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ASTRONOMY AND ASTROPHYSICS

High Resolution Profiles in A-type Stars

II. Vega Ca II H and K Lines Observed at the Meudon Solar Tower

R. Freire[1], J. Czarny[2], P. Felenbok[2] and F. Praderie[1].

[1] Institut d'Astrophysique 98 bis, Bd Arago, F-75014 Paris, France
[2] Observatoire de Meudon, DAPHE, Group de Recherches 24 du CNRS, F-92190 Meudon, France

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Summary. Using the Meudon Solar Tower in a spectrographic study of A-type stars, we recorded, in 1975 and 1976, six H and K Ca II profiles of Vega (AO V) with a spectral resolution between 35 and 60 mÅ.

Within the error bar, all K line profiles are symmetrical, there is no emission in the core in either H or K.

A nLTE analysis of K line profiles gives a Ca abundance of Ca/H$=1.10^{-6}$ for a rotational velocity of v sini$=18$ km s^{-1} and a microturbulence $\xi=1$ km s^{-1}.

The K line profiles in Vega, as well as the previously published profiles of Sirius (A1 V) and γ Gem (AO IV), place an upper limit on the continuum optical depth of any chromosphere that these stars may possess.

Key words: high spectral resolutions — A stars — chromospheres

I. Introduction

A preceding article (Freire et al., 1977; here in after called Paper I) presented a research program on chromospheric indicators in A-type stars, based mainly on high spectral resolution study of selected strong lines. Observations of the Ca II K line profiles of two binary early A-type stars (α CMa, γ Gem) were discussed. This paper reports observations of the H and K line of Ca II in Vega (α Lyr, HR 7001, type AO V). Vega is a single star. Its projected rotational velocity is a little higher than that of α CMa and γ Gem (18 km s^{-1}, instead of 10 or 12 km s^{-1}, see references below and Paper I), a circumstance that increases the difficulty of detecting small emissions in the core. We decided to repeatedly observe Vega, also with the intent to confirm the emission reported in the H line by Linsky et al. (1973), using the scanner at KPNO Solar Tower.

We describe in this paper the observations obtained with the Meudon Solar Tower and we restrict the interpretation to the K line, which, in the Ca II resonance doublet, is the stronger and unblended component.

Send offprint requests to: R. Freire

II. Observations

The characteristics of the instrument (telescope, spectrograph) of the Solar Tower and the reduction of the data were described in Paper I.

The H and K lines were recorded in the 6th order, with a dispersion of 0.82 Å/mm in the focal plane. Kodak IaO plates were used during these observations. The spectral resolution lies between 35 and 60 mÅ.

Table 1 is the log of observations of the H and K lines in Vega. We analyse only those profiles with a good signal to noise ratio.

The selected plates were reduced using the PDS computer-controlled microphotometer of Nice Observatory (CDCA). Additional scans of the thorium comparison spectrum were made to determine the instrumental profile.

Various sources of errors (instrumental, observational or statistical) are discussed in Paper I. For a single spectrum the combined effect of the statistical error and of the error introduced by the characteristic curve is of the order of 15% (of the continuum) in the wings and 5% in the center of the lines. We located the continuum and the zero level as described in Paper I. The choice of the local continuum for the H and K lines is difficult as in the A-type stars the Balmer lines contribute to the continuum. For each observation, we have drawn by eye the local continuum as the envelope of the more intense windows; on each plate the spectrum extended over about 14 Å.

a) Ca II H *Line*

One must note that the Ca II H line (Fig. 1) which is weaker than the K line, is a rather weak blend in the strong Hε line. Six different observations of the Ca II H line in Vega do not reveal emission features (Fig. 2) within the 5% error bar and we do not confirm the

