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IMPORTANCE OF STARK DAMPING IN THE STUDY OF ABUNDANCE STRATIFICATION IN AP STARS

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Abstract. In this paper I point out the importance of the accurate Stark widths and shifts for abundance stratification study in the atmospheres of Ap stars. The cases of Ca, Ba and Si empirical distributions are discussed.

1. INTRODUCTION

Among the stars of the Upper Main Sequence (UMS) there is a large class of late A - early B stars which have anomalously strong or anomalously weak lines of different chemical elements in their spectra. This class has a common name – chemically peculiar or Ap stars. A variety of peculiarities are observed in the form of underabundances (He in He-weak stars; CNO in magnetic Ap stars; Ca and Sc in Am stars, metals in λ Boo stars) as well as overabundances (He in He-rich stars, Si in Si-stars; Mn, Hg and other heavy elements in HgMn stars; iron peak (Cr in particular), rare-earths elements in most of Ap and Am stars). A temperature range occupied by Ap stars is 6500 – 20000 K. Most of Ap stars have global magnetic field from hundreds of Gauss to a few dozens of kG. Ap stars are usually slow rotators compared with the normal stars of the same effective temperature. This is sufficient to stabilize stellar atmosphere and to allow chemical element separation while in the normal UMS star atmosphere, where rotational velocities are large enough, rotationally-induced mixing or turbulent stellar winds homogenize the atmosphere, and we do not observe any significant abundance anomalies.

To explain the observed abundance anomalies in Ap stars Michaud (1970) has proposed a radiative diffusion, which together with the gravitational settling may produce both underabundances and overabundances of the chemical elements. The net result of the element separation in stabilized stellar atmosphere is the abundance stratification.

Babel (1992, 1994) was the first to performe theoretical and empirical stratification analysis in the atmospheres of cooler part of Ap stars. He provided theoretical distributions versus optical depth (or *abundance profiles*) for Ca, Ti, Cr, Mn and Sr, which may be represented by simple step-like function. According to his model the Fe-peak elements are underabundant in the upper atmospheric layers and are accumulated at the optical depths below $\log \tau_{5000} = -1$. Recent self-consistent diffusion model calculations for Ap star β CrB by F. Leblanc (see Ryabchikova, Wade and LeBlanc, 2003) supported the results by Babel and provided similar abundance profiles for many other chemical elements. Still theoretical abundance profiles differ from the empirically derived element distributions. The latter mainly depend on our knowledge of the accurate atomic parameters of spectral lines and atmospheric models.

2. THE ROLE OF STARK EFFECT IN ABUNDANCE STRATIFICATION STUDY

There are a number of spectroscopic features in Ap stars which cannot be described with the best chemically homogeneous atmospheric models. They are discussed in details by Ryabchikova et al. (2003). The most significant spectroscopic evidence for stratification is the impossibility to fit the core and the wing of the strong spectral line with the same abundance. This phenomenon is observed in UMS peculiar stars through the entire temperature range of chemical peculiarity. In hot Ap stars He I lines usually have wider wings and less deep line cores compared to the normal stars (see, for example, Figs. 5, 6 of the paper by Bonifacio, Castelli and Hack, 1995). In HgMn stars the core and wing anomaly is observed in the resonance UV Ga II and Ga III lines (Smith, 1995 - Fig. 1 of his paper). The spectra of the cooler Ap stars will be considered below.

Theoretical abundance profiles in most of Ap stars predict element overabundances in rather deep atmospheric layers where the temperature and electron density are high even in the cooler Ap stars thus favouring the Stark effect. In the next subsections I shall give a few examples where Stark shifts and widths are very important in abundance stratification study.

2. 1. CALCIUM LINES

The pioneering stratification studies in the atmospheres of Ap stars by Babel (1992, 1994) were based on the resonance Ca II lines. Babel stressed that 'Ca II K and H lines in Ap stars give precious information about abundance stratification'. This is illustrated in Fig. 1 for the Ap star γ Equ ($T_{\rm eff}$=7700 K) taken from Ryabchikova et al. (2002). Ca II K line is fitted rather well with the Ca abundance distribution similar to theoretical abundance profile from Babel's calculations (Fig. 2).

