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Properties of He-rich stars

III. Model atmospheres and diagnostic tools*

M. Zboril

Astronomical Institute, 059 60 Tatranská Lomnica, Slovakia

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Abstract. We present a study of helium rich atmospheres in the interval He/H 0.1–1.0 as derived from fully consistent model computations for effective temperature (from 15000K up to 32000K) and surface gravity (log g=3.5 and 4.0). Also the basic diagnostic tools are re-examined, particularly, broad-band UBV and intermediate photometric systems, hydrogen line profiles, continuum fluxes and helium equivalent widths.

Photometric systems were found to be affected by the helium abundance (He/H number ratio): the Geneva [U-B] index by 0.025 mag. per 0.4 of He abundance and Strömgren $u-v$ index and $c1$ index by 0.04 mag. in the most sensitive cases.

The hydrogen γ profile is also affected by up to 7% at FWHM for both luminosity classes. Generally the physical properties of a model (effective temperature T_{eff} and total particle pressure) in the line forming region change with the He abundance most strongly in the hottest models and for the subgiant class (log g=3.5). In particular, the line forming region of visible HeI ($\sim$-1 in depth mass variable units) is pushed down and enlarged in the atmosphere when increasing the He abundance. The colours, helium line profiles and hydrogen gamma profiles are tabulated and can be handled by simple Fortran software which is also provided.

Finally, the third part of curve of growth for helium lines is better described by a slope of 0.36 $\pm$0.1 instead of the square root law for both luminosity classes (log g=4.0 and log g=3.5).

Key words: stars: abundances – stars: atmospheres – stars: chemically peculiar

1. Introduction

He-rich (CP3) stars, sometimes called *intermediate* helium stars, are the most massive chemically peculiar (CP) stars with spectral type around B2 and belonging to the main sequence. Consequently, they evolve more quickly than other CP stars. A good determination of their age would allow us to study the evolution of the characteristics of He-rich stars (He abundance, magnetic fields, etc.) as a function of age. This is important since the main sequence lifetime of He-rich stars ($\sim$ 2.8x10^7) is about one order of magnitude larger than the typical diffusion timescale ($\sim 10^6$ years). In earlier works, some loose correlation between the He abundance and surface gravity (age) was found by Glagolevskij (1992) in a sample of only 10 stars based on homogeneous CCD spectra from Kitt Peak and by Zboril et al. (1994) based on spectra from ESO but using pure photometry to derive stellar parameters (temperature and surface gravity). In the most detailed (and critical) work, Zboril et al. (1997) reached on a sample of 19 stars (resolving power R=4150) only 70% and 98% probabilities that the correlation between helium abundance (He/H ratio) and age is real, based on purely spectroscopic estimates and spectroscopic values with photometric T_{eff} corrected for the effect of He abundance. There is still considerable difference in the age obtained from the two methods. Also, the derived surface gravities in that paper are, however, systematically shifted by $\sim$ 0.2 against evolutionary tracks (log g_{ZAMS} $\sim$4.3). Importantly, the problems and properties, including model atmospheres, of helium rich stars were discussed in Hunger (1975), i.e. a quarter of a century ago. Thus, more consistent models and an extended grid and scaling are desirable.

2. Model atmosphere and spectrum synthesis

Model atmospheres for He-rich stars are being built up under basic physical assumptions: the hydrostatic, radiative and statistical equilibria. The stellar atmosphere is approximated by a semi-infinite plane-parallel layer with no macroscopic fields and incident radiation.

For this purpose we constructed the following sequence of models: LTEGray-LTE- NLTEC-NLTEL, where LTEGray stands for initial LTE-gray model atmosphere, while NLTEC and NLTEL are for NLTE models for continua and bound-bound transitions respectively. Models are computed for a set of helium abundances, 0.1,0.2,0.4, 0.6, 0.8 and 1.0 with respect to hydrogen and temperatures, T_{eff}=15000, 16000, 18000, 20000, 22000, 24000, 26000, 28000, 30000 and 32000K. Only a few helium rich stars might be still hotter but the basic grid of temperatures is sufficient for calibration purposes. The luminosity classes were considered wit log g=3.5 and 4.0 respectively. The

* Table 1 and the databank are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/

