

INVESTIGATION OF DISTRIBUTION OF CHEMICAL ELEMENT ABUNDANCE WITH DEPTH IN THE ATMOSPHERE OF

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ABSTRACT. From investigations of spectrograms of the chemically peculiar star $\alpha^2\text{CVn}$ we found a small increase of iron abundance in its upper atmosphere layers. The spectra were obtained on the 6 m telescope with the reciprocal linear dispersion $D=6.7 \text{ A/mm}$ with the Zeeman achromatic analyzer.

1. PROBLEM STATEMENT

Investigation of chemical element abundance distribution with depth in the atmospheres of CP stars is absolutely necessary in order to check the correctness of our notions on the peculiarity nature of CP stars.

Nowadays the most understandable explanation of the observed chemical composition anomalies is to treat them as surface effects. The theory of chemical element diffusion in calm atmospheres of CP stars, developed by Michaud's group (Michaud, 1970), is a theoretical basis here. According to this theory, due to the influence of gravity, magnetic field and emission pressure different chemical elements can gradually "sink" or "surface" in the upper atmosphere layers of CP stars. In numerical description of these processes one comes across a lot of complicacies and uncertainties, therefore the question at what depth they occur still remains open. The determination of the chemical element abundance distribution with depth on the basis of observations has some peculiarities, because of which there are still no significant results obtained. The most difficult thing is that every spectral line is formed in a considerably thick atmosphere layer, therefore to divide lines according to their formation region depth appears to be extremely difficult. We decided to avoid this difficulty by dividing weak lines into two groups: with wavelengths $\lambda > 3647 \text{ \AA}$, and $\lambda < 3647 \text{ \AA}$.

The depths of formation of these lines considerably differ due to the strong change of the hydrogen atom continuous absorption coefficient at $\lambda=3647\text{ \AA}$. At smaller wavelength the hydrogen atom continuous absorption is well greater, therefore weak lines will be formed higher than the lines with $\lambda>3647\text{ \AA}$. In order to answer the question on possible stratification of elements with depth, a high precision of determination of chemical composition at different depths is needed. The allowance for blending of different lines in rich spectra of CP stars, the increase of accuracy of the observed equivalent line widths of W_λ and the selection of lines with reliable values of atom parameters are of paramount importance here. Another difficulty is introduced by inhomogeneous surface distribution of chemical elements in CP stars. The bright peculiar star $\alpha^2\text{CVn}$ was selected for the investigation. The distribution of many chemical elements over its surface had been investigated earlier by Pyper (1969), Goncharskij (1983), and Khokhlova and Pavlova (1983).

As far as the calculations of theoretical line profiles were carried out in one-dimensional (in depth) approximation, we used the spectra obtained at phases, corresponding to two spots on the surface of $\alpha^2\text{CVn}$, correspondingly. In the calculations we used different atmosphere models for the spots.

The work has been started for four chemical elements: iron, chromium, europium and gadolinium. Here we present the first results, which evidence on a small increase of iron abundance in the upper layers of $\alpha^2\text{CVn}$ atmosphere.

2. OBSERVATIONAL MATERIAL

The observed W_λ of the lines in $\alpha^2\text{CVn}$ were measured from photographic spectra, obtained on the 6 m telescope with a reciprocal linear dispersion of 6.7 $\text{\AA}/\text{mm}$ in the spectral region 3300 \AA - 4000 \AA during 1979 - 1985. For this purpose we obtained Zeeman spectra of this star at different phases of the rotational period with the circular polarization achromatic analyzer. The magnetic fields were measured on all spectrograms. The results were published by Romanyuk (1986; 1991).

All in all we have investigated 30 spectrograms at different phases, 8 spectrograms are used in this paper, their data are presented in Table 1.