One can easily see that it is enough to have a precise observed profile of this spectral line to reconstruct Ca abundance distribution in stellar atmosphere. Unfortunately Ca II K line is situated between two hydrogen lines, whose wings are overlapped with Ca II K wings. Also, the core of Ca II K line is certainly affected by NLTE effects. Therefore we need to investigate other spectral lines of both Ca I and Ca II to reconstruct the empirical Ca distribution. There are two Ca II lines in the red spectral region with less severe blending, which show anomalously wide wings in

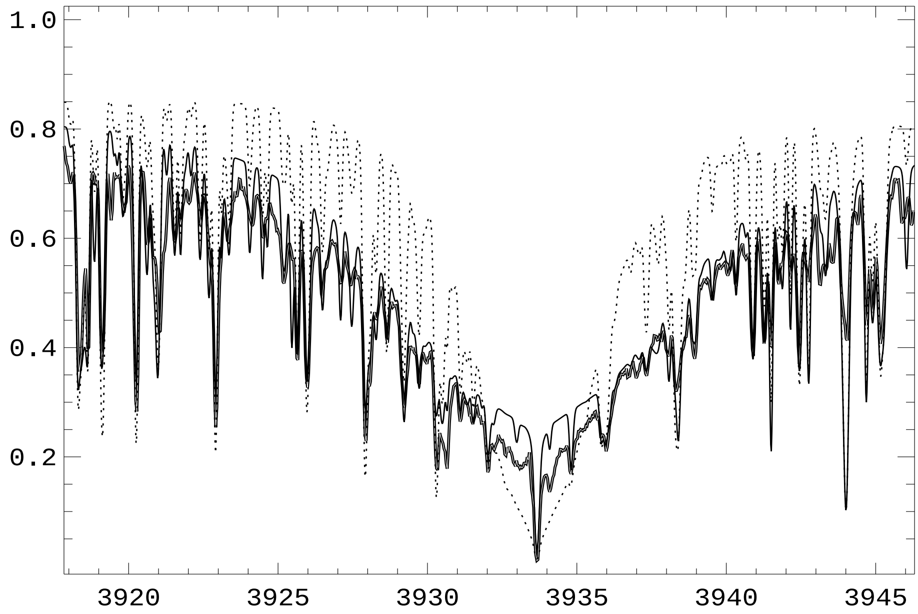

Fig. 1: Ca II K line in the spectrum of γ Equ (left panel). Observations are shown by the double line, the synthetic spectrum using the best homogeneous Ca abundance is shown by dotted line, while the synthetic spectrum calculated with an empirically-derived Ca abundance profile (Fig. 2) is shown by solid line.

