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VERTICAL CHROMIUM DISTRIBUTION IN THE ATMOSPHERES OF CP STARS. II. MODELING

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Vertical chromium distributions in the atmospheres of several Ap and Am stars are fitted using detailed modeling of the profiles of CrII lines. The vertical distributions obtained for Ap stars are consistent with Babel's results of an investigation of Cr lines in the spectrum of the Ap star 53 Cam. It is shown that the observational data cannot be interpreted in terms of the hypothesis that microturbulent velocity varies with depth.

1. Introduction

In this work we continue a study of vertical stratification of chemical elements in the atmospheres of chemically peculiar (CP) stars. Earlier, on the basis of new observations, we diagnosed the vertical Cr distribution in the atmospheres of four Am, two Hg–Mn, and two magnetic Ap stars [1]. In the present paper we give the results of a quantitative calculation of the vertical Cr distribution in the atmospheres of certain Ap and Am stars and consider the possibility of interpreting our observational material in terms of an alternative hypothesis that the microturbulent velocity ξ_t varies with depth.

2. Modeling the Vertical Chromium Distribution

The next natural step after obtaining the Cr abundance as a function of $\Delta\lambda$ is to determine the vertical Cr distribution on the actual scale of geometrical or optical depths in the stellar atmosphere. Such a calculation is needed to compare observational data with theoretical predictions. The original dependence of log(Cr/N) on $\Delta\lambda$ can be interpreted as evidence of the very fact that vertical Cr stratification is present, but it cannot be used for quantitative analysis of the stratification. Romanyuk and Topil'skaya [2], in analyzing the equivalent widths of CrII lines obtained for α^2 CVn by Khokhlova and Topil'skaya [3] and Zverko and Ziznovskij [4], calculated the optical depths of formation ($W\lambda$) of lines

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of the 30th multiplet of Cr, thus obtaining log(Cr/N) as a function of optical depth. In our investigation, based on the calculation of synthetic spectra, we rejected the use of such a procedure for the following reasons: first, there is disagreement about the very definition of the concept of the depth of formation of monochromatic emission (see, e.g., the discussion of this question by Smith [5] and Magain [6]); second, the use of spectral synthesis to analyze Cr lines presumes an analysis of the formation of each point of the spectrum and does not admit of the natural use of the concept of depth of formation of a spectral line as a whole. Moreover, since a spectral line is formed, in general, over a fairly large range of optical depths, Gray [7] has raised doubts about the fundamental possibility of associating an entire spectral line with some definite depth of formation.

