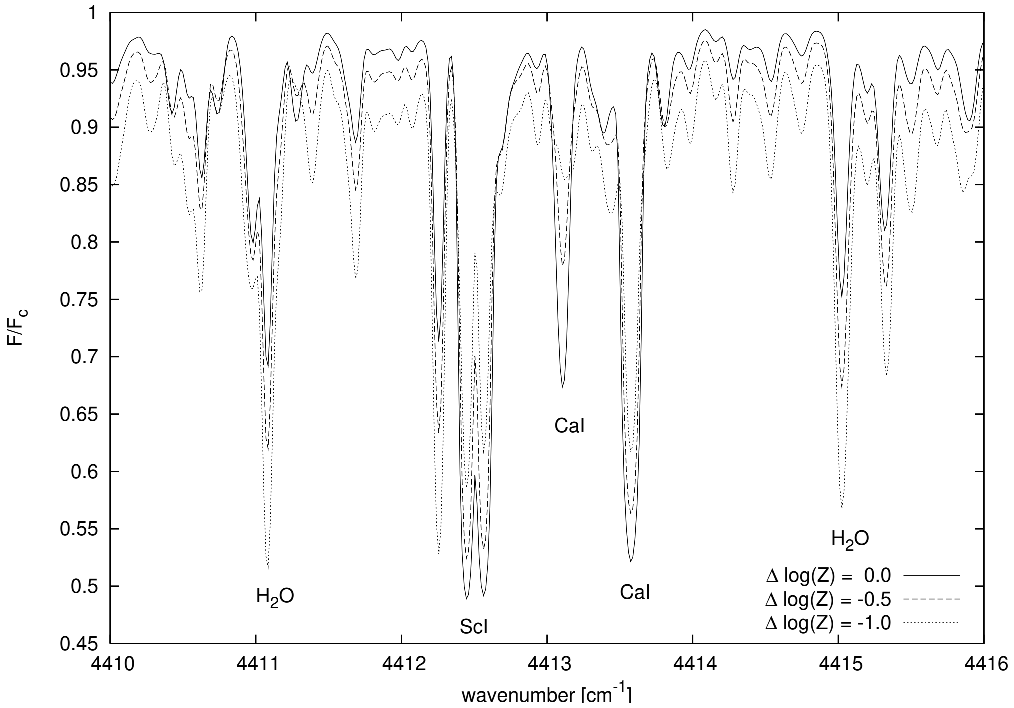

Fig. 2. Complex behaviour of molecular lines as a function of abundances: The spectra shown are based on atmospheric models with solar mass, $T_{\rm eff}$= 3000 K and $\log(g)$ = 0. The metallicity is varied where $\Delta\log(Z)$ indicates the change with respect to the solar value. For a comparison some metal and water features are identified. Note the increasing strength of the water features while the metallicity drops.

ning through the atmosphere and the occurence of mass loss. Dynamic models have a significantly shallower global density profile in comparsion to hydrostatic (inital) models thus representing very extended objects. Sphericity effects are this way enhanced and are coupled to dynamic phenomenons which are important for the formation of spectral lines.

Taking the movement of the atmospheric layers in radiative transfer calculations into account is essential for spectral synthesis. Nowotny et al. (2005a,b,c) investigated the variation of line profiles due to the influence of macroscopic gas velocities and succeeded in characterizing the behaviour of lines sampling different regions of typical Mira atmospheres. Lebzelter et al. (2003) showed changes in the equivalent width of several lines typically used for determining C and O abundances (C/O ratio, Fig. 4). The dependence on the phase is obvious as is the large difference to the ratio determined from a hydrostatic model. Based on these results the transition from qualitative to quantitaive modelling of dynamic atmospheres of cool stars seems closely at hand.

4. Homogenous object sample from globular clusters

Nucleosynthesis models describe the abundance pattern in dependence on mass, metallicity, and luminosity. Testing these models with observations therefore requires knowledge of these three quantities for any given star observed. Yet, the majority of the available observational constraints are derived from the low mass companions in binary systems which received their abundance pattern from the higher mass star via mass transfer. Observing the results of nucleosynthesis and TDU in single

