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Element stratification in roAp stars

10 Aquilae (HD 176232)

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Abstract. We present the results of our analysis of the vertical element stratification in the atmospheres of 9 roAp stars. Using high resolution observations ($R \approx 100\,000$) obtained with the ESO-VLT spectrograph UVES and state of the art model atmosphere and spectral synthesis codes, we analysed the inhomogeneous vertical distribution of Mg, Si, Ca, Cr, Fe and Sr in 10 Aquilae (HD 176232) and Fe stratification in the whole sample. We present the derived vertical abundance map of 10 Aquilae's atmosphere and compare our findings with Fe stratification profiles of all roAp stars.

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

1. Introduction

Abundance anomalies of roAp stars, a cool pulsating subgroup of Ap stars, have been spectroscopically analysed in very much detail over the past years. Several studies (e.g. Ryabchikova *et al.*, 2004) revealed that in atmospheres of roAp stars Fe-peak elements are generally solar or overabundant (with the overabundance of Fe and Cr increasing with effective temperature $T_{\rm eff}$). Rare earth elements (REE) are enhanced by up to 4 dex in all Ap stars, while we observe a difference in abundances of up to 2 dex between the first and second REE ions in the pulsating members of this group. Previous results of abundance stratification analyses of roAp stars are presented by Ryabchikova and others in this conference. The vertical distribution of the elements can be described by a simple step profile, as was first shown by Babel (1992). So far, it has been found that elements like Fe, Cr, Ca, Si and Mg are concentrated in deeper atmospheric layers, whereas the upper atmospheric layers often appear even underabundant in these elements.

In this paper we focus mainly on the detailed abundance analysis of 10 Aql (HD 176232), a narrow-lined roAp star with a very small magnetic field. We also present preliminary results for the first attempt at a systematic study of abundance stratification profiles in roAp stars with different fundamental parameters and magnetic field strengths.

2. Observations and analysis

This work is based on 9 objects included in the observing programmes 68.D-0254(A) (HD 217522, HD 122970, HD 24712, HD 965, HD 137949, HD 176232, HD 201601, HD 116114) and 60.A-9022(A) (HD 18610) carried out with the ESO-VLT UVES spectrograph, which focussed on high resolution, high S/N spectroscopic observations of narrow-lined magnetic Ap stars. Observations typically cover a large wavelength range (3300 - 8000 Å) which provides access to a vast number of spectral lines of various elements. For HD 18610 a slightly shorter region from 4270 to 6900 Å was observed. Data reduction was performed using a pipeline optimized for our targets (Lyashko *et al.*, 2007).

As a first step fundamental parameters were derived from calibrations of Strömgren photometry (Moon, Dvoretsky 1985) using *TempLogG* (Kaiser, 2006). Then an initial scaled solar model atmosphere was computed with *ATLAS9* (Kurucz, 1993). Atomic line data for spectral synthesis were extracted from the VALD database (Piskunov *et al.*, 1995; Kupka *et al.*, 1999). After an analysis of a number of Fe lines, based on equivalent-width measurements and a modified version of the *WIDTH9* code (Kurucz, 1993), fundamental atmospheric parameters could be refined.

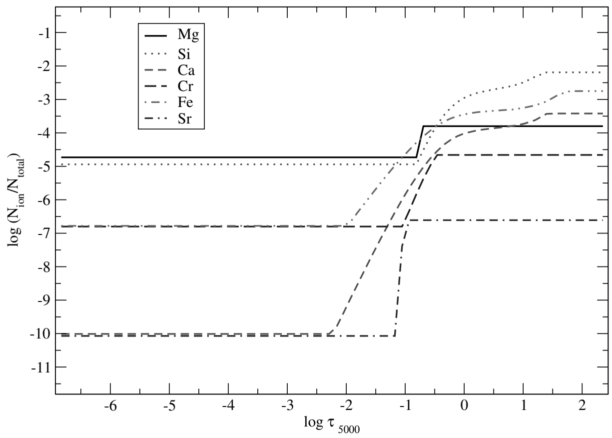

Figure 1. Stratification profiles of 6 elements.