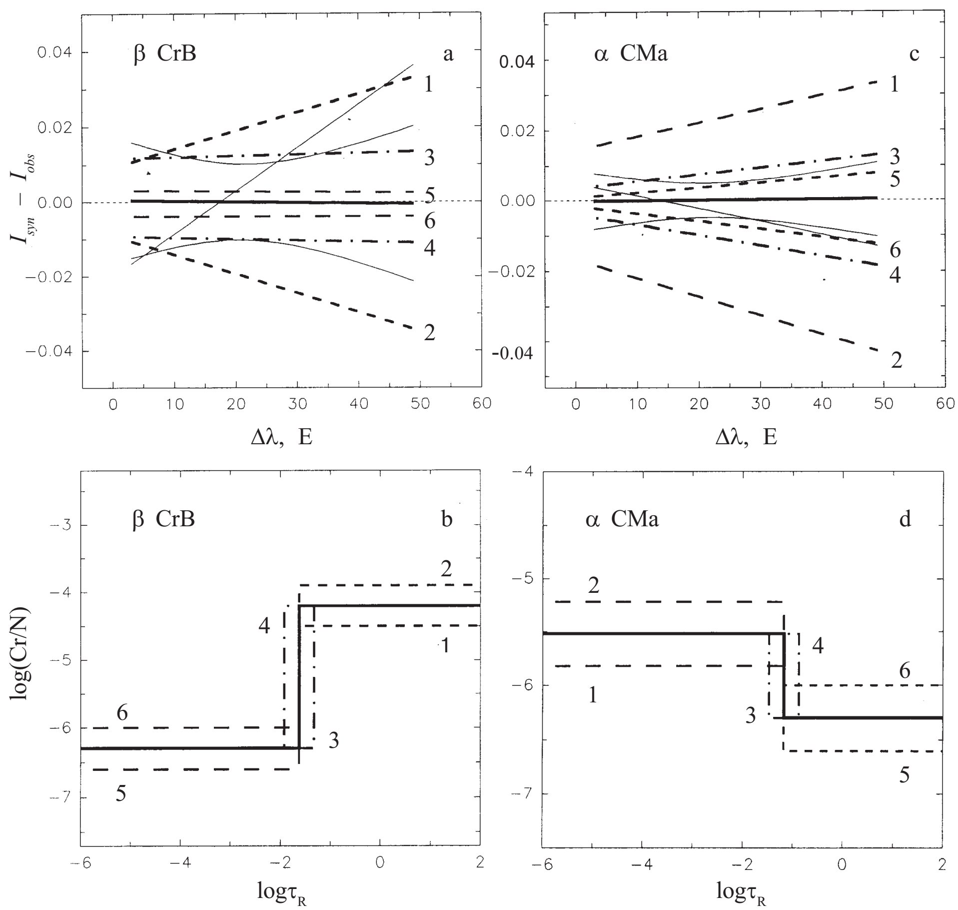

Fig. 1. a) Linear approximation of dependences of $I_{syn} - I_{obs}$ on $\Delta\lambda$ for different vertical Cr distributions in the atmosphere of β CrB. Thin solid line) uniform distribution with log(Cr/N) = <log(Cr/N)> (see Table 1); heavy lines) stepwise variations in log(Cr/N): solid line) optimal distribution; dashed, dash–dot, and short-dashed lines) variations by ±0.3 dex of optimal values of $\log(Cr/N)_1$, $\log\ \tau_j$, and $\log(Cr/N)_2$. The 95% confidence interval of the linear approximation of the dependence of $I_{syn} - I_{obs}$ on $\Delta\lambda$ for the optimal Cr distribution is shown by thin solid curves. b) Stepwise Cr distributions in the atmosphere of β CrB used to construct dependences of $I_{syn} - I_{obs}$ on $\Delta\lambda$ shown in a). All notation and numbering coincide with those adopted in a). c) Same as in a) but for different vertical Cr distributions in the atmosphere of Sirius. d) Stepwise Cr distributions in the atmosphere of Sirius used to construct the dependences of $I_{syn} - I_{obs}$ on $\Delta\lambda$ shown in c). All notation and numbering coincide with those adopted in a).

Taking these considerations into account, we decided to determine the vertical Cr distribution in the atmospheres of CP stars by choosing the Cr distribution that best reproduces the observed intensities of lines of that chemical element. The comparison of theoretical distributions with observations was done graphically, by constructing the dependence of the difference between the theoretical and observed central intensities ($I_{syn} - I_{obs}$) on $\Delta\lambda$, for each version of the vertical Cr stratification. Here we considered the best vertical Cr distribution to be the one that minimized a) the slope of the straight line approximating the dependence of $I_{syn} - I_{obs}$ on $\Delta\lambda$ and b) the departure of the approximating line from the line $I_{syn} - I_{obs} = 0$. We note that using only the central intensities of CrII lines for the comparison with observations does not mean a loss of any information included in line profiles. Indeed, all the investigated chromium lines are fairly weak in the spectra of Ap and Am stars, so one can scarcely expect such influence of stratification on the shape of their profiles as was found for the CaII K resonance line [8, 9], the GaIII λ 1495E resonant ultraviolet line [5], or strong HeI optical lines [10].

It is important to note that we determined the theoretical central intensities I_{syn} of CrII lines for each vertical distribution of this element by a calculation of synthetic spectra in the vicinity of the Cr lines. Using synthetic spectra enabled us to adequately allow for effects of blending of Cr lines and broadening of spectral lines due to stellar rotation and the instrumental profile. The synthetic spectra were calculated based on V. V. Tsymbal's SYNTHMN program, which makes it possible, for any chemical element, to specify the abundance varying with depth and/or the microturbulent velocity varying with depth. The folding of synthetic spectra with the rotation profile and the instrumental profile was done using the STARSP system [11].

TABLE 1. Vertical Cr Distributions Obtained for Ap and Am Stars

Star	$\log(Cr/N)_1$	$\log\tau_j$	$\log(Cr/N)_2$
	Ap stars		
HR 7575	$-6.30 \pm^{0.70}_{\infty}$	$-2.62 \pm^{0.55}_{0.30}$	$-4.15 \pm^{0.16}_{0.22}$
β CrB	$-6.30 \pm^{0.60}_{\infty}$	$-1.68 \pm^{0.20}_{0.30}$	$-4.19 \pm^{0.15}_{0.15}$
γ Equ	$-6.30 \pm^{0.23}_{0.30}$	$-0.31 \pm^{0.18}_{0.15}$	$-4.72 \pm^{0.45}_{0.45}$
	Am stars		
α CMa	$-5.52 \pm^{0.05}_{0.05}$	$-1.18 \pm^{0.18}_{0.20}$	$-6.30 \pm^{0.23}_{0.40}$
o Peg	$-5.21 \pm^{0.25}_{0.39}$	$-2.68 \pm^{0.32}_{0.61}$	$-6.30 \pm^{0.20}_{0.38}$
γ Gem	$-6.02 \pm^{0.45}_{0.07}$	$-2.31 \pm^{0.57}_{1.54}$	$-6.30 \pm^{0.06}_{0.06}$
32 Aqr	$-5.87 \pm^{0.22}_{0.31}$	$-2.06 \pm^{0.63}_{1.31}$	$-6.30 \pm^{0.13}_{0.14}$

Note. The symbol ∞ means that, in accordance with our adopted procedure for estimating the errors in the parameters of the vertical Cr distribution, this chemical element may be entirely absent from the upper layers of the atmospheres of HR 7575 and β CrB.

