IMPROVED NON-LTE MODEL ATMOSPHERES FOR SUBLUMINOUS O-STARS

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ABSTRACT. Improved non-LTE model atmospheres designed for the analysis of very hot subluminous O stars are presented. The calculations are based on the new method of the accelerated lambda iteration (ALI) which proves capable of treating up to 100 levels of various ions. Presented here are improved calculations for (i) pure hydrogen model atmospheres including Stark broadening, (ii) for hydrogen- and helium-composed model atmospheres and (iii) first preliminary models which include in addition a detailed carbon model atom. These models remove an apparent mismatch of Balmer line profiles noted previously and fit high S/N, high-resolution hydrogen and helium spectra obtained with the ESO-Cassegrain echelle spectrograph very well.

1. INTRODUCTION

The sublumious O stars are amongst the hottest known pre-white dwarfs, with effective temperatures ranging from about 40000 K to 100000 K. Their evolutionary status, however, is still not well understood. In the absence of reliable distance determinations for these stars, the best way to discuss their properties is to find their positions in the (g, T_{eff})-diagram by means of model atmosphere analyses. In view of the very high effective temperatures it is clear that deviations from LTE inevitably occur and detailed non-LTE calculations are required.

In conventional NLTE model atmosphere calculations, hydrostatic equilibrium and planeparallel geometry is assumed. The sdO atmospheres meet these assumptions very closely, since their surface gravities are high ($4.5 \lesssim \log g \lesssim 6$) and mass loss rates are small ($\lesssim 10^{-9}$ M☉/yr, Hamann et al., 1981). In some cases the atmospheres are so calm that diffusion (gravitational settling) occurs, which means that the mass outflow must be greatly suppressed (Heber, 1986) in order to maintain downward diffusion. Different from massive O stars (see Bohannan et al., these proceedings), wind blanketing can be neglected for the subluminous O stars. Therefore, the sdO stars are ideal test objects for conventional NLTE model atmospheres.

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2. NLTE MODEL ATMOSPHERES

The classical method of computing NLTE model atmospheres is the complete linearization approach of Auer and Mihalas (1969), which has been applied frequently to calculate hydrogen- and helium-composed model atmospheres for sdO stars (e.g. Kudritzki and Simon, 1978). The complete linearization method accounts for the coupling of all variables amongst all depth points in the model atmosphere. Due to numerical limitations the method allows no more than 100 variables to be treated. The most urgent point is the large number of transfer equations needed to describe the radiation field adequately. Therefore, only a small number of levels can be allowed to depart from LTE. Typical applications use 9 (hydrogen and helium) levels, 6 line transitions and 65 frequency points. The question arises whether such crude models can reproduce high S/N observations (ESO-CASPEC) which became available recently.

Such a comparison immediately reveals a mismatch for the Balmer line cores (see Fig. 1): the observed cores are somewhat deeper than predicted by theory. According to our experience the discrepancy in the Balmer line cores is a general phenomenon which is always observed for sdO stars whenever high S/N spectra are obtained (Heber and Kudritzki, 1986; Herrero, 1987). Obviously, there is a need for more elaborate model atoms.

The first attempt to construct such models was made by Anderson (1985), who reduced the set of unknown variables by dividing the frequency spectrum into several blocks which are characterized by their total energy density of radiation. The detailed distributions within the blocks are updated afterwards by lambda iteration.

We followed a different approach using the so-called accelerated lambda iteration (ALI). This method was first applied to line formation calculations by Werner and Husfeld (1985) and Herrero (1987). Werner (1986) demonstrated that the ALI method is a powerful tool to construct model atmospheres in NLTE. (A detailed description of the method is given by Werner, 1987a,b.) The basic aim is to remove the radiation field variables altogether from the set of linearized equations which have to be solved simultaneously. Simply separating the treatment of the radiative transfer from the constraint equations (i.e the equations of statistical equilibrium, of hydrostatic and radiative equilibrium, of number and charge conservation), however, results in a lambda iteration which is known to converge very slowly at large optical depths. Hence the radiative transfer has to be solved simultaneously with the constraint equations. Following an idea of Scharmer (1981) the radiative transfer can be simplified by using approximate lambda operators and can be iterated to obtain the exact solution. In this way the radiation field variables can be removed from the set of linearized equations if the approximate lambda operator chosen is either local or one-directional. This approach results in an iteration scheme that consists of two nested iteration cycles. In the inner cycle, the linearized constraint equations are solved by Newton-Raphson iteration. In the outer iteration cycle ("Scharmer"-iteration), the radiative transfer is updated. It turned out that it is not necessary to include the equation of hydrostatic equilibrium in the Newton-Raphson iteration which makes the method more flexible since it can be started from the inner boundary as well as from the outer one.

