# On possible stratification of chemical elements with depth in the atmospheres of CP stars

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Abstract. Different problems concerned with the stratification of chemical elements with depth are described. Results of investigation of vertical stratification of Cr in the well-known star $\alpha^2$ CVn obtained by different authors is compared. A study of the vertical stratification of rare-earth element in future investigations is proposed.

## 1 Introduction

For long it has persistently been attempted to inquire into the matter of distribution of chemical elements in the atmospheres of CP stars with depths, for it is of great theoretical importance. The present-day science cannot admit chemical anomalies in CP stars to represent the chemical composition of the whole star - these must be of surface nature. But what the characteristic depth of occurrence of various anomalies in stars of different types is - this depends on a great number of parameters and mechanisms and is determined ambiguously as a result of complicated theoretical calculations. Therefore the problem of actual processes of separation of chemical elements in the atmospheres of CP stars, can be resolved on the basis of observations. However, to pick from observations the information on the depth of concentration of chemical elements, one needs, firstly, high-quality spectral data with low noise, high resolution, secondly, accurate values of atomic parameters of spectral lines, especially, oscillator strengths, thirdly, accurate theoretical calculations of spectra, taking into account the magnetic field, inhomogeneous distribution of elements over the surface and other individual properties of every star.

All these requirements are difficult to meet, therefore the obtained observational results are often ambiguous. A condensed survey of various techniques of spectral analysis which can be helpful in solving the problem was presented at the last meeting of the magnetic star investigators (Zboril, 1994). Here we will analyze the attempts of different authors to investigate the depth distribution of chemical elements in the atmosphere of one of the well-studied CP stars, $\alpha^2$ CVn, state our assumptions concerning some peculiarities of its spectrum and plans of its further investigation.

## 2 Is there inhomogeneity in the distribution of iron peak elements in the upper layers of $\alpha^2$ CVn?

The iron-peak elements in the atmospheres of the Si-Cr-Eu magnetic star $\alpha^2$ CVn are largely overabundant, by 1-3 orders, and their abundances vary with phase (Cohen, 1970) i.e. the elements are inhomogeneously distributed over the surface of the star. Mapping of the surface distribution of Ti, Cr, Fe in $\alpha^2$ CVn has been performed by Khokhlova and Pavlova (1983). We know four papers in which attempts have been made to derive the distribution of these elements with depth in the atmosphere. Romanyuk et al. (1992) studied the distribution of iron, while Khokhlova and

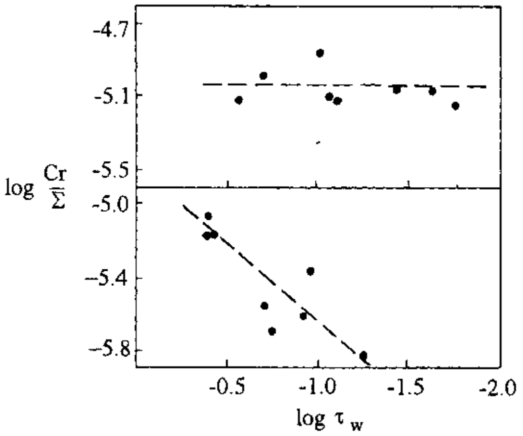

Figure 1: Chromium abundance of $\alpha$ CVn as a function of optical depth of the line formation, obtained by KhT (top) and from the results of ZZa (bottom).

Topilskaya (1992, further KhT) and Zverko and Ziznovsky (1994, ZZa; 1995, ZZb) studied the distribution of chromium. In the last three papers the chromium distribution was investigated from the same lines of Cr II of the 30-th multiplet, which were located in the wings of $H_\beta$ .

The results were contrary: KhT established that the inhomogeneity distribution of chromium in the upper atmosphere layers is inconsistent with observations, whereas ZZ(a,b) found it to decrease in the upper atmosphere. Let us compare the results in detail.

KhT used photographic spectra taken at the 6 m telescope with D = 1.3 Å/mm at the phase of maximum chromium, $\phi$ = 0.25. The Kurucz (1979) model with the parameters $T_e$ = 11500K, lgg = 4.0, $z$ = 0 was used in the analysis, equivalent widths of isolated lines of Cr II with $v_t$ = 2.0 km/s were calculated using the program KONTUR (Leushin and Topilskaya, 1986) and compared with the observed $W_\lambda$ .