As the first approximation we used a stepwise Cr distribution determined by three parameters: the Cr abundance above the jump [$\log(\mathrm{Cr/N})_1$], that below the jump [$\log(\mathrm{Cr/N})_2$], and the optical (Rosseland) depth of the jump itself ($\log\tau_j$). For the Cr abundance in atmospheric layers above the jump for Ap stars we chose the solar abundance $\log(\mathrm{Cr/N})_1 = \log(\mathrm{Cr/N})_\odot = -6.30$ and varied the position of the jump and its size $(\Delta\log(\mathrm{Cr/N}) = \log(\mathrm{Cr/N})_2 - \log(\mathrm{Cr/N})_\odot)$; for Am stars, on the contrary, we fixed the solar Cr abundance below the jump, $\log(\mathrm{Cr/N})_2 = \log(\mathrm{Cr/N})_\odot$, and varied the position of the jump and the Cr abundance in the upper layers of the stellar atmosphere. At this stage of the investigation, we assumed the microturbulent velocity to be constant over the entire extent of the stellar atmosphere and equal to the value of ξ_t found in earlier research on stellar chemical composition (see, e.g., Table 2 in [1] and Table 2 in [12]).

Similar stepwise distributions have been used in all previous research on vertical stratification of chemical elements (see, e.g., [5, 9, 13]). The quality of the observational material at present obviously prevents the determination of more complicated vertical distributions of elements. As Babel showed [8], moreover, stepwise distributions describe very well the theoretical variations in the abundances of many elements with depth for the Ap star 53Cam. We can thus

