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Variability of Balmer lines in Ap stars

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Summary. We present an extensive set of β index measurements for 22 Ap stars. In case of 17 stars, photometry reveals periodic variability of the β index with the rotational phase, and for the remaining 5 Ap stars we can estimate upper limits of variations. Typical amplitudes (maximum – minimum) of β index variations are equal to 0.02 mag. The largest one (0.06 mag), observed for HD 221568, corresponds to 30% variation of equivalent width of Hγ line (Kodaira, 1967). For the majority of the investigated stars, the minimum of β index occurs close to the phase of maximum light at wavelengths longer than the "null wavelength", with the exception of 56 Ari and CU Vir. We notice also, that the shapes of the β index curve and light curve for a given star are very similar. We discuss two mechanisms, which were proposed as an explanation of the Balmer line variations. On the basis of a model atmosphere and of Balmer line profile calculations we demonstrate, that the first of them – horizontal and vertical chemical inhomogeneity caused by diffusion of elements – can qualitatively explain the similarity and observed phase relations between photometric and Balmer line variations, as well as the observed mean amplitudes of the β variations for the majority of investigated Ap stars. The second mechanism accounting for β variations, can be associated with strong electric currents distorting the atmosphere of a magnetic star. We discuss in detail the cases of 56 Ari and CU Vir, for which we found significant phase shifts between β and light curves. In both stars only the latter, electromagnetic model of variations, can qualitatively explain the observed phase shifts.

Key words: Ap stars – Balmer lines – variations

1. Introduction

The first reliable measurements of Balmer line variations with the rotational phase of an Ap star were published by Kodaira (1967) for Osawa's star, HD 221568. This star exhibits the largest variations of the Balmer line equivalent widths among all investigated Ap stars. In many other publications we find data on variations of Balmer lines for over 20 Ap stars. Since typical variations are not so prominent as in the case of HD 221568, the results of most of the existing investigations are not reliable or have very low signal-to-noise ratio.

Peterson (1970) proposed a mechanism which could account for the variability of both the light and the Balmer lines. The variations were caused in it by the overabundance of silicon in the atmosphere, on some patches on the stellar surface. A similar mechanism was suggested by Kodaira (1973), who analyzed the spectral variations in HD 221568. According to it, at the rotational phase of enhanced concentration of metals the visible part of the stellar atmosphere is apparently hotter due to blanketing mechanism, and consequently, all the Balmer lines should be weaker at that phase.

Woltjer (1971) and Rakosch et al. (1974) have suggested another mechanism of magnetic star variability, assuming that the magnetic field of an Ap star deviates from force-free configuration, and the corresponding electromagnetic (Lorentz) forces can modify the structure of the atmosphere in some regions on the stellar surface. Consequently, stratification of various opacities over surface of the star is not uniform, while its chemical composition remains the same at any point. This idea has been analyzed numerically by Stepien (1978) and Madej (1978, 1983a) who showed, that in extreme cases magnetic forces reduce effective gravitational acceleration near the magnetic equator by a factor 3 as compared with gravity at unperturbed magnetic poles (the whole model still remains in radiative and hydrostatic equilibrium). Consequently, we should expect variations of the Balmer lines with rotational phase of the star (cf. Madej, 1983a).

Musielok (1986) noticed, that non-uniform helium contents over the stellar surface should also be taken into account, when interpreting variability of the Balmer lines in Ap stars. According to his paper, all existing measurements of the Balmer line variations at that time did not contradict the hypothesis, that these variations are consequence of variations of observed chemical composition with rotational phase of a star.

The purpose of the paper is to present new, high accuracy photometric β measurements for 22 Ap stars, supplemented by the best results published in the literature. We made an attempt to explain the variability of Balmer lines with the above mentioned mechanisms.

2. Observations

2.1. Hβ photometry

Observational data discussed in this paper were collected in the period 1984–1986 with the 60 cm Cassegrain reflector at the Białków Station of the Astronomical Institute of the Wrocław University (Poland). Part of them have been presented in a preliminary paper by Musielok (1986). All observations were obtained with a standard one-channel photon-counting photo-

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Send offprint requests to: B. Musielok (at present address below) meter with digital output and a pair of double-half-wave (DHW) interference filters, centered at Hβ (cf. also Madej, 1983b). Half widths of transmission profiles of wide and narrow filters, equal to 200 Å and 36 Å, respectively, were chosen to reproduce the standard β system defined by Crawford and Mander (1966).

DHW interference filters exhibit well defined non-zero spectral transparency range, outside which transparency decreases practically to zero (Bousquet et al., 1972; Macleod, 1973; Pelletier et al., 1973). Thus, DHW filters are ideal to study the Hβ line variability through β photometry, since the variations of the surrounding continuum have a rather negligible impact on the observed β indices (Madej, 1983b). Widely used Fabry-Perot interference filters (with their wide nonzero transparency wings) may be not useful for these purposes, since they can sweep up a significant amount of the continuum radiation, which is also variable in most Ap stars.

Reduction of raw observational data to the standard β system should be described in more detail. The single set of DHW filters was used during the whole 3-year observing period, but the instrumental photometric system was not fixed due to secular shifts of their transmission profiles of the center of the Hβ line. Fortunately, this effect could be corrected by inclining slightly both filters to the optical axis. Before we have started the observations in 1984 and 1986 both filter transmission profiles were shifted to the center of Hβ, by inclining the filters. As a result of these changes, we have separated the 1984–85 and 1986 seasons, and transformations to the standard β system were determined independently.