ZZa worked with reticon spectra with D = 8.5 Å/mm, S/N = 350 out of phase of maximum chromium, $\phi$ = 0.8. They used the same model but calculated by the program ATLAS 9 (Kurucz, 1993), the analysis was made by the synthetic spectrum method using the program SYNSPEC (Hybeny, 1987), taking the atomic data from the list of Kurucz (1993). In both works the whole analysis was made in the LTE approximation.

We measured the observed equivalent widths of the lines used in ZZa from the fragment of the spectrum available in literature and computed for them the chromium abundance and effective depths of line formation using the procedure that was applied in KhT. At the same time we repeated the calculations with $W_\lambda$ from KhT. The only distinction was that we calculated the line Cr II 4376 as the doublet of Cr II 4876.40 and Cr II 4876.47 and took into account the blending of CrII 4856.19 with Ti 4855.91 , lg $gf$ = -1.32, lg Ti/Σ:= -5.95. This made the agreement with the observed $W_\lambda$ better. All the results are given in Table 1 and Fig.1. Our new computations confirmed the results obtained previously by KhT and ZZa: the chromium abundance does not change at depths $\tau_W$ from 0.01 to 0.3 in $W_\lambda$ from KhT and decreases outward according to $W_\lambda$ from ZZa. Thus, the reason for the discordance of the results lies not in the difference of the procedures applied by KhT and ZZa, but in the difference in observational data. This is well represented in Fig.2: $W_\lambda^{ZZ}/W_\lambda^{KhT}$ decreases with decreasing distance of the lines Cr II from the $H_\beta$ center. There might be two causes of the discrepancies: 1) different chromium distribution with depth in different areas of the surface of $\alpha^2$ CVn; 2) differences in calibration of spectra (photographic spectra — density/intensity relation,

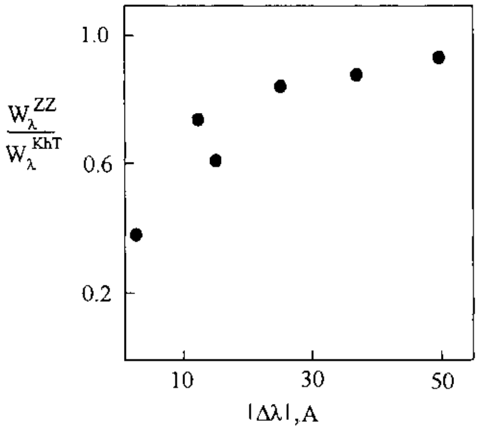

Figure 2: Relation of the observed chromium equivalent widths, measured by ZZa and KhT as a function of the line distance from the centre of $H_\beta$ line.

Table 1: Chromium abundance in $\alpha$ CVn, determined by KhT and ZZa near $H_\beta$

| | | Khokhlova, Topilskaya | | | Zverko, Ziznovsky | | | |
|---|---|---|---|---|---|---|---|---|
| $\lambda$, Å | $(\Delta\lambda)$, Å | $W_\lambda$, mÅ | $\lg Cr/\Sigma$ | $\lg \tau_W$ | $W_\lambda$, mÅ | $\lg Cr/\Sigma$ | $\lg \tau_W$ | $\lg gf$ |
| 4860.20 | 1.13 | 4.6 | -5.14 | -1.77 | | | | -2.04 |
| 4864.32 | 2.29 | 32 | -5.06 | -1.62 | 12.5 | -5.82 | -1.25 | -1.36 |
| 4856.19 | 5.14 | 33 | -5.06 | -0.92 | 16 | -5.69 | -0.74 | -2.03 |
| 4848.21 | 13.09 | 81 | -5.12 | -1.10 | 60 | -5.61 | -0.91 | -1.15 |
| 4876.40 | 15.08 | 110 | -4.86 | -1.00 | 68 | -5.55 | -0.70 | -1.46 |
| 4884.61 | 23.25 | | | | 47 | -5.06 | -0.39 | -2.13 |
| 4836.22 | 25.11 | 60 | -4.99 | -0.69 | 51 | -5.17 | -0.42 | -1.93 |
| 4824.14 | 37.20 | 103 | -5.10 | -1.06 | 92 | -5.34 | -0.95 | -0.96 |
| 4812.35 | 48.49 | 53 | -5.12 | -0.55 | 50 | -5.17 | -0.38 | -1.99 |