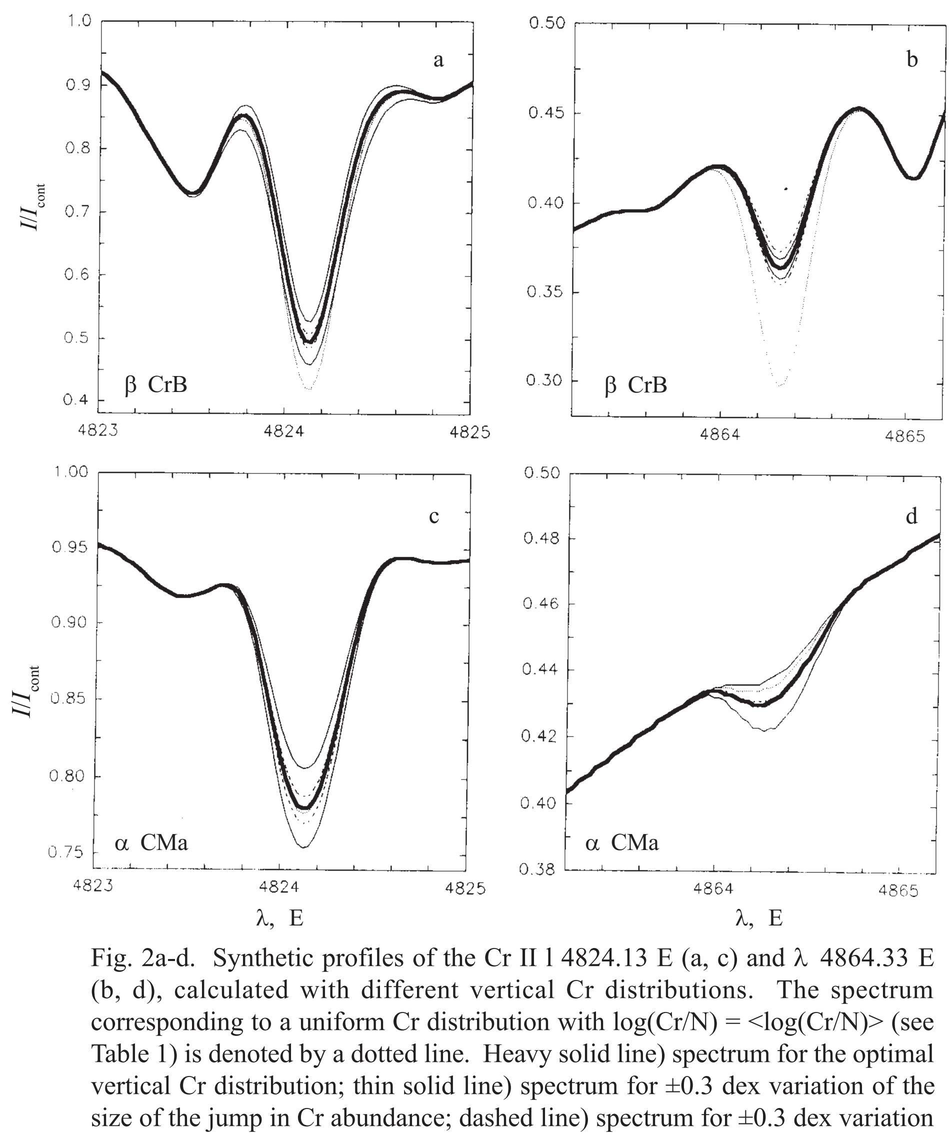

Fig. 2a-d. Synthetic profiles of the Cr II l 4824.13 E (a, c) and λ 4864.33 E (b, d), calculated with different vertical Cr distributions. The spectrum corresponding to a uniform Cr distribution with log(Cr/N) = <log(Cr/N)> (see Table 1) is denoted by a dotted line. Heavy solid line) spectrum for the optimal vertical Cr distribution; thin solid line) spectrum for ±0.3 dex variation of the size of the jump in Cr abundance; dashed line) spectrum for ±0.3 dex variation of the optical depth of the jump. The corresponding stepwise Cr distributions are shown in Fig. 1b for β CrB and in Fig. 1d for Sirius.

be confident that a stepwise Cr distribution is a good approximation of the actual stratification, at least for Ap stars.

Later in this paper we give concrete results on the choice of optimal vertical Cr distributions in the atmospheres of Ap and Am stars.

2.1. Ap Stars. Vertical Cr distributions were chosen for β CrB, HR 7575, and γ Equ — Ap stars that exhibit the strongest dependence of log(Cr/N) on Δλ. In Table 1 we give the parameters $\log(\mathrm{Cr/N})_1$, $\log(\mathrm{Cr/N})_2$, and $\log \tau_j$ of the optimal stepwise Cr distributions obtained for the three Ap stars. There we also give an estimate of the probable errors in determining those parameters. The process of choosing the vertical Cr distribution for β CrB is illustrated by Fig. 1a, b. The linear approximation of the dependence of $I_{syn} - I_{obs}$ on Δλ for different versions of the vertical Cr stratification is shown in Fig. 1a and the corresponding vertical distributions of that element are given in Fig. 1b. After determining the optimal stratification version, we fixed two parameters of the resulting stepwise distribution and varied the third until the corresponding linear approximation of the dependence of $I_{syn} - I_{obs}$ for Cr II lines on Δλ was within the 95% confidence interval of the linear approximation corresponding to the optimal vertical distribution. The maximum allowable departures of the parameters $\log(\mathrm{Cr/N})_1$, $\log(\mathrm{Cr/N})_2$, and $\log \tau_j$ from their optimal values are also given in Table 1 as the possible errors in determining those parameters.

It is interesting to note the very low sensitivity of Cr II line intensities to the Cr abundance in the upper layers of the atmospheres of Ap stars. But the maximum possible Cr abundance above the jump, $\log(\mathrm{Cr/N})_1^{\max}$ despite the considerable error in determining $\log(\mathrm{Cr/N})_1$, is still an order of magnitude lower than the minimum possible Cr abundance, Cr $\log(\mathrm{Cr/N})_1^{\min}$ in the lower layers of the atmospheres of Ap stars.

