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VERTICAL CHROMIUM DISTRIBUTION IN THE ATMOSPHERE OF A CHEMICALLY PECULIAR STAR. I. DIAGNOSTICS

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On the basis of CCD spectrograms obtained with high resolution at the Coudŭ focus of the 2.6-m telescope of the Crimean Astrophysical Observatory, Cr II lines lying in the wings of the Hβ hydrogen line are investigated. Vertical chromium stratification in the atmospheres of two normal and eight chemically peculiar stars is diagnosed using the method of spectral synthesis. An increase in Cr abundance with depth is found for the cool Ap stars β CrB, HR 7575, γ Equ, and 10 Aql. Some increase in Cr abundance in the upper layers of the atmosphere is presumed for all Am stars and for both Hg–Mn components of 46 Dra. The vertical chromium distribution in the atmospheres of the hot, spotted Ap stars 17 Com and α^2 CVn is evidently uniform.

1. Introduction

The experimental detection and investigation of vertical stratification of chemical elements in the atmospheres of chemically peculiar (CP) stars form a necessary step in the construction of a consistent theory to explain the anom chemical composition observed in these objects. The diffusion theory, which is presently the best developed [1, 2], treats anomalies of chemical composition as a purely surface effect, arising in a stable stellar atmosphere as a result of vertical stratification of chemical elements under the action of gravitation and radiation pressure. According to the diffusion theory, many elements can have considerable vertical abundance gradients in regions of production of the line spectrum. This prediction of the diffusion theory can be tested by direct quantitative estimation of the stratification of chemical elements. Observational material of this kind undoubtedly makes it possible to impose far greater restrictions on the domain of variation of the free parameters in the diffusion theory than does a simple comparison with the theory of *surface* (i.e., averaged over the entire region of production of the spectral lines) abundances.

Two principal means of studying vertical stratification are now employed: analysis of the shapes of the profiles of strong spectral lines and the differential investigation of lines produced at different depths in a stellar atmosphere.

The first means was used by Smith [3] to analyze the Ga III λ 1495 Å resonance line in the spectra of Hg–Mn stars and by Babel [4, 5], who investigated the Ca II K line in the spectra of stars of the Sr–Cr–Eu type. The presence of vertical

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stratification of the chemical elements under consideration was demonstrated in both works. Attempts to explain the anomalous profiles of He lines observed in the spectra of He-r and He-w stars by vertical stratification have been made in a number of works. Hunger [6] showed that for the He-w star HD 49333, the profile of the He I λ 4771 Å and 4388 Å lines can be described satisfactorily only using a model with He stratification. At the same time, Bohlender [7] found that two alternative models can explain the anomalous profiles of the He I λ 4471 Å and 4437 Å lines for the star δ Ori C: surface inhomogeneity of the He distribution and vertical stratification of that chemical element.

Khokhlova [8] and Romanyuk et al. [9] used the latter means to investigate spectral lines lying before and after the Balmer jump and produced in the stellar atmosphere at considerably different depths. No significant difference between the abundances determined from different lines was found in [4] for the Ap star HD 168733. At the same time, evidence for some increase in Fe abundance in the upper layers of the atmosphere of the magnetic Ap star α^2 CVn was obtained in [9]. A difference in abundances determined from visible and ultraviolet lines was also noted by Lanz et al. [10] for Ga and by Babel and Lanz [11] for elements of the iron group (Cr and Fe). Khokhlova and Topil'skaya [12] suggested the use of differential analysis of spectral lines lying at different distances from the cores of hydrogen Balmer lines to detect vertical stratification. In this case, stratification should be manifested as a dependence of elemental abundance on distance Δλ from the center of a hydrogen line. The most suitable for such an analysis are lines of the 30th multiplet of Cr II, lying in the wings of Hβ. In [12] lines of this multiplet were studied in photographic spectra of α^2 CVn and Sirius. Zverko and Ziznovskij [13, 14] made a similar investigation of reticon spectra of α^2 CVn, ε UMa, Sirius, and Vega. We discussed the results of this research in detail in our preceding paper [15], which was devoted to an analysis of lines of the 30th multiplet of Cr II in the spectra of several Ap and Am stars. The detection of a pronounced increase in Cr abundance with depth in the atmospheres of cool Ap stars became the main result of that investigation. Some increase in Cr abundance in the upper layers of the atmospheres of metallic-line stars was proposed in [15].

In the present work we continue the study of vertical stratification of chemical elements in the atmospheres of CP stars. In addition to refining the conclusion that there is no vertical Cr stratification in the atmospheres of normal stars, drawn on the basis of a study of lines of the 30th multiplet in the spectra of Procyon and ι Peg, we tried to determine whether it is possible to investigate the stratification of other chemical elements with spectral lines lying in the wings of Hβ. On the basis of new observations, we diagnosed the vertical Cr distributions in the atmospheres of four Am stars, two Hg–Mn stars, and two magnetic Ap stars.

2. Observational Material and Procedure for Its Analysis

The new observations of stars in the program for the investigation of vertical Cr stratification were made in October 1997 and January 1998. Two spectrograms with a span of 67 Å, centered on the red and the blue wings of Hβ, were obtained in the first spectrograph camera at the Coudй focus of the 2.6-meter telescope of the Crimean Astrophysical Observatory (CrAO) for each of six CP stars and the normal star ι Peg. The observations as a whole cover the wavelength range of λ 4800-4920 Å. A CCD camera from the Photometrix Co. was used as the receiver. At a spectral resolution $\lambda/\Delta\lambda$ = 32,000, a signal-to-noise ratio $S/N \simeq 150-200$ was achieved. Observations of Sirius, for which spectra with a lower noise level, $S/N \simeq 400$, could be obtained, were the exception.