At first for each standard star the initial mean instrumental β index (denoted as β_{instr}) was determined as an average value of the observed β indices (β_{obs}) for all observing nights of a given season. Then, the following relation has been solved for each night with the least squares method, yielding coefficients A, B, and C:

$$\beta_{\mathrm{obs}} = A + B\,\beta_{\mathrm{instr}} + C\,(b-y). \tag{1}$$

With known A, B, C, and β_{obs}, new β_{instr} have been computed for each night, yielding an improved mean value of β_{instr} for all stars in this season. Then, this procedure was iterated until stable, final β_{instr} values were obtained. The program stars (i.e. actually investigated Ap stars) were also included in this procedure: at each iteration and for each variable star we have computed the relation between the instrumental β index and phase by fitting the indices to a trigonometric polynomial of the first or second order. This finally yielded mean instrumental indices for the standard and variable stars, and additionally amplitudes and phases of variations for variable stars. Finally, the mean β_{instr} of standard stars were used to define the transformation to the standard Crawford system (Crawford and Mander, 1966), and subsequently all individual β_{instr} of observed Ap stars were transformed to the standard system.

Relations between the mean instrumental system and the Crawford system are shown in Fig. 1 for both seasons. Transformation coefficients are equal to 0.85 ± 0.01 and 0.75 ± 0.01 for the observational seasons 1984–1985 and 1986, respectively. The mean seasonal values of β indices for standard and Ap stars observed at both seasons are not the same. The differences are small and do not exceed 0.005 mag. They arise from use of different photometric systems (filter inclinations) and different sets of standards (5 additional stars in 1986) during the two observational seasons. Final relations between β values in the Crawford system and phase for Ap stars observed in both seasons were obtained by individually shifting seasonal curves according to the calculated mean values. Such procedure may affect the resulting β curves if the measurements in both seasons cover different phase intervals of the rotational period. For most of the stars the observations were uniformly distributed over the rotational period or the measurements were made during one observational season. The only exception was HD 188041 which rotates with a period of 224.5 days, and we obtained observations at different phase intervals for both seasons. But even for this star the amplitudes of β index and phases of maximum β calculated separately for both seasons agree very well: $A_1 = 0.022 \pm 0.006$, $A_2 = 0.020 \pm 0.009$ and $\varphi_1 \pm 0.90 \pm 0.04$, $\varphi_2 \pm 0.85 \pm 0.07$. The tabulations of individual observations are available from the authors.

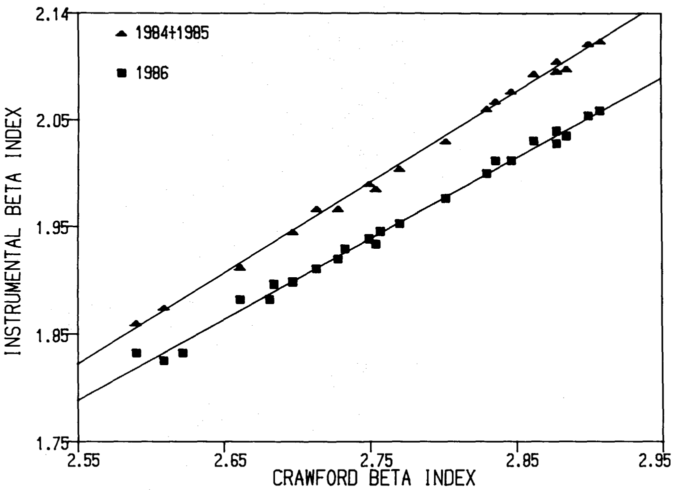

Fig. 1. Transformation of the instrumental system to the standard Crawford β system in the 1984–1985 and 1986 observational seasons

2.2. *Observational results*

Measured variations of the β index of all Ap stars with their rotational phases are exhibited in Figs. 2–4, and the most important parameters are summarized in Table 1. Points and minuses with error bars in Figs. 2–4 represent the observations obtained during the first and second observational season respectively. Solid lines represent least-squares fits of trigonometric polynomials of the null, first or second order to the observational points. We claim variability of β index with phase in those cases, where the ratio of amplitude to its error is equal or exceeds 3. From 5 stars, for which variability has not been detected, 49 Cam show the largest scatter of observational points. Observations in Fig. 2 for this star were plotted with the period given by Winzer (1974). We have also reduced the observations with other periods: 4.285 determined by Bonsack et al. (1974), 4.284, 4.032, and 3.939 determined from the present photometry. For all periods the ratio of amplitude to its error does not exceed 3.0. Additional measurements are necessary to state the possible variability of β index for this star.

We obtained only a few observational points for 53 Cam and HD 51418. Fortunately, observations by other authors are available in the literature for both stars. In Fig. 4 we have combined our results with β indices published by Pyper and Adelman (1983) for 53 Cam and HD 51418 (open circles), and that of Gulliver and Winzer (1973) for HD 51418 (filled circles). Since these authors did not publish observational errors their measurements in Fig. 4 are without error bars. We have found from sine fits mean square