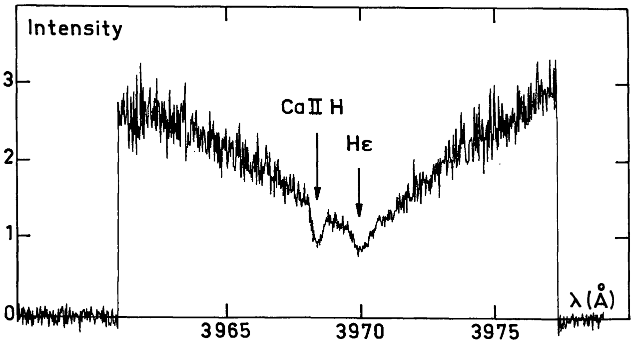

Fig. 1. The observed flux in the Ca II H line ($\lambda=3968.47$ Å)+Hε blend; July 30, 1975; arbitrary units

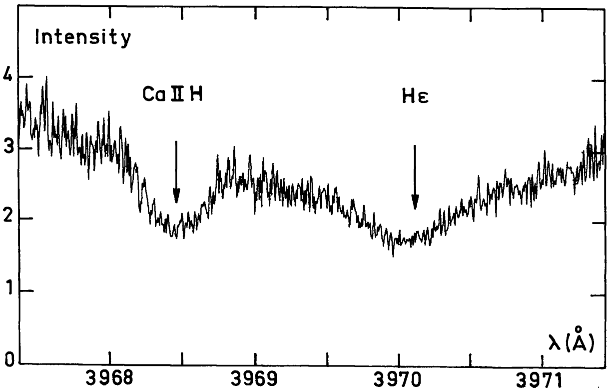

Fig. 2. Details of 1: cores of the blend

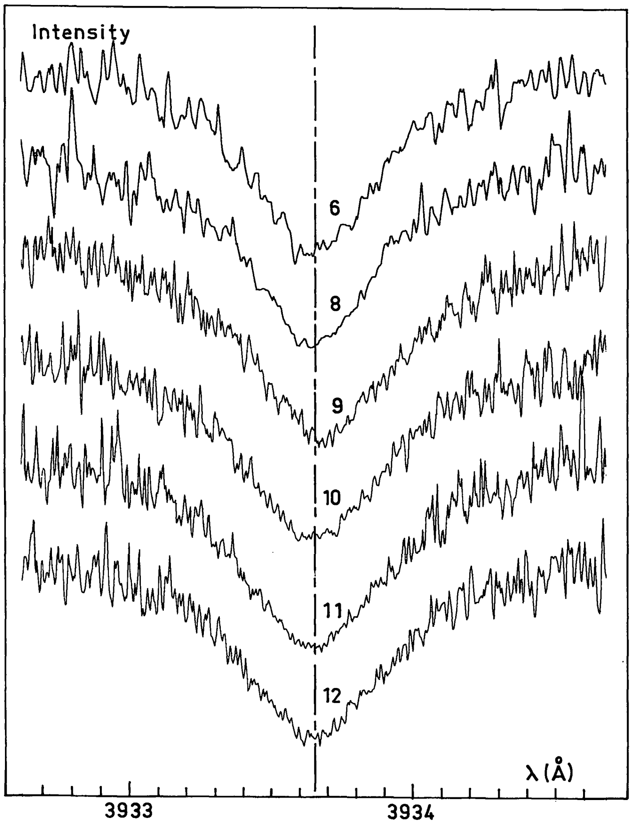

Fig. 3. Individual spectra of the Ca II K line ($\lambda=3933.67$ Å); arbitrary units in intensity. The serial number on each spectrum refers to the index given in Table 1

Table 1

Index	Date	Observation time (UT)	Line	Slit width (μ)	FWHM (mÅ)
1	Oct. 9, 74	17:30–23:00	H	400	50
2	Oct. 21, 74	17:30–23:00	H	400	50
3	Dec. 10, 74	16:45–17:45	H	400	54
4	Dec. 11, 74	16:45–17:45	H	400	54
5	Jun. 26, 75	21:50–22:50	H	400	60
6		23:00–24:00	K	400	60
7	Jul. 30, 75	20:46–21:46	H	200	40
8		21:53–22:53	K	200	40
9	Aug. 26, 76	20:15–21:15	K	200	35
10		21:30–22:30	K	200	35
11	Sept. 20, 76	19:45–20:45	K	200	35
12		20:54–21:54	K	200	35

presence of emission as it was claimed by Linsky et al. (1973). In addition, the Ca II H line in Sirius as reported in Paper I, does not show any emission.

b) Ca II K Line

The six raw profiles presented on Figure 3 do not show any discrepancy within an error bar. By difference with the observations of Paper I, asymmetries and bumps keep within the uncertainty. For this reason we adopted the mean profile (Fig. 4) which does not present any emission or asymmetry. On the mean profile, the total error bar is 10% of the continuum in the wings and 5% of the continuum in the core.

