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# Technetium in AGB stars: spectral synthesis and observations

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**Abstract.** We present an overview on the current status of our atmosperic models for pulsating AGB stars. The dynamical models are in a transition from qualitative agreement with spectra to a status where quantitative conclusions can be drawn. The classical, hydrostatic models are used for the early type, small amplitude variable red giants. A recent result gained from observations is information on presence or absence of Technetium in the atmospheres of AGB stars. It is shown that many of the observed AGB giants which are above the threshold luminosity for the third dredge-up (TDU) do not show Tc in their spectra, independent of the galactic environment.

**Key words.** AGB stars – Atmospheric Models – Synthetic Spectra – Elemental abundances – Technetium

## 1. Pulsating red giants

The atmospheres of stars on the Asymptotic Giant Branch (AGB) are characterized by (at least) three important physical phenomena: (i) low temperatures, allowing the formation of molecules and dust; (ii) pulsations, leading to strong temporal and radial variations in the temperature-pressure structure and (iii) a stellar wind, driven by pulsation and radiation pressure on dust, resulting in very extended atmospheres. The high luminosity and mass loss of these stars make them interesting targets for galactic studies. But although these stars are the longest known group of variable stars and hence huge sets of observational data exist, detailed models of light curves or spectral variations are just emerging. Modelling the atmospheres and the spectral appearance of pulsating red giants thus is still one of the major challenges in stellar astrophysics. AGB stars are also important sites of nucleosynthesis of heavy elements. Determining abundances for these stars is therefore of high interest, but requires reliable model atmospheres. It is our intention to use our new model atmospheres for red giants

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(Section 2) for abundance determination in AGB stars.

## 2. Model atmospheres and synthetic spectra

Model atmospheres of red giants may be grouped into three categories: 'classical', i.e. hydrostatic and dust-free models, 'dynamical', i.e. taking into account the effects of pulsation, and 'dusty', i.e. one of the previous including circumstellar dust.

The model atmospheres presented here are either computed with an improved version of the hydrostatic (classical) MARCS code (Jørgensen et al. 1992) or with the latest generation of dynamical models by Höfner (1999) and Höfner et al. (2003). The dynamical models are obtained by combining time-dependent hydrodynamics with frequency-dependent radiative transfer. The stellar pulsation is simulated by applying a variable inner boundary (piston) moving sinusoidally with a velocity amplitude $\Delta u_p$ and a periode $P$. The luminosity variation follows from the variable inner radius and the assumption of constant flux at this radius.

The molecular abundances are computed on the basis of equilibrium chemistry. Opacities are treated in the opacity sampling approximation for the atmospheric models, for high resolution spectroscopy they have to be taken from linelists. The models include most of the molecular species relevant for the studied range of pressures and temperatures, i.e. CO, TiO, SiO, OH, CH, $C_2$, CN, $H_2O$, $CO_2$, $C_3$, HCN, $C_2H_2$, CS, and others. For $H_2O$, $C_2$, $C_3$, HCN, and $C_2H_2$, improved opacity data are used (Jørgensen et al. 2000 and Jørgensen et al. 2001). The radiative transfer is done in spherical geometry.

Generally, the treatment of dust formation and dust emission is a major difficulty; only in the rare cases where the dust emission is dominating the spectrum, the treatment is simplified. For M-type stars, where the formation process and the composition of the dust is still poorly known, our models currently either omit the dust or we use a purely photospheric spectrum as the central source for a superposed model of the dusty envelope (Aringer et al. 1999). For stars with weak mass loss this approximation should be acceptable out to the mid-IR, since the dust formation takes place in regions where not much emission from molecular rotational-vibrational transitions is expected anymore. For C-type stars, a detailed description of dust formation is included (moment method). Only the opacity of amorphous carbon is considered in our calculations (for a detailed discussion see Höfner et al. 2003).