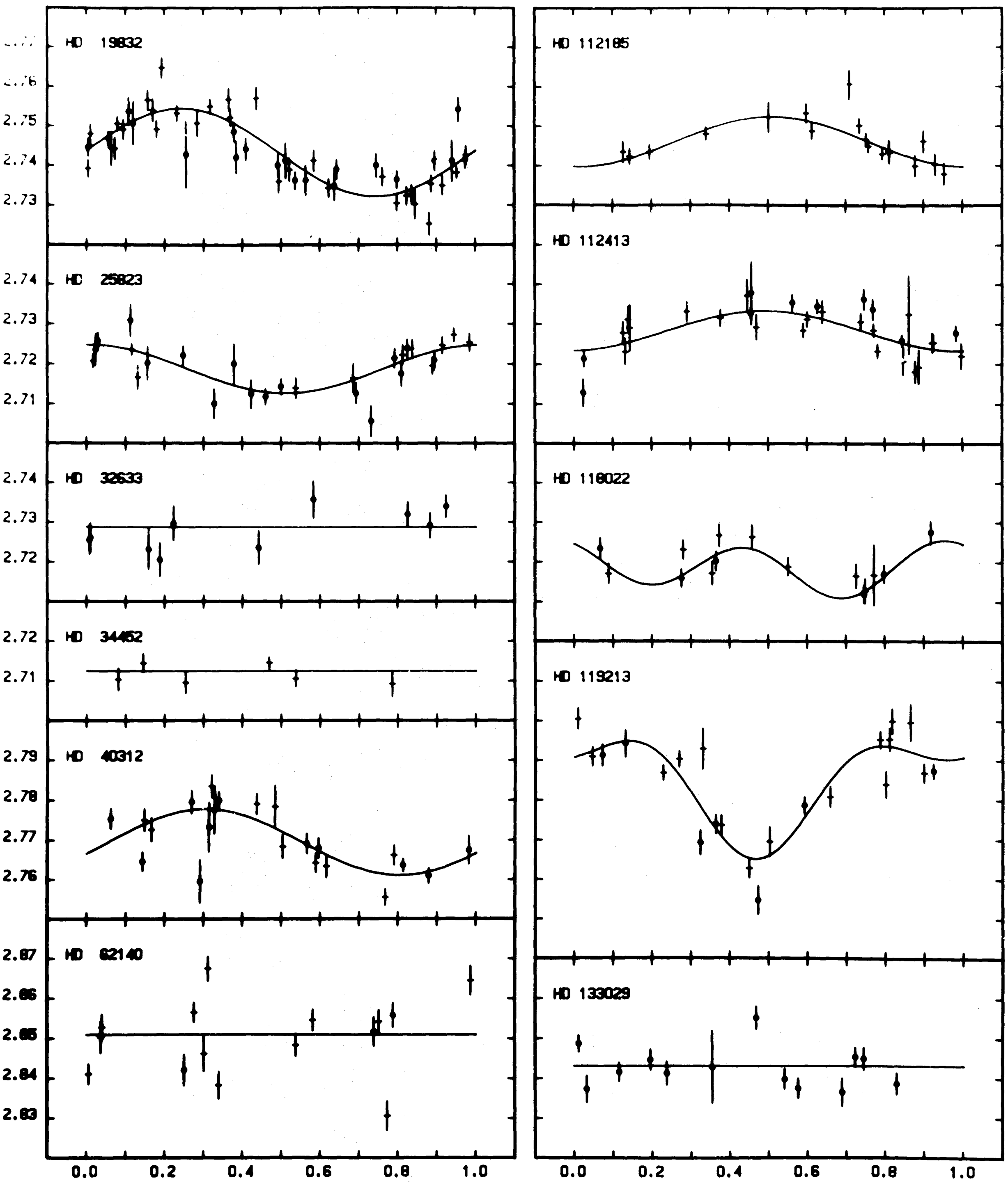

Fig. 2. Results of β photometry for the Ap stars HD 19832 (56 Ari), HD 25823 (41 Tau), HD 32633, HD 34452, HD 40312 (θ Aur), HD 62140 (49 Cam), HD 112185 (ε UMa), HD 112413 (α^2 CVn), HD 118022 (78 Vir), HD 119213 (CQ UMa), and HD 133029. Symbols: points with error bars – observations from the 1984–1985 observational season, minuses with error bars – observation from the 1986 observational season

errors equal to 0.01 mag for Pyper's and Adelman's (1983) data and 0.005 mag for Gulliver's and Winzer's (1973) data.

2.3. *Summary of previously published data*

There exist a number of papers on Ap stars where results of β photometry or measurements of variations of the Balmer line equivalent width are available. Let us first consider papers which give results on our program stars (Table 1). In the previous section we already mentioned measurements of the β index for 53 Cam and HD 51418 made by Pyper and Adelman (1983) and by Gulliver and Winzer (1973). A detailed discussion of the already published measurements for θ Aur, φ Dra, 56 Ari, α^2 CVn (Madej et al., 1984). φ Dra (Musielok, 1984) and HD 221568 (Kodaira,

