ATMOSPHERES OF CARBON STARS
Models and Observations

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ABSTRACT.
We summarize the status of our model atmosphere calculations and their agreement with various sets of observational data. We then explore the possibilities for deriving abundances and other basic stellar parameters of carbon stars from low resolution spectroscopy.

1. Introduction

Carbon stars are probably the most obvious evidence for abundance changes in AGB stars. Therefore the analysis of their atmospheres has been of great importance for a long time. However, the presence of many (polyatomic) molecules, dust condensation and dynamic phenomena related to the variability of AGB stars, has made this task a very sophisticated one. During the last decade considerable progress has been made with regard to all these aspects (e.g. Höfner 1999, Winters 1998, Jørgensen 1997) and therefore the model atmospheres of C-rich giants have reached a rather high level of reliability. In this contribution we compare such state of the art models with several sets of available observations and explore the prospects for deriving abundances and other basic stellar parameters from low resolution spectroscopy.

2. Model atmospheres of carbon stars

The hydrostatic model atmospheres used for this work are based on the MARCS code (Gustafsson et al. 1975) with some improvements and modifications concerning the molecular opacities, the chemical equilibrium and the radiative transfer. The molecular opacities are treated in the opacity sampling approximation (e.g. Jørgensen 1992) and include CO, CN, C_2, CH, HCN, C_2H_2 and C_3. We use here only hydrostatic model atmospheres computed in plane parallel and spherical geometry and exclude the effects of dust. For further details we refer to Jørgensen et al. (1999). Results for dynamic model atmospheres can be found in Loidl et al. (1999).

In order to allow a better comparison with observational data the model atmospheres were computed for two stellar luminosities (5000 and 9000 L_{sun}), with the temperatures and masses being taken from the evolutionary tracks of Bessell et al. (1989). We have included models with solar and half solar metallicities and the models were calculated for

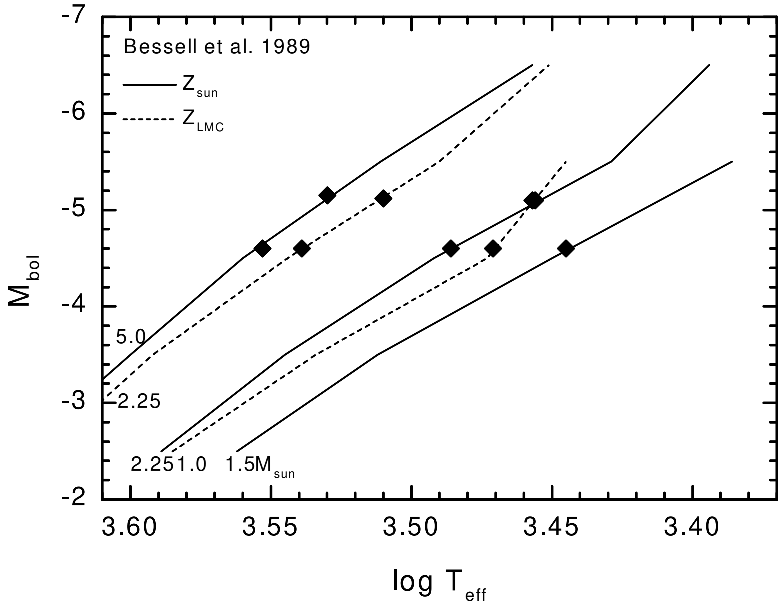

Fig. 1. Location of our models in a theoretical HR diagram. The full and dashed lines denote AGB evolutionary tracks from Bessell et al. (1989) for solar and LMC abundances, respectively. The stellar masses are also indicated.

two values of C/O: 1.1 and 1.3. These C/O ratios are within the range found by Lambert et al. (1986) for optically bright carbon stars and are also consistent with estimates for C-rich Miras observed by ISO (Hron et al. 1999). Figure 1 shows the location of our models in a theoretical HR-diagram. We note that due to numerical reasons not all parameter combinations could actually be computed.

3. Comparison with observations

Several observational data sets are available for a comparison with our models: Jørgensen et al. (1999) present a comparison of hydrostatic models with ISO-SWS spectra of carbon stars with low-amplitude variability. These authors show that in general there is very good agreement, the main discrepancy appears around 14μm. The C_2H_2/HCN feature located in this region is much weaker than the theoretical predictions which may be due to emission from cool dust clumps. An extension towards C-stars with large-amplitude variability and dynamic model atmospheres was made by Hron et al. (1998) and Hron et al. (1999). The observed range in the strengths of the C_2H_2/HCN, CO and C_3 features between 3μm and 5μm are well reproduced by hydrostatic models with different temperatures and C/O ratios. Given the still early stage of dynamic model atmospheres, there is also remarkable agreement between dynamic models and multi-epoch observations with the ISO-SWS.