reticon — relatively short segment of spectra and uncertainties of drawing the continuum). The paper of ZZb, where the analysis of $\alpha^2$ CVn was performed from spectra at six different phases, did not clear up the situation either: similar results were obtained for all phases — the chromium abundance decreases outward, but the phase $\phi$ = 0.25, which was examined in KhT, was lacking in ZZb. Unfortunately, the quality of spectral data in ZZb was somewhat worse, S/N~ 150, and this is a likely cause of the scatter of chromium abundances from different lines, so the possible relationship between the abundance and depth is smeared by this spread. The paper of ZZb is more remarkable because four stars were analyzed using the same procedure, but only for $\alpha^2$ CVn, after averaging the data obtained at all phases, the chromium abundance was found to decrease outward. Three other stars — Sirius, Vega and $\varepsilon$ UMa — did not show any depth stratification of chromium.

The detailed analysis of the two papers allows the conclusion to be drawn that the method of analysis of the lines of one multiplet, which are located in the wings of H line can be used for diagnostics of distribution of an element with depth in the atmosphere. The level of theoretical calculation — the accuracy of construction of model atmospheres and computation of theoretical absorption lines and fragments of synthetic spectra — makes it possible to obtain reliable results, given accurate atomic parameters of lines. However, for this to be done, further improvement of accuracy of spectral data and allowance for inhomogeneous distribution of elements over the star surface are needed.

The distribution of iron abundance in the atmosphere of $\alpha^2$ CVn was studied in the paper of Romanyuk et al. (1992) from the lines Fe I and Fe II located on both sides of the Balmer jump at two phases: $\phi = 0.0$ and $\phi = 0.5$. The work was done using photographic spectra taken at BTA with D = 6.7 Å/mm. It turned out that at both phases the iron abundance increases in the upper atmospheric layers. The accuracy of this result is not high because of the unreliable line oscillator strengths in the blue region of the spectrum, strong line blending and uncertainty in the plot of the continuum, which is invisible due to the large number of atmospheric lines, although, in order to improve the accuracy, the analysis was made using 3 spectra at phases close to 0.1 and 4 spectra at phases close to 0.5.

Note that if one compares the result of the work described above with the results of the present paper, which are obtained from chromium with $W_\lambda$ from ZZ(a,b), iron will turn out to concentrate in the atmosphere of $\alpha^2$ CVn quite unlike chromium: the iron abundance at a depth $\lg\tau_W$ = —1.5 is higher than at $\lg\tau_W$ = —0.1, both inside and outside the spot, whereas the chromium abundance outside the spot is lower at $\lg\tau_W$ = —1.0 than at $\lg\tau_W$ = —0.5.

It seems to us that despite the great difficulties in the analysis of lines on both sides of the Balmer jump, this method has the advantage that in this wide spectral region one can find a comparatively large number of lines of different chemical elements suitable for analysis. It would be of great interest to check the chromium distribution with depth from lines on both sides of the Balmer jump at different phases.

## 3 On possible investigation of vertical stratification of rare-earth elements in the atmospheres of Cp stars

Stratification of rare-earth elements in the atmospheres of Cp stars deserves special attention. There are much evidence that ions of rare-earth elements in the atmospheres of peculiar stars are concentrated, as a rule, in very sharp spots that coincide with the poles of magnetic dipole (for instance, Floquet, 1979).

The atmosphere depth in Cp stars is only 0.1% of their diameter, therefore the non-uniform distribution of elements over the surface strongly affects the results of investigation of stratification with depth.

Examining the lines of rare-earth elements with a wavelength larger or smaller than 3646 Å at different phases of the rotation cycle, one can derive new important information, provided that the information is interpreted by the model atmospheres which take into account the two-dimensional non-uniformity.

In order to avoid the uncertainties associated with inaccurate estimates of oscillator strengths, temperature and other effects, it is most intelligent to use for analysis the lines of one multiplet, which are formed from sublevels of the same level which have similar excitation potentials.