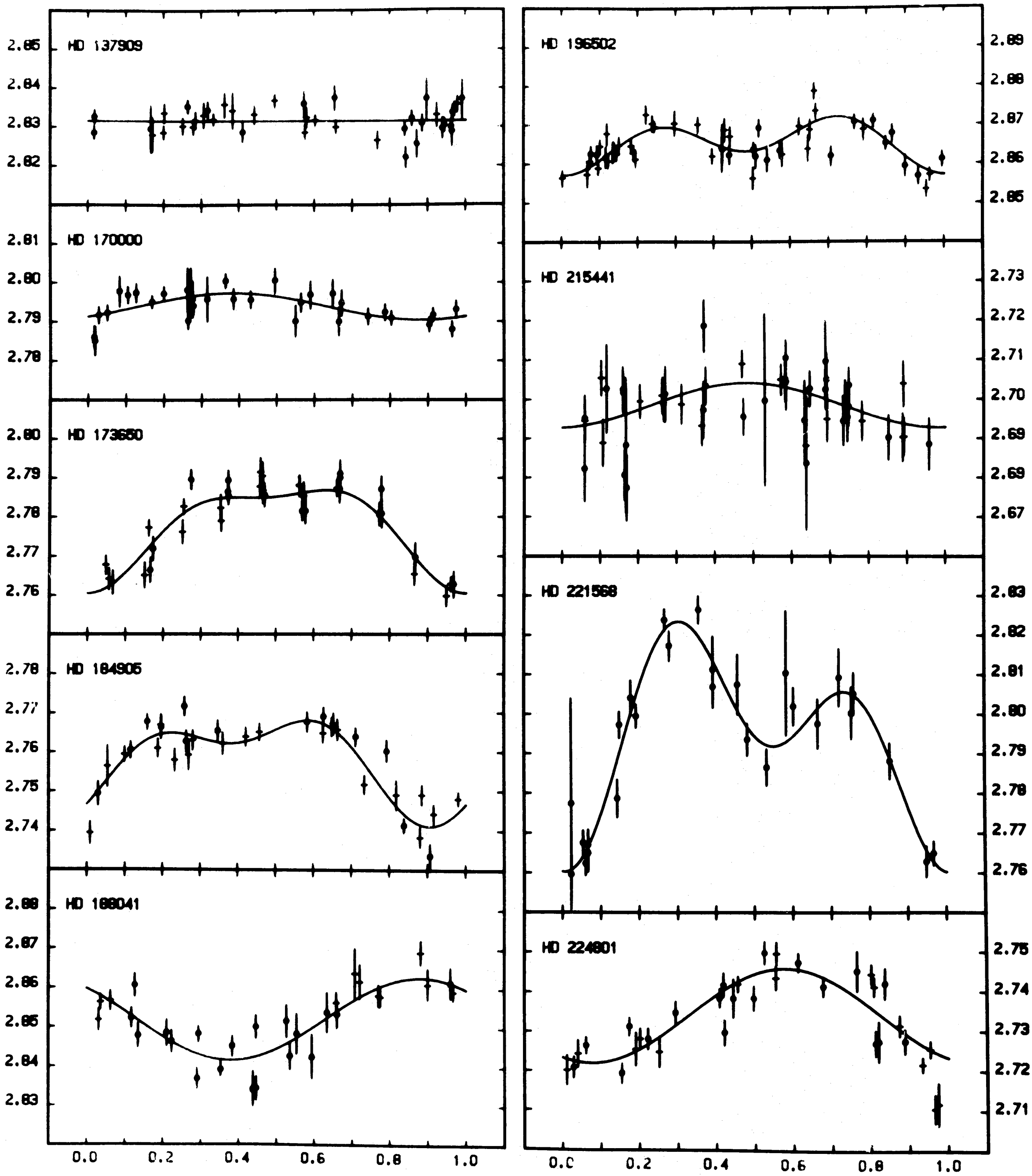

Fig. 3. Results of β photometry for the Ap stars HD 137909 (β CrB), HD 170000 (φ Dra), HD 173650, HD 184905, HD 188041, HD 196502 (73 Dra), HD 215441, HD 221568, and HD 224801. The symbols are the same as in Fig 2

1967) is given in the paper by Musielok (1986). Pyper and Adelman (1983 and 1985) publish values of β indices over rotational periods for HD 34452, ε UMa, CQ UMa, and β CrB. The mean square error of the latter data equals to 0.01 mag, and is large relatively to the mean square error of our measurements equal to 0.004 mag. Nevertheless, we note good agreement between both sets of data.

Madej (1983b) published observations of the β index in 73 Dra. A comparison of Fig. 3 of that paper with the present results shows, that the shapes of both β vs. phase curves differs significantly. Although a slight difference of mean β values in both papers could be attributed to some systematic errors, the change of single-wave curve in 1981 to double-wave curve a few years later remains unexplained. We call the attention of the reader to this Ap

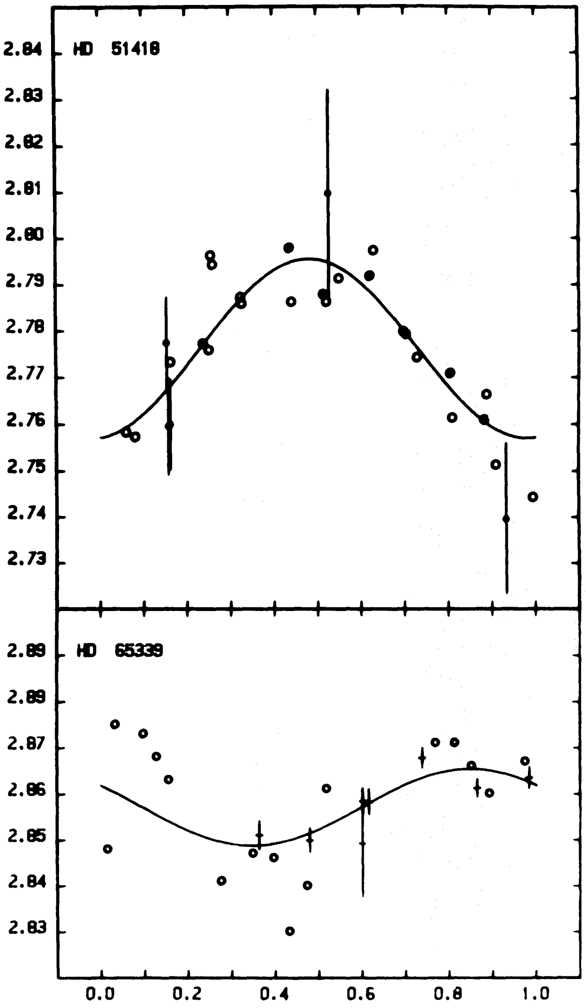

Fig. 4. Results of β photometry for HD 51418 and HD 65339 (53 Cam) (symbols are the same as in Fig. 2) combined with data from Pyper and Adelman (1983) for 53 Cam and HD 51418 (open circles) and Gulliver and Winzer (1973) for HD 51418 (filled circles)

star which perhaps exhibits long-term variability of the Hβ line. However, it should be mentioned that the present observations, made in the time interval of 460 days, show no indications for variations in shape of β index curve.

There exist also measurements of Balmer line variability for stars not included in our observational program. The already mentioned papers by Pyper and Adelman (1983 and 1985) give observational β values for the Ap stars CU Vir, κ Psc, and CS Vir. However, their β points for κ Psc and CS Vir give only upper limits for possible periodic variations. In case of CS Vir this upper limit is equal to 0.017 mag, and exceeds measured amplitudes of many Ap stars from Table 1. Thus, no useful information can be extracted concerning variations in this star. In case of CU Vir, the authors present a well defined β curve, which agrees very well with the earlier curve, published by Weiss et al. (1976). CU Vir exhibits relatively large variations of the Balmer lines, and there exist reliable spectroscopic data on this matter (Riabchikova, 1972; and Krivosheina et al., 1980). The spectroscopic data agree quantitatively very well with the photometric ones (Musielok, 1986). Variations of the Balmer lines in CU Vir will be extensively discussed in the next Sections.