In the present work we also investigated Cr II lines in the spectrum of the binary mercury–manganese star 46 Dra. The observational material that we used was described by Tsymbal et al. [16] and consists of two echelle spectrograms obtained for the phases 0.067 and 0.169 of the orbital motion of 46 Dra's components. From each echelle spectrum we extracted two orders, covering the wavelength range λλ 4769-4913 Å. The spectra of 46 Dra were obtained with the echelle spectrograph of the 2.7-m telescope of McDonald Observatory (USA). The resolution of the spectrograms is $\lambda/\Delta\lambda \simeq 10^5$, while the noise level is $S/N \simeq 200$.

TABLE 1. Basic Information on the Observations

HD	HR	Star	Date	HJD 2400000+	Phase	Wavelength
27962	1389	68 Tau	18.01.1998	50832.435	-	4797-4864
			18.01.1998	50832.448	-	4849-4917
33524	1672	16 Ori	18.01.1998	50832.480	-	4797-4864
			18.01.1998	50832.491	-	4850-4917
47105	2421	γ Gem	19.01.1998	50832.523	-	4850-4918
			19.01.1998	50832.527	-	4798-4865
48915	2491	α CMa	18.01.1998	50832.462	-	4850-4918
			18.01.1998	50832.465	-	4798-4865
60179	2891	α Gem	19.01.1998	50832.562	-	4798-4865
			19.01.1998	50832.565	-	4851-4918
108662	4752	17 Com	19.01.1998	50832.609	0.114	4851-4918
			19.01.1998	50832.628	0.117	4798-4865
112413	4915	α^2 CVn	19.01.1998	50832.639	0.128	4798-4865
			19.01.1998	50832.649	0.130	4851-4918
173524	7049	46 Dra	03.05.1996	50206.947	0.067	4769-4913
			04.05.1996	50207.943	0.169	4769-4913
210027	8430	ι Peg	16.10.1997	50738.323	0.516	4802-4869
			16.10.1997	50738.340	0.518	4855-4922

A complete description of our observational material is given in Table 1. Besides the names of the stars, their HD and HR numbers, the times of the observations, the Julian dates, and the limits of the spectral ranges, we give the phases of rotation of α^2 CVn and 17 Com, calculated for values of the period and ephemeris obtained from [17] and [18], respectively. For the spectroscopic binaries 46 Dra and ι Peg we give the phase of the orbital motion in accordance with spectroscopic orbits found in [19] and [20], respectively.

We note that we have already considered the magnetic Ap star α^2 CVn and the Am star γ Gem [15]. An additional investigation of α^2 CVn is necessary because this star exhibits pronounced variability of Cr spectral lines. It is possible that the variation of Cr surface abundance is closely connected with variation of the vertical distribution of that chemical element. As for γ Gem, in [15] we analyzed spectrograms obtained in 1995 with inadequate resolution and signal-to-noise ratio. The new observations were made to improve the results of diagnostics of the veritical Cr distribution and made our observational material more uniform.

Besides our own observations, we also used an echelle spectrum of Procyon obtained with the 1-meter telescope of the Special Astrophysical Observatory, Russian Academy of Sciences (SAO). This observational material was reduced and kindly provided by SAO colleagues.

The reduction of our observations included the standard procedures of allowance for the dark current of the CCD matrix, graduation into a flat field, subtraction of the sky background, and plotting of a dispersion curve using a comparison spectrum. For this we used the SPE program developed by S. G. Sergeev at the Crimean Astrophysical Observatory (CrAO). Just as in [15], the level of the continuous spectrum was determined from calculations of synthetic Hβ spectra. After drawing the continuum, individual sections of spectra of the investigated stars were combined into complete Hβ line profiles.

TABLE 2. Main Parameters of the Investigated Stars

Star	T_{eff}	log g	ξ_t	$[M/H]$	Ref.
46 Dra A	11700	4.00	0.0	+0.2	[19]
α^2 CVn	11500	4.00	2.0	+0.5	[12]
46 Dra B	11100	4.10	0.0	+0.2	[19]
17 Com	10300	4.30	1.5	+0.5	[21]
α Gem	10200	4.00	3.0	0.0	[22]
α CMa	10150	4.30	2.0	0.0	[23]
68 Tau	9300	3.75	4.0	0.0	[24]
γ Gem	9300	3.40	2.0	0.0	[25]
16 Ori	7900	4.35	6.0	0.0	[26]
ι Peg A	6750	4.35	1.5	0.0	[27]
α CMi	6650	4.00	1.8	0.0	[28]
ι Peg B	5350	4.57	1.0	0.0	[27]

The parameters of model stellar atmospheres adopted in the calculations of general hydrogen line profiles and those of individual Cr II lines are given in Table 2. After a star's name we give its effective temperature, gravitational acceleration at the surface, microturbulent velocity, and metallicity relative to the solar chemical composition. In the last column we give references to works in which the atmospheric parameters that we used were determined. From the same investigations we took data on the chemical compositions of the atmospheres needed to calculate synthetic spectra. All the model atmospheres were calculated using the STARSP system [29], in which a modified ALTLAS9 program and Kurucz's ODF tables [30] are used.

The Cr II lines of the 30$^{\text{th}}$ multiplet were analyzed by the spectral synthesis method through a calculation of Cr line profiles using the STARSP program. The method of calculating synthetic spectra and broadening them to allow for the instrumental profile and stellar rotation was described in detail in [15]. There one can also find a discussion of the choice of the system of oscillator strengths for Cr II spectral lines and a list of blended lines.

