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Vertical Stratification of Cr in the Atmospheres of CP Stars

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Abstract—We study the vertical stratification of Cr in the atmospheres of nine chemically peculiar (CP) Am and Ap stars. Based on high-spectral-resolution CCD spectrograms from the *coude* spectrograph of the 2.6-m Crimean Astrophysical Observatory telescope, we analyze the Cr II lines in the wings of the Balmer Hβ line by the method of spectrum synthesis. We suspect the same small Cr enhancement in the upper atmospheric layers of all the Am stars studied; no evidence of noticeable Cr stratification has been found in the Ap star α^2 CVn, while β CrB, HR 7575, 10 Aql, and γ Equ exhibit an increase in the Cr abundance with depth. Using β CrB as an example, we show that our results depend only slightly on the uncertainties in choosing the stellar-model-atmosphere parameters.

INTRODUCTION

A study of vertical stratification of chemical elements in the atmospheres of CP stars is essential to the correct understanding of the nature of chemical anomalies observed in these objects. The fact that the observed elemental overabundances or underabundances correspond to a thin superficial layer of the stellar atmosphere, while the average chemical composition of a CP star is nearly normal, is now a generally accepted point of view. The chemical-diffusion theory, which was developed by Michaud (1970), provides a theoretical basis for these assumptions. According to this theory, different chemical elements can sink or rise in the upper atmospheric layers of a CP star under its gravitational field, radiation pressure, and magnetic fields, and the observed anomalies of spectral lines can be explained by a large overabundance or an underabundance of a given element in a very thin superficial layer of the stellar atmosphere (Alecian 1981). The variability of spectral lines in many CP stars suggests that, apart from the presumed vertical stratification, there is a nonuniform distribution of chemical elements over the stellar surface.

It should be noted that theoretical calculations of vertical stratification by using Michaud's theory are rather complicated and involve large uncertainties. The inclusion of additional physical factors (for example, mass loss by the star) in the calculations can change radically the predictions of the diffusion theory (Michaud *et al.* 1983). Thus, only direct experimental detection of vertical stratification of chemical elements can provide a decisive argument for the diffusion theory. However, in contrast to several tens of successful studies devoted to the analysis of nonuniformities in the surface distribution of chemical elements, we know a relatively small number of studies whose objective was to investigate the change in elemental abundances with depth. This is explained, to a large extent, by the scarcity of spectral features that are suitable for such an analysis.

Among the methods of studying the stratification of chemical elements, we can mention an analysis of the profile of the Ca II K line, which makes it possible to draw some conclusions about the nonuniformities in the distribution of this element (Babel 1992, 1994). Such an analysis of the profiles of the ultraviolet Ga resonance lines was performed for several Hg-Mn stars by Smith (1993). Since the diffusion theory gives more definitive predictions about the expected anomalies in isotopic composition of He and Hg (Michaud *et al.* 1974, 1987) than it does for the relative abundances of individual elements, data on the anomalies in isotopic He and Hg composition also impose certain constraints on the ranges of free parameters in the diffusion theory. Finally, there is a direct method of studying vertical stratification — a comparative analysis of spectral lines formed in the stellar atmosphere at different depths. For example, several authors (e.g., Lanz *et al.* 1993; Roby *et al.* 1993) reported a significant difference between the elemental abundances derived from spectral lines at ultraviolet and visible wavelengths. Khokhlova (1978) and Romanyuk *et al.* (1992) compared the abundances obtained by analyzing spectral lines before and after the Balmer jump. Khokhlova and Topil'skaya (1992) and Zverko and Ziznovskij (1994, 1995) studied the Cr II lines in the wings of the hydrogen Hβ line. We chose the latter method to study the possible vertical stratification of Cr in the atmospheres of several CP stars.

The essence of the method of comparative analysis of spectral lines in the wings of Balmer lines is that, for stars of spectral types from B to F with well-developed hydrogen lines, the intensity of a metallic line in the

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wing of a hydrogen line can depend on its distance $\Delta\lambda$ from the center of this hydrogen line for a fixed elemental abundance and at constant atomic parameters. This dependence is determined by the dependence of the sum of the absorption coefficients in the continuum and in the hydrogen line on $\Delta\lambda$. If there is stratification in the stellar atmosphere, and if some element forms a thin superficial layer with an enhancement, then, compared to the case of a homogeneous atmosphere, the dependence of the intensities of spectral lines of this element on $\Delta\lambda$ will be markedly different: the spectral lines that are closest to the center of the hydrogen line and that are formed in the superficial atmospheric layer of a CP star must be anomalously strong.

The difficulty of this method of studying the stratification lies in the scarcity of metallic lines in the wings of hydrogen lines that are suitable for such an analysis in the spectra of upper-main-sequence CP stars. The nine Cr II lines from the 30th multiplet in the Hβ wings, which cover a fairly wide range $\Delta\lambda$ from 1.1 to 49.0 Å, apparently offer a unique opportunity. The advantage of using lines from the same multiplet is that, for these lines, the relative oscillator strengths are known better, and that the possible errors in the general depth dependence of the temperature, which are attributable to the use of several approximations in choosing the parameters and in computing the stellar model atmosphere, have a smaller effect on the results. In addition, since the Cr II lines from the 30th multiplet (except for the λ4876.4 Å line) have similar effective Lande factors, one might expect the presence of a magnetic field to change the profiles of the Cr II lines in the same way and that it does not conceal the expected dependence of the Cr abundance on the distance to the Hβcenter.

PREVIOUS STUDIES OF VERTICAL STRATIFICATION IN THE ATMOSPHERE OF α^2CVn

Of the nine CP stars considered here, the magnetic Si-Cr-Eu star α^2 CVn (HD 112413, HR 4915) has been studied most extensively. The rotation period of α^2 CVn is $5\overset{d}{.}46939$ (Farnsworth 1932). The chemical composition of this star and the variability of the lines of some elements were extensively studied by Cohen (1970). Pyper (1969) analyzed the nonuniformities in the surface distribution of chemical elements by using mainly the variations in the equivalent widths of spectral lines with rotation phase. The currently available methods of mapping the surfaces of CP stars were applied to α^2 CVn by Goncharskii *et al.* (1983) when making a map of the Eu distribution and by Khokhlova and Pavlova (1984) who studied the nonuniformities in the distribution of Ti, Fe, and Cr.