HD 216533 was spectroscopically observed by Floquet (1977). She published 16 measurements of Hγ line with a rather high signal-to-noise ratio. The data were reduced with the period 17.20 days determined by Wolff and Morrison (1973). The minimum of equivalent width of Hγ coincides with the minimum of brightness in V band. This phase relation is opposite to that observed in the majority of Ap stars. We have redetermined the period of HD 216533 on the basis of all available data. The measurements of Floquet for Hγ line yield the period 17.247 ± 0.012, whereas the c_1 index of photometry by Wolff and Morrison (1973) yields $P = 17.249 \pm 0.026$. Using the average value 17.248 the phase of maximum brightness coincide with the phase of minimum β index as in most other stars. We have included this star into our future observational runs.

Recently Schneider (1986) has detected variations of the β index in the Ap star BD +24°3675. The amplitude of these variations is equal to 0.058 mag, and this is one of the largest amplitudes measured ever for an Ap star.

Table 2 exhibits the results of photometric and few spectroscopic investigations obtained by various authors. We have selected only those results, which have signal-to-noise ratio larger than 3 (assumed confidence limit). As a result very few spectroscopic data were included in Table 2. Amplitudes of the Balmer line variations in Ap stars are usually so small that this technique with its large random or systematic errors is irrelevant in such investigations and in most cases yields rather imaginary results. Often reported large variations of Balmer lines obtained from spectroscopic investigations were not confirmed in most cases by photometric methods.

2.4. *Discussion*

The majority of the results discussed in this paper concern the Hβ line. However, Table 2 includes 3 Ap stars with variations of Hγ line measured spectroscopically. In two cases there exist both spectroscopic data for Hγ line and photometric measurements of the β index (HD 221558 and CU Vir).

Balmer line variations with rotational phase are rather a typical phenomenon in Ap stars. From all 22 investigated stars 17 show clearly variations of the β index during rotational period. If we add previously published observations collected in Table 2 to our results, then the number of Ap stars with variable Balmer lines increases to 20, whereas in 6 of investigated stars Hβ line is either constant or possible variations are below the detection limit. Typical amplitudes of variations of β index are equal to 0.02 mag. The largest (0.06 mag), observed for HD 221568, corresponds to 30% variation of equivalent width of Hγ line (Kodaira, 1967). In most cases variations of the β index can satisfactorily be described by a simple sine wave, and those stars exhibit also sine-like or nearly sine-like light curves (56 Ari, 41 Tau, θ Aur, HD 51418, 53 Cam, ε UMa, α^2 CVn, CU Vir, φ Dra, HD 188041, HD 215441 and HD224801). Remaining stars (CQ UMa, HD 173650, HD 184905, 73 Dra, and HD 221568) exhibit non-sinusoidal both β and light curves. The similarity of both curves is especially good when one takes as the light curve the one obtained with the DR filter ($\lambda_{\text{eff}} = 7650$ Å) of the 10 color system (Schoeneich et al., 1976).

Similarity between the light and β phase curves in the investigated stars extends apparently to phases of their extreme values. For the majority of investigated stars with well known periods, the maximum of β index coincides with minimum of light at wavelengths longer than the "null-wavelength".

Table 1. The main parameters of our program stars

Name	HD HR	Mean β index	Ampl. of β index	Phase maximum β	Phase minimum light	Phase maximum field	JDo period	References (light), (field), (elements)
56 Ari	19832	2.743	0.022	0.24	0.04	0.17	2437667.728	(19), (4), (27)
SX Ari	954		2	2	(DR) 2	5	0.7278972	
41 Tau	25823	2.719	0.012	0.01	0.00	—	2421944.74	(19), (—), (24)
GS Tau	1268		2	3	(DR)		7.227424	
HZ Aur	32633	2.729	<0.011	—	—	—	2439499.99	(—), (—), (17, 4)
			4				6.42998	
IQ Aur	34452	2.712	<0.005	—	—	—	2437295.88	(—), (—), (16)
			6				2.4662	
θ Aur	40312	2.769	0.017	0.30	0.25	0.00	2442766.55	(1), (1), (1)
	2095		4	4	(V)		3.6190	
NY Aur	51418	2.776	0.039	0.48	0.50	0.00	2441241.654	(11), (8), (6)
			4	1	(DR)		5.4379	
49 Cam	62140	2.851	≦0.025	—	—	—	0.0	(—), (—), (22)
BC Cam	2977		10				4.2348	
53 Cam	65339	2.857	0.017	0.85	0.90	0.218	2435855.652	(11), (4), (2)
AX Cam	3109		4	4	(DR)	4	8.0267	
ε UMa	112185	2.856	0.013	0.51	0.50	—	2426437.01	(11), (—), (21)
	4905		3	2	(V)		5.0887	
α^2 CVn	112413	2.768	0.010	0.49	0.50	0.49	2419869.720	(15), (4), (5)
	4915		2	4	(V)	1	5.46939	
78 Vir	118022	2.879	0.014	0.96	0.50	0.01	2434816.9	(26), (4), (14)
CW Vir	5105		5	3	(y)	3	3.7220	
CQ UMa	119213	2.885	0.030	0.15	0.00	0.00	2441450.74	(11), (9), (11)
	5153		5	6	(DR)		2.44988	
	133029	2.793	<0.003	—	—	—	2441461.7	(—), (—), (—)
	5597		5				2.88739	
β CrB	137909	2.832	<0.004	—	—	—	2434217.5	(—), (—), (4)
	5747		2				18.487	
φ Dra	170000	2.794	0.007	0.38	0.40	0.72	2442229.40	(11), (4), (10)
	6920		2	5	(DR)		1.71649	
V535 Her	173650	2.777	0.025	0.51	0.50	0.50	2438543.8	(11), (18), (7, 11)
	7058		2	1	(DR)		9.9754	
V1264 Cyg	184905	2.758	0.027	0.59	0.50	—	2440800.27	(11), (—), (11)
			3	2	(DR)		1.84539	
90 G Aql	188041	2.852	0.021	0.88	0.95	0.55	2432323	(11), (23), (23)
V1291 Aql	7575		3	3	(DR) 2		224.5	
73 Dra	196502	2.865	0.015	0.73	0.80	0.50	2426907.6	(19), (13, 25), (13)
AF Dra	7879		2	2	(DR)		20.2754	
GL Lac	215441	2.698	0.011	0.48	0.50	0.00	2436864.88	(19), (4), (7, 3)
			3	4	(DR)	2	9.4875	
V436 Cas	221568	2.795	0.063	0.31	0.30	—	2438666.0	(20), (—), (12)
			4	2	(DR)		159.0	
CG And	224801	2.734	0.024	0.58	0.50	—	2441152.67	(19), (—), (7)
	9080		3	2	(DR)		3.73975	