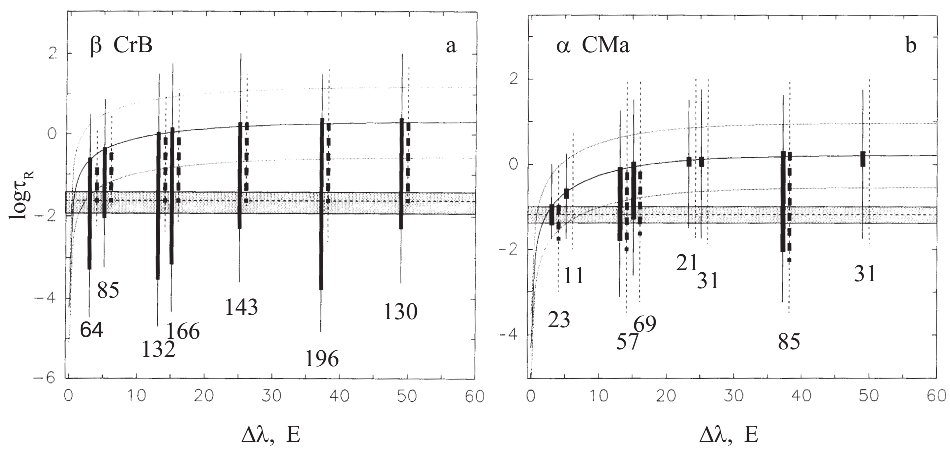

Fig. 3. Dependence on Δλ of the optical depths of formation of Cr II spectral lines in the atmospheres of β CrB (a) and Sirius (b). The range of the intervals of optical depths within which 90% of the emission flux is formed at wavelengths from the cores of the CrII lines to the quasi-continuum of the Hβ line is shown by thin vertical bars. The heavy bars correspond to the range of variation of the position of the absolute maximum of the contribution functions for the same wavelengths. The results of calculating optical depths under the assumption that the vertical Cr distribution is uniform are shown by solid bars, while those with the optimal stepwise distribution are shown by dashed bars (shifted by 1 E for convenience of presentation). The variation with Δλ of the maximum of the contribution function for the Hβ line itself is shown by the solid curve, while the dotted curves correspond to the limits of the range of formation of 90% of the emission flux in the Hβ line. The observed equivalent widths of the investigated Cr lines are also indicated. The optimal optical depth of the jump in Cr abundance is shown by a horizontal dashed line, and the hatched region corresponds to the error in its determination.

The sensitivity of the profiles of the Cr II l 4824.13 and 4864.33 E lines to variations in the vertical Cr distribution in β CrB's atmosphere is illustrated by Fig. 2a, b. Calculations show that the λ 4864.33 E line is sensitive primarily to the position of the jump in Cr abundance, whereas the λ 4824.13 E line is sensitive primarily to the size of the jump. The intensities of both spectral lines is lower in the presence of Cr stratification than under the assumption of a uniform Cr distribution with log(Cr/N) = <log(Cr/N)>.

We were able to obtain additional information about the conditions under which lines of the 30th multiplet of CrII are formed in β CrB's atmosphere by calculating the optical depths of formation of the emission at wavelengths corresponding to the CrII lines. We calculated the contribution function for each point of a synthetic profile of an investigated chromium line from its core out to the quasi-continuum, formed by a wing of the Hb line. This made it possible to determine for each wavlength a) the optical depth corresponding to the absolute maximum of the contribution function and b) the range of optical depths within which 90% of the emission flux is formed. The intervals within which the aforementioned characteristics of the contribution functions fall are denoted by vertical bars in Fig. 3a for each investigated CrII line. Solid bars denote the results of calculations with a uniform Cr distribution while dashed ones denote those for the optimal version of the discontinuous distribution found above.

An analysis of Fig. 3a enables us to draw the following conclusions. First, owing to the extremely high average Cr abundance in β CrB's atmosphere and the considerable intensity of the CrII lines (it can be judged from the value of $W\lambda$, also indicated in Fig. 3a), all the Cr lines under consideration are formed over fairly large ranges of optical depths. This confirms the inadequacy of the use of any average depth of formation for an entire line as a whole. Second, because of their strength, even CrII lines that are at a considerable distance from the Hβ core are sensitive to the presence of a relative Cr deficit in the upper layers of β CrB's atmosphere. Third, in addition to the distance from the center of Hβ, the depth of formation of a CrII line also depends essentially on the line strength. The λ 4824.13E line, for example, is partly formed in the same atmospheric layers as the λ 4856.19 and 4864.33E lines, which are closest to the Hβ core. Thus, in diagnosing the vertical distribution of a chemical element, it would be preferable to compare log(Cr/N) values obtained from spectral lines of the same strength. At the same time, excluding the Cr abundance obtained for Ap or Am stars from the λ 4824.13E line hardly changes the value of the parameter *a* given in Table 4 of [1].

The results of fitting vertical Cr distributions in the atmospheres of Ap stars are represented graphically in Fig. 4a. The optimal distributions for β CrB, HR 7575, and γ Equ are shown by heavy lines, and the hatched regions correspond to the errors in their determination. The theoretical Cr distribution obtained by Babel [8] for 53 Cam and confirmed in [14] on the basis of a study of ultraviolet Cr lines in that star's spectrum is shown in the same figure. We can thus state that there is good qualitative agreement between the results of two independent studies of Cr stratification in the atmospheres of stars of the same type, carried out on the basis of different observational materials and using different methods of determining the vertical nonuniformity in the Cr distribution. A direct comparison of the two methods will be possible in the future using a detailed analysis of lines of the 30th CrII multiplet in the spectrum of 53Cam.