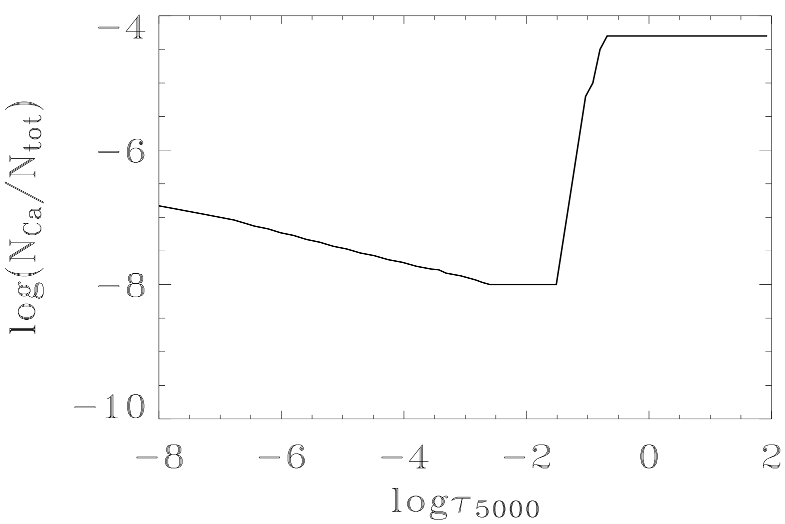

Fig. 2: Ca distribution in the atmosphere of Ap star γ Equ

practically all Ap stars with $T_{\rm eff}\leq$9000 K. These lines, λ 5339.19 Å and λ 6456.87 Å belong to the transitions between the common low level 4f ^2F and the upper levels 7g ^2G, 6g ^2G. In VALD database (Kupka et al., 1999) the corresponding Stark broadening constants for these lines are –3.35 and –4.31, respectively. Stark damping constants here are written in the form log($\gamma_S/N_{\rm e}$, where $N_{\rm e}$ – is electron density in cm^{-1}. I synthesized both lines for γ Equ atmospheric model using the uniform mean Ca abundance from Ryabchikova et al. (1997) and the stratified abundance shown in Fig. 2. Oscillator strengths for both lines are taken from TOPBASE (Seaton et al., 1992) as the best representing the same solar lines. Note that Stark damping constants in VALD were calculated by Kurucz (1993). A comparison between the observed spectrum and my calculations is shown in Fig. 3 by dotted line (homogeneous atmosphere) and by dashed line (stratified atmosphere, Kurucz γ_S data). Using the same $\log(\gamma_S/N_{\rm e}) = -3.7$ for both lines I get better agreement between the observed and synthetic spectra (solid line in Fig. 2). Stratified Ca abundance in γ Equ is necessary to fit simultaneously Ca I lines $\lambda\lambda$ 6449.81 and 6455.50, which have the lower levels with different excitation energies. New calculations of the Stark widths and shifts for more Ca II lines are needed to improve the empirical Ca distribibution in the atmospheres of γ Equ and other cool Ap stars.

2. 2. BARIUM LINES

In most of Ap stars Ba is ionized, therefore we observe only Ba II lines and mainly the strongest ones. It is not possible to make a differential analysis of the strong and weak Ba II lines to search for the possible stratification effects. At the same time in the coolest Ap stars, like one of the craziest representative of the whole class, the famous Przybylski's star (HD 10165, $T_{\rm eff}$=6600 K), a few Ba I lines were identified and measured (see Cowley et al., 2000). It was not possible to fit both Ba I and Ba II line profiles and/or total line intensities (equivalent widths) with the same homogeneous Ba abundance. But a simple step-like Ba distribution, shown in Fig. 6 by dashed line, where the upper limit of Ba abundance was found by fitting Ba II λ 6141 line wings seems to produce a satisfactory fit of the strong Ba II and weak Ba I lines. In these calculations I used the approximation formulae for Stark damping constant as introduced by Cowley (1971) and used in SYNTH code (Piskunov, 1992). A small extra abundance step is required fot proper fit if the Ba II line wings are concerned. Comparison of the observed and synthetic spectra with the homogeneous and stratified Ba abundance is shown in Fig. 4.

If instead I use Stark widths calculated for Ba II lines by Dimitrijević and Sahal-Bréchot (1997) then I need to correct a little bit Ba distribution near the top of the abundance jump (solid line in Fig. 6) to obtain the same fit as before for Ba II λ 6141 line (top panel in Fig. 5 - solid line). It is evident that an improved Ba distribution provides better fit also for Ba I λ 6063 line (bottom panel in Fig. 5 - solid line). It illustrates the importance of accurate Stark damping constants for abundance stratification studies. With the accurate Stark parameters we hope to get as accurate empirical element distributions as possible with the current models of stellar atmospheres.

And finally, I would like to demonstrate that not only Stark widths, but also Stark shifts may play a significant role in abundance stratification analysis.