From the hydrostatic models two important conclusions can be drawn: due to the strong interaction between molecular absorption and atmospheric structure and due to the competition between different molecular species, no simple relations between atomic abundances and the strengths of molecular features can be expected. Furthermore, there may be ambiguities or degeneracies in the relations between stellar parameters and spectral features or photometric indices. The hydrodynamical models generally show an enhanced molecular opacity in the outer regions (mostly due to polyatomic molecules) compared to the hydrostatic models and strong temporal and spatial variations of the molecular abundances. The pulsation amplitude has the strongest influence on the atmospheric structure and spectral appearance (Loidl et al. 1999). A detailed comparison of synthetic carbon star spectra with observations with large wavelength coverage can be found in Gautschy-Loidl et al. (2004). Some first quantitative estimates of the effect of variability on the determination of the C/O ratio derived from synthetic spectra based on dynamic atmospheres are described by Lebzelter et al. (2003). Aringer et al. (2002) discuss for which stars hydrostatic models can and for which stars dynamic models should be used.

In this context we want to emphasize the importance of consistent treatment of opacities

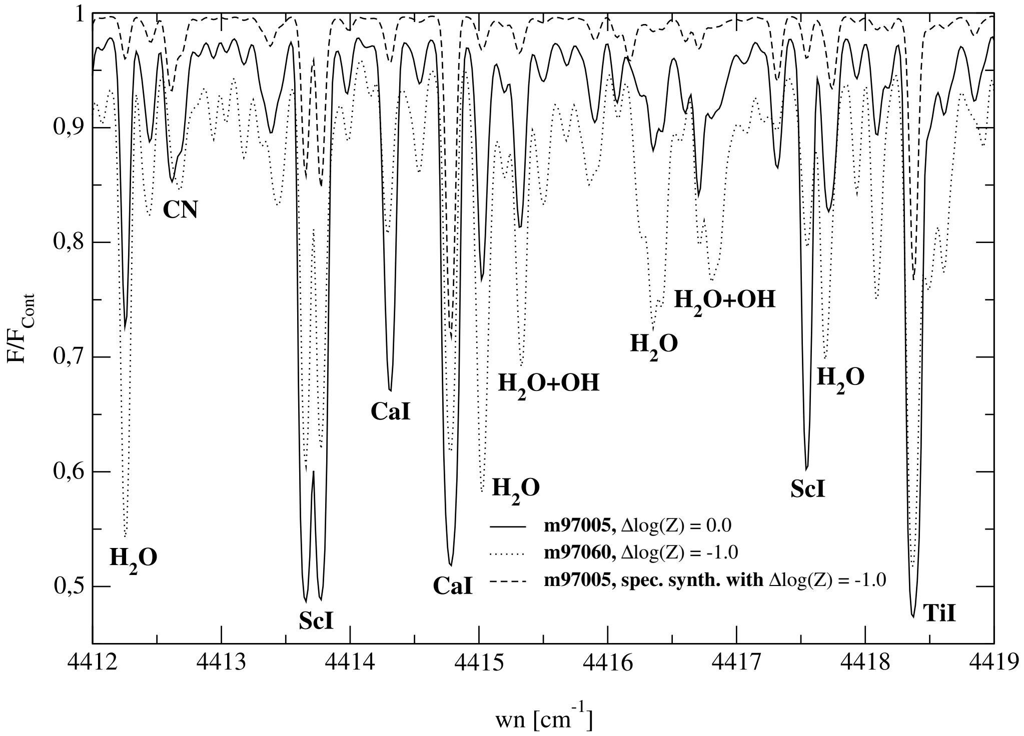


**Fig. 1.** Synthetic spectra based on two MARCS models with $T_{eff} = 3000K$, $\log(g[cm/s^2]) = 0.0$, one solar mass, and different metallicities. The result of an inconsistent calculation (solar abundance model and spectrum synthesis with $\Delta\log(Z) = -1.0$, dashed line) is also shown. The spectra are normalized to a computation without molecular and atomic opacities. Figure taken from Aringer (2004).