We know a total of four papers in which attempts were made to analyze the vertical stratification of chemical elements in the atmosphere of α^2 CVn.

Romanyuk *et al.* (1992) studied the Fe distribution with depth by using Fe I and Fe II lines before and after the Balmer jump. The observational data comprised photographic spectra (D = 6.7 Å mm^{-1}, S/N = 20) obtained at phases 0.0 and 0.5, which correspond to two spots of enhanced Fe (Khokhlova and Pavlova 1984). An analysis of the equivalent widths of the Fe lines revealed a small enhancement of Fe in the superficial layer relative to the underlying layers at these two phases.

Khokhlova and Topil'skaya (1992) investigated the Cr II stratification in the atmosphere of α^2 CVn by using lines from the 30th multiplet. Their analysis was based on photographic spectra (D = 1.3 Å mm^{-1}, S/N = 70) obtained with the Special Astrophysical Observatory (SAO) telescope at the rotation phase 0.25, which corresponds to one of the peaks of the observed Cr abundance (Khokhlova and Pavlova (1984). For α^2 CVn, Khokhlova and Topil'skaya used the model-atmosphere parameters $T_{\rm eff}$ = 11500 K and $\log g$ = 4.0, which were recommended by Muthsam and Stepien (1980) for phase 0.0. Since the model computed by Muthsam and Stepien turned out to be in poor agreement with the observed Hβ profile, in their subsequent computations Khokhlova and Topil'skaya used the standard model of Kurucz (1979), which better describes the Hβ profile for the same values of $T_{\rm eff}$ and $\log g$. Khokhlova and Topil'skaya computed the theoretical equivalent widths of the Cr lines for the microturbulent velocity ξ_t = 2.0 km s^{-1} and compared them with the observed equivalent widths. As a result, they concluded that the model with a uniform Cr distribution was in reasonably good agreement with the observed values of W_λ, while the model with enhanced Cr in the superficial layer was inconsistent with the observations.

Zverko and Ziznovskij (1994) analyzed a Reticon spectrum of α^2 CVn (D = 8.5 Å mm^{-1}, S/N = 350) at phase 0.8. They used the model atmosphere with the same parameters as that of Khokhlova and Topil'skaya (1992) but computed by means of the ATLAS9 code (Kurucz 1993). Having analyzed the same Cr II lines from the 30th multiplet by the method of spectrum synthesis, Zverko and Ziznovskij found the Cr abundance in the atmosphere of α^2 CVn to increase with depth.

In their subsequent paper, Zverko and Ziznovskij (1995) studied six Reticon spectra of α^2 CVn at different phases. However, since the signal-to-noise ratio was lower (S/N = 150) and since there were no observational data for phase 0.25, they were able only to confirm the previous result: the Cr abundance increases with depth. It should be noted that, in contrast to their previous paper, in this paper Zverko and Ziznovskij used the model atmosphere with $T_{\rm eff}$ = 11500 K and $\log g$ = 3.8 computed by means of the ATLAS12 code (Castelli and Kurucz 1994) and studied the Cr stratification in the atmospheres of Sirius, Vega, and ε UMa by the same method of spectrum synthesis. For these three stars,

Table 1. Basic data on the observations

HD	HR	Star	Data	HJD 2400000+	Phase	Wavelengths, Å
41705	2421	γ Gem	Mar. 4, 1995	49781.332	–	4845–4875
			Mar. 4, 1995	49781.349	–	4812–4842
			Mar. 18, 1995	49795.206	–	4862–4892
			Mar. 18, 1995	49795.288	–	4829–4859
112413	4915	α^2 CVn	May 19, 1997	50588.283	0.451	4852–4919
			May 19, 1997	50588.295	0.451	4800–4867
			Aug. 18, 1997	50679.248	0.083	4854–4921
			Aug. 18, 1997	50679.267	0.087	4801–4868
			Aug. 19, 1997	50680.280	0.272	4855–4922
			Aug. 19, 1997	50680.291	0.274	4802–4869
137909	5747	β CrB	Aug. 18, 1997	50679.304	0.453	4855–4922
			Aug. 18, 1997	50679.314	0.454	4802–4869
176232	7167	10 Aql	Aug. 18, 1997	50679.338	–	4801–4868
			Aug. 18, 1997	50679.360	–	4855–4922
188041	7575		Aug. 20, 1997	50681.329	–	4855–4922
			Aug. 20, 1997	50681.351	–	4802–4869
189894	7653	15 Vul	Oct. 16, 1994	49642.292	–	4779–4926
201601	8097	γ Equ	Aug. 19, 1997	50680.330	–	4855–4922
			Aug. 19, 1997	50680.341	–	4801–4868
209625	8410	32 Aqr	Sept. 2, 1997	50694.330	–	4801–4868
			Sept. 2, 1997	50694.339	–	4854–4921
214994	8641	o Peg	Aug. 22, 1997	50683.353	–	4855–4922
			Aug. 22, 1997	50683.364	–	4802–4869

they obtained a nearly uniform Cr distribution with depth.

Romanyuk and Topil'skaya (1997) performed an in-depth comparative analysis of all studies of Cr stratification in the atmosphere of α^2 CVn and attempted to elucidate the cause of the disagreement between the results of Khokhlova and Topil'skaya (1992) and Zverko and Ziznovskij (1994). They reanalyzed the two sets of observational data by using the same technique (by the method of equivalent widths) and a single set of oscillator strengths, but the previous results of these two studies were fully confirmed: the equivalent widths of Khokhlova and Topil'skaya correspond to a uniform Cr distribution, while the values W_λ obtained from the spectra published by Zverko and Ziznovskij provide evidence for an increase in the Cr abundance with depth.

Thus, the general questions of Cr stratification in the atmospheres of CP stars and of the possible use of Cr II lines from the 30th multiplet for its detection, as well as the particular question of Cr stratification in the atmosphere of α^2 CVn, have remained open questions. It is these outstanding questions that determined the formulation of our problem here.