References:

(1) Adelman et al. (1984)
(2) Borra and Landstreet (1977)
(3) Borra and Landstreet (1978)
(4) Borra and Landstreet (1980)
(5) Farnsworth (1932)
(6) Gulliver and Winzer (1973)
(7) Hildebrandt et al. (1985)
(8) Jones et al. (1974)
(9) Mikulasek (1984)
(10) Musielok (1986)
(11) Musielok et al. (1980)
(12) Nakagiri and Yamashita (1979)
(13) Preston (1967)
(14) Preston (1969)
(15) Pyper (1969)
(16) Rakosch (1962)
(17) Renson (1984)
(18) Rice (1970)
(19) Schoeneich et al. (1976)
(20) Schoeneich and Zelwanowa (1985)
(21) Swensson (1944)
(22) Winzer (1974)
(23) Wolff (1969)
(24) Wolff (1973)
(25) Wolff and Bonsack (1972)
(26) Wolff and Wolff (1971)
(27) This paper

Table 2. The main parameters for stars taken from the literature

Name	HD HR	Mean β or $W(\mathrm{H}\gamma)$	Ampl. of β or $W(\mathrm{H}\gamma)$	Phase maximum β or $W(\mathrm{H}\gamma)$	Phase minimum light	Phase maximum field	References (β or $W(\mathrm{H}\gamma)$), (light), (field)
NY Aur	51418	2.772	0.037 5	0.50 2	0.50 (DR)	0.00	(3), (8), (4)
NY Aur	51418	2.775	0.042 7	0.45 3	0.50 (DR)	0.00	(10), (8), (4)
CU Vir	124224 5313	2.755	0.028 9	0.16 5	0.99 (y) 1	0.11 2	(11), (11), (1)
CU Vir	124224 5313	2.748	0.030 4	0.13 2	0.99 (y) 1	0.11 2	(15), (11), (1)
CU Vir	124224 5313	9.8	1.9 4	0.18 3	0.99 (y) 1	0.11 2	(6), (11), (1)
73 Dra AF Dra	196502 7879	2.848	0.020 4	0.50 3	0.80 (DR)	0.50	(7), (13), (9, 16)
κ Psc	220825 8911	2.871	<0.009 7	—	—	—	(10), (—), (—)
MX Cep	216533	14.1	4.1 9	0.60 3	0.50 (V)	—	(2, 18), (17, 18), (—)
	221568	12.3	4.2 6	0.30 5	0.30 (DR)	—	(5), (14), (—)
BD +24°3675		2.767	0.058 14	0.21 4	0.20 (y)	—	(12), (12), (—)

References:
(1) Borra and Landstreet (1980)
(2) Floquet (1977)
(3) Gulliver and Winzer (1973)
(4) Jones et al. (1974)
(5) Kodaira (1967)
(6) Krivosheina et al. (1980)
(7) Madej (1983b)
(8) Musielok et al. (1980)
(9) Preston (1967)
(10) Pyper and Adelman (1983)
(11) Pyper and Adelman (1985)
(12) Schneider (1986)
(13) Schoeneich et al. (1976)
(14) Schoeneich and Zelwanowa (1985)
(15) Weiss et al. (1976)
(16) Wolff and Bonsack (1972)
(17) Wolff and Morrison (1973)
(18) This paper

There are two stars (56 Ari and CU Vir), with a significant phase shift between the light and β index curves. As shown in Tables 1 and 2, the difference between phase of maximum β and minimum light is equal to 0.20 ± 0.04 and 0.15 ± 0.03 for 56 Ari and CU Vir, respectively. In the case of CU Vir this phase shift cannot be explained as a consequence of the slightly incorrect rotational period, because both data sets by Weiss et al. (1976) and Pyper and Adelman (1985) were made simultaneously with *uvby* photometric measurements. We have also excluded this possibility for 56 Ari, by determining the rotational period from all existing photoelectric data in the U band (Provin, 1953; Hardie and Schroeder, 1963: Blanco and Catalano, 1970; Hildebrandt et al., 1985). These observations give the period equal to 0.7278972 ± 0.0000003 days. All the data collected in Table 1 were reduced with that period.