III. Theoretical Profiles: The K Line

We have compared the observations of the Ca II K line with nLTE theoretical profiles, using a model atom with three levels and a continuum, as in Paper I.

We also have studied the modifications in the line source function S_L and in the departure coefficients b_i when one increases the number of bound levels in the Ca II atom from 3 to 5.

1. Model Atmospheres and UV *Continuous Energy Distributions*

We used the following models:

i) LTE, radiative equilibrium (RE) model (Schild, Peterson and Oke, 1971), extended out to $\tau_c(5000)\simeq 10^{-9}$ by a RE temperature plateau; its basic parameters are $T_{\rm eff}=9650$ K, $\log g=4.05$. The minimum temperature $T_{\rm min}$ is 7450 K.

ii) nLTE, RE model in pure hydrogen (Frandsen, 1974); $T_{\rm eff}=10000$ K, $\log g=4$. In this model, a radiatively induced temperature rise occurs above $\tau_c(5000)=4.10^{-4}$ and reaches 1300 K at maximum over $T_{\rm min}$ ($T_{\rm min}=7350$ K).

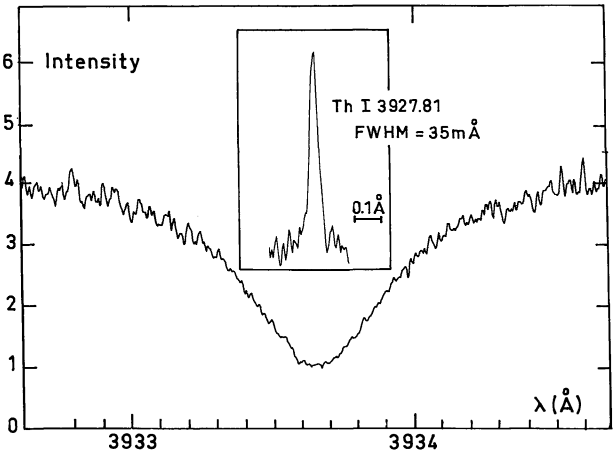

Fig. 4. Mean adopted Ca II K line profile. The inset diagram shows a Thorium I comparison line profile ($\lambda = 3927.81$ Å)

iii) Simulated chromospheres, containing a hot temperature plateau connected to the photosphere by a linear T versus geometrical altitude h relation. The plateaux are located either at 10000 K, or 15000 K, or 20000 K, and all start at the same value of h. A first set of such models (denoted by Chr 1) extrapolate the radiative temperature rise of Frandsen's model, therefore the start of the temperature increase is $\tau_0 = \tau_c(5000) = 4\,10^{-4}$. He/H was kept zero, as in model ii).

A second set (denoted by Chr 2) mimicks what we call a "deep chromosphere": here $\tau_0 = \tau_c(5000) = 10^{-3}$ for the onset of the temperature outer rise. Here too, He/H = 0.

Model i) reproduces satisfactorily the visible energy distribution in α Lyr (it was built so that this criterium is fulfilled), and also the continuous UV flux observed by TD 1 (Jamar et al., 1976) to within 10% (Fig. 5). We note that the TD 1 observations (λ 1350–2550 A, 36 A resolution) exhibit a spectrum slightly depressed by the effect of line absorption. In the figure, error bars indicate the absolute uncertainty on the observations.