The great advantage of the ALI method is that it is no longer limited by the number of frequency points (NF) as is the complete linearization method. For the ALI method the computing time scales as $c_1 NF + c_2 (NL+3)^3$ (NL is the number of levels), and the limiting quantity is NL which must be lower than about 100 due to numerical limitations (matrix inversion in the Newton-Raphson iteration).

In the following sections we shall discuss recent applications of the ALI method.

3. IMPROVED HYDROGEN AND HELIUM COMPOSED NLTE MODEL ATMOSPHERES

As a first application of the ALI method, improved NLTE models for pure hydrogen atmospheres were calculated (Rauch, 1987) allowing for up to 15 NLTE levels, up to 105 line transitions and up to 1845 frequencies. An internal accuracy of 1% in the line profiles as well as in the temperature structure is achieved if ten levels and all corresponding line transitions are considered. (The absorption coefficient is approximated by a Doppler profile. Including Stark-broadening in the statistical equilibrium calculations has a marginal effect only.) The outermost layers of the atmospheres are found to be heated considerably by the additional line transitions. The new models predict deeper line cores than the previous ones (up to 10% deeper for Lyman lines, 20% for Balmer lines and 40% for Paschen lines), while the line wings remain unchanged.

In the second step helium was added (Werner, 1987b) and hydrogen- and helium- composed models constructed. In these calculations, 23 NLTE levels (the lowest 10 levels of H I and He II, respectively, the lowest level of He I and the levels of H II and He III) and 72 line transitions are considered. (The overlap of H I and He II lines is accounted for.) 478 frequency points are needed to describe the radiation field adequately. These models have already been used for the analysis of high-resolution, high-S/N spectra of very hot sdO stars (see Heber, Hunger and Werner, these proceedings).

To give an example for the improvements achieved by the ALI models, we compare theoretical $H\gamma$-line profiles to a high-resolution spectrum of the helium-deficient sdO LB 3459 obtained with the ESO-CASPEC (see Fig. 1). Low-resolution spectra of LB 3459 have already been analyzed for the atmospheric parameters (Kudritzki et al., 1982), which yielded T_{eff} = 40000 K, log g = 5.3, n_{He}/n_H = 0.003 (by number). As can be seen from Fig. 1, the ALI model fits the entire $H\gamma$ profile very well. Further examples for improved line-profile fits from high-resolution, high-S/N visual spectra are given by Herrero (1987). We can therefore conclude that the Balmer line discrepancy mentioned above is completely removed when the improved ALI models are used.

4. METAL LINE BLANKETED NLTE MODEL ATMOSPHERES

Of course, the next step for improving the model atmospheres is to include metal ions in the calculations. Recently, Werner (1987b) added the important element carbon represented by 12 NLTE levels (10 levels for C IV and the ground-state levels of C III and C V, respectively). First model calculations were carried out for T_{eff} = 75000 K, log g = 5 and solar helium and carbon abundances. Fig. 2 shows the temperature structure for models with and without carbon. As can be seen, considerable cooling occurs around log m $\approx$ -3 when carbon is included. This can be traced back to the desaturation of the carbon resonance lines in these layers. The emergent H- and He-line profiles, however, remain almost unchanged because they are formed deeper inside the atmosphere.

The latter result is important since it gives us some confidence that simple H- and He-composed NLTE atmospheres (used up to now in all analyses) might be sufficiently accurate for the analysis of the visual spectra, provided the metal abundances are low (say of solar type). (Additional metals, of course, have to be included to check this.) However, in some hot pre-white dwarfs some metals are known to be strongly enriched. For the (pulsating) hydrogen-deficient PG 1159 stars (GW Vir stars), for instance, it has been conjectured that C and O dominate their envelopes (Starrfield et al., 1984). The ALI method is ideally suited to the construction of carbon and oxygen rich models, which shall be used to analyse high S/N CCD spectra of PG 1159 stars obtained recently with the 3.5m telescope at the DASZ (Calar Alto, Spain).