3. Interpretation

3.1. Model atmosphere and line profile computations

Our interpretation of the properties of observed curves reported in Sect 2.4 is based partially on model atmospheres obtained with the ATM74 computer code, described by Madej (1980). This program was designed to compute model atmospheres in radiative and hydrostatic equilibrium in LTE, with most of the important *b–f* and *f–f* opacity sources relevant to *B–A–F* atmospheres of main sequence stars included in the code. In addition 16 strongest Balmer lines are included. Their profiles in ATM74 are computed as a schematic convolution of thermal and natural profiles with quasistatic Stark broadened profiles, the latter ones given by Edmonds et al. (1967).

Detailed calculations of the Balmer line profiles and their equivalent widths were done with an independent computer program LINE 2 (for details see Madej, 1983a). This code performs an accurate convolution of line opacity broadening profiles, with effects of pressure broadening taken again from Edmonds et al. (1967).

We have also written a new code in order to investigate profiles and equivalent widths of neutral helium lines arising from transitions between triplet terms of He I: $\lambda 4026.2$ Å ($2^3\mathrm{P}^0$–$5^3\mathrm{D}$), $\lambda 4471.5$ Å ($2^3\mathrm{P}^0$–$4^3\mathrm{D}$), and $\lambda 4120.8$ Å ($2^3\mathrm{P}^0$–$5^3\mathrm{S}$). This was necessary for the determination of the variation of the helium abundance of the stars, for which variations of these lines were observed (56 Ari and CU Vir). Given a model atmosphere, this program accurately solves monochromatic radiative transfer equations for many frequency points inside the helium line profile using the Feautrier method (cf. Mihalas, 1978). The relevant subroutines are taken from ATM 74 and LINE 2. Atomic data on Stark broadening of these lines were taken from Dimitrijevic and Sahal-Brechot (1974), who computed both electron and ion impact widths and shifts for many He I lines. Pressure-broadened profiles were numerically convoluted with normalized radiative and thermal profiles. Data used for radiative damping computations were taken from extensive tables by Wiese et al. (1966). Our computations included also the effects of pressure shifts, hence the final line profiles are slightly asymmetrical. He I line profiles of all three lines were compared and tested with observational profiles published by Leckrone (1971).

3.2. *Influence of metal overabundance*

In order to study quantitatively the influence of the horizontal chemical inhomogeneities in atmospheres of Ap stars an β index, we used the results from the recent paper by Lester et al. (1986), who calculated β indices for the published and unpublished model atmospheres computed by Kurucz. It follows from this paper that for a given effective temperature β remains practically constant if $\log A$ increases from 0.0 to 1.0, where A is the abundance of the elements heavier than helium, relatively to the Sun. This result is valid for the whole range of T_{off} characteristic for Ap stars. We therefore conclude, that the increase of a metal content in the whole atmosphere does not affect the equivalent widths of Balmer lines.

The diffusion model of magnetic Ap stars (Michaud et al., 1981), predicts that overabundances of metals are formed in the uppermost layers of the atmosphere. In order to investigate the influence of such a stratification of metal concentration on Balmer lines, we calculated a model atmosphere in radiative equilibrium with the following parameters: $T_{\text{eff}} = 13000$ K, $\log g = 4.0$, $\log A_{\text{tau}<0.1} = 2$, $\log A_{\text{tau}>0.1} = 0$. Then the Balmer line profiles were computed for this model. The resulting β index turned out to be smaller than β from the homogeneous solar composition model with the same T_{eff} and $\log g$ by the amount 0.025 mag. At the same time the continuum flux at $\lambda 7650$ Å was increased compared to the homogeneous model by 0.09 mag. The obtained change of β is in an approximate agreement with observed amplitudes of β variations (cf. Tables 1 and 2). Also the relation between the increase of continuum flux at $\lambda 7650$ Å and decrease of β agrees well with observations.

Our model results, quoted above, and those of Lester et al. (1986) were performed under the simplified assumption, that the increase of metal contents in atmospheres applied uniformly to all elements heavier than helium. However, Peterson (1970) shows that variations of silicon abundance (with abundance of other metals kept at solar values) can also cause significant response in light and Balmer lines.

The assumption that some chemical inhomogeneities exist in the atmosphere of an Ap star can therefore explain the phase relations between light and β index in most of the observed stars. The disadvantage of the model is that it cannot explain the observed variations of the β index in the case of two short period Ap stars 56 Ari and CU Vir.

3.3. *56 Ari and CU Vir*

The Ap stars 56 Ari and CU Vir exhibit a significant shift between phase of minimum β and phase of maximum light at wavelengths longer than the "null wavelength". Both stars have well determined periodic variations of hydrogen, helium and silicon lines, and good photometric observations exist in the literature. They have almost the same effective temperature equal to 13000 K – Adelman (1983), and Pyper and Adelman (1985) for 56 Ari and CU Vir, respectively. Both stars exhibit maximum intensity of neutral helium lines at phases of minimum light (Peterson, 1966); Shore and Adelman, 1976; Aslanov and Khokhlova, 1972) for 56 Ari and Peterson (1966), Khokhlova and Riabchikova (1970), Hardorp and Megessier (1977), and Pedersen (1978) for CU Vir.

The presence of such phase shifts between the β index on one side and light and He I line curves on the other, makes it impossible to explain observed variations of β index as a consequence of variation of the observed chemical composition during rotation.

Nevertheless, we have calculated the effect of variable helium contents on the β index curve. First, we have determined variations of the $N(\text{He})/N(\text{H})$ ratio on the basis of observations of equivalent width variations of neutral helium lines ($\lambda 4026$ Å and 4472 Å), published by Peterson (1966), Shore and Adelman (1976), Aslanov and Khokhlova (1972) for 56 Ari, and Peterson (1966), Khokhlova and Riabchikova (1970), Hardorp and Mégessier (1977), and Pedersen (1978) for CU Vir, and calculated equivalent widths of helium lines in models with different helium and metal contents. Metal abundance for the phase of minimum light (maximum He I lines) was assumed to be solar, whereas for other phases it was calculated from an increment of flux in V band (for CU Vir) and DR band (for 56 Ari), assuming that light variations in these photometric bands are caused solely by variations of a metal content over the stellar surface. The observed helium content $N(\text{He})/N(\text{H})$ in 56 Ari varies between 0.01 at phase of maximum light, and 0.10 at minimum light. In case of CU Vir, the corresponding limits are 0.01 and 0.15. Our abundance determinations agree very well with the results by Khokhlova (1972) for CU Vir (<0.01, 0.15) but differ slightly from results by Aslanov and Khokhlova (1972) for 56 Ari (also <0.01, 0.15).