The continuous opacities used in our calculations are H I, H^-, He I, H_2^+, the Stark wing of Ly α (Vidal et al., 1973), the H+H resonance broadening (Praderie, Stecher, 1973), the Rayleigh scattering by H and H_2, and metallic opacities due to neutral C, Si, Mg, Al, Fe. Helium abundance is taken to be 0.1. The energy distribution corresponding to model i) has been computed in LTE, with abundances of C and Si derived elsewhere (Freire, 1977) for α Lyr: $C/H = 2.10^{-4}$, $Si/H = 3.10^{-5}$. The UV spectrum exhibited on Figure 5 is mainly of deep photospheric origin, as witnesses Figure 6, on which $\tau_c(5000)$ corresponding to $\tau_c(\lambda) = 2/3$ is plotted for λ larger than 1250 A, and model i). The LTE approximation in the UV is shown to be acceptable by the agreement between the observations and our computations. A more detailed analysis of a specific absorber, C I, due to Snijders (1977), shows that the photoionization of

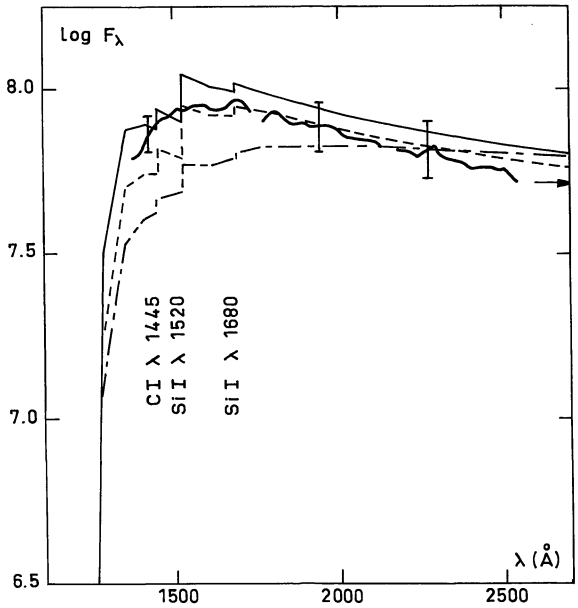

Fig. 5. Comparison of UV observations and the continuum computed with various models. Flux is normalized at $\lambda = 5556$ Å (its value is depicted by an arrow). In ordinate is the flux radiated at the star (erg cm^{-2} s^{-1} Å^{-1}) in the Schild et al. model scale.——— TD 1 S 2/68 experiment (Jamar et al., 1976); ——— Schild et al. (1971) model; ----- Frandsen's (1974) model; –·–·– Simulated chromosphere of type Chr 2: plateau at 10000 K, $\tau_0 = 10^{-3}$

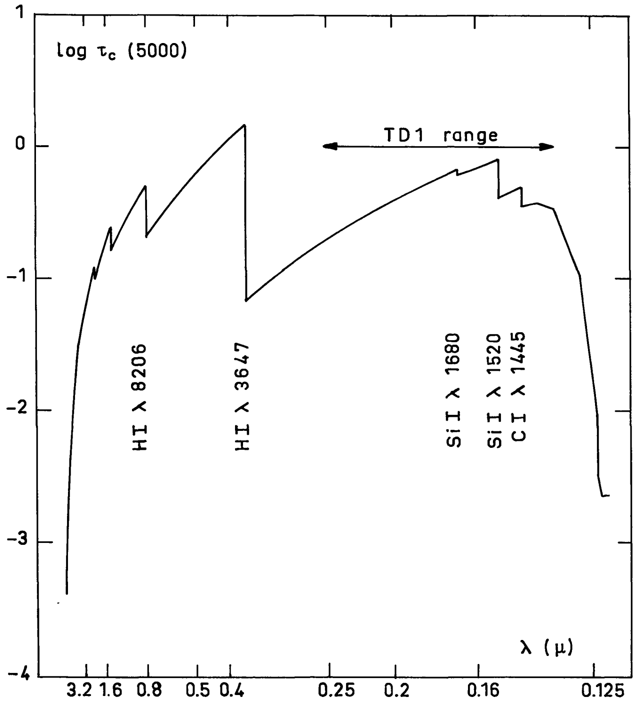

Fig. 6. Depth of formation of the continuous radiation for Schild et al. model. τ_c (5000) corresponds at each λ to $\tau_\lambda = 2/3$

this atom can be treated in LTE from the second excited level on (i.e. $\lambda > 1239$ A).