In calculating the synthetic spectra, we found that the spectrum of α^2 CVn is described best by a synthetic spectrum broadened with $V\sin i = 15$ km/sec. For Procyon we used the value $V\sin i = 6$ km/sec, found earlier [15] based on the atlas of Griffin and Griffin [31]; for 16 Ori, 68 Tau, α Gem, and γ Gem we found $V\sin i = 7$, 10, 18, and 8 km/sec, respectively. With allowance for the error in determining $V\sin i$, which in our investigation does not exceed 2-3 km/sec, the projection of the rotational velocity onto the line of sight found for γ Gem is consistent with the value of $V\sin i = 10.2 \pm 0.2$ km/sec obtained by Scholz et al. [32]. In studying Cr II lines in the spectra of 17 Com and Sirius, we took $V\sin i = 19$ and 16 km/sec in accordance with [21] and [33]. The spectral lines of ι Peg and 46 Dra turned out to be so narrow that they are already approximated satisfactorily after allowance for the spectrograph's instrumental profile.

Tables 3a and b summarize the results obtained in the calculations of Cr line profiles. In the tables' first column we give the wavelengths of the Cr II lines, in the second we give the distance from the center of the Hβ line, which is a characteristic of the depth of the line's production, and in the third column of Table 3a we give the improved oscillator strengths of lines of the 30$^{\text{th}}$ multiplet [34, 35], taken from the VALD database [36]. Then in Tables 3a and b we give the Cr abundances that we obtained for eight CP stars, ι Peg, and Procyon.

TABLE 3a. Results of the Investigation of Cr II Lines in the Spectra of Normal Stars and Hg–Mn Stars

λ (Å)	Δλ (Å)	log *gf* VALD	α CMi Atlas [31]	α CMi SAO	ι Peg A	ι Peg AB	46 Dra A	46 Dra B
4812.34	48.98	-1.96	-6.38	-6.27	-6.35	-6.44	-6.46	-5.96
4824.13	37.19	-0.97	-6.38	-6.10	-6.26	-6.40	-6.38	-5.71
4836.23	25.09	-1.96	-6.33	-6.31	-6.38	-6.43	-6.33	-5.85
4848.24	13.08	-1.15	-6.48	-6.44	-6.39	-6.58	-6.30	-5.70
4856.19	5.13	-2.14	-6.30	-6.27	-6.27	-6.37	-6.27	-5.60
4864.33	2.98	-1.36	-6.35	-6.25	-6.40	-6.48	-6.12	-5.58
4876.40	15.08	-1.46	-6.53	-6.24	-6.39	-6.50	-6.35	-5.85
4884.61	23.29	-2.10	-6.45	-6.30	-6.40	-6.32	-6.33	-5.90

TABLE 3b. Results of the Investigation of Cr II Lines in the Spectra of Ap and Am Stars

λ (Å)	Δλ (Å)	α^2CVn $\varphi = 0.13$	17 Com $\varphi = 0.12$	α Gem	α CMa	68 Tau	γ Gem	16 Ori
4812.34	48.98	-5.24	-3.79	-6.11	-5.82	-6.02	-6.37	-6.05
4824.13	37.19	-5.69	-3.51	-6.20	-5.80	-6.20	-6.49	-6.20
4836.23	25.09	-5.18	-3.72	-6.02	-5.70	-5.85	-6.24	-5.90
4848.24	13.08	-5.65	-3.50	-6.20	-5.71	-6.07	-6.35	-6.15
4856.19	5.13	-4.80	-3.41	-5.90	-5.65	-5.78	-6.20	-5.72
4864.33	2.98	-5.05	-3.64	-5.90	-5.60	-5.88	-6.18	-5.80
4876.40	15.08	-5.28	-3.56	-6.10	-5.72	-5.99	-6.33	-5.96
4884.61	23.29	-4.99	-3.60	-6.05	-5.78	-5.90	-6.32	-5.86

3. Diagnostics of Vertical Cr Stratification

In Fig. 1a-c we give Cr abundances as functions of distance Δλ from the center of the Hβ line, obtained for the 10 investigated stars. For Sirius we also show the Cr abundances found by Zverko and Ziznovskij [13] from lines of the 30th multiplet.

The results of this work and of our preceding investigation [15] are summarized in Table 4, in the second column of which we give the linear regression coefficient a and its error σ_a, found in an approximation of the Cr abundance as a function of Dl by the formula $\log(\mathrm{Cr/N}) = a \cdot \Delta\lambda + b$. In the third column of Table 4 we give the average chromium abundance $\langle \log(\mathrm{Cr/N}) \rangle$ obtained from lines of the 30th multiplet. The coefficient a equals the tangent of the angle of inclination of the dependence of log(Cr/N) on Δλ and is a quantitative characteristic of the vertical Cr abundance gradient. Negative values of a correspond to increasing chromium abundance in upper layers of the stellar atmosphere, whereas $a > 0$ indicates the opposite effect. The numerical representation of the results of the analysis of Cr II lines supplements the graphical representation used in [15] and makes it possible to estimate the significance of the results more accurately and bring out general relationships of vertical Cr stratification in the atmospheres of CP stars.