OBSERVATIONS AND THE METHOD OF ANALYZING CR LINES

Our main observational data for α^2 CVn were three spectrograms that were obtained at different rotation phases of the star. Each of these spectra consists of two 67-Å-long segments, which cover together the wavelength interval λ4800–4918 Å. We took these spectrograms in May and August 1997 in the first chamber of the *coude* spectrograph attached to the 2.6-m Crimean Astrophysical Observatory (CrAO) telescope. The detector was a Photometrics CCD camera.

We also studied the vertical stratification of Cr in the atmospheres of several other CP stars of spectral types Am (15 Vul, 32 Aqr, o Peg, and γ Gem) and Ap (10 Aql, β CrB, γ Equ, and HR 7575). Thus, in a single study, we attempted to cover anomalous stars of different types with different Cr abundances—from a nearly solar value (moderate Am stars) to an enhancement by a factor of 10 to 100 (the Ap stars HR 7575 and β CrB).

The spectroscopic data for 32 Aqr, o Peg, and all the Ap stars were obtained in August-September 1997 with the 2.6-m CrAO telescope. As in the case of α^2 CVn, the CCD spectrograms were taken in two intervals centered on different wings of the Hβ line. We obtained the

Table 2. Fundamental parameters of the stars under study

Star	T_{eff}, K	log*g*	ξ_t, km s^{-1}	[M/H]	Source
α^2 CVn	11500	4.0	2.0	+0.5	Khokhlova and Topil'skaya (1992)
o Peg	9800	3.8	3.5	0.0	Savanov (1985)
γ Gem	9300	3.4	2.0	0.0	Savanov and Khalilov (1985)
HR 7575	8500	4.5	2.0	+0.5	Renson *et al.* (1991)
β CrB	8300	4.0	2.0	+0.5	Savanov and Malanushenko (1990)
15 Vul	8100	3.5	4.8	0.0	Lyubimkov and Savanov (1984)
10 Aql	7750	4.0	2.0	+0.5	Renson *et al.* (1991)
γ Equ	7700	4.2	2.0	0.0	Ryabchikova *et al.* (1997)
32 Aqr	7500	3.4	4.4	0.0	Bolcal *et al.* (1992)
α CMi	6650	4.0	1.8	0.0	Kato and Sadakane (1982)

spectra of γ Gem on March 4 and 18, 1995, with the *coude* spectrograph of the 2.6-m CrAO telescope by using an Astromed CCD-2000 camera (Huovelin *et al.* 1986). In this case, to analyze the Cr stratification, we used four 30-Å-long spectrograms, which covered together the spectrum of γ Gem from 4812 to 4944 Å. The observations of 15 Vul were carried out on October 16, 1994 with the echelle spectrograph of the 1-m SAO telescope. These observational data were described in detail by Bikmaev *et al.* (1997). From the 40 orders of the CCD echelle spectrum of 15 Vul, we chose for our study the 27th, 28th, and 29th orders, which cover the interval λ4779–4926 Å.

The spectral resolution of all the CrAO spectrograms is $\lambda/\Delta\lambda$ = 27000. The observational data for 15 Vul were obtained with a slightly higher resolution, $\lambda/\Delta\lambda$ = 32000. The signal-to-noise ratio for all our spectra was typically S/N = 150–200.

Of the CP stars considered here, only α^2CVn exhibits an appreciable variability of Cr lines, while for the remaining stars we found no reference to any variability of these lines in the literature. For this reason, we studied the changes in the lines of the 30th multiplet with rotation phase for α^2 CVn alone.

Our observational data are summarized in Table 1. In addition to the star names, their HD and HR numbers, times of observation, Julian dates, and wavelength ranges covered, this table gives the rotation phases of α^2 CVn and β CrB that we computed for the period and the ephemeris from Farnsworth (1932) and Oetken and Orwert (1984), respectively.

Testing the atomic data for the Cr II lines and the method of calculations on an extensively studied standard star with normal chemical composition featured prominently in our work. For this purpose, we used a portion of Procyon's atlas between 4800 and 4900 Å from Griffin and Griffin (1979).

The reduction of the CrAO spectra included the standard procedures of allowing for the dark current of the CCD array, subtracting the sky background, and constructing the dispersion curve from a comparison spectrum. To this end, we used the SPE code developed by S.G. Sergeev. The echelle spectrum of 15 Vul was reduced at the SAO by G. Galazutdinov by using the DECH20 code (Galazutdinov 1992).

All of the lines from the 30th Cr II multiplet considered here lie in the wings of the hydrogen Hβ line. For this reason, when the spectra were reduced, particular attention was given to drawing the continuum. Our observational data are peculiar in that all the spectrograms were obtained with a high dispersion in narrow wavelength intervals, none of which covered completely at least one of the Hβ wings. Thus, we could not independently draw the continuum on the basis of our stellar spectra alone. Under these circumstances, when drawing the continuum, we relied heavily on the synthetic Hβ profiles that we computed by using the STARSP code (Tsymbal 1996). After drawing the continuum, we combined individual segments of the spectra of our stars into full Hβ profiles. For α^2 CVn, which exhibits a significant spectroscopic variability, we combined the pairs of spectra obtained at close rotation phases: 0.451 and 0.454, 0.083 and 0.087, 0.272 and 0.274.

The model-atmosphere parameters for our CP stars that we adopted when computing the general hydrogen-line profiles and the profiles of individual Cr II lines are given in Table 2. The star name is followed by its effective temperature, surface gravity, metallicity relative to the solar chemical composition, and microturbulent velocity. The last column gives references to the papers in which the atmospheric parameters we used were determined. We took the model atmospheres for α^2 CVn and 10 Aql from the grid of Kurucz (1993) and computed the models for the remaining stars by means of the STARSP code, which uses a modified ATLAS9 code and the ODF tables from Kurucz (1993).