Frandsen's model shall be considered as a schematic one, because it was not specially built to match the star Vega. Whatsoever, it allows to predict a UV energy dis-

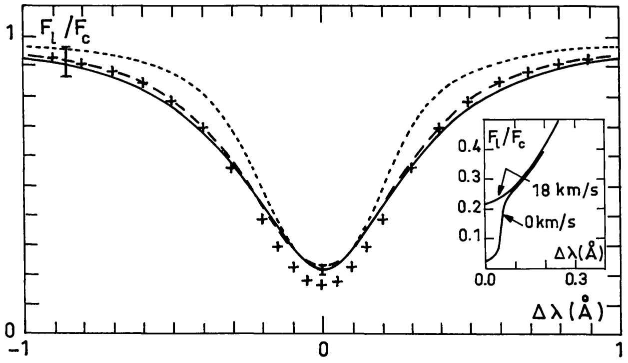

Fig. 7. Comparison of observed and computed profiles for the K line. The model used is due to Schild et al. (1971). ——— Reduced data after smoothing (6 observations); ..... nLTE calculations: Ca/H $=5.(-7)$; $\xi=3$ km s^{-1}; ------ nLTE calculations: Ca/H$=1.(-6)$; $\xi=0$ km s^{-1}; ++++++ nLTE calculations: Ca/H$=1.(-6)$; $\xi=3$ km s^{-1}. The inset diagram shows the core for Ca/H$=1.(-6)$, $\xi=1$ km s^{-1} with and without rotational broadening

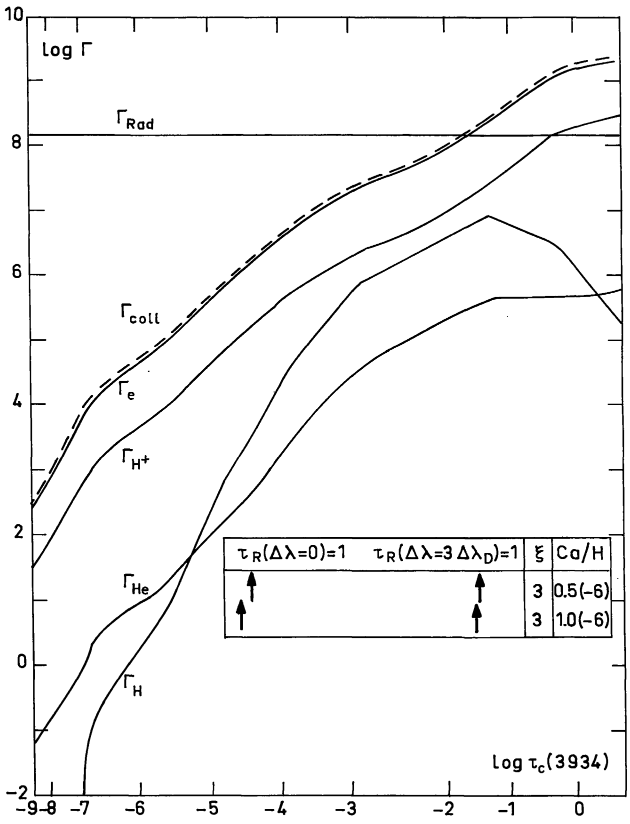

Fig. 8. Broadening parameters versus continuum optical depth (at $\lambda=3934$ Å) for Schild et al. model. Γ_{coll} designates $\Gamma_e+\Gamma_H+\Gamma_{He}+\Gamma_{H^+}$ All Γ's in s^{-1}. Arrows indicate line optical depth=1 for $\Delta\lambda=0$ and $\Delta\lambda=3\,\Delta\lambda_D$ for two Ca abundances

tribution and Balmer discontinuity D_B which are not inconsistent with the observations (Fig. 5); so do our simulated chromospheres Chr 1 (see Table 2). In the latter computations, the continuous spectrum is still computed in LTE, except for H I; but, as explained in Paper I, we did not solve the hydrogen ionization equation to build these simulated chromospheres and simply adopted at each altitude the H I departure coefficients b from Frandsen's model. Due to this approximation, we do not consider it meaningful to give the D_B values computed for simulated chromospheres with plateaux at 15000 K or 20000 K. Note that D_B listed in Table 2 is simply log (F_{3647}/F_{3647^-}); the observed value due to Divan (1966) is to be slightly increased (+0.010 to +0.015) due to a revision in the zero of the absolute scale (Divan, private communication).