During this analysis the classical indicators for chemical stratification were observed for some elements in all stars of our sample: i) abundances differ largely between different ions or weak and strong lines of the same element, ii) for some doubly ionized species, abundances obtained from high excitation lines ($E_{\rm low} > 10\,$eV) are up to 2 dex larger, iii) the “core - wing anomaly” makes it impossible to model wings and cores of strong spectral lines with the same abundance value because line cores are formed in shallower atmospheric regions than line wings and the continuum. Consequently, in order to account for stratification effects in the magnetic spectral synthesis with *SYNTHMAG* (Kochukhov, 2007), we applied the step function model (Babel, 1992) for further analysis of vertically stratified elements. We used the *DDAFIT* code (Kochukhov, 2007) together with *SYNTHMAG* for automatic fitting of a parameterised step function to a carefully selected set of lines for each element. This way, the following parameters could be determined: inner abundance $N_{\rm in}$, outer abundance $N_{\rm out}$, abundance step location $rhox_{\rm step}$ and abundance step width $\Delta rhox_{\rm step}$. For better illustration the depth variable *rhox* (column mass), which is commonly used in atmosphere models like *ATLAS9*, was then transferred to the monochromatic optical depth scale $\log\tau_{5000}$.

In addition to the complete chemical analysis of the atmosphere of 10 Aql so far only the vertical distribution of Fe was studied in the 8 other stars using the same procedure.

3. Results

3.1. 10 Aquilae (HD 176232)

For the analysis of 10 Aql, a well known sharp lined roAp star (see Sachkov *et al.*, 2008) the comparison of observed and synthetic line profiles was based on a model atmosphere with individual chemical composition calculated with the *LLModels* code (Shulyak, 2004) and spectral synthesis with *SYNTHMAG* (Kochukhov, 2007). Through an iterative process average element abundances were determined for 35 species. Tab. 1 lists the fundamental parameters used in this analysis. The error for $T_{\rm eff}$ was estimated to be ±150 K, by comparison with synthetic hydrogen lines profiles and spectrophotometric observations (Adelman, 1981). We estimate the uncertainty of $\log g$ to be of the order of ±0.2 based on hydrogen lines profiles. In magnetic stars no real microturbulence is expected. For non-magnetic synthesis codes one would have to assume $v_{\rm mic} = 1\,{\rm km\,s^{-1}}$ in order to account for the additional line broadening.

Table 1. Fundamental parameters used in the analysis of 10 Aql

$M_{\rm v}$	$T_{\rm eff}$	$\log g$	$v_{\rm mic}$	$v\sin i$	$B_{\rm surf}$
5.9 mag	7 550 K	4.0	0 km s^{-1}	< 2 km s^{-1}	1 250 G

Fig. 1 shows the derived stratification profiles for Mg, Si, Ca, Cr, Fe and Sr, each of which could not be modelled with one single abundance value. Deviations from pure step functions are caused by the conversion from the *rhox* depth scale used in calculations to $\log\tau_{5000}$. For each element, uncertainties of the fitting procedure for each step function pameter are given in Tab. 2.

Table 2. Uncertainties of the automatic step-function fitting procedure.

	N_{out}	N_{in}	τ_{step}	$\Delta\tau_{\mathrm{step}}$
Mg	±0.077	±0.045	±0.138	±0.407
Si	±0.046	±0.033	±0.012	±0.229
Ca	±0.557	±0.150	±0.034	±0.103
Cr	±0.064	±0.120	±0.014	±0.106
Fe	±0.552	±0.559	±0.049	±0.298
Sr	±0.367	±0.232	±0.021	±0.106

The global abundance pattern of HD 176232 is presented in Fig. 2. This differential abundance plot shows abundances for all the species we studied in this star, including the stratified elements. The element abundances are plotted in grey scale. The radial coordinate, $\log \tau_{5000}$, ranges between inner and outer atmospheric boundaries of 2.3 and -6.8, respectively. These values are typically used for model atmosphere calculations. The circles at $\log \tau_{5000} = 0$ and -2 mark the atmospheric region where abundance steps occur. Fig. 2 illustrates the inhomogeneous distribution of Mg, Si, Ca, Cr, Fe and Sr as well as the strong overabundance of REE and the anomalous enhancement of their second ions. We suggest this kind of plot as a new and more intuitive way to display the complete chemical composition of the atmosphere of a chemically peculiar star. Analogous to the surface abundance maps we know from Doppler Imaging studies of other objects (see Lueftinger *et al.*, 2008) this plot represents the first **vertical abundance map** of the atmosphere of 10 Aql.