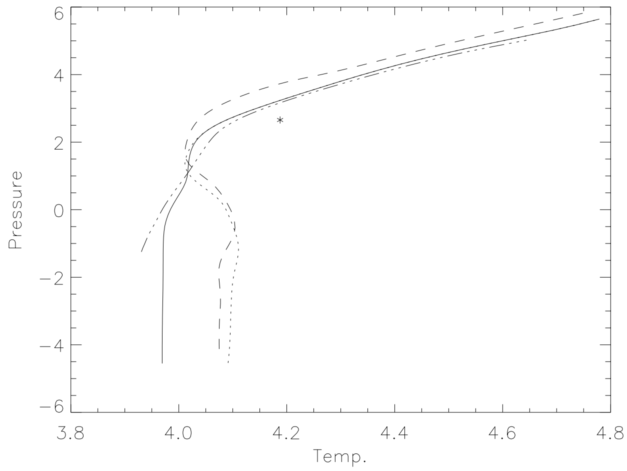

Fig. 1. The temperature-pressure diagram in logarithmic scale for T_{eff}=15000K and log g=4.0. **Solid** line- LTE model with n(He)=0.1 and **dotted** line- NLTE model, **dashed** line-NLTE model and n(He)=1, **dash dot dot dot** line-Kurucz model and n(He)=0.1. **The asterisk** stands for depth point with T=T_{eff}.

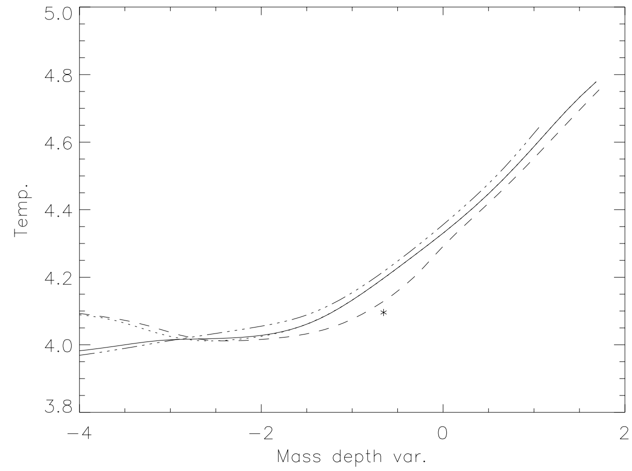

Fig. 2. The temperature-mass depth variable in logarithmic scale for model T_{eff}=15000K and log g=4.0. **Solid** line- LTE model with n(He)=0.1 and **dotted** line- NLTE model, **dashed** line-NLTE model and n(He)=1., **dash dot dot dot** line-Kurucz LTE model model and n(He)=0.1. **The asterisk** stands for depth point with T=T_{eff}.

interval of the effective temperature and surface gravity were chosen guided by Fig. 16 (Hunger 1975) and Table 1 (paper I).

We used the NLTE code Tlusty (Hubeny & Lanz 1992) from the CCP7 library to perform the computations. The code uses the complete linearization with some helpful acceleration schemes to converge the model and level populations. The criterion of convergence was that the maximal relative change of any physical quantity in the model (temperature, total particle number and electron densities) and level population does not exceed 0.001 at each depth point in the atmosphere.

The spectrum synthesis was performed by another CCP7 code, Synspec which has undergone some practical modifications (Hubeny et al. 1994, original version; Zboril 1996 modified). The standard VCS broadening theory for hydrogen was implemented in the code as well as the broadening theory for helium after Barnard et al. (1974), the HeI4471 line profile and Shamey (1969) for the rest of the HeI profiles.

3. Physical quantities of models and temperature structure

The physical quantities of models from Tlusty are given in the form of temperature, electron number density and particle number density vs. depth-mass variable or Rosseland optical depth.

Converting the electron and particle densities to pressure, it is easy to construct the T-p diagram to compare the models of different helium abundances (Fig. 1). The line-blanketing is very critical for cool models and Figs. 1 and 2 allow one to evaluate the line blanketing effect in our coolest model. While there are some differences in the temperature vs. mass depth variable scale (Fig. 2), probably due to backwarming in the fully line-blanketed LTE model, the overal differences in NLTE and the blanketed LTE model quantities in the visual continuum forming regions (Fig. 1) are very small and the line blanketing in our model is in practice appropriate.

4. Results

Having built up NLTE model atmospheres for a He-rich star, we investigate both photometric and spectroscopic diagnostic tools developed from the stellar atmosphere.