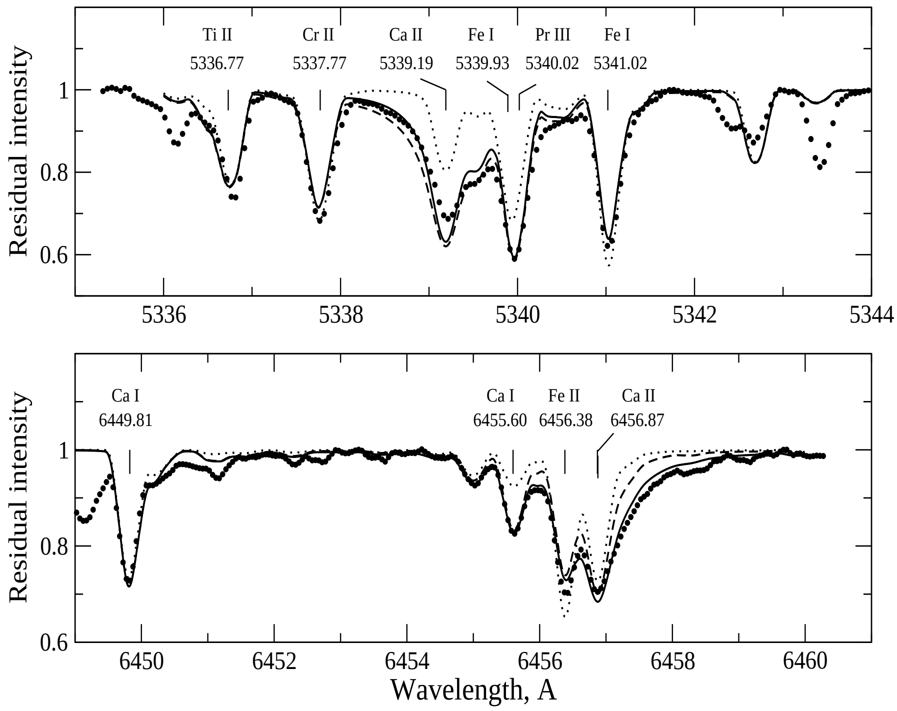

Fig. 3: A comparison between the observed and synthetic spectra in Ap star γ Equ in the region of Ca II $\lambda\lambda$ 5339.19 and 6456.87 lines. Dotted line – calculations with the uniform mean Ca abundance, dashed and solid lines – calculations with different Stark widths discussed in the text.

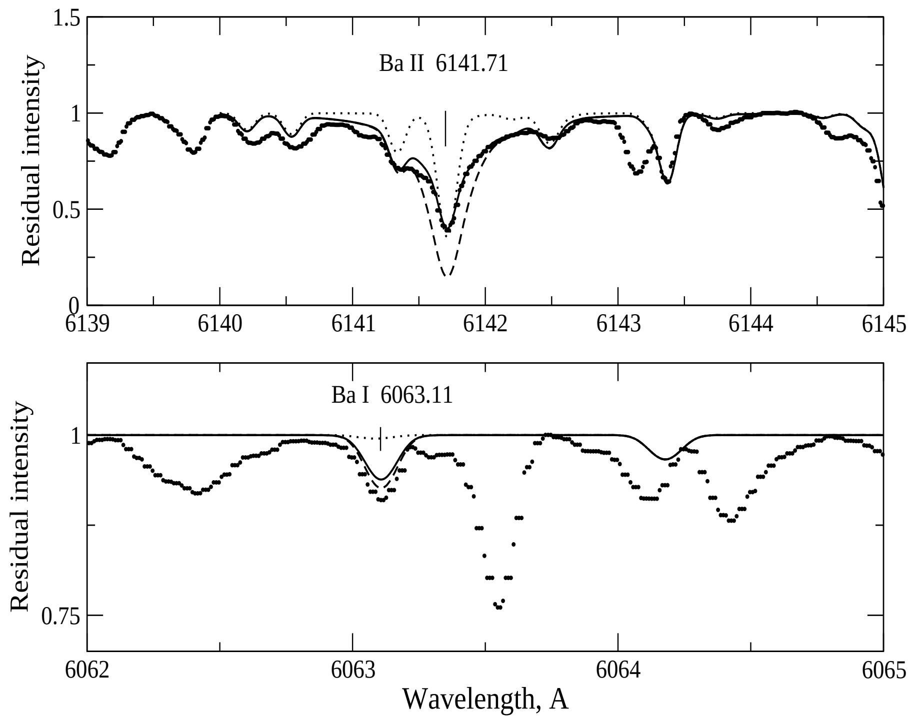

Fig. 4: Ba I and Ba II lines in the spectrum of Przybylski's star, HD 101065 (filled circles). Residual intensity means an observed flux relative to continuum. Dotted and dashed lines represent the synthetic spectra calculated with a homogeneous Ba abundance designed to fit the line core ($\log(Ba/N_{tot})$=-9.20) and the line wing ($\log(Ba/N_{tot})$ = -7.60) of the Ba II λ 6141 line. The solid line represents synthetic spectra calculated with the Ba distribution shown in Fig. 6 by dashed line. The position of the Ba features is marked by vertical lines.