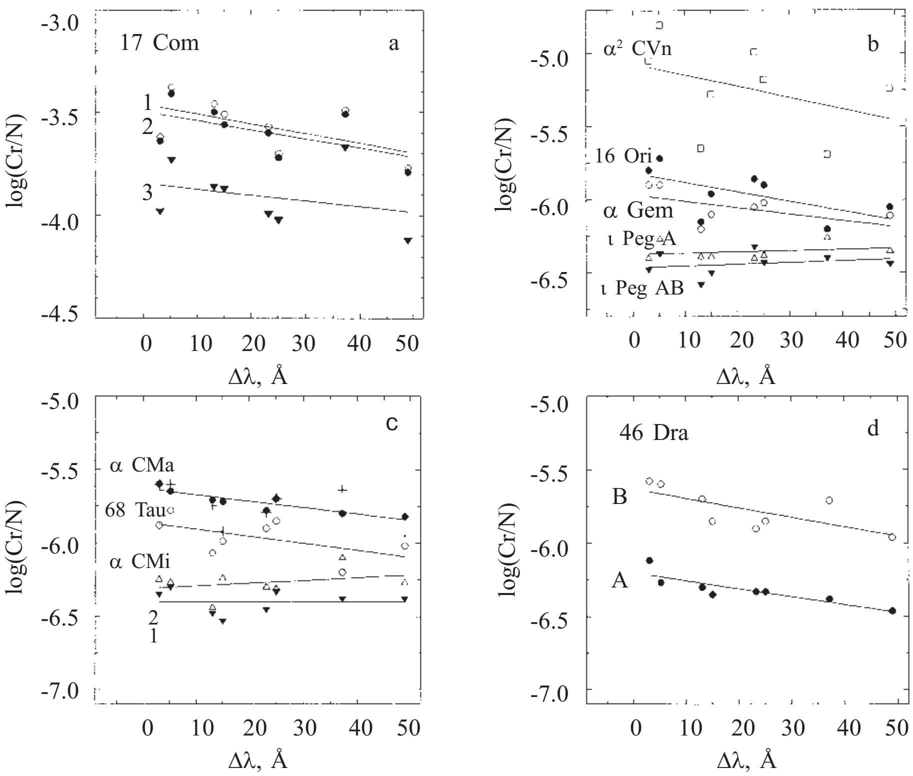

Fig. 1. a) Linear approximation of the dependence of Cr abundance on distance from the center of the Hβ line for 17 Com, found using model atmospheres with T_{eff} = 10,300 K, log g = 4.3, and [M/H] = +0.0 (straight line 1, open circles), T_{eff} = 10,300 K, log g = 4.3, and [M/H] = +0.5 (line 2, filled circles). Results found from a model atmosphere with T_{eff} = 11,000 K, log g = 4.0, and [M/H] = +0.0 used in [40] are denoted by filled triangles and line 3. b) Same as in a), but for 16 Ori (filled circles), α Gem (open circles), α^2 CVn (squares), and ι Peg (triangles). Results of an analysis with allowance for the duplicity of ι Peg are shown by open triangles and are designated as ι Peg A, while those without such allowance are shown by filled triangles and are designated as ι Peg AB. c) Same as in a) but for Sirius (filled circles), 68 Tau (open circles), and Procyon (triangles). Data for Sirius in [13] are indicated by crosses. Filled triangles and line 1 correspond to the results of an analysis of the atlas of Procyon of [31], while open triangles and line 2 correspond to the spectrum of Sirius obtained at the SAO. d) Same as in a) but for 46 Dra A (filled circles) and 46 Dra B (open circles).

Strictly speaking, the dependence of log(Cr/N) on Δλ can be interpreted in different ways. In Sec. 3 of the present paper, for convenience in presenting our results, we shall talk about a precisely as a parameter of the vertical Cr stratification, although it would be more correct to call it a "characteristic of the dependence of log(Cr/N) on Δλ obtained in the approximation of constancy of log(Cr/N) with depth and of ξ_t with depth and the absence of a magnetic field." In our next paper we shall test how consistent the hypothesis of vertical inhomogeneity of the Cr distribution is with the observed intensities of lines of the 30th multiplet, and we shall also investigate the possibility of an alternative explanation of the observations under the assumption that ξ_t varies with depth.

TABLE 4. Results of an Analysis of Chromium Abundances Obtained

Star	$(a \pm \sigma_a) \times 10^3$	$\langle \log(\mathrm{Cr}/N) \rangle$
	Ap stars	
α^2 CVn		
φ = 0.08	-3.3±7.0	-5.36±0.27
φ = 0.13	-7.7±7.4	-5.26±0.31
φ = 0.27	-2.6±4.7	-5.04±0.18
φ = 0.45	-4.5±5.4	-5.24±0.22
φ = 0.80[1]	7.3±3.5	-5.26±0.18
17 Com	-4.4±2.7	-3.59±0.12
HR 7575	7.0±2.0	-4.68±0.14
β CrB	14.8±3.9	-5.04±0.29
10 Aql	4.4±4.1	-5.83±0.17
γ Equ	10.6±3.5	-6.18±0.22
	Am stars	
α Gem	-4.3±2.5	-6.06±0.12
α CMa	-4.3±0.9	-5.72±0.07
α CMa[1]	-4.5±3.0	-5.74±0.14
o Peg	-5.3±2.8	-6.00±0.14
68 Tau	-4.7±2.9	-5.96±0.14
γ Gem	-4.6±1.8	-6.31±0.10
15 Vul	-6.2±2.4	-6.38±0.13
16 Ori	-6.4±3.5	-5.96±0.17
32 Aqr	-3.6±2.6	-6.19±0.11
	Hg–Mn stars	
46 Dra A	-5.4±1.3	-6.32±0.10
46 Dra B	-6.4±2.5	-5.76±0.14
	Normal stars	
α CMi[2]	0.0±2.0	-6.40±0.08
α CMi[3]	1.9±2.3	-6.27±0.09
ι Peg A[4]	0.8±1.5	-6.36±0.06
ι Peg AB[5]	1.2±2.0	-6.44±0.08

[1]Based on data of Zverko and Ziznovskij [13]; [2]results of an analysis of the Procyon atlas of [31]; [3]results of an analysis of Procyon's spectrum obtained at the SAO; [4]analysis of Cr II lines with allowance for the star's duplicity; [5]analysis of Cr II lines without allowance for the star's duplicity.