3.2. Fe stratification in other Ap stars

Stratification profiles for the 8 other programme stars are presented in Fig. 3. The errors for parameters of the step functions are of the same order as given for 10 Aql. Refinement of the fits to some stars is currently ongoing. In the complete sample, including 10 Aql, which covers the T_{eff} region from 6900 to 8100 K where the roAp phenomenon occurs, we detect a correlation of T_{eff} with the location of the abundance step $\log rhox_{\mathrm{step}}$. With higher T_{eff} the step position moves towards outer layers. These results should be further investigated and compared with predictions from diffusion models. No other clear correlations between T_{eff} or magnetic field with other properties of the step function model were found.

4. Conclusions

We have derived stratification profiles of Mg, Si, Ca, Cr, Fe and Sr for 10 Aql and Fe in 8 additional cool Ap stars. In our sample we detect a shift of the Fe step location towards the outer layers with increasing T_{eff}. This finding is consistent with the overall abundance pattern studies which show an increase

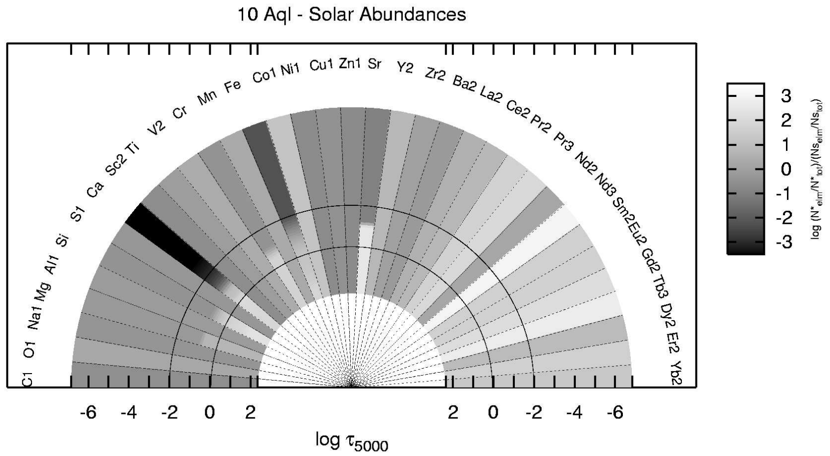

Figure 2. Differential abundances and stratification patterns throughout the atmosphere of 10 Aql. Solar reference values are those of Asplund *et al.* (2005). Darker areas correspond to underabundant species, lighter areas denote a high overabundance. The abundance scale is given as $\log(N^{\star}_{\rm elm}/(N^{\star}_{\rm tot}/N{\rm s}_{\rm elm}/N{\rm s}_{\rm tot})$.

of Fe abundance with $T_{\rm eff}$ (Ryabchikova *et al.*, 2004) and predictions from theoretical models. No correlation between Fe stratification profiles and magnetic field strength was detected in our sample of stars.

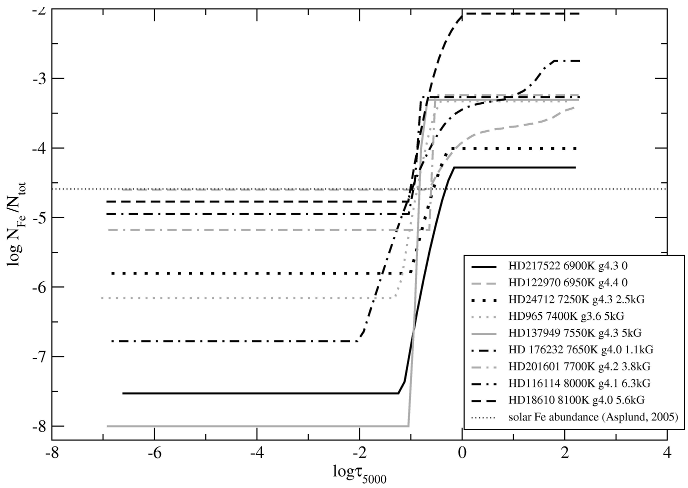

Figure 3. Fe stratification profiles for 9 stars with different magnetic field strength (0-6.5 kG), and effective temperature.

Future studies of the chemical composition of Ap stars should continue to derive stratification profiles for more stars and more elements in a *consistent* manner. Observed Fe stratification profiles should be compared to sophisticated magnetic atmospheric models including diffusion calculations.

In order to obtain 3-dimensional abundance maps for a representative number of Ap stars observers should find more stars which provide suitable conditions to simultaneously study magnetic field geometry, surface and vertical element distribution.

A major part of the work in the near future will however, have to be dedicated to a thorough investigation of errors in these sorts of analyses.

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