4.1. Theoretical colours

The theoretical colours are, as is known, important tools for determination of basic stellar parameters, the effective temperature and surface gravity. It has been shown that they are especially critical for nonstandard atmospheres. In fact, we met the problem of calibration in Zboril et al. (1997) as compared the values (the effective temperature and surface gravity) derived from colours and spectroscopy.

Here we present theoretical colours for standard UBV(RI), Geneva and $uvby$ systems (Table 1).

Similar to the Geneva [U-V] index, the Stromgren $u-v$ and c1 indexes are affected by the helium abundance most severely, providing the absolute changes of 0.025 and 0.04 magnitudes respectively per 0.4 of helium abundance at the most sensitive grid points. These results differ somewhat from our earlier paper (paper I) but in the present paper the colours were produced from fully consistent models. Specifically, the colours from paper I were essentially a half step; the helium overabundance was treated in the synthetic spectrum mode and not in the model calculations.

4.2. Hydrogen gamma profile

The next tools for diagnose is the hydrogen line profiles, especially the Hγ profile. This strong absorption feature is relatively unblended. We adopted as a criterion for comparison the residual normalized flux at 4336Å against a model with A_{He}=0.1

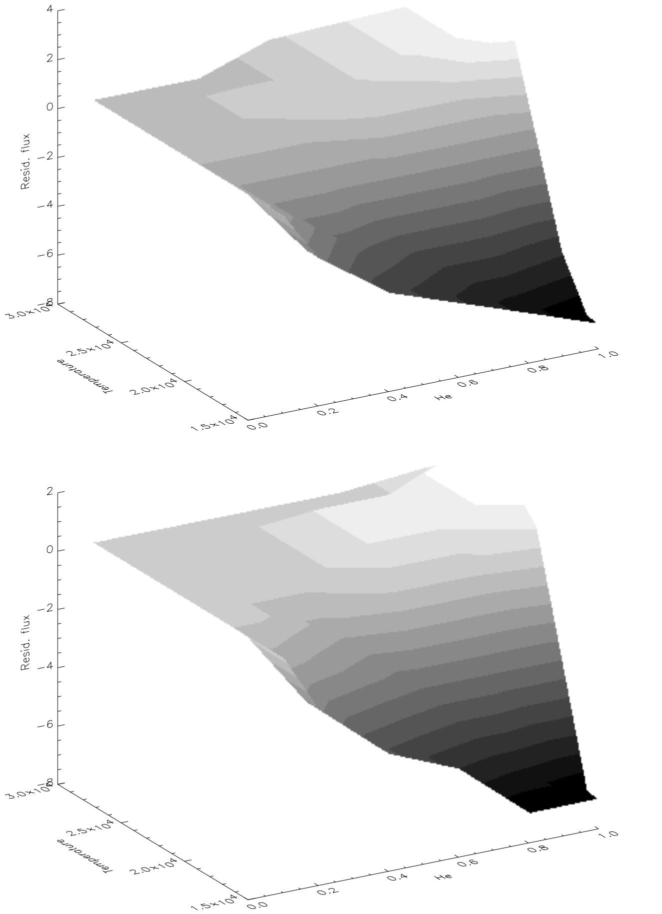

Fig. 3. H_γ residual flux at 4336Å upon helium abundance and effective temperature. Lower section log g=3.5. See text.

abundance for temperature and surface gravity. The residual flux is roughly at FWHM of the Hγ profile.

Fig. 3 displays the multidimensional view of all relevant quantities: He/H number ratio varies from 0.1 to 1. and the effective temperature from 15000K up to 32000K. Residual flux at 4336A is given in percent. There are two main sources responsible for modification of residual fluxes: the physical conditions in the model stellar atmosphere (e.g. line broadening) and indirectly the continuum flux level and its rectification. In fact, in the helium abundance interval 0.1 up to 0.4 and assuming (Gray 1992)

$$p_e \sim const.[1 + 4.A_{He}]^{1/3} \tag{1}$$

we get $\frac{p_e^{0.25}}{p_e^{0.1}} \sim 1.13$ yielding about 10% changes in hydrogen line profile for a helium abundace 0.25.