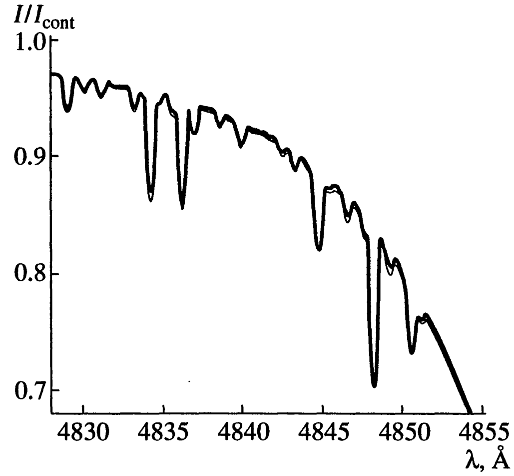

Fig. 1. Comparison of the synthetic profiles for a segment in the Hβ wing computed for the models of α^2 CVn with metallicity enhanced by 0.5 dex (thick line) and with normal metallicity (thin line).

Note that Khokhlova and Topil'skaya used the model of Kurucz (1979) with solar metallicity for α^2 CVn. However, since the abundances of most iron-group elements in the atmosphere of α^2 CVn are enhanced by one or two orders of magnitude compared to the normal chemical composition (Cohen 1970), we used a model with enhanced metallicity in our computations. In our view, this model better describes the atmosphere of α^2 CVn. The computations of synthetic spectra show that, although the general Hβ profiles computed for models with normal metallicity and with metallicity enhanced by 0.5 dex are virtually coincident, the difference becomes significant for some metallic lines, including Cr II lines. The synthetic spectra in a narrow interval in the Hβ wing that we computed for the models with different metallicities are compared in Fig. 1. We see that for the model with enhanced metallicity, the lines turn out to be slightly less deep.

Based on the method of spectrum synthesis, we analyzed the Cr II lines by computing their profiles with the aid of the STARSP code (Tsymbal 1996), by broadening them to allow for the instrumental profile and the star's rotation using the same code, and by comparing the resulting spectra with the observations. The instrumental profile was fitted by a Gaussian with the half-width $\Delta\lambda = 0.18$ Å. The spectra broadened by means of the ROTATE code (Piskunov 1992) are essentially in agreement with those broadened by means of the STARSP code. When computing the synthetic spectra, we established that at phase 0.27, which is close to one of the intensity peaks of the Cr lines, the spectrum of α^2 CVn was best described by a synthetic spectrum broadened with $V\sin i = 15$ km s^{-1}, while for α CMi, γ Gem, and 15 Vul, we found $V\sin i = 6$, 4, and 5 km s^{-1}, respectively. The spectral lines of all the remaining stars were so narrow that they were satisfactorily fitted even after allowance for the instrumental profile.

We used a list of lines from the VALD database (Piskunov *et al.* 1995) to construct the synthetic spectra for α^2 CVn, which we studied extensively. An advantage of extracting data on spectral lines from the VALD is that, for a specified model atmosphere and an assumed chemical composition of the star, one of its utility programs makes it possible to choose those lines in a specified wavelength interval whose depth exceeds the accuracy of measuring the residual intensity, which is determined by the signal-to-noise ratio. In addition, the VALD contains the most reliable atomic data and oscillator strengths. For α^2 CVn, whose atmosphere shows an anomalous chemical composition, in particular, enhanced abundances of rare earths whose lines have not been studied adequately and are absent in old lists, the data obtained from the VALD, have made it possible to improve the estimate of the contributions of these lines to the Cr II profiles studied and thereby to increase the reliability of our results.

In general, the chemical composition of the Am stars included in our program is nearly solar, and the Cr lines are blended in their spectra only slightly. For this reason, in our study of the Am stars, we used the "solar" line list of Kurucz (1988), which is built into the STARSP code, with the oscillator strengths of the Cr II lines replaced by the refined data from the VALD. For the Ap stars, in whose spectra the lines of the 30th multiplet are blended to an even greater extent than for α^2 CVn due to the lower temperature of these stars, we used an extensive list of Kurucz (1988) by supplementing it with the refined data on the Cr II lines studied and by including all blending components from the VALD.

It should be noted that when computing the profiles of the Cr II λ4876.40 Å line, we took into account the blending of this line by the weaker Cr II line (λ4876.47 Å, $\log gf = -1.94$) from the same multiplet.

As a first approximation in our computations of synthetic spectra for o Peg, γ Gem, β CrB, 15 Vul, γ Equ, 32 Aqr, and α CMi, we used the chemical composition derived in the same papers in which the atmospheric parameters were determined; for α^2 CVn, we took the abundances from Cohen (1970).

The observed profiles of the Cr II λ4824.13 and 4848.24 Å lines are compared with their computed profiles in Figs. 2–6; the changes in the profiles of these lines, as the Cr abundance increases and decreases by 0.30 dex, are also shown in this figure. These additional profiles allow us to estimate the accuracy of fitting the synthetic spectrum to the observed spectrum. We estimated it to be, on the average, 0.05 dex for the Ap stars with the highest Cr abundance (α^2 CVn, β CrB, and HR 7575) and a factor of 2 lower for the Am stars in whose spectra the Cr II lines are not so strong but are more sensitive to changes in the chemical composition.

The results of our computations of the Cr line profiles are summarized in Tables 3a and 3b. The columns

Table 3a. Cr II lines and the derived Cr abundances in the Am stars and Procyon

λ	$\Delta\lambda$	log*gf* VALD	log*gf* KP	Lande factor	α CMi	15 Vul	γ Gem	o Peg	32 Agr
4812.34	48.98	–1.96	–2.23	1.50	–6.38	–6.45	–6.25	–6.03	–6.25
4824.13	37.19	–0.97	–1.20	1.34	–6.38	–6.60	–6.25	–6.23	–6.30
4836.23	25.09	–1.96	–2.22	1.52	–6.33	–6.32	–6.13	–5.99	–6.09
4848.24	13.08	–1.15	–1.40	1.25	–6.48	–6.45	–6.23	–6.12	–6.35
4856.19	5.13	–2.14	–2.29	1.48	–6.30	–6.20	–5.97	–5.80	–6.05
4864.33	2.98	–1.36	–1.66	1.03	–6.35	–6.20	–6.05	–5.85	–6.05
4876.40	15.08	–1.46	–1.70	0.41	–6.53	–6.40	–6.18	–6.02	–6.23
4884.61	23.29	–2.10	–2.44	1.50	–6.45	–6.40	–6.25	–5.96	–6.17