3.1. Normal Stars. α **CMi (Procyon).** In our preceding work [15] we used Procyon as a standard star with a normal chemical composition, in the atmosphere of which Cr stratification is definitely absent. In fact, we found no dependence of Cr abundance on Δλ based on lines of the 30th multiplet for Procyon. This conclusion was based not on our observations, however, but on Griffin and Griffin's atlas of Procyon [31]. In this connection, there was concern that such nonuniformity of the observational material prevents the reliable ruling out of a weak dependence of log(Cr/N) on Δλ, due not to stratification but to incorrect calculation of the Hβ profile or to errors in the scale of relative oscillator strengths of lines of the 30th multiplet of Cr II. In the present work, therefore, we investigated the spectrum of another standard star, ι Peg (see below), and also analyzed Cr II lines in the echelle spectrum of Procyon obtained with the 1-meter telescope of the SAO (the same telescope–spectrograph–receiver combination was used to obtain an echelle spectrum of 15 Vul, showing Cr stratification typical of other Am stars from [15]).

In Table 3a we compare the results of the analysis of an echelle spectrum of Procyon (fifth column) with previous results obtained from the atlas of Griffin and Griffin (fourth column). In Fig. 1d we give a linear approximation of the dependences of log(Cr/N) on Δλ obtained from heterogeneous observational material. The probable reason for the increase in the average Cr abundance obtained from the echelle spectrum is, evidently, a not entirely adequate allowance for the instrumental profile of the spectrograph on the 1-meter telescope when comparing our calculated synthetic spectra for Procyon with observations. Despite the small difference in ⟨log(Cr/N)⟩ between the two spectra, the conclusion that the Cr abundance does not depend on Δλ also remains valid for the results of the analysis of Procyon's echelle spectrum (as before, the coefficient a does not exceed the error σ_a in its determination; see Table 4).

ι **Peg.** Spectra of ι Peg were used, just like the observations of Procyon, as a standard for comparison with the spectra of CP stars, as a control on the method of reduction of the observations, and for calculating synthetic spectra in the region of the 30th multiplet of Cr lines.

A peculiarity of ι Peg is that it is a spectroscopic binary, the components of which differ relatively little in mass and effective temperature. The elements of i Peg's spectroscopic orbit were obtained by Fekel and Tomkin [20]. The parameters of the model atmospheres of the components were determined by Lyubimkov et al. [27] (also see [37] and [38]) and are given in Table 2. The effective temperatures of the primary and secondary components of ι Peg are $T_{\mathrm{eff}}(\mathrm{A}) = 6750 \pm 150$ K and $T_{\mathrm{eff}}(\mathrm{B}) = 5350 \pm 350$ K. With such a small difference between the effective temperatures, it would be incorrect to neglect the contribution of the secondary component to the total spectrum. As Lyubimkov showed [39], this can lead to substantial errors in determining the chemical composition of the primary, even up to obtaining spurious anomalies in the abundances of certain elements. The only proper approach in this case is to construct the total synthetic spectrum of the binary.

In the investigation of Cr II lines in the spectrum of ι Peg, we calculated synthetic spectra using the STARSP program [29], as in our preceding work. The spectra of ι Peg A and B were combined using the BINARY subprogram, which is part of the STARSP complex. To obtain the total spectrum we used the equation

$$\left(\frac{I}{I_C}\right)_{SB} = \frac{I^A + I^B \cdot \left(R_B/R_A\right)^2}{I_C^A + I_C^B \cdot \left(R_B/R_A\right)^2}, \tag{1}$$

where $(I/I_C)_{SB}$ is the total normalized spectrum, and the fluxes I and I_C in the line and in the continuum are calculated for the spectroscopic binary's components based on the given model atmospheres; the ratio of radii R_A/R_B can be found from the parameters of the model atmospheres and the elements of the spectroscopic orbit using the simple equation

$$\frac{R_A}{R_B} = \sqrt{\frac{g(B)}{g(A)} \cdot \frac{M_A}{M_B}}. \tag{2}$$

For ι Peg we determined R_A/R_B using the mass ratio of the components found by Fekel and Tomkin [20] and the gravitational accelerations from the work of Lyubimkov et al. [27]: $R_A/R_B = 1.64 \pm 0.25$ (the error is due mainly to the uncertainty in log g, which is estimated in [27] to be 0.05 dex for the primary component and twice that for ι Peg B). In combining the spectra we also allowed for the fact that for the phase 0.517 of the orbital motion, at which our observational material was obtained, the difference in the radial velocities of the components should be ΔV_r = 36.5 km/sec, according to the orbital elements of [20].

The Cr II abundances obtained from lines of the 30th multiplet are given in the sixth column of Table 3a. The corresponding dependence of the Cr abundance on distance from the center of Hβ is shown in Fig. 1b. As expected, there is no Cr stratification in ι Peg's atmosphere.

For comparison, in the seventh column of Table 3a and in Fig. 1b we also give the results (designated as i Peg AB) obtained in an investigation of ι Peg's spectrum without allowance for the contribution of the secondary. It is interesting to note that, although a lower average Cr abundance was obtained in such a simplified approach than with allowance for the star's duplicity, the general character of the dependence of Cr abundance on Dl did not change noticeably. This fact enables us to assume that the possible errors associated with neglecting the duplicity of certain stars investigated in [15] (such as γ Gem and β CrB) are able to distort only the absolute Cr abundance, but evidently cannot cause the appearance of the characteristic dependences of log(Cr/N) on Δλ.