It would be good luck to find a rare-earth element multiplet, one part of which would have $\lambda$ > 3646 Å, the other — $\lambda$ < 3646 Å. In the tables of Moore (1945) we have found the second multiplet of Gd II, which complies with these requirements.

The data on the lilies of this multiplet are given in Table 2.

In the columns of Table 2 are presented: line wavelength (Å), line intensities (both taken from Moor's (1945) tables); four subsequent columns follow from the Vienna Atomic Line Database (VALD, Piskunov et al., 1995): logarithms of oscillator strengths (lg *gf*), Lande factors (z), excitation potentials (eV) and central depth of Gd II lines for a typical peculiar star with the effective

Table 2: Second multiplet of Gd II

| Wavelength Å | Moore Intens. | lg $gf$ | Lande factor | Excit (eV) | VALD Intens. |
|---|---|---|---|---|---|
| 3422.466 | 10000 | 0.519 | 1.15 | 0.240 | 0.528 |
| 3545.797 | 3000 | 0.140 | 1.25 | 0.144 | 0.428 |
| 3646.19 | 3000 | 0.328 | 1.65 | 0.240 | 0.440 |
| 3671.20 | 1500 | -0.330 | 1.24 | 0.079 | 0.686 |
| 3716.36 | 1000 | -0.555 | 1.12 | 0.032 | 0.593 |
| 3743.47 | 2000 | 0.048 | 1.70 | 0.144 | 0.794 |
| 3759.00 | 300 | -0.842 | 1.00 | 0.000 | 0.387 |
| 3768.39 | 2000 | 0.257 | 1.80 | 0.079 | 0.822 |
| 3796.37 | 2500 | -0.035 | 1.97 | 0.032 | 0.786 |
| 3813.97 | 2000 | -0.215 | 2.36 | 0.000 | 0.741 |
| 3844.579 | 500 | -1.125 | 1.77 | 0.144 | 0.140 |
| 3850.69 | 800 | -0.206 | 1.86 | 0.079 | 0.720 |
| 3850.97 | 1200 | -0.094 | 2.15 | 0.000 | 0.772 |
| 3852.45 | 1000 | -0.137 | 1.97 | 0.032 | 0.758 |
| 3855.56 | 200 | -0.895 | 1.78 | 0.240 | 0.290 |

temperature $T_e$ = 10000 , acceleration of gravity lg g = 4.0 and Gd II abundance =-8.1. (In VALD the abundance of Gd II= -10.92 is adopted as normal.)

Remember that some of the lines indicated are in the wings of hydrogen lines (high members of the Balmer series):
H (9) = 3835.39; H (10) = 3797.90; H (11) = 3770.63;
H(12) = 3750.12; H (13) = 3734.37; H (14) = 3721.96;
H(15) = 3711.95.

As is seen, some lines of the second multiplet of Gd II (3768.39; 3796.37) will be difficult to measure, because they are actually located in the cores of hydrogen lines. Table 2 demonstrates that the lines of the second multiplet of Gd II must be observable in peculiar stars (provided that the abundance of Gd II is 2-3 times higher than that of solar).

A detailed study is the matter of the future, however some considerations can be stated even now.

In real peculiar stars the lines of rare-earth elements are strongly variable. The lines of the same multiplet must show synchronous variability which expedites the identification.

On the basis of the results of different authors a conclusion can be drawn that the intensity of the Gd II lines in $\alpha^2$ CVn in the region of spectrum shortward the Balmer jump is lower. If the regularity is confirmed, this may imply that the abundance of Gd II in the atmospheres of $\alpha^2$ CVn decreases outward. Certainly, one has to make accurate measurements of equivalent width of the second multiplet of Gd II in the spectra obtained at different phases of the rotation period of the star. Only then can definite conclusions be made.

It seems to us that new high-precision observations of peculiar stars will call for new model atmospheres allowing for the two-dimensional non-uniformity in the distribution of chemical elements for interpretation of results. This problem is very involved. However, it is only by investigation of vertical stratification of chemical composition and magnetic field in the atmospheres of peculiar stars that one can attempt to understand the mechanism producing anomalies.

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