2.2. Am Stars. We chose the Am stars Sirius, oPeg, γ Gem, and 32 Aqr for calculating the vertical Cr distribution. The effective temperatures of these metal-rich stars fully covers the T_{eff} range for Am stars studied in the present work and earlier in [12]. The results of fitting the optimal Cr distributions are given in Table 1 and in Fig. 4b, c. The errors in the parameters of these stepwise vertical distributions were determined just as for Ap stars.

Fitting of the vertical Cr distribution is illustrated using the example of Sirius (Fig. 1c, d). In contrast to Ap stars, the dependence of $I_{syn} - I_{obs}$ on $\Delta\lambda$ is fairly sensitive to the variation of each of the three parameters of the stepwise Cr distribution. It should be noted that the results given in Table 1 for the coolest Am stars, γ Gem and 32Aqr, are not entirely unambiguous: our observational material admits of a simultaneous increase in the jump in Cr abundance and its shift to higher layers of the atmosphere. This ambiguity may be a consequence of the inadequate quality of our observational material and/or of the existence of a smoother variation of log(Cr/N) with depth.

Profiles of the λ 4824.13 and 4864.33 E Cr II lines for Sirius, calculated with different versions of the vertical Cr distribution, are given in Fig. 2c, d. Both spectral lines are sensitive to a change in the jump in Cr abundance, while

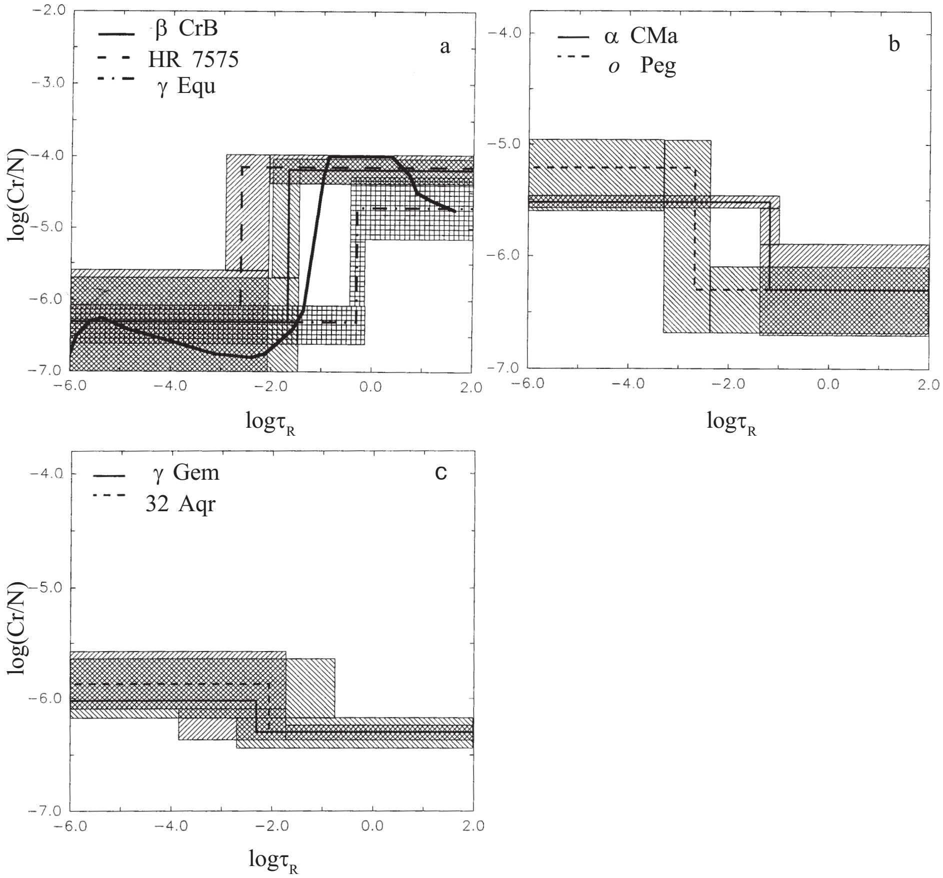

Fig. 4. Results of modeling vertical Cr stratification for Ap stars. The vertical Cr distributions in the atmospheres of β CrB (solid line), HR 7575 (dashed line), and γ Equ (dash–dot line) are shown by heavy lines. The heavy curve corresponds to the dependence of log(Cr/N) on optical depth found for the Ap star 53 Cam in [7]. The hatched regions correspond to the errors in determining $\log(Cr/N)_1$, $\log\ \tau_j$, and $\log(Cr/N)_2$. b) The same for the Am stars Sirius (solid line) and *o*Peg (dashed line). c) The same for γ Gem (solid line) and 32 Aqr (dashed line).

the λ 4824.13E line is also sensitive to variation in the optical depth of the jump.