Table 3b. Cr II lines and the derived Cr abundances in the Ap stars

λ	$\Delta\lambda$	α^2 CVn 0.08	α^2 CVn 0.27	α^2 CVn 0.45	β CrB	HR 7575	γ Equ	10 Aql
4812.34	48.98	–5.25	–5.00	–5.15	–4.75	–4.50	–5.98	–5.72
4824.13	37.19	–5.75	–5.30	–5.60	–4.70	–4.55	–6.00	–5.88
4836.23	25.09	–5.30	–5.00	–5.25	–4.80	–4.55	–5.88	–5.69
4848.24	13.08	–5.80	–5.30	–5.45	–5.10	–4.65	–6.35	–6.00
4856.19	5.13	–5.10	–4.78	–4.95	–5.15	–4.85	–6.27	–5.70
4864.33	2.98	–5.20	–5.00	–5.10	–5.45	–4.75	–6.45	–6.05
4876.40	15.08	–5.40	–5.10	–5.35	–5.30	–4.85	–6.35	–6.00
4884.61	23.59	–5.10	–4.85	–5.05	–4.20	–4.15	–5.70	–5.60

of Table 3a are: (1) the wavelengths of the Cr II lines; (2) the distance to the center of the Hβ line, which characterizes the depth of line formation; (3) the refined oscillator strengths for the lines of the 30th multiplet (Pinnington *et al.* 1993; Sigut and Landstreet 1990) from the VALD database; (4) the oscillator strengths of the same lines, as computed by Kurucz and Peytermann (1975); (5) the effective Lande factors; and the last columns give the Cr abundances that we obtained for the nine CP stars and Procyon. For α^2 CVn, we provide the abundances for three different rotation phases of the star.

DISCUSSION OF THE RESULTS

Figures 7a–7c show plots of the Cr abundance versus the distance to the Hβ center for the ten stars we studied. The corresponding plots for α^2 CVn and Sirius from Zverko and Ziznovskij (1994) are also shown in these figures.

As expected, the vertical distribution of Cr for Procyon turns out to be uniform, which provides evidence for the validity of our atomic data, the method of data reduction, and the computations of synthetic spectra. Since there is a marked difference between the results for the Am and Ap stars, below we consider these two classes of anomalous objects separately.

Am Stars

The Cr abundance in γ Gem, 32 Aqr, 15 Vul, and o Peg slightly increases toward the stellar surface. The average Cr abundance gradient is –0.0050 ± 0.0011, which corresponds to an increase in the abundance of this element by approximately 0.2 dex as one goes from the λ4812.34 Å line to the λ4864.33 Å line. Interestingly, although the difference in the assumed effective temperatures of our Am stars reaches 2300 K, for all the Am stars we obtained a similar gradient which closely matched the slope of the curve for Sirius from Zverko and Ziznovskij (1994). Based on these results alone, so far we apparently cannot speak of the real Cr stratification in the atmospheres of the Am stars. On the one hand, the possibility of the same error in choosing the model-atmosphere parameters for the Am stars seems unlikely: we used the *a fortiori* nonuniform parameters determined by different authors on the basis of different methods. In addition, further computations of synthetic spectra in the region of the Hβ core show that, for a uniform Cr distribution, the observed intensity of the Cr II

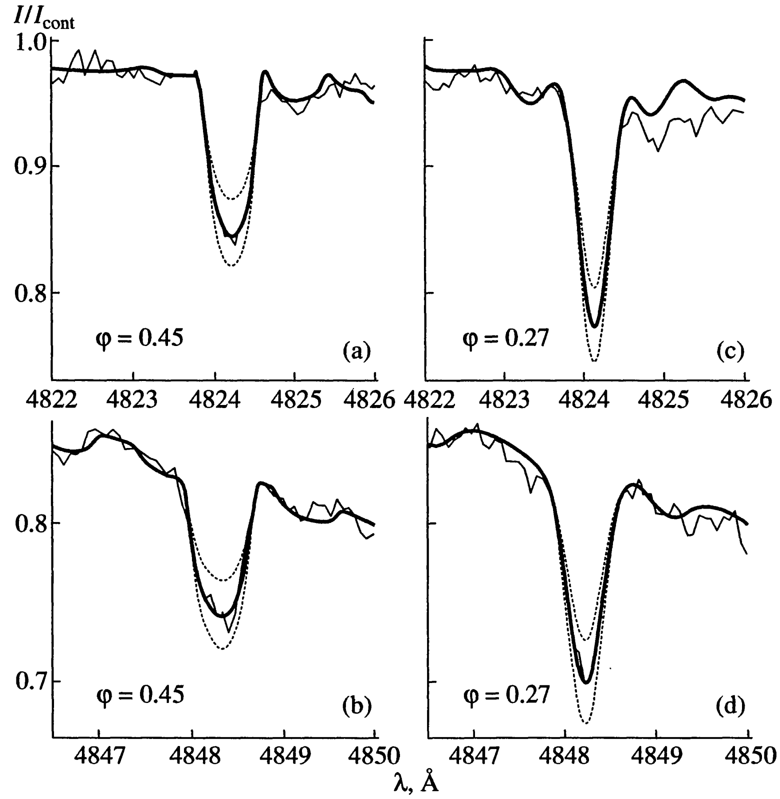

Fig. 2. Comparison of the observed (thin line) and computed (thick line) profiles of the Cr II λ4824.13 and 4848.24 Å lines in the spectrum of α^2 CVn at phases 0.45 (a, b) and 0.27 (c, d). The dotted lines represent the synthetic spectra that correspond to variations in the Cr abundance by ±0.3 dex.

λ4856.19 and 4864.33 Å lines must be 1 to 2% lower, which obviously exceeds the noise level of our spectra. On the other hand, the evidence for the validity of the relative scale of oscillator strengths for the Cr lines that we obtained by analyzing these lines in Procyon's spectrum should not be overestimated either. The use of Procyon's Atlas instead of our own observations of "standard" stars made our spectroscopic data inhomogeneous, which could somehow affect the behavior of the plots of the Cr abundance versus the distance to the Hβ center. In our opinion, further observations of this type of stars over a wide range of effective temperatures with the obligatory recording with the same instruments of the spectra of "standard" stars whose atmospheres are known to have no Cr stratification are required to finally confirm or reject the existence of a slight Cr enhancement in the superficial atmospheric layers of the Am stars. Our study at least shows that, first, the depth dependence of the Cr abundance is essentially the same for Am stars with different T_{eff}, and, second, the behavior of this dependence differs sharply from the Cr abundance gradients in magnetic CP stars from the same range of effective temperatures.