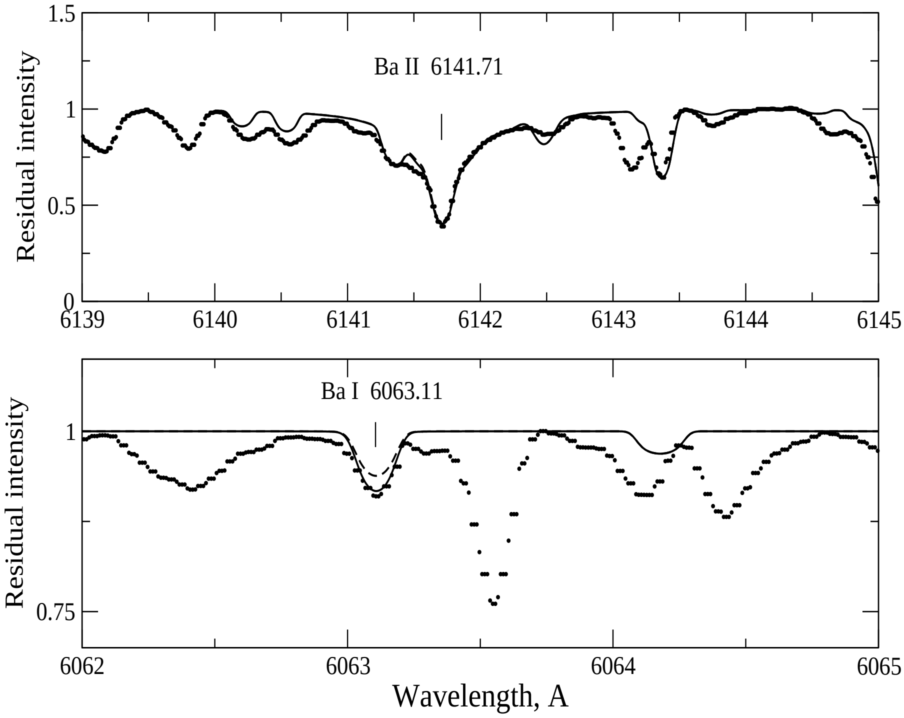

Fig. 5: A comparison between the observed (filled circles) and calculated Ba I and Ba II lines. Calculations with the Stark constants from an approximation formula and with the corresponding Si distribution from Fig. 5 are shown by dashed line, while calculations with the Stark widths from Dimitrijević and Sahal-Bréchot (1997) and with the improved Ba stratification profile are shown by solid line.

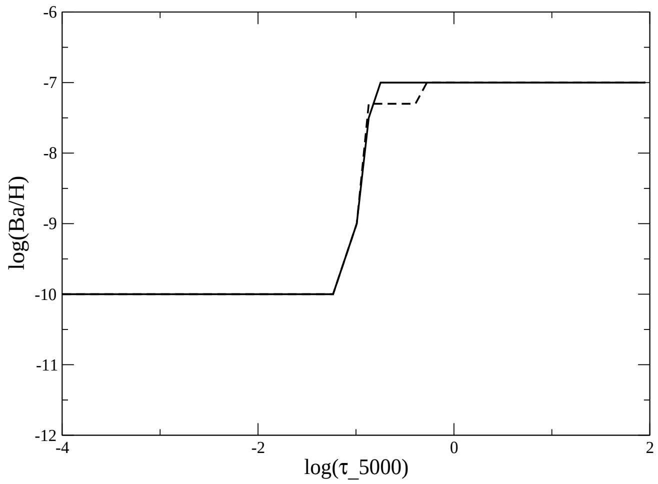

Fig. 6: Ba abundance distribution in the atmosphere of HD 101065 as derived using approximate formulae for Stark damping (dashed line) and with semiclassical Stark calculations by Dimitrijević and Sahal-Bréchot (1997) (solid line).