On the basis of our model calculations we determined the variations of the β index caused by the variations of $N(\text{He})/N(\text{H})$ ratio in CU Vir and 56 Ari. Expected amplitudes of variations are equal to 0.011 and 0.009 mag for CU Vir and 56 Ari, respectively, with maximum of β at the phase of minimum light. After subtraction of the calculated β index curves from the observed ones, the maxima of β curves of both stars shifts by Δ (phase) $\simeq 0.1$ to higher values, whereas amplitudes practically do not change.

We also examined the influence of variations of silicon lines lying near Hβ on the β index for both stars. Silicon lines are the only known variable metallic lines in these stars. From the list of Shenstone (1961) we have selected all (13) Si II lines, which lie near Hβ line (± 70 Å). For 12 of them we have found or estimated gf values. Then we have calculated spectrum around Hβ including 12 Si II lines with Si/H ratio equal to 300. Such a value was obtained by Krivosheina et al. (1980) for the two strongest Si spots on CU Vir. Influence of Si II lines on the β index was not larger than 0.001 mag, which is negligible as compared with the observed variations of the β index in CU Vir or 56 Ari.

3.4. *Impact of the electromagnetic forces*

Let us suppose, in contrast to Sect. 3.2, that the chemical composition in the atmosphere of a magnetic star remains uniform horizontally as well as vertically. However, strongly magnetized plasma in the presence of electron pressure gradients generates non-zero electric currents (Spitzer, 1956). As a result magnetic field deviates from the force-free configuration, and this alters both hydrostatic and radiative equilibrium in stellar atmosphere (Woltjer, 1971; Rakosch et al., 1974). Consequently, the appearance of the whole spectrum and particular lines emitted from a given surface element becomes a function of the local electric current density. Given the configuration of electric currents over a magnetic star surface, one can obtain periodic spectral variations of the star while it rotates.

There exist only few selfconsistent numerical models relevant to this approach (Stepien, 1978; Madej, 1978 and 1983a), where model stellar atmospheres modified by the assumed electric currents have been constructed.

The paper by Madej (1983a) gives computed predictions on the variability of the Balmer lines in a model with $T_{\mathrm{off}} = 12000$ K, $\log g = 4.0$ and $N(\mathrm{He})/N(\mathrm{H}) = 0.01$. Surface integrations have been performed in many points inside $\mathrm{H}\beta$–H_5 line profiles, yielding phase variations of total equivalent widths of these lines. In case of $\mathrm{H}\beta$, this allowed to reproduce variations of the equivalent width approaching 8 percent, either in form of single- or double-wave (depending on aspect angles), with maximum (maxima) at phase (phases) of best visibility of the magnetic pole (poles). The calculated amplitude correspond roughly to $\Delta\beta$ equal to 0.02 mag (cf. analysis of 73 Dra by Madej, 1983b). In all theoretical models maximum of β occurs at phase of best visibility of the magnetic poles, and at phase of minimum light at wavelengths larger than "null wavelengths". This conclusion does not depend on geometry of the problem. The correlation between the phases of photometric, Balmer line and magnetic field extrema, predicted by this model agrees with these observed.

One should note, that the above models have been computed under rather strong assumptions, that the stratification of electric currents is highly symmetric i.e. currents flow only in an azimuthal direction. Moreover, the resulting total magnetic field of the model star has been assumed to be dominated by its dipole component. It is possible, that in more realistic situations the dynamical effect of electric currents on the atmosphere (proportional to vector product $\vec{j} \times \vec{B}$) will not necessarily exhibit such azimuthal symmetry. Since the effect can depend on depth in the atmosphere, all three calculated phase curves: effective magnetic field, β, and light, can exhibit phase shifts as in CU Vir and 56 Ari.

Perhaps it is not accidental, that such phase shifts occur in the two stars with the shortest rotational periods. We can speculate, that rapid rotation enforces asymmetries in both magnetic field and electric currents stratification.

4. Concluding remarks

This paper summarizes an extensive set of new photometric β measurements vs. rotational phase of many Ap stars, appended by data selected from the literature. We conclude, that variability of the $\mathrm{H}\beta$ and other Balmer lines with phase is common among Ap stars, but is rather undetectable with the classical spectrographic techniques, except in some of the most prominent cases. For the majority of stars we found that light and β index curves or variations of Balmer line equivalent widths are in antiphase relative one another. Two short period Ap stars 56 Ari and CU Vir do not satisfy this correlation.

We made an attempt to explain the variability of Balmer lines with the existing models of Ap star variability. We conclude the following:

1. Chemical inhomogeneity over the surface of an Ap star can explain both observed amplitudes of Balmer line variations as well as the phase relationship between β index and light variations observed in all but two Ap stars investigated. The effect is strongly dependent on details of assumed chemical composition and its vertical stratification.
2. Such models cannot explain the observed shift between light and β variations in the case of 56 Ari and CU Vir, even after correction of the observed β variability for variations of $N(\mathrm{He})/N(\mathrm{H})$ ratio (a significant effect), and for the impact of silicon lines lying near $\mathrm{H}\beta$ on its line profile (a negligible effect).
3. We argue, that some special stratifications of electric currents in the atmosphere can also explain the observed β variations in Ap stars, including those in 56 Ari and CU Vir.

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