Although the ISO mission provided us with perfect data sets to check and improve

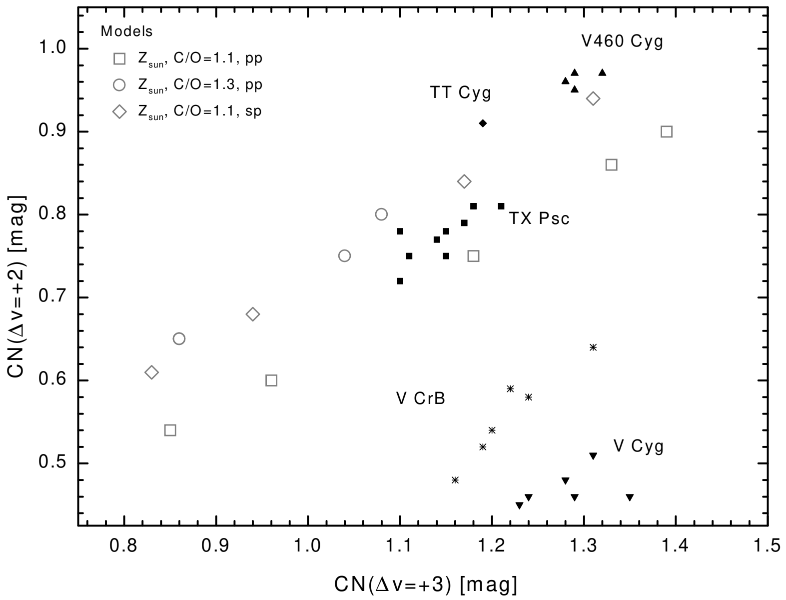

Fig. 2. Comparison of observed CN-indices in the Wing system (see text) with results from model atmospheres. The different solid symbols denote different stars with V CrB and V Cyg being Mira variables and the other objects Semiregular variables. The open symbols show models with solar abundances. The squares and circles denote plane parallel models with C/O 1.1 and 1.3, respectively, while the open diamonds show models with C/O=1.1 but computed in spherical geometry.

the models, the number of observed objects is very small and restricted to the nearest carbon stars. Thus it is also important to compare the models with data obtained from the ground since such measurements are available for many more objects. In this respect, (spectro)photometric observations are of special relevance.

Baumert (1972) has observed 362 stars in the Wing eight-colour narrow band system. In Fig. 2 we compare the (multi-epoch) observations of a few C-rich ISO-SWS targets with our set of models. The CN(Δv=+3) and CN(Δv=+2) indices are defined as $-2.5\log(F_{\rm band}/F_{\rm cont.})$+const. and measure the intensities of CN bands located at 7117Å and 8122Å with respect to nearby pseudo-continuum points. The zero point in the theoretical magnitudes is (still) based on one single K5 giant, which means that it is somewhat uncertain. Nevertheless, the hydrostatic models reproduce the observations of stars with low-amplitude variability quite well, while the two Miras are significantly offset from the models. This is probably due to dynamical effects which cause additional absorption in the pseudo-continuum points. Similar results are found for other CN bands in the optical. We note that the model parameters used to fit the ISO-SWS spectra of carbon stars with low-amplitude variability also reproduce the Baumert data (Jørgensen et al. 1999). A further analysis incorporating the whole data set of Baumert is in progress.

Low-resolution near infrared spectra of C-stars have been obtained by Lázaro et al. (1994). They defined an index measuring the depth of the C_2H_2/HCN feature at 3μm. Also for this index there is good agreement between models and observations (Loidl 1999).

Observed near infrared broad band colours are currently only qualitatively reproduced by the models (Loidl et al. 1998), but such data sample a very large depth range in the atmospheres and are thus more difficult to model.

4. Estimating stellar parameters from low resolution spectra

Since the comparison between our models and various sets of observations generally shows good agreement it seems appropriate to draw some general conclusions about the dependence of selected molecular band intensities on the basic stellar parameters. For this purpose we will restrict ourself to the above described small grid of models and molecular bands which are more or less easily observable from the ground with low resolution spectroscopy. The latter restriction is guided by the fact that (unfortunately) instruments for high resolution infrared spectroscopy are almost non existent and that low resolution spectroscopy is the only technique applicable to large sets of stars at large distances which are the prime targets for testing stellar evolution models.

In Fig. 3 we show the expected variations in the CN(Δv=+3) and 3μm C_2H_2/HCN bands with temperature, metallicity and C/O. In contrast to Fig. 2 we have now plotted just the logarithm of the flux ratio between continuum and molecular band. As one might expect, the bands get roughly stronger towards lower temperatures (at constant luminosity). Reducing the metallicity leads to a slight *increase* in the plotted band intensities at constant temperature. This has two reasons: the strong interplay between molecular opacity and atmospheric structure (see Jørgensen 1989 for illustrative examples) and the lower mass of a lower metallicity AGB track (at fixed luminosity). Increasing the C/O ratio leads to a general weakening of the shown features, especially at $T_{\rm eff}$ below 3200 K. This is suprising at first sight but easily understood by the influence of C_3 which forms around 2200 K. This molecule causes a change in the abundances of the other carbon bearing molecules which in turn also influences the structure of the whole atmosphere due to the large opacities of the molecules. Therefore it can be quite dangerous to interpret the depth of features like the 3μm C_2H_2/HCN band by simple qualitative arguments (e.g. van Loon et al. 1999).