An analysis of the depths of formation of the Cr II lines for Sirius is made in Fig. 3b. In contrast to β CrB, a moderate excess in Cr abundance is observed in Sirius, the spectral lines of the 30th multiplet are not so strong, and they are formed in a smaller range of optical depths. Just as for β CrB, however, the λ 4824.13E line, although it does lie fairly far from the Hβ core, is partially formed fairly high in α CMa's atmosphere.

3. Microturbulent Velocity as a Function of Optical Depth

In an investigation of the chemical compositions of the atmospheres of a number of supergiants of types A, F, and G, it was shown that the microturbulent velocity ξ_t increases with height in the atmosphere from 1-2 km/sec in its lower layers to 10-20 km/sec in its upper ones {see, e.g., [15], in which the dependence $\xi_t(\tau)$ was obtained for the supergiant γ Cyg). In his detailed non-LTE analysis of Fe lines in Vega's spectrum, Gigas [16] also found a dependence $\xi_t(\tau)$. According to that study, ξ_t varies from 1 to 2 km/sec in Vega's atmosphere. For γ Gem, Nishimura and Sadakane [17] found it necessary to introduce a value of ξ_t 0.6 km/sec lower for Ti, Fe, and Ni ultraviolet spectral lines than in an analysis of lines of the same elements in the visible range. This can also serve as a basis for assuming that ξ_t varies with depth in the atmosphere of a main-sequence A or F star.

Is it possible to interpret our dependence of log(Cr/N) on $\Delta\lambda$ by introducing such a microturbulent velocity that varies with depth for a chemically uniform stellar atmosphere? Within the framework of this hypothesis, the relative Cr deficit observed in the surface layers of an Ap star is explained by a decrease in ξ_t in those layers in comparison with the remaining atmosphere; for metal-rich stars, on the contrary, one must assume an increase in ξ_t in the surface layers of the atmosphere.

To test the hypothesis that ξ_t varies with depth for β CrB and Sirius, we tried to choose dependences $\xi_t(\tau)$ that would liquidate the variation of $I_{syn} - I_{obs}$ with $\Delta\lambda$. To estimate the suitability of one or another dependence $\xi_t(\tau)$, we used the same method as that used earlier to determine vertical Cr distributions. Despite the multitude of functions $\xi_t(\tau)$ tried,