3.2. Ap Stars. The results of the analysis of α^2 CVn's spectrum obtained for the rotational phase 0.13 are consistent with the preceding results [15] for other phases. All the values of the stratification parameter *a* and ⟨log(Cr/N)⟩ that we found for α^2 CVn are collected in Table 4. The scatter of the Cr abundances determined from lines of the 30th multiplet for all the spectra is fairly large. For this reason, systematically negative values of *a* cannot be treated as rigorous proof of an increase in Cr abundance in the upper layers of α^2 CVn's atmosphere. In fact, since we have $|a| \simeq \sigma_a$, our results are consistent with the data of Khokhlova and Topil'skaya [12], who found that the observed (for the phase 0.25) equivalent widths of Cr II lines agree well with the hypothesis of a uniform Cr distribution. As for the work of Zverko and Ziznovskij [14], who investigated α^2 CVn spectra at several phases (including phases close to those of our observations) and obtained an increase in log(Cr/N) with depth for all phases, we think that those results should treated cautiously for the following reasons. First, Cr II lines were investigated by the method of equivalent widths in [14]. This method is hardly suitable for α^2 CVn, whose spectrum is extremely rich in strong and variable lines of rare-earth elements that blend with Cr II lines. Second, a significant difference of *a* from zero was obtained only after correcting the relative oscillator strengths of lines of the 30th multiplet. In this case, the original dependence of log(Cr/N) on Δλ obtained in [14] is not statistically significant.

The results of Zverko and Ziznovskij's earlier work [13], in which they used the method of spectral synthesis and, without any correction of log *gf*, obtained a pronounced increase in log(Cr/N) in lower layers of α^2 CVn's atmosphere, evidently merit greater attention. (The results of [13] are given together with our data in Table 4. The parameter *a* does not exceed $3\sigma_a$, but it differs significantly from the negative values of *a* that we obtained.) Unfortunately, we have not yet been able to obtain observations of α^2 CVn for the phase 0.80 investigated in [13]. At the same time, the good agreement between the Cr abundances obtained in [13] and by us for Sirius (see below) indicates that their results can be compared with our data for other phases of α^2 CVn's rotation.

In the present work we analyzed the spectrum of another hot, spotted, Sr–Cr–Eu star, 17 Com. The results of the investigation of Cr II lines in its spectrum are given in Fig. 1a and in the fourth column of Table 3b. The observations of 17 Com were obtained for the rotational phase 0.12, which does not correspond to any characteristic features (spots with a Cr excess or deficit), according to Rice and Wehlau's maps of the Cr surface distribution [40]. In contrast to α^2 CVn, 17 Com has a fairly high chromium abundance and lower rare-earth abundances. The Cr II lines dominate in its spectrum and are virtually free of blending, despite the higher rotational velocity than α^2 CVn. On the whole, the dependence of log(Cr/N) on Δλ has the same form as for α^2 CVn, but with a somewhat smaller scatter about the approximating straight line ($|a| \simeq 1.7\sigma_a$). There is no doubt that, just as for α^2 CVn, a complete picture of the character of Cr stratification can be obtained only by investigating 17 Com's spectra over its entire rotational period.

In Fig. 1a we also give the results of an investigation of the sensitivity of Cr abundances determined from lines of the 30th multiplet to the choice of parameters of 17 Com's model atmosphere. A decrease in metallicity by 0.5 dex results in the same increase in Cr abundance by 0.02-0.05 dex and does not change the slope of the dependence of log(Cr/N) on $\Delta\lambda$. (Here the remaining parameters of the stellar atmosphere, taken in accordance with Savanov et al. [21], $T_{\rm eff}$ = 10,300 K, log g = 4.3, and ξ_t = 1.5 km/sec, did not vary with a change in [M/H].) A far more pronounced decrease in all the abundances occurs when the model atmosphere used by Rice and Wehlau for 17 Com [40] ($T_{\rm eff}$ = 11,000 K, log g = 4.0, ξ_t = 2.3 km/sec) is used to calculate the synthetic spectra. Even a change in $T_{\rm eff}$ by 700 K and in log g by 0.3 dex (values corresponding to the most conservative estimates of the accuracy in determining the atmospheric parameters of A stars), however, cannot result in a change in the sign of a. Thus, the general character of the Cr stratification determined from Cr II lines is insensitive to the choice of the main parameters of 17 Com. Recall that we obtained a similar result in our preceding work [15] for the cool Sr–Cr–Eu star b CrB.

In Table 4 we give a quantitative analysis of the Cr abundances that we obtained in [15] for β CrB, HR 7575, γ Equ, and 10 Aql. Such a numerical representation of the results of the investigation of Cr II lines differs somewhat from the qualitative graphic representation used earlier in [15] and in Fig. 1a-c of the present paper. This does not alter the interpretation of the data obtained, however: the coefficients a for β CrB, HR 7575, and γ Equ are positive and differ from zero by more than $3\sigma_a$. For this reason, we can, with considerable confidence, speak of a decrease in the Cr abundances in the surface layers of the atmospheres of these three stars in comparison with the underlying layers. We note that in calculating a and ⟨log(Cr/N)⟩ for β CrB, HR 7575, and γ Equ we did not use the Cr abundances found from the Cr II λ 4484.61 Å line, which in the spectra of those stars is blended with an unknown spectral line and therefore yields a strongly overstated Cr abundance. For 10 Aql we have $a > 0$, as for other cool Sr–Cr–Eu stars, but $a \simeq \sigma_a$, which prevents us from drawing definite conclusions about Cr stratification. As noted above, the latter is also valid for the spotted Ap stars α^2 CVn and 17 Com. For them we have $a < 0$ and $|a| < 2\sigma_a$, with the picture being made considerably more complicated by the nonuniform surface distribution of Cr.