In a plot of CN(Δv=+3) versus CN(Δv=+2) the models with different metallicities and C/O ratios follow nicely separated tracks. Unfortunately, the separation is only of the order of a few percent and thus lower than the scatter which has to be expected from the variability of the objects and calibration uncertainties.

The results presented so far were restricted to plane parallel hydrostatic atmospheres without dust. These are problematic assumptions for luminous large-amplitude variables and/or stars with significant mass loss. Sphericity effects for C-rich stars have been studied already by Jørgensen et al. (1992). Sphericity leads to a cooling of the outer layers of the atmosphere and thus influences mainly the polyatomic molecules. From our set of models we find a noticable effect for stars with $\log g < 0$ and an increase in the 3μm band intensity equivalent to a temperature decrease of about 300 K. However, this

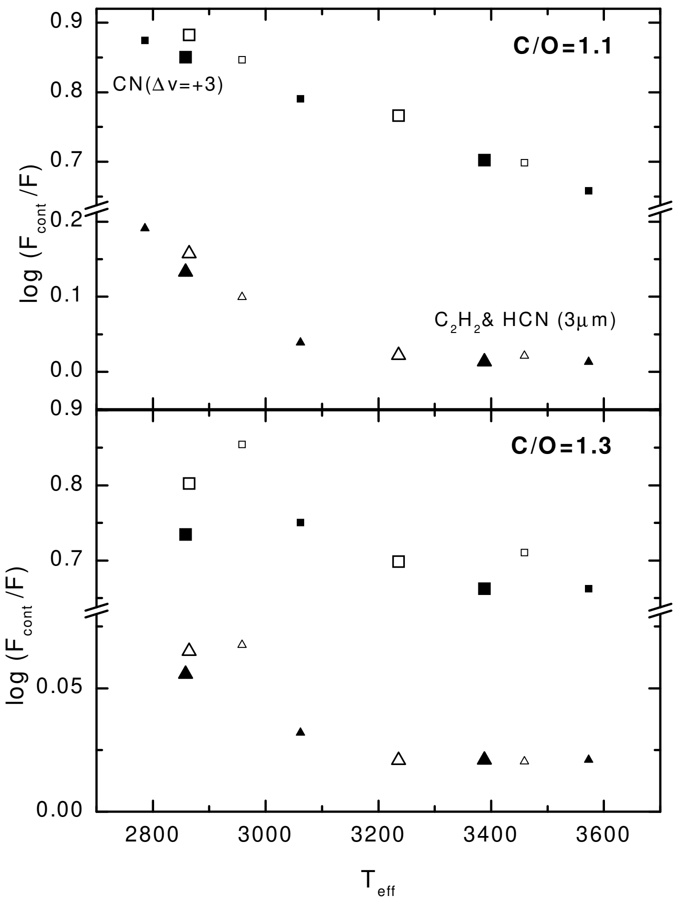

Fig. 3. Synthetic band intensities for the CN(Δv=+3) (squares) and 3μm band (triangles) versus effective temperature (see text for the definition of the band strengths). The upper and lower panels are for C/O 1.1 and 1.3, respectively. The full and open symbols show models with solar and half solar metallicity, respectively, while small and large symbols are used for the 5000 and 9000 $L_{\rm sun}$ models.

would mainly enhance the effects discussed above. As shown by Loidl et al. (1999), dyna mical phenomena influence mostly the molecular features originating further out in the atmosphere like those from C_2H_2. Thus the 3μm-index will show rather pronounced variations in dynamic models and it can be stronger *or* weaker than in a hydrostatic model with an otherwise comparable temperature. This is due to the effects of the shock waves on the partial pressures of this molecule. The emission from circumstellar dust causes a general apparent weakening of the molecular absorption which is important longward of about 2μm (Hron et al. 1999). For example, the 3μm feature of a typical C-rich Mira can be weakened by 50% !

5. Conclusions

Hydrostatic models for carbon star atmospheres are quite realistic now. The models nicely demonstrate the complex interaction between atmospheric parameters and molecular band intensities which, however, makes a simple interpretation of observational results very difficult. The predicted effects of metallicity and C/O on (spectro)photometric indices observable from the ground are unfortunately rather small compared to variability effects and calibration uncertainties. Furthermore, the interpretation of (low resolution) spectra of C-rich stars is complicated by the effects of pulsation and dust. Good progress is made in modelling these effects, but the results can be only used in a qualitative way so far.

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