Table 1. Observational data

No spectrogram	Date J. D.	Phase	$\lambda\lambda, \text{\AA}$
319	244 4422.26	0.081	3490 - 3970
320	4422.27	0.085	3515 - 4020
416	4533.61	0.440	3480 - 3980
524	4659.58	0.472	3384 - 3990
525	4659.59	0.474	3430 - 3967
552	4712.23	0.109	3386 - 3893
553	4712.30	0.111	3444 - 3950
800	5414.25	0.453	3490 - 3955

Here are presented: the spectrum number, Julian date of observations, the wavelength range and the period phase at the moment of observations. The line equivalent widths, measured at phases 0.081, 0.085, 0.109, 0.111 were approximated and arbitrarily referred to 0.0 phase; the average equivalent line widths for the phase 0.5 were determined from the spectra, obtained at phases 0.440, 0.453, 0.472, 0.474.

The Zeeman ultraviolet spectra are unique, which require long exposures on the 6 m telescope even for bright stars. The methods how one can obtain them are described in detail by Romanyuk (1986), here we will only mention the fact, that they are applicable for both the measurements of Zeeman effect and for spectrophotometry investigations.

During the observations we tried to obtain homogeneous observational material; we used one and the same grating, D=6.7 Å/mm, Kodak plates IIaO, and MWP-2 developer. During the entire run the method of calibration remained unchanged. However, some factors, which were impossible to oversee, caused the impairment of the homogeneity and quality of spectrograms: IIaO plates in different packs had various veil density (as a rule high), the ultraviolet spectrum end was systematically underexposed, and the red one overexposed, a change of weather conditions during the exposure caused variable integration rate, in contrast with the calibration, etc. Although the calibrating plate (from the same pack) was developed simultaneously with the star spectrum, it was exposed on an individual plate on the spectrograph at the lab, that, of course, leads to discrepancies in the conditions of obtaining the calibration spectrum and the spectrum under investigation. The photoemulsion characteristic curve in the spectral region under investigation was changed a little with wavelength, therefore we performed conversion of the spectrum into intensities by only one curve. All the above mentioned reasons noticeably decrease the accuracy, according to our estimates the calibration inaccuracies cause the errors of the order of 5% in residual intensities. All spectrograms are recorded digitally by the photometric system of SAO (with the automatic microdensitometer AMD-I). The conversion into intensities and other reduction were performed applying the standard technique by Nazarenko's program (1988), the spectrum in intensities was drawn with the plotter. The continuum was plotted and spectral lines were identified. The wrong plotting of the continuum, especially in the spectral region 3700 - 3800 Å (with strongly overlapped hydrogen line wings) can cause the appearance of considerable errors in determination of line equivalent widths. Fortunately, $\alpha^2\text{CVn}$ is a well investigated CP star, therefore it is possible to compare the equivalent widths with those obtained by other authors. Since only a weak variability of hydrogen lines with a phase of the star rotation period was detected, then the monitoring of the continuum tracing was performed from the intensity of HI lines also. As a result of it, we managed to plot the continuum in the spectrum region with $\lambda > 3647$ Å considerably accurately.

For example let us compare the equivalent widths of some lines measured by us with those determined by Burbidge and Burbidge (1955), Fig. 1. As seen from Fig. 1, our

equivalent widths on the average are reduced in comparison with the values presented by Burbidge and Burbidge (1955) by 10% approximately. In a wavelength region shorter than Balmer discontinuity there are no comparisons with other authors, but since this region is more sensitive to changes in observational conditions, and the spectra have the most diverse density exactly in this region, let us compare the equivalent widths of one and the same lines obtained from different density spectra, but at close phases. The result of the comparison is presented in Table 2. In its columns there are the spectrum number, the phase, D - the spectrum density at the wavelength 3600 Å, and the equivalent widths of lines of different elements in mA.

Fig. 1. A comparison of our (W^0) equivalent line widths with those of Burbidge and Burbidge (1955) (W^B).