Let us consider some general relationships in the vertical Cr distribution in the atmosphere of an Ap star. Based on the data collected in Table 4, we constructed dependences of the vertical stratification parameter a on $T_{\rm eff}$ (Fig. 2a) and on ⟨log(Cr/N)⟩ (Fig. 2b). A pronounced decrease in the vertical gradient of Cr abundance with increasing $T_{\rm eff}$ is observed in Fig. 2a. For the investigated stars there is an apparent change in a from considerable vertical stratification in the

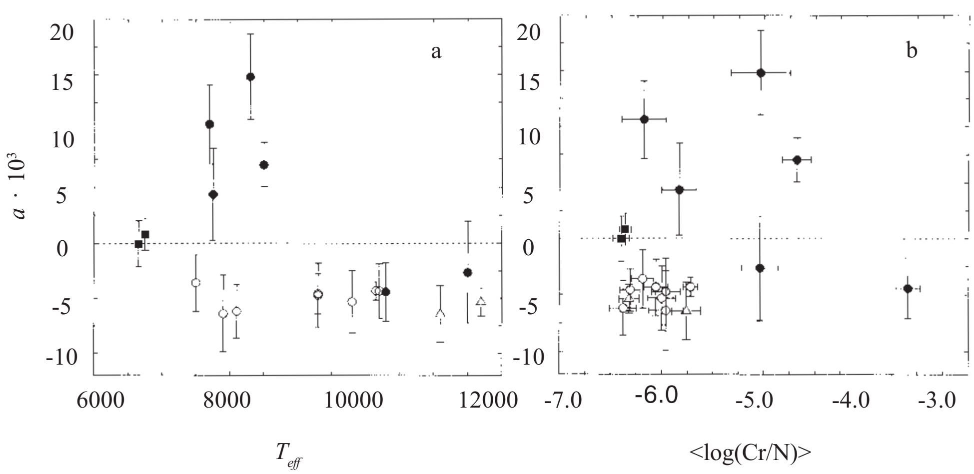

Fig. 2. a) Dependence of the stratification parameter a on a star's effective temperature. Filled circles denote Ap stars, open circles denote Am stars, and open triangles denote the Hg–Mn components of 46 Dra. Squares correspond to normal stars. Data obtained for a CVn's rotational phase 0.27, close to the phase of maximum intensity of Cr II lines, are shown. b) Stratification parameter a as a function of Cr abundance. Notation same as in Fig. 2a.

atmospheres of cool Ap stars with narrow spectral lines to a virtual absence of stratification in the atmospheres of hot Sr–Cr–Eu stars. It is possible that a changes sign at $T_{эфф} \simeq 9000$K.. The proposed dependence of a on T_{eff} is consistent with the research of Zverko and Ziznovskij [14] and of Babel [4] and Babel and Lanz [11]. In [14] the same dependence of log(Cr/N) on Δλ was obtained for the spotted Ap star ε UMa (T_{eff} = 9500 K) as for Sirius. Thus, ε UMa turns out to be similar to 17 Com in the character of Cr stratification. It was shown in [4, 11] that the abundances of many elements, including Cr, increase sharply with depth in the atmosphere of 53 Cam. That star's effective temperature (T_{eff} = 8500 K) suggests that 53 Cam occupies a position in Fig. 2a close to the positions of β CrB and HR 7575.

A study of the dependence of a on ⟨log(Cr/N)⟩ (Fig. 2b) does not reveal such a definite dependence as that of a on T_{eff}. In contrast to the uniform group of Am stars, the Ap stars occupy an extensive domain in Fig. 2b, from a Cr abundance close to the solar value to a Cr excess by two or three orders of magnitude and from a considerable increase in Cr abundance with depth to its slight decrease. The amount of Cr stratification evidently does not depend on its average abundance. In fact, for a given Cr abundance one encounters Ap stars both with positive (β CrB) and with negative (α^2 CVn) values of a.

It should be noted that the group of Ap stars with negative a consists entirely of hot, spotted, Sr–Cr–Eu stars, while an increase in Cr abundance with depth is observed in cooler stars without pronounced variability of spectral line intensities. The number of Ap stars that we have investigated is still too small to connect this relationship to a physical mechanism of generation of vertical stratification.

Figure 2a, b thus suggests the existence of certain relationships in Cr stratification in the atmospheres of Ap stars. Additional investigation of the spectra of many CP stars is needed to confirm them. At the same time, we can state two fundamental results of our investigation at the present stage: a) the characters of Cr stratification in the atmospheres of Ap and Am stars is considerably different; b) the group of Ap stars is characterized by a broad spectrum of observed values of the vertical Cr abundance gradient.

3.3. Am Stars. A reanalysis of the spectrum of γ Gem and a study of the spectra of α Gem, Sirius, 68 Tau, and 16 Ori made it possible to confirm results obtained earlier [15] for metallic-line stars.

The Cr abundances found for the five Am stars are collected in Table 3b and shown in Fig. 1b, c. The parameter a found for γ Gem coincides to within the error limits with its earlier determination. This fact points to the stability of the method used to analyze Cr II lines and to the small change in the observational material.

As for the character of the Cr stratification, for all the metallic-line stars we have $a < 0$ and some increase in log(Cr/N) in the upper layers of their atmospheres can be suspected. As compared to the results of our preceding work, this conclusion now seems more reliable to us for the following reasons. First, virtually the same values of a were obtained for all eight Am stars in the observing program. Second, a detailed investigation of Cr II lines in the spectra of normal stars (Procyon and ι Peg) showed no dependence of log(Cr/N) on Δλ ($a < \sigma_a$). Finally, because of the small scatter of the relative abundances about the approximating straight line, the parameter a for Sirius considerably exceeds $3\sigma_a$. This consistency of the values of log(Cr/N) obtained from different Cr II lines was evidently achieved due to the high quality of our observations of Sirius and to the small uncertainties of the parameters of that star's model atmosphere. In Fig. 1c our data are compared with the values of log(Cr/N) obtained for Sirius by Zverko and Ziznovskij [13]. Despite the small differences in relative abundances, the values of a and of ⟨log(Cr/N)⟩ agree to within the errors of their determination (see Table 4). The good agreement between the two independent measurements of a and ⟨log(Cr/N)⟩ also indicates the correctness of the method of reduction and analysis of stellar spectra and the reality of the results obtained.