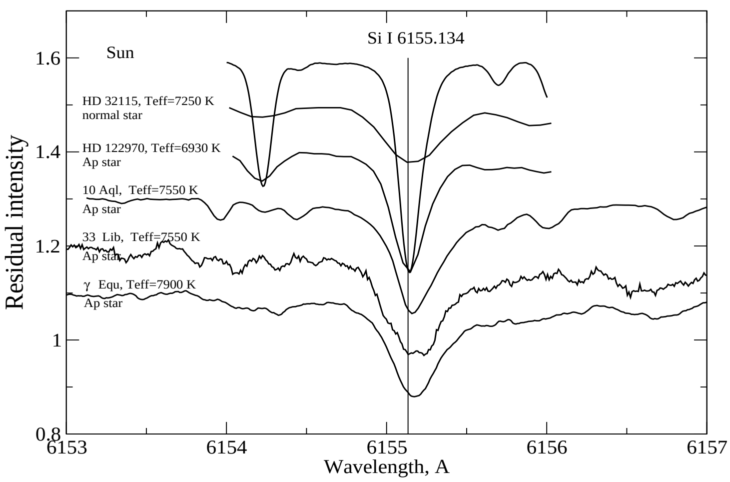

Fig. 7: Si I λ 6155 line in spectra of a few stars with different effective temperatures. The laboratory position of the line is marked by vertical line.

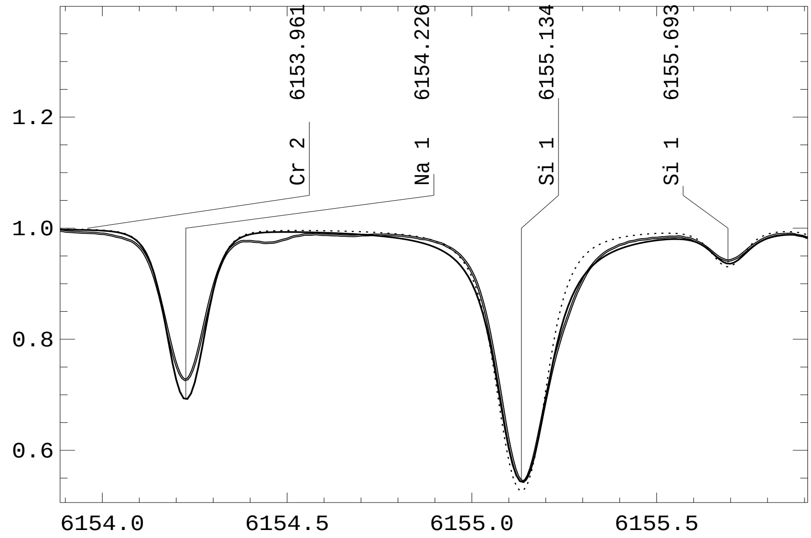

Fig. 8: A comparison between the observed Si I 6155 Å line profile in the solar spectrum and synthetic spectra calculated with Stark widths and shifts (solid line) and with Stark width calculated by approximate formulae and without Stark shift taken into account (dotted line). X- and Y-coordinates are wavelenghths and residual intensities.

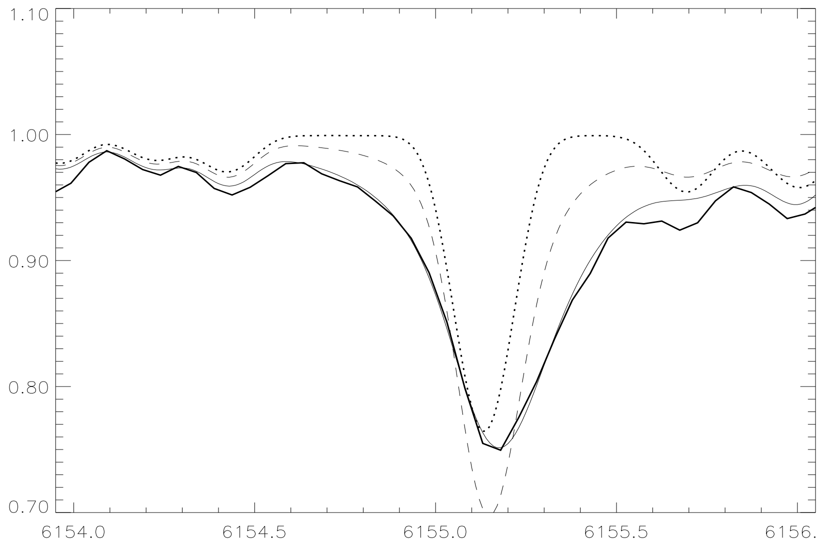

Fig. 9: A comparison between the observed Si I 6155 Å line profile in the spectrum of Ap star 10 Aql (heavy line) and synthetic spectra calculated with Stark widths and shifts and Si abundance stratification (light line), with the same Stark parameters but for homogeneous Si distribution (dashed line), and with Stark width calculated by approximate formulae for the same stratification (dotted line). X- and Y-coordinates are wavelenghths and residual intensities