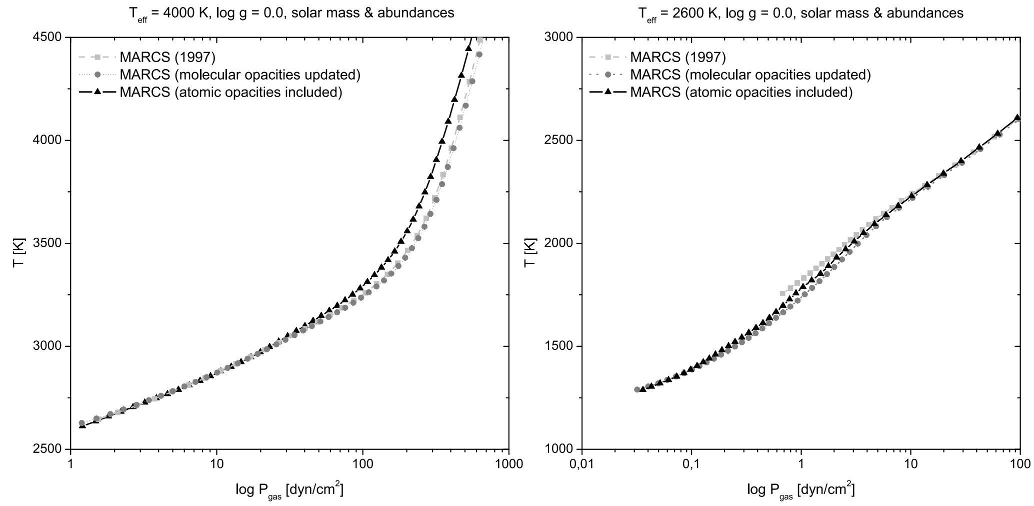

Fig. 3. Changes in the atmospheric structure due to changed opacity data. The left panel shows a model with $T_{\rm eff}$= 4000 K, whereas in the right panel $T_{\rm eff}$= 2600 K. Squares indicate depth points of a MARCS model in the version of Aringer et al. (1997). Circles belong to a model with updated opacities in the far infrared range. This affects especially cool models that now can be extended to lower optical depths (right panel). The inclusion of atomic opacities (triangles) has the most pronounced effects on the inner region of models with a higher effective temperature (left panel).

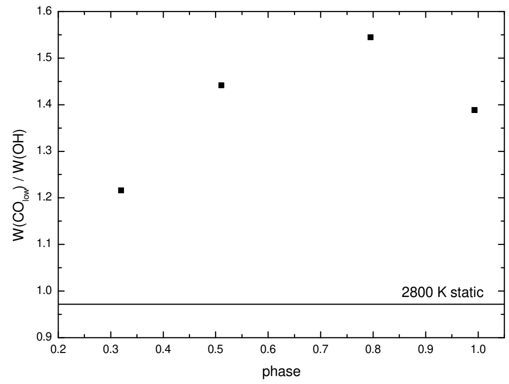

Fig. 4. Ratio of equivalent widths of low excitation 2-0 CO lines (average of several lines) and the OH 3-1 P_{1f} 15.5 line for different phases of a dynamic model atmosphere. The horizontal line indicates the value derived from a hydrostatic model atmosphere. (Figure adapted from Lebzelter et al. 2003.)

AGB stars would naturally allow a deeper insight into the involved mechanisms. In the case of field stars, however, fundamental parameters like mass or luminosity are typically known only with low accuracy. Stars in galactic and extragalactic globular clusters offer a possibility to circumvent this problem, but only recently these objects have become accessible to high-resolution spectroscopy.

However, relying on the parameters of a globular cluster for deriving the actual mass of an AGB star can be misleading as mass loss processes on the RGB and early AGB may reduce the stellar mass significantly. Direct mass loss determinations during different evolutionary phases are rare. Recent findings from Lebzelter & Wood (2005) may help to solve this problem: A reduction in mass changes the pulsational behaviour of a star (note that most AGB stars are radial pulsators). Fitting pulsational models to a period-luminosity diagram of the RGB/AGB variables of a globular cluster (with known turnoff mass) allows a derivation of the current mass of these stars. Such a comparison was done by Lebzelter & Wood (2005) for the nearby cluster 47 Tuc (based on a large number of newly detected long-period variables).

A sample of AGB stars well-defined in mass, metallicity, and luminosity, together with information about the mass loss during earlier evolutionary phases of these stars makes abundance determination of C, O and their isotopes for these stars feasible by using state-of-the-art model atmospheres including sphericity and dynamical effects. Fig. 1 emerges from our ongoing research which is based on the approach outlined above.

5. Conclusions and outlook

There are still considerable uncertainties in stellar evolution and nucleosynthesis models with respect to the details of the dredge-up processes. Investigating the abundances of the elements C, N, and O and their isotopic ratios (like $^{12}C/^{13}C$, $^{16}O/^{17}O$, and $^{16}O/^{18}O$) delivers important information on the physical conditions in the interior of AGB stars as these abundances are influenced by H-burning via the CNO-cycle, by He-burning which produces ^{12}C, and by the depth and efficiency of the TDU events.

The application of dynamical model atmospheres will show for which stars hydrostatic models can be used and which lines are least affected by dynamical effects. Arriving at a stage where accurate abundance determination from dynamical model atmospheres is possible, we will be able to follow the footprints of the TDU along the AGB. The observed abundances of C, O and their main isotopes as a function of luminosity will give insight into the efficiency of the TDU as a function of mass. The results can then be used to test stellar evolutionary models particularly with regard to nucleosynthesis and mixing.

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