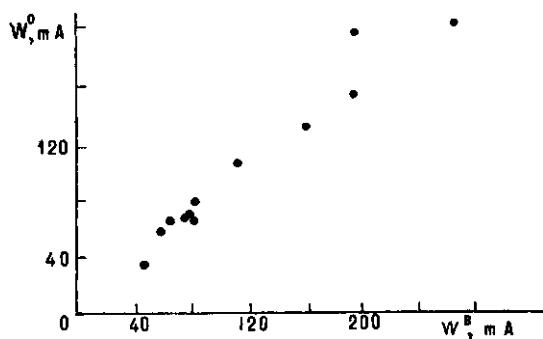


Table 2. The comparison of line equivalent widths in different density spectra.

No spectrum	Phase	D	Equivalent widths W_λ of lines				
			3621.3 FeII	3614.9 FeI	3613.2 CrII	3585.3 CrII	3571.6 CrII
319	0.081	0.63	44	67	49	120	35
320	0.085	0.63	26	82	40	130	38
553	0.111	0.75	44	109	44	118	41
416	0.440	0.44	47	72	66	109	29
800	0.453	0.33	48	94	67	103	-
524	0.472	0.63	44	57	57	111	32
525	0.474	0.65	52	81	89	123	30

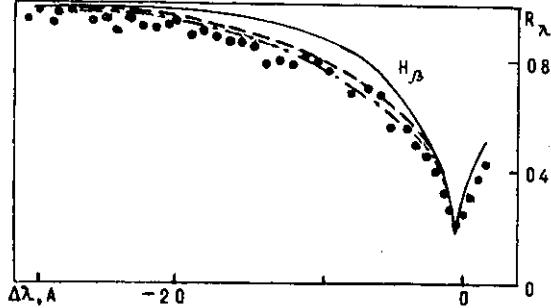
In spite of the considerable scattering one can see, that there are no systematic differences in determination of W_λ for different density spectra. Therefore we believe, that in our work there are no systematic differences, exceeding 10% in determination of the equivalent width of iron lines in spectral region from both sides of Balmer discontinuity for $\alpha^2\text{CVn}$.

3. CALCULATIONS

The detailed spectrophotometric analysis of $\alpha^2\text{CVn}$ was carried out by Cohen (1970), where he determined $T_e=12000$ K, $\lg g=4.0$ and the abundance of many elements at phases 0.0 and 0.5.

Muthsam and Stepień (1980) compared the observed energy distribution in a wide region of $\alpha^2\text{CVn}$ spectrum, from 1200 Å to 7000 Å, with the theoretical one for the list of blanketed atmosphere models with chemical composition defined by Cohen (1970). It was shown, that at the phase 0.0 $\alpha^2\text{CVn}$ has a lower temperature $T_e=11500$ K than at the phase 0.5 where $T_e=12000$ K. Therefore, Muthsam and Stepień (1980) suggested models which give an exquisite description of the observed energy distribution in the spectrum of this star. However, these models poorly agree with the observed profiles of hydrogen lines. We calculated the profiles of Balmer hydrogen lines by BALMER program for two models from (Muthsam and Stepień, 1980) and compared with the theoretical profiles for some Kurucz's models (Kurucz, 1975) and with the observed profiles of $\alpha^2\text{CVn}$ from (Gray and Evans, 1973). The example of this comparison is presented in Fig.2. It is seen, that Kurucz's models, $T_e=11500$, $\lg g=4.0$ and $T_e=12000$, $\lg g=4.0$, describe the observed profile very well. Therefore, we chose these models, using them for phases 0.0 and 0.5, respectively.