An analysis of the dependence of a on T_{eff} (Fig. 2a) suggests that the character of the variation of log(Cr/N) with Δλ remains constant over the entire range of effective temperatures of the investigated Am stars (T_{eff} = 7,500-10,200 K). In Fig. 2b, illustrating the dependence of a on ⟨log(Cr/N)⟩, metallic-line stars, in contrast to Ap stars, form a very tight group with an average stratification parameter $a_{Am} = (-4.9 \pm 1.0)\cdot 10^3$ and an average Cr abundance $\langle \log(\mathrm{Cr/N}) \rangle_{Am} = -6.07 \pm 0.21$. The average Cr abundance for the group of Am stars that we investigated differs insignificantly from that element's solar abundance $\log(\mathrm{Cr/N})_\odot = -6.30$ [41].

3.4. Hg–Mn Stars. Among the CP stars that we investigated earlier in [15], there were no objects classified as mercury–manganese stars. In the present work we were able to fill this gap by investigating high-quality, echelle spectra of the spectroscopic binary, Hg–Mn star 46 Dra.

The components of 46 Dra have effective temperatures that differ relatively little and a mass ratio $M_A/M_B = 1.12$ [19]. The parameters of the model atmospheres of the primary and secondary components were obtained by Adelman et al. [19]. The chemical compositions of the atmospheres of 46 Dra A and B were investigated in the same work. Tsymbal et al. [16], who used the atmospheric parameters of [19], found the abundances of a large number of chemical elements. The results of [16] and [19] agree well, on the whole: the differences between the abundances found rarely exceed 0.2-0.3 dex.

In calculating the synthetic spectra of 46 Dra's components, we used the chemical compositions found in [16]; for elements of the iron group (Ti, Fe, and Mn), which were not studied in [16], we used the data of [19]. The total synthetic spectrum of 46 Dra was constructed by the method described above for ι Peg. The ratio of radii of 46 Dra's components was taken to be $R_A/R_B = 1.23$ [19], and the components' synthetic spectra were shifted relative to one another by an amount corresponding to the difference in radial velocities: $\Delta V_r = 60$ and 25 km/sec (for the phases 0.067 and 0.169, respectively). The chromium abundances found from lines of the 30th multiplet for both components are given in Table 3a, and the dependence of log(Cr/N) on $\Delta\lambda$ is shown in Fig. 1d. The average Cr abundances and the average vertical stratification parameters *a* for 46 Dra A and B are given in Table 4. We did not find any changes in Cr II line profiles with the phase of the orbital motion. The Cr abundances given in Table 3a describe equally well the spectra of 46 Dra for the phases 0.067 and 0.169. It is interesting to note that the values of ⟨log(Cr/N)⟩ for 46 Dra's components differ by about 0.5 dex. This result is in fair agreement with the data of Adelman et al. [19], according to whom 46 Dra A has a lower Cr abundance than the secondary component by 0.4 dex.

On the whole, the dependences of log(Cr/N) on Dl for the investigated Hg–Mn stars agree with the results obtained for metallic-line stars. The Hg–Mn stars in Fig. 2a (*a* as a function of T_{eff}) extend the sequence of Am stars toward higher effective temperatures, while the points corresponding to 46 Dra A and B in Fig. 2b [*a* as a function of ⟨log(Cr/N)⟩] lie in the domain occupied by Am stars. All this supports the repeatedly advanced hypothesis that a genetic connection exists between mercury–manganese and metallic-line stars.

4. Principal Results

In conclusion, let us generalize the principal results of our investigation of vertical Cr stratification in the atmospheres of CP stars.

1. Eight lines of the 30th multiplet of Cr II in the spectra of 18 stars of various spectral types were investigated by the method of spectral synthesis. The chromium abundances in the atmospheres of two normal stars, two Hg–Mn, eight Am, and six magnetic Ap stars were found.

2. Using an analysis of Cr II lines lying at different distances from the center of the Hβ hydrogen line, we diagnosed the vertical stratification of this element in the atmospheres of Ap, Am, and Hg–Mn stars. An increase in Cr abundance with depth was found for the cool Ap stars β CrB, HR 7575, γ Equ, and 10 Aql. Some increase in Cr abundance in the upper layers of the atmospheres is suggested for all Am stars and for both Hg–Mn components of 46 Dra. The vertical chromium distributions in the atmospheres of the hot, spotted Ap stars 17 Com and α^2 CVn are evidently uniform.

3. The dependences of the vertical stratification parameter *a* on a star's effective temperature and average Cr abundance were investigated. A significant difference between magnetic (Sr–Cr–Eu) and nonmagnetic (Am and Hg–Mn) CP stars was found for both dependences: the vertical gradient of Cr abundance in the atmospheres of Ap stars evidently decreases with increasing T_{eff}, while for Am stars it does not depend on T_{eff}. No correlation between *a* and ⟨log(Cr/N)⟩ was found for stars of any type.

4. The character of the possible Cr stratification in the atmospheres of the Hg–Mn stars 46 Dra A and B agrees with

the results obtained for metallic-line stars. This confirms once again the existence of a close connection between these two types of chemically anomalous objects.

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