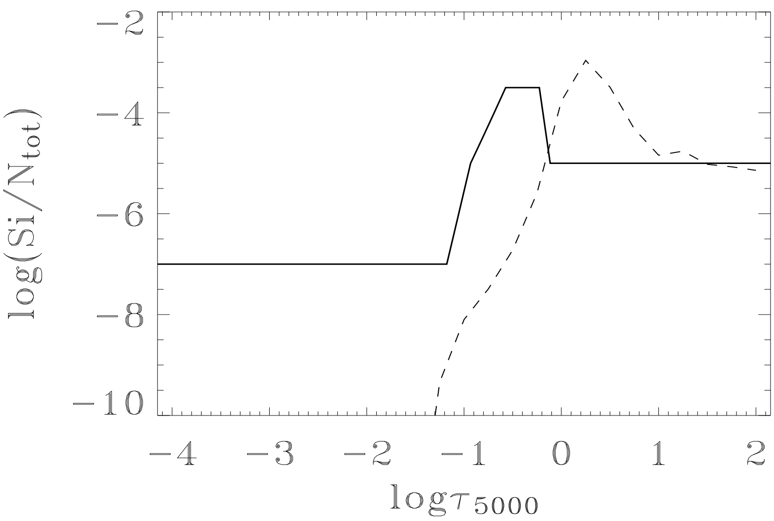

Fig. 10: Si distribution in the atmosphere of Ap star 10 Aql as obtained from analysis of Si I 6155 Å line profile (solid line). Theoretical Si distribution obtained from self-consitent model diffusion calculations is shown by dashed line.

2. 3. SILICON LINES

Silicon is one of the most peculiar elements in the atmospheres of hotter members of magnetic Ap stars which gives the name for a whole subgroup – Si-stars. Usually we observe the lines of the singly-ionised Si, and rather accurate Stark widths for Si II lines are available (Lanz et al., 1988). Working on the abundance analysis of the cooler Ap stars with $T_{\rm eff}\leq$8000 K I have noticed an anomaly in the line profile of Si I λ 6155. This line is shifted to the red and has rather strong asymmetry in the red wing. It is illustrated in Fig. 7. Even the solar line is slightly asymmetric.

Stark constants calculations performed by Dimitrijević et al. (2003) for a few neutral Si lines revealed rather large values for Stark widths and also shifts. First we have modelled Si I lines in the solar spectra. Next two Figs. are taken from Dimitrijević et al. (2003). A fit of the synthetic spectrum to the observed solar Si I λ 6155 line is shown in Fig. 8.

Then spectral synthesis was performed for the same line in Ap star 10 Aql, where Si I λ 6155 line has very pronounced asymmetry (Fig. 9). With the homogeneous Si abundance in stellar atmosphere it was not possible to fit the line profile properly (dashed line in Fig. 9). Again, a rather simple step-like Si distribution shown in Fig. 10 is enough to reproduce successfully an observed line profile (solid line in Fig. 9).

It is possible to compare an empirical Si stratification with the results of the self-consistent model diffusion calculations by F. Leblanc (Ryabchikova et al., 2003). Theoretical Si distribution for slightly hotter model ($T_{\rm eff}$=7700 K) is shown by dashed line in Fig. 10. While theoretical and empirical Si distributions are shifted by about

0.5 dex in optical depth scale, both provide the same abundance gradients in stellar atmosphere. It is encouraging that both empirical and theoretical distributions provide similar abundance profiles, although they are shifted from each other in the optical depths.

3. CONCLUSIONS

An empirical study of the abundance stratification in the atmospheres of Ap stars is difficult, even impossible without accurate data for Stark damping constants. Stark wings of the spectral lines allow to reconstruct vertical abundance gradients produced by element separation processes operating in stabilized stellar atmospheres. It imposes very important constraints for the theories of these separation processes.

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