Ap Stars

The spectra of the Ap stars studied here differ markedly in appearance from the spectrograms of the Am stars: enhanced heavy-element abundances result in a very high degree of blending of the Cr II lines and in an extremely unreliable placement of the continuum. These two factors are reflected in the accuracy of the derived Cr abundances: as can be seen from Figs. 7a–7c, the agreement between the results obtained for the Ap stars from different Cr lines is rather poor. Note, however, that the Cr abundance in the atmospheres of our Ap stars also exceeds considerably the solar value, and, although the Cr II lines from the 30th multiplet are components of complex blends, they nevertheless continue to dominate in the corresponding wavelength intervals and yield consistent Cr abundances. The λ4884.61 Å line, which is obviously part of an unresolved blend with an unknown line of comparable intensity in the spectra of HR 7575, β CrB, and γ Equ, constitutes an exception. For this reason, we drew the

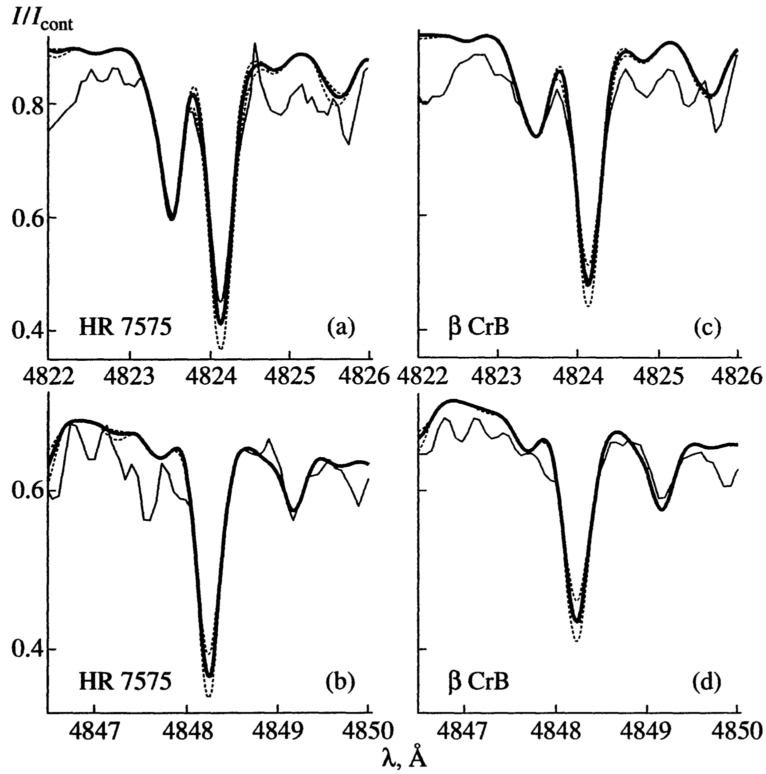

Fig. 3. The same as Fig. 2 for HR 7575 (a, b) and β CrB (c, d).

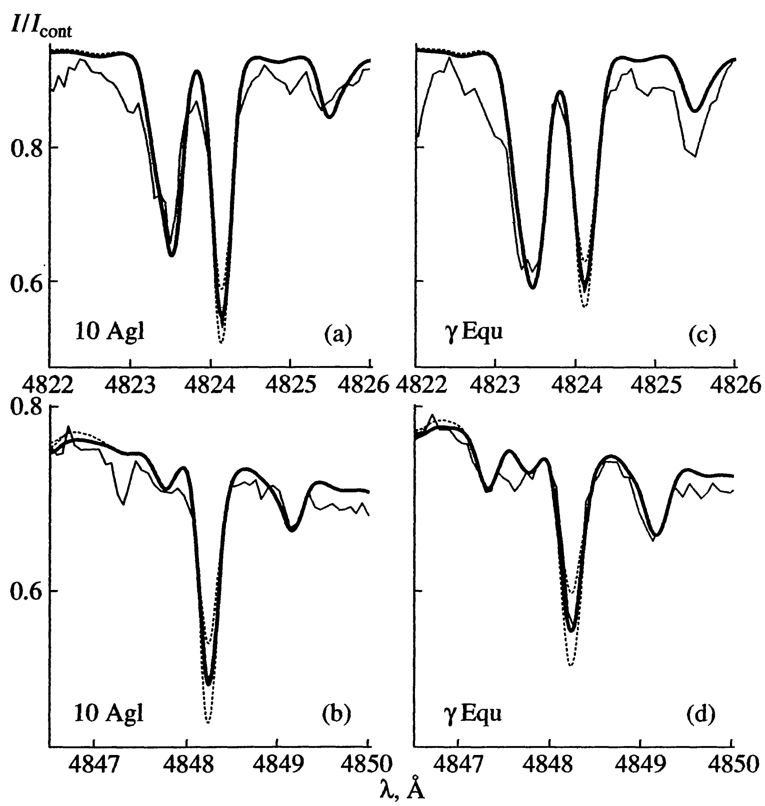

Fig. 4. The same as Fig. 2 for 10 Aql (a, b) and γ Equ (c, d).