and radiative transfer in the calculations of the atmospheric model and the spectral synthesis if one wants to determine accurate elemental abundances. In Fig. 1 we present synthetic spectra based on two hydrostatic MARCS models with different metallicity (m97005 with solar abundances and m97060 with 1/10 of the solar value). As one would expect, the intensity of the strong metal lines increases with $\Delta\log(Z)$. In contrast, the water features show just the opposite behaviour, although the oxygen abundance is scaled in the same way as the metallicity and $H_2O$ is effectively formed in the outer parts of both models. In this context one must not forget that $H_2O$ dominates the opacity and thus the temperature-pressure structure in the cooler outer layers of the atmosphere (Jørgensen et al 2001). If more water can be produced because of the composition, the whole atmosphere will be readjusted affecting again the chemical equilibrium. Of course, also changes of the absorption from other species like TiO play an important role. This interaction between opacity, structure and chemical equilibrium results in a complex behaviour of line intensities. We also expect complex behavior for metal lines due to the structural effects discussed above and due to quasi-continous molecular absorption (discussed e.g. in Aringer 2004). It may even happen that metal lines become weaker with increasing $\Delta\log(Z)$ in some cases. As a consequence, it is very important to treat the molecular opacities used for the construction of the model atmosphere and the synthetic spectra in a consistent way,

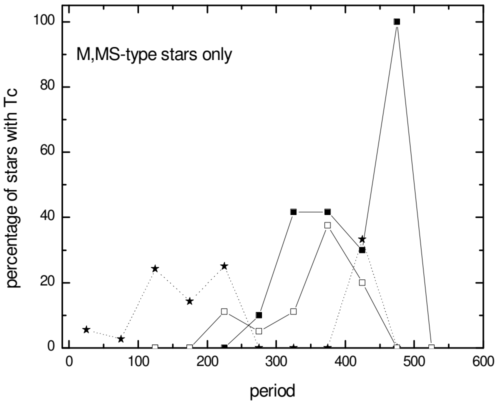


**Fig. 2.** Fraction of field-stars with Tc lines within each period bin. Filled and open boxes mark Mira variables clearly and possibly showing Tc, respectively. (connected by a solid line). Asterisks mark semiregular variables (connected by a dotted line). Only stars with spectral Type M and MS have been plotted here (Lebzelter & Hron 2003).

especially with regard to completeness of opacity data and abundances. In Fig. 1 we also demonstrate what may happen, if one does not keep to this rule. A combination of a solar composition model with a spectrum synthesis asuming $\Delta \log(Z) = -1.0$ (dashed line) results in unrealistic extremely weak metal and $H_2O$ lines corresponding to an object with much lower metallicity and higher temperature. Also, the sphericity of the model atmosphere and the velocity fields have to be treated in a consistent way.

## 3. Technetium in bulge and field stars

The first application of our models will be an abundance determination of *s*-process elements, especially Tc, in AGB stars. By now, the Tc content was estimated from the central position and the shape of atomic line blends including a Tc line in the blue optical region. Tc, as an unstable *s*-process element, is a reliable indicator for the evolutionary status of AGB stars, because due to the short life time any Tc we see in a star has been produced in the interior during its previous evolution on the thermally pulsing AGB (TP-AGB).

New observational data on the occurence of Tc in AGB stars have been recently presented by Lebzelter & Hron (2003). In that paper, the occurrence of Tc in stars in the solar neighborhood was studied as a function of luminosity. This provides constraints on the minimum luminosity for the third dregeup (TDU) as estimated from recent stellar evolution models (Herwig et al. 2000). The observations are consistent with the approximate TDU luminosity limit, as discussed in Lebzelter & Hron (2003): only stars brighter than this limit show Tc. However, a large number of AGB stars above the estimated theoretical limit for TDU are found not to show Tc. The authors confirmed previous findings that only a small fraction of the semiregular variables (SRVs) show Tc lines in their spectra. Contrary to earlier studies by Little et al. (1987), they find also a significant number of Miras without Tc (cf. Fig. 2). The study of Lebzelter & Hron (2003) is hampered by the fact that distances (mainly from Hipparcos parallaxes) to and thus luminosities of the field stars are rather uncertain. A second study (Hron et al., in prep.) thus investigated AGB stars in the outer galactic bulge. Properties of the AGB population of the selected field PG3 are discussed by Schultheis et al. (1998). The result (Fig. 3) is similar, although the percentage of stars above the luminosity limit without Tc may be even lower. The dashed lines in Fig. 3 are two isochrones up to the AGB tip from Marigo & Girardi (2001), the left one for $Z = 0.004$ and 10 Gyr age, the right one for $Z = 0.02$ and 5 Gyr age. Two important conclusions can be drawn from this colour-magnitude diagram: (i) It is evident that the theoretically predicted maximum luminosity on the AGB falls well below the most luminos stars. This can not be explained by the uncertainty in absoltue magnitude, as this is just ±0.5 mag. The K-magnitudes are a mean of the 2MASS-catalogue value and of earlier observations by Schultheis et al. (1998). It is also unlikely that the bright stars are in the foreground, since the contamination by foreground stars is well studied in this field. (ii) The stars in these regions barely have the mass (numbers beside diamond symbols on the isochrones, in units of $M_\odot$) necessary for TDU. The minimum (current) total mass for TDU thus is about 1.1 $M_\odot$ (see Lebzelter & Hron 2003 for discussion).