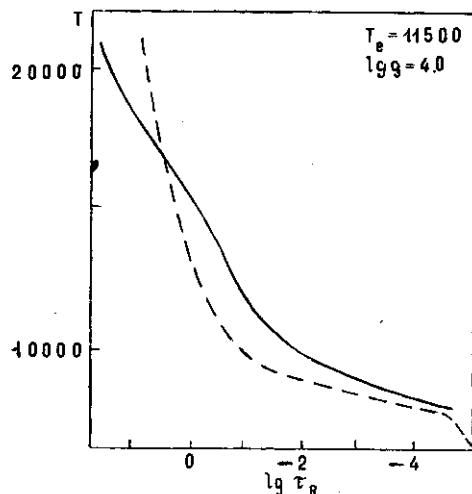
Fig.2. A comparison of the observed and calculated H_β line:
points - observed in $\alpha^2\text{CVn}$,
solid line - calculated from
Muthsam model, $T_e=11500$,
 $\lg g=4.0$;
dashed line - from Kurucz
model, $T_e=11500$, $\lg g=4.0$;
dash-and-dot - from Kurucz
model, $T_e=12000$, $\lg g=4.0$.



The choice of atmosphere model is very significant for the problem of investigation of the distribution of elements with depth, since the models from (Muthsam and Stepień, 1980) and (Kurucz, 1979) with equal parameters of T_e and $\lg g$, but different blanketing effect, have a considerably different distribution of temperature with depth (Fig.3).

The next very important step, necessary to increase the accuracy in the determination of abundance of elements, was the selection of isolated lines in the spectrum of $\alpha^2\text{CVn}$. For this purpose from the chosen Kurucz's models we calculated the synthetic spectrum in the wavelength region 3300 Å to 4000 Å with the chemical composition, defined by Cohen (1970) for phases 0.0 and 0.5. The list of lines and atom parameters

from (Kurucz and Peytremann, 1975) was used in the calculations. The analysis of the



*Fig. 3. Temperature as a function of depth in blanketing models:
solid line - Muthsam's
dashed line - Kurucz's.*

synthetic spectrum has shown, that there are few isolated lines sufficiently strong to be measured, therewith they do not fall on the wings or between wings of hydrogen lines (which are many in the selected spectrum region). Therefore for the analysis we had to use the lines, consisted of one element blends or where the blend of other element made a small contribution. When calculating the profiles and theoretical W_λ of lines all the blends were taken into account, but there remained some uncertainty connected with the abundance of different elements constituting the blend. The calculations were made using "Contour" program (Leushin and Topilskaya, 1986) in LTE-approximation. The abundance of element and the theoretical depth of line formation region were determined by the comparison of the theoretical curve of growth with the observed equivalent width.

$$\tau_\lambda = \int_0^\infty \frac{H_\lambda - H_{\lambda}^{\text{cont line}}}{H_\lambda} \cdot \tau_\lambda d\lambda / \int_0^\infty \frac{H_\lambda - H_{\lambda}^{\text{cont line}}}{H_\lambda} d\lambda, \quad \text{where}$$

$$\tau_\lambda = \int_0^\infty S_\lambda(t) E_2(t) dt / \int_0^\infty S_\lambda(t) E_2(t) dt$$

Therefore for every line we determined the depth in the atmosphere, making a maximum contribution in its formation.

4. FIRST RESULTS

Here we present the first results of determination of iron abundance at various depths in $\alpha^2\text{CVn}$

Since in the list of lines (Kurucz and Peytremann, 1986), we used to calculate the synthetic spectrum, there are considerable errors in oscillator strengths, we used other sources of atom parameters for calculations of lines selected for determination of chemical composition. For FeI lines we used the data of Boyarchuk and Savanov (1985) and for FeII of Boyarchuk and Savanov (1986), which in fact, form a unified system of oscillator strengths for iron. The results of calculations for the lines with a wavelength less than 3647 Å are presented in Table 3 and for the lines with a wavelength more than 3647 Å in Table 4. There are presented: ions and the line wavelengths, constituting the blend, oscillator strengths $\lg gf$, the observed equivalent width w_λ in mA, its error, $\sigma = \{\sum(\bar{w} - w_i)/n(n-1)\}^{1/2}$, found from four spectra for every phase,

$$\alpha(\text{Fe}) = \lg\{N(\text{Fe})/\sum N\}_{\alpha^2\text{CVn}} - \lg\left(\frac{N(\text{Fe})}{\sum N}\right)_\odot$$

at $\lg\left(\frac{N(\text{Fe})}{\sum N}\right)_\odot = -4.50$ and $\lg \tau_w$ for phases 0.0 and 0.5.