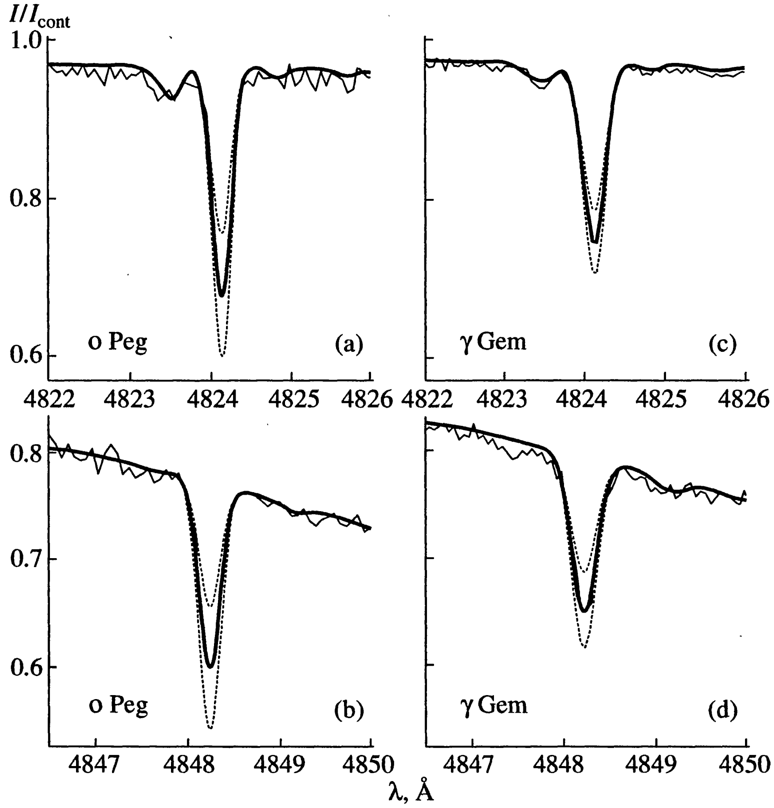

Fig. 5. The same as Fig. 2 for o Peg (a, b) and γ Gem (c, d).

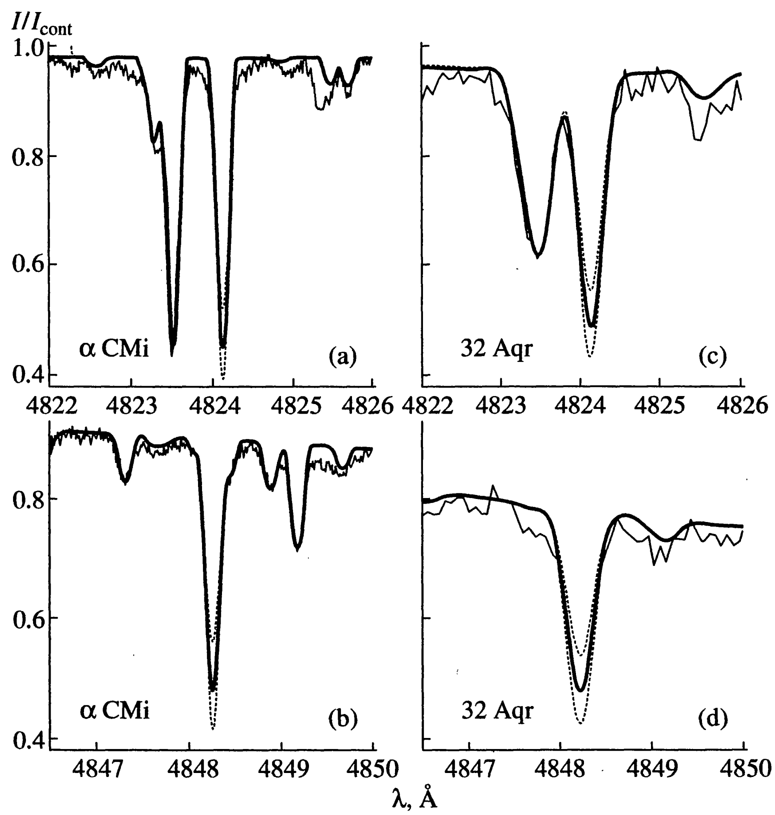

Fig. 6. The same as Fig. 2 for Procyon (a, b) and 32 Aqr (c, d).

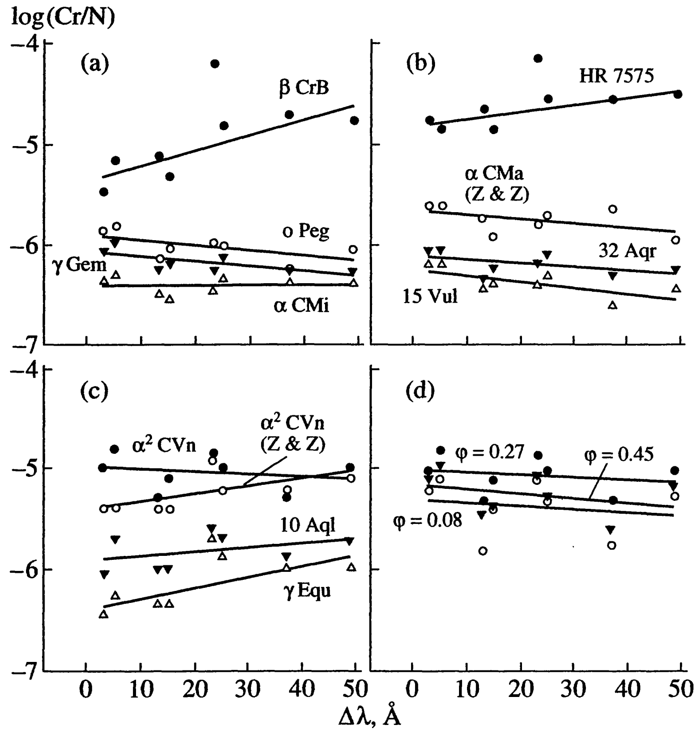

Fig. 7. The Cr abundance versus the distance to the Hβ center for (a) β CrB (filled circles), o Peg (open circles), γ Gem (filled triangles), and Procyon (open triangles); (b) for HR 7575 (filled circles), 32 Aqr (filled triangles), 15 Vul (open triangles), and Sirius (open circles), as derived by Zverko and Ziznovskij (1994); (c) for α^2 CVn (filled circles), 10 Aql (filled triangles), γ Equ (open triangles), and α^2 CVn (open circles), as derived by Zverko and Ziznovskij (1994); and (d) for various rotation phases of α^2 CVn: the filled circles, open circles, and triangles correspond to phases 0.27, 0.08, and 0.45, respectively.

straight-line fits to the dependence of the Cr abundance on the distance from the Hβ center for HR 7575, β CrB, and γ Equ by disregarding this line; it should be noted, however, that its allowance merely displaces the dependence as a whole without changing the Cr abundance gradient.