The presence or absence of Tc does not necessarily mean the absence of TPs but rather the absence of TDU for several TPs. This could be caused by a too low initial mass on the TP-AGB or by a too high mass loss rate at the end of the AGB-evolution. For stars without Tc which are brighter than the minimum luminosity there are two plausible explanations in terms of mass: (a) the stars have core (and maybe also envelope) mass smaller than the TDU-limit but are in a phase of the TP-cycle with luminosities higher than the minimum surface luminosity; (b) the stars have core masses higher than the TDU limit (hence higher luminosities) but envelope masses below the minimum value required for TDU. Case (a) would correspond to stars with a initial mass below about 1.5 $M_\odot$ in early stages of the TP-AGB. For case (b) a wider mass range is allowed (i.e. also masses above 1.5 $M_\odot$) but the stars have to be in advanced stages of the TP-AGB and the more massive objects would need to have high mass loss.

## 4. Conclusions

We presented an overview on the current status of our model atmospheres for AGB stars. We emphasized the importance of consisten treatment of abundances, velocity fields and sphericity in the calculation of the model atmosphere and in the calculation of synthetic spectra based on these models. The dynamical models available now are in a state where quantitative measurements become possible. One of the first applications will be to derive Tc and *s*-process abundances from observed spectra with the help of synthetic spectra based on the new models. The measurements on the Tc content of AGB stars in the field and in the galactic bulge so far have led to very interesting findings: (i) As expected, no stars below the theoretical limit for TDU were found to contain Tc; (ii) Many stars above this threshold luminosity do not show Tc either. Future work will concentrate to find out more about the evolutionary status of these Tc-poor stars and why these stars seem not to show signs for recent dredge-up.

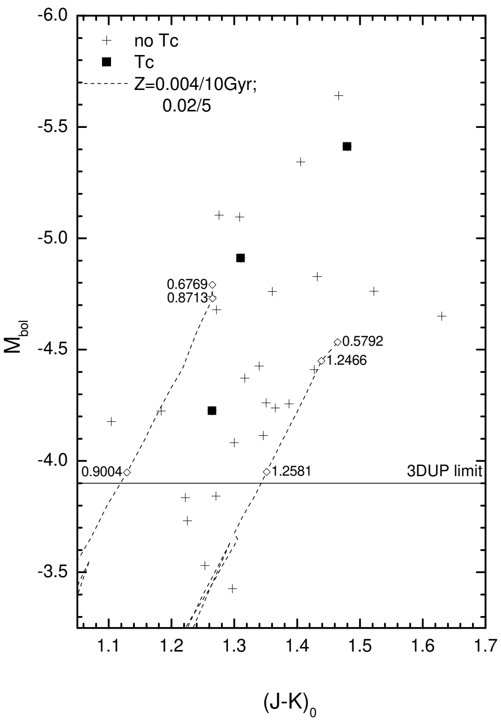


**Fig. 3.** Colour-magnitude diagram of the observed bulge stars. The symbols for stars with and without Tc in their atmospheres are indicated in the legend. The dashed lines are two isochrones, the left one for a metallicity $Z = 0.004$ and 10 Gyr age, the right one for solar metallicity and 5 Gyr age. The numbers beside the diamond symbols on the isochrones indicate the current mass of the stars in units of $M_\odot$. The full horizontal line indicates the estimated theoretical luminosity limit for third dredge-up (here designated 3DUP limit). For the definition of the luminosity limit, see Lebzelter & Hron (2003).

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