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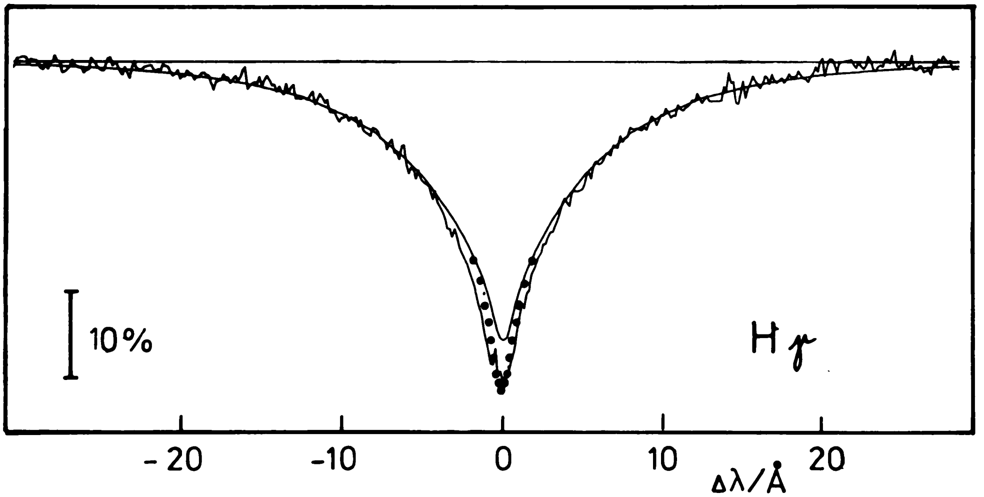

Figure 1. Comparison of a CASPEC spectrum of LB 3459 to theoretical Hγ line profiles. Fully drawn: models calculated using the complete linearization method. Dotted: improved models calculated using the ALI method. The model parameters are T_{eff} = 40000 K, log g = 5.3, no helium.

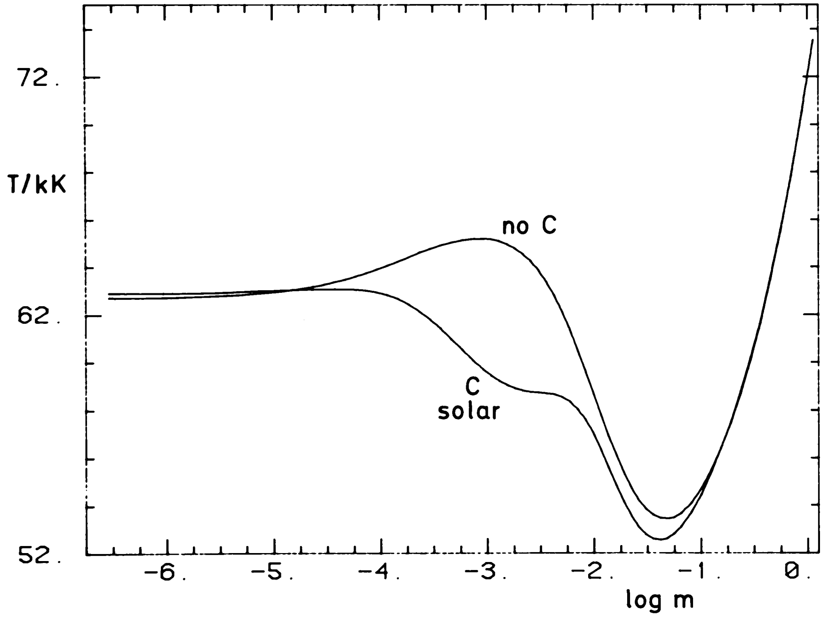

Figure 2. Temperature structure of two ALI models (T_{eff} = 75000 K, log g = 5, solar helium abundance), computed without any carbon and for a solar carbon abundance.

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DISCUSSION

LINSKY What signal-to-noise is required for your spectra ?

HEBER The S/N ratio required for the analysis depends on the individual case, especially whether He I lines are observed or not. In the case of ROB 162, S/N ≈ 25 is sufficient since He I 4471 and 4713 are observed, which give an accurate Teff. If He I lines are not observed, higher S/N is required since the atmospheric parameters (Teff, log g and He abundance) have to be determined from He II and Balmer lines alone.

MAGAIN Don't you have problems to define the continuum for such broad lines on Echelle spectra ?

HEBER Yes, indeed. The rectification of CASPEC data is tedious and time consuming. The best results were obtained when suitable standard stars were used to define the Echelle blaze functions. In this case, Helium-B-giants are well suited because they display only very weak Balmer lines in their spectra (W_λ < 200 mÅ).

GRAY Could you give us some indication of the resolution of the observations you use to test your theory and how well the H-line cores are actually resolved in the regions critical to your comparison.

HEBER The ESO-CASPEC spectra have a resolution of 0.25 A and the Balmer line cores are well resolved. The line profiles are well defined in all parts (wings and cores). Hence their is no need for higher resolution.

BOHANNAN What helium abundances do you get for these stars ?

HEBER The range in helium abundances is very large. In some cases helium is depleted (by up to a factor 100). In other cases we cannot find a trace of hydrogen and the atmospheres seem to consists almost entirely of helium.

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