Figures 7a–7c show that α^2 CVn stands out sharply from our program Ap stars by the pattern of Cr stratification. For this star, the Cr abundance gradient is comparable in absolute value to the gradient for the Am stars, which, given a much larger scatter in the experimental data, suggests that there is no appreciable Cr stratification. For the other group, which includes HR 7575, β CrB, and γ Equ, we obtained substantial positive Cr abundance gradients, i.e., the superficial layer of the stellar atmosphere turns out to be noticeably depleted compared to the underlying layers.

As can be seen from Fig. 7c, of all the Ap stars, the experimental points for α^2 CVn and 10 Aql exhibit a maximum scatter about the straight-line fit. The same scatter in the abundances derived from different Cr II lines of the 30th multiplet was obtained by Zverko and Ziznovskij (1995). They explain this effect by the inaccuracies in the relative scale of oscillator strengths for the Cr II lines and propose to correct the atomic data used. However, the agreement between our results for the Am stars that we obtained by using the same set of atomic data gives grounds to question the need for a substantial correction of the oscillator strengths. As before, the problem most likely lies in the incompleteness of the line lists used to compute the synthetic spectra. For α^2 CVn, which exhibits an extremely anomalous chemical composition and above all high abundances of rare earths, even the most up-to-date lists of lines from the VALD appear not to contain data on all the spectral blended with Cr II lines.

The variability of α^2 CVn severely complicates the analysis of its spectra and makes it difficult to obtain unambiguous results on the Cr stratification. The profiles of the Cr II λ4824.13 and 4848.24 Å lines at phases 0.27 and 0.45 are shown in Figs. 2a–2d. We see that not only the intensities of the lines but also their widths vary. For instance, the synthetic spectrum provides the best fit to the observational data at phase 0.27 for $V\sin i$ = 15 km s^{-1}, in good agreement with $V\sin i$ = 16 km s^{-1} from Zverko and Ziznovskij (1995) and $V\sin i$ = 17 km s^{-1} from Khokhlova and Pavlova (1984). At phases 0.45 and 0.08, the Cr line profiles are better described by a synthetic spectrum broadened with $V\sin i$ = 18 and 10 km s^{-1}, respectively. The change in the intensity of the Cr II lines and the scatter in our values of $V\sin i$ are entirely explained by spottedness of the surface of α^2 CVn. Indeed, according to the maps of Cr distribution constructed by Khokhlova and Pavlova (1984), there are two nearly diametrically opposite spots with enhanced Cr; the abundance gradients at the edges of these regions are very large, and their boundaries are rather sharp. One of the Cr spots is seen at the center of the α^2 CVn disk at phase 0.25, and, accordingly, the Cr II lines in our spectrum at phase 0.27 are intense and narrow. Since the two spots at phase 0.45 are seen at the opposite edges of the disk and have different radial velocities, the Cr II lines are greatly broadened, are less intense, and have anomalous cores. At phase 0.08, only one spot on the limb appears to be seen, and, accordingly, the Cr lines are slightly redshifted and very narrow.

As for the Cr stratification in the atmosphere of α^2 CVn, our analysis of the spectrograms at phase 0.27 confirmed the result of Khokhlova and Topil'skaya (1992) at a close phase: the radial Cr distribution is most likely uniform. At the same time, this result cannot be considered to be in conflict with the study of Zverko and Ziznovskij (1994); they analyzed the behavior of Cr II lines at phase 0.8, which, according to the map of Khokhlova and Pavlova (1984), corresponds to another large Cr spot. The mean Cr abundance derived by Zverko and Ziznovskij (1994) essentially matches our result in absolute value (see Fig. 7c). In addition, as can be seen from Fig. 7d, the abundances determined from the Cr II lines vary with rotation phase differently, which appears to be attributable to the nonuniform distribution of the elements whose lines are blended with the Cr II lines over the surface of α^2 CVn. Thus, the dependence found for some phase by Zverko and Ziznovskij (1994) may well be valid. Moreover, in light of the results for HR 7575, β CrB, and γ Equ, the same dependence for α^2 CVn would not be unexpected. In our view, in order to clarify the question of Cr stratification in the atmosphere of α^2 CVn, it is necessary to carry out a simultaneous self-consistent study of nonuniformities in the surface and radial Cr distributions by taking into account spots of all the other elements whose lines are blended with the Cr II lines.

The Cr abundance gradients for 10 Aql, HR 7575, β CrB, and γ Equ seem to be more pronounced than that for α^2 CVn. Note that the Cr lines in these stars are presumably nonvariable.

While not setting the objective of a theoretical justification of the appreciable increase in the Cr abundance with depth that we found here for the three Ap stars, we attempted to find out how sensitive was this result to the errors in choosing the model-atmosphere parameters for fixed atomic parameters of the Cr lines by using β CrB as an example. To this end, we additionally computed the Cr II line profiles for the model with T_{eff} = 8300 K, $\log g$ = 4.0, and metallicity [M/H] = +1.0, which Hack *et al.* (1997) propose to use for β CrB, and for the model with $\log g$ = 4.0, [M/H] = +0.5, and T_{eff} decreased to 7750 K from Faraggiana and Gerbaldi (1993).

The increase in the metallicity turns out to result in a very small change in the intensities of the Cr lines, which is offset by a change in the abundance by an amount of the order of 0.05 dex, a value that is comparable to the accuracy of fitting the observed spectrum by the synthetic spectrum. As regards the decrease in T_{eff}, it strongly affects the model atmosphere due to a sharp increase in the size of the convection zone. In this case, the Cr abundance must be decreased by 0.2-0.4 dex; in order to obtain agreement with the observations, the Cr abundance for the lines near the Hβ core should be decreased by a larger amount than for the lines in the far Hβ wings. Thus, the Cr abundance increases with depth even more rapidly than for our model with T_{eff} = 8300 K. Since the errors in choosing T_{eff} and [M/H] affect the general pattern of Cr stratification determined from the lines of the 30th multiplet only slightly, the gradient in the radial Cr distribution for HR 7575, β CrB, and γ Equ appears to be attributable to the real stratification of this element in the atmospheres of these stars.

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