Table 3. Calculated iron lines in the spectrum region with $\lambda < 3647$ Å.

Ion	$\lambda, \text{\AA}$	$\lg gf$	$\phi=0.0$			$\phi=0.5$		
			w_λ	α	$\lg \tau$	w_λ	α	$\lg \tau$
FeI	3632.29	-2.76	46±4	1.54	-1.52	43±4	1.21	-1.35
FeII	2.51	-1.10						
TIII	3624.83							
FeII	4.89	-2.23		0.39				
VII	3621.20	-1.17	90±8	1.11	-1.57	77±7	1.30	
FeII	1.27	-1.56						
FeII	1.30	-1.64						
FeI	1.46	1.12						
ZrII	3614.77	-0.10						
FeII	4.87	-2.42	48±4	1.04	-1.40	50±3	1.28	-1.47
FeI	3610.15	-0.03	22±4	0.85	-1.10	30±3	1.16	-1.10
	0.33	-2.95						
FeII	3493.47	-1.41	47±8	0.60	-1.63	48±3	0.49	-1.52

During calculations the abundance of S, Zr, V, Ti, appearing in some lines was taken in accordance with (Cohen, 1970).

It is seen, that average depths of the formation of faint lines, formed from both sides of Balmer discontinuity differ more than an order. The abundance of iron in the upper layers of the atmosphere appears to be two times higher approximately. Unfortunately an error of the determination of iron abundance is still very great. But the effect seems significant, since it manifests at both phases, whose analyses are performed independently. We will continue the work with the aim to measure and calculate

more isolated lines of iron and to obtain more reliable results.

Table 4. Calculated iron lines in the spectrum region with $\lambda > 3647 \text{ \AA}$.

			$\phi=0.0$			$\phi=0.5$		
ion	$\lambda, \text{\AA}$	$lg g_f$	w_λ	α	$lg \tau$	w_λ	α	$lg \tau$
FeII	3935.96	-1.95	76±7	1.13	-0.63	69±14	1.05	-0.28
FeI	3927.92	-1.53	32±6	0.79	-0.02	30±3	1.24	-0.01
FeII	3906.03	-1.93	69±6	0.97	-0.54	69±6	1.03	-0.54
FeI	3899.71	-1.53		0.14	0.14		0.53	0.21
FeI	9.99							
FeI	3859.91	-0.71		0.05			0.41	
SII	3783.17	-0.89	61±3					
FeII	3.35	-3.35						

Table 5. The abundance of iron at different depths for $\alpha^2 C_{\text{Vn}}$

$\lambda\lambda$	$\phi=0.0$		$\phi=0.5$	
	$\alpha(\text{Fe})$	$lg \tau$	$\alpha(\text{Fe})$	$lg \tau$
$\lambda < 3647$	0.95±0.19	-1.49±0.08	1.11±0.16	-1.36±0.08
$\lambda > 3647$	0.58±0.18	-0.13±0.12	0.83±0.13	-0.10±0.11

It is seen, that average depths of formation of weak lines, formed from both sides of Balmer discontinuity differ by than an order. The abundance of iron in the upper layers of the atmosphere appears to be about two times higher. Unfortunately the error in the iron abundance is still very great. But the effect seems significant, since it manifests at both phases, whose analyses are performed independently. We will continue the work with the aim to measure and calculate more isolated lines of iron and to obtain more reliable results.

It should be noted also, that even at $\lambda > 3647$ we obtained a considerably smaller abundance of iron than in (Cohen, 1970) (+1.8 and +2.0) at phases 0.0 and 0.5, respectively, which is connected, most probably, with the use of different systems of oscillator strengths.

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