4.3. Helium abundance

Helium abundance is the primary criterion upon which we assign the status He-rich to a star. There are almost no doubts about such status as an absolute measure, however, care should be taken about relative changes with respect to theoretical models when applying constraints on them. Therefore, we evaluate fully consistent line profiles for helium bound-bound transitions as commonly applied in the literature. Leone & Lanzafame (1998) studied visible neutral helium lines in main sequence B-type stars by comparing observations to NLTE calculations. Noticeably, there are important differences between theory and observations, especially beyond spectral type B2 towards hotter temperatures. For several helium transitions, microturbulence was used to explain the effect, but they demonstrated that HeI lines 438.7, 447.1 and 492.1 nm are closest to the observations and in addition insensitive to microturbulent velocity, so these EW's should be used preferrentially to derive helium abundance. The visual helium transitions are presented: HeI 4009,4026,4121,4387,4438,4471,4713,4921,5015,5047,5876, 6678,7065,7281 and HeII 4541,4685,4859,5411Å.

A majority of helium lines are on the third part of the curve-of-growth but the slope is not 0.5 in a log-log diagram as one might expect. Qualitatively, for a strong line under the assumption of absorption matter in front of the source with continuous emission, we can write for the equivalent width (Gray 1992)

$$W = (const. \langle\gamma\rangle .A_{He})^{1/2}. \int_0^\infty [1 - exp(-1/u^2)]du \tag{2}$$

resulting in a decrease of the exponent 1/2 to 0.37, on average, since the damping parameter $\langle\gamma\rangle$ is larger in helium rich atmospheres. We also expect a higher total pressure in such atmospheres.

4.4. Neutral helium forming regions and level populations

For the model atom of helium we considered 14 levels of neutral helium and 1 level of singly ionized helium as a first iterate. All states with principal quantum number 3 and higher were combined but singlet and triplet states were kept separate. The next model consists of 30 levels of neutral helium and 1 level of ionized helium combining states starting with principal quantum number 6. It is difficult to judge about the overall impact of the NLTE equivalent widths since up to level 3 only the reliable atomic data were taken from the Opacity project while for rest of the levels the photo-ionization cross sections were treated in the hydrogenic approximation. Generally, the departure coefficients differ slightly from unity in the line forming regions, resulting in small changes in equivalent width (typically less than 10%). The NLTE effects thus may be comparable with those obtained by changing the value of macroscopic turbulent velocity in B type stars.

On the other hand, the line forming region interval (based on the monochromatic optical depth 2/3) changes if a fully consistent model atmosphere is used. A helium-rich model atmosphere responds to the line forming region to shift it in the atmosphere as well as to effectively enlarge the extent of that region for red helium lines in the hottest model. This seems to be important in studies of vertical helium stratification. In summary, consistent helium abundances should be preferred in calculations, exceptionally supplemented with the NLTE line forming calculations (especially for transitions with reliable atomic data, see discussion above).

5. Conclusions

We produced fully-consistent NLTE models for He-rich stars from normal helium abundance (0.1) to 1.0 for effective temperatures in the interval 15000K to 32000K and surface gravities from 3.5 up to 4.0. It can be readily understood that a star is helium-rich by looking at the spectrum but it is more difficult to determine to what extent. The results can be summarized as follow:

1. a helium rich model atmosphere differs more severely from a solar abundance atmosphere with increasing temperature and surface gravity.
2. the line-forming region for visual HeI lines differs from a normal atmosphere (A_{He}=0.1), for red helium lines (lambda $>$ 5000Å) it is pushed down in the atmosphere and enlarged.
3. the basic diagnostic tools are definitely affected by helium abundance based on synthetic values, the hydrogen gamma profile by up to 10% (source: model+abundance) and photometric systems up to 0.01 mag/0.1 of the abundance.
4. the NLTE treatment plays a remarkable role only in the Lyman alpha core; the departure coefficients for visual HeI lines are small and marginal changes in the equivalent widths are found (in most cases $< 8\%$). The partial redistribution treatment as an additional opacity source is negligible in comparison with the enhanced abundance in Lyman series.
5. evolutionary status as derived from hydrogen line shape is affected by helium abundance.
6. the curve-of-growth for helium lines is better described by a slope of 0.37, on average.

The models, synthetic colours, hydrogen gamma and helium detailed line profiles (flux at the stellar surface) are tabulated in electronic form and supplemented with simple standard *Fortran* routines.

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