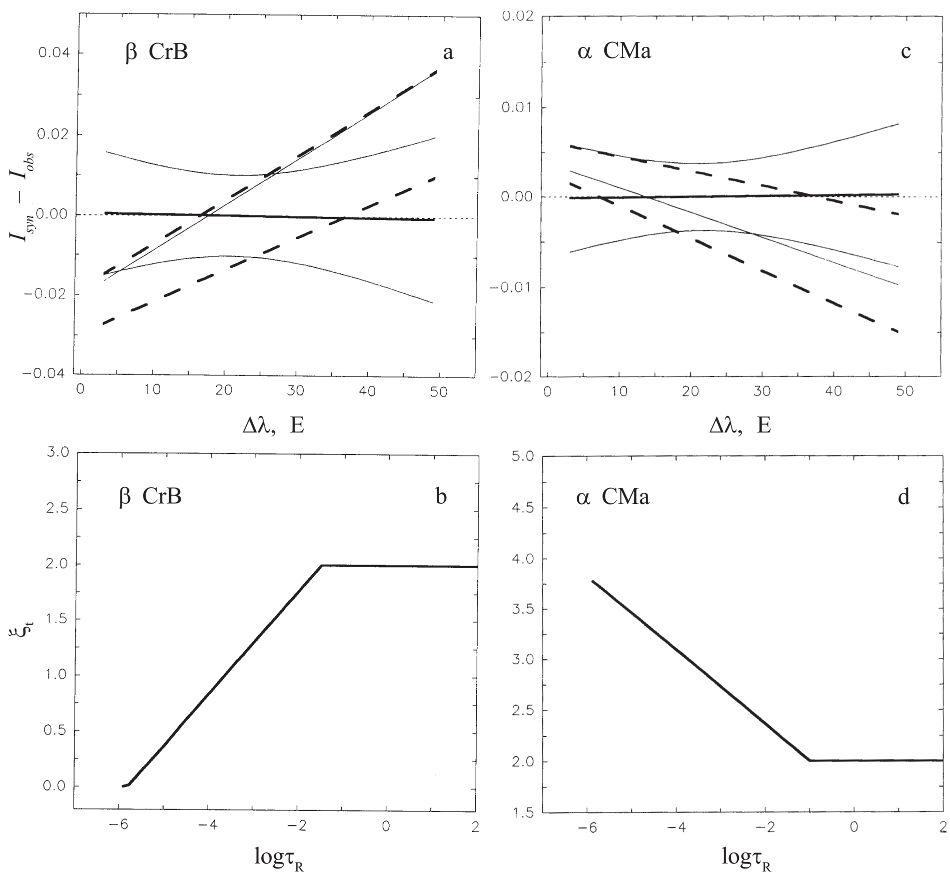

Fig. 5. a) Linear approximation of the dependences of $I_{syn} - I_{obs}$ on Dl for different $\xi_t(\tau)$ in the atmosphere of β CrB. Thin solid line) uniform distribution with log(Cr/N) = <log(Cr/N)> (see Table 1); heavy solid line) optimal stepwise Cr distribution; heavy dashed lines: uniform Cr distribution with log(Cr/N) = –5.65 and –5.85 and with the dependence $\xi_t(\tau)$ shown in b). The 95% confidence interval for the linear approximation of the dependence of $I_{syn} - I_{obs}$ on $\Delta\lambda$ for the optimal version of Cr stratification is shown by thin solid curves. b) One version of the dependence $\xi_t(\tau)$ in the atmosphere of β CrB. c) The same as in a), but for Sirius. The linear approximation of the dependences of $I_{syn} - I_{obs}$ on Dl calculated for a uniform Cr distribution with log(Cr/N) = –4.65 and –4.85 and with the dependence $\xi_t(\tau)$ shown in Fig. 5d. d) The same as in b), but for Sirius.

we were unable to choose a depth dependence of the microturbulent velocity that would explain the observed relative intensities of CrII lines in the spectra of β CrB and Sirius as well as does the hypothesis of vertical Cr stratification. Detailed calculations showed that the introduction of a variable ξ_t hardly affects the faint λ 4856.19 and 4864.33E lines, which lie closest to the Hβ core. At the same time, the intensities of strong lines (λ 4824.13, 4848.24, and 4876.40E) do vary, and as a result, the spread between the Cr abundances determined from strong and weak lines increases considerably. The dependence of $I_{syn} - I_{obs}$ on $W\lambda$ becomes dominant and prevents one from liquidating the dependence of $I_{syn} - I_{obs}$ on $\Delta\lambda$. An approximation of the dependences of $I_{syn} - I_{obs}$ on $\Delta\lambda$ for several "unsuccessful" versions of the depth dependence of ξ_t in the atmospheres of β CrB and Sirius is given in Fig. 5a and c. The corresponding dependences $\xi_t(\tau)$ are shown in Fig. 5b and d.

The hypothesis that x_t depends on optical depth cannot explain the observed relative intensities of CrII lines. It should be added that the traditional method of determining ξ_t, which requires the absence of variation of log(El/N) with $W\lambda$, is scarcely correct when there is vertical stratification of the given element. Indeed, strong spectral lines are sensitive to an element's abundance in a wide range of optical depths, while weak ones are sensitive only to the element's abundance near the region of formation of the continuum. For this reason, when vertical stratification is present one can expect the element's abundance to depend on line strength, in no way related to the improper choice of ξ_t.

As for Ap stars, for them the situation is complicated by the presence of strong magnetic fields. One should expect additional stabilization of the stellar atmosphere in this case and smallness of the true value of ξ_t. The microturbulent velocities introduced in the analysis of the chemical compositions of magnetic Ap stars are most likely an effective allowance for magnetic broadening of the spectral lines. In the case of magnetic Ap stars, therefore, the dependence of log(Cr/N) on $\Delta\lambda$ can, in principle, be explained by variation of the magnetic field strength with depth in the absence of Cr stratification. Romanyuk [18] attempted to determine the vertical magnetic field gradient using a comparative analysis of spectral lines located before and after the Balmer jump. In that investigation he found an increase in field strength with depth for α^2 CVn and a uniform magnetic field for β CrB. Detailed modeling of the profiles of these spectral lines with allowance for their broadening in a magnetic field may provide a conclusive answer to the question of the influence of a vertical magnetic field gradient on the relative intensities of CrII lines.

4. Principal Results

In conclusion, we generalize the main results of our investigation of vertical Cr stratification in the atmospheres of CP stars.

1. Vertical chromium distributions were fitted for several Ap and Am stars by modeling Cr II line profiles. Those calculations confirmed the correctness of interpreting the dependence of log(Cr/N) on $\Delta\lambda$ based on the hypothesis that a vertical gradient of the investigated element exists. The vertical distributions obtained in the case of Ap stars are consistent with the results of studies [8, 14] of Cr lines in the spectrum of the Ap star 53Cam.

2. The conditions of formation of CrII lines in the atmospheres of β CrB and Sirius were analyzed in detail by investigating the contribution functions.

3. It was shown that the alternative hypothesis that the microturbulent velocity ξ_t varies with depth is incapable of explaining the observed relative intensities of CrII lines.

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