The simulated "deep" chromospheres, on the contrary, are no more able to predict neither a Balmer discontinuity compatible with the observations, nor the general slope of the flux in the TD 1 region (Fig. 5). We will comment more on this key point after having computed the K line profiles.

Table 2. UV continuum and Balmer discontinuities

Model	Maximum of UV flux	$\tau_c(5000)$ for $\tau_\lambda=2/3$ at 3647^-	D_B
i) RE, LTE (Schild et al., 1971)	1520^+	0.068	0.555
ii) RE, nLTE (Frandsen, 1974)	1520^+	0.068	0.566
iii) Simulated chromospheres			
Chr 1 10000, 10^{-4}	1520^+	0.069	0.566
Chr 2 10000, 10^{-3}	2071	0.063	0.484

Observed value of D_B for α Lyr: 0.530 (Divan, 1966)

2. *The Computed* nLTE *Profiles, with Schild et al.* RE *Model*

The computational method has been described in Paper I. The calcium abundance Ca/H and the microturbulence parameter ξ are adjusted until the observed profile is fitted. The theoretical profiles are also convoluted with a rotational broadening function following Unsöld (1955), with $v\sin i=18\pm2$ km s^{-1}, as determined by Milliard et al. (1977).

The best agreement between observed and calculated (3 levels+continuum) profiles has been obtained with Ca/H$=1.10^{-6}$ and $\xi=1$ km s^{-1} (Fig. 7). Actually, on Figure 7, profiles have been plotted for $\xi=0$ km s^{-1} and $\xi=3$ km s^{-1}. The latter value is taken from an LTE analysis of equivalent widths in α Lyr, due to Hunger (1960). We checked that the LTE equivalent widths of the K line is only slightly modified when computed either with $\xi<3$ km s^{-1} or with $\xi=3$ km s^{-1}, for the same value of Ca/H. In the case $\xi<3$ km s^{-1}, the theoretical profiles are deeper and narrower in the core than when $\xi=3$ km s^{-1}; after rotational convolution, the profiles calculated with $\xi=0$ or 1 km s^{-1} lie higher than when $\xi=3$ km s^{-1}; this is caused by the fact that the core is narrower in the first case.

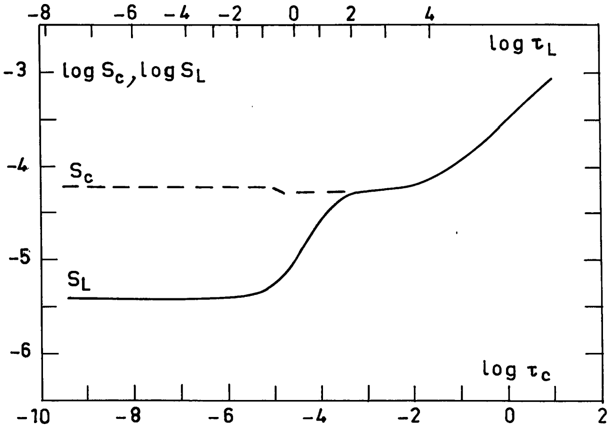

Fig. 9. Source function in the continuum (S_c) and in the line (S_L) for Schild et al. model. τ_c is computed at $\lambda = 3934$ Å

Complete redistribution has been assumed at all frequencies in the K line source function, on the following grounds: the radiative width of the upper level is larger than the sum of all other collisional widths only in the region of core formation ($\Delta\lambda \leqq 3\Delta\lambda_D$) for the values of Ca/H used (Fig. 8); but at $\Delta\lambda \leqq 3\Delta\lambda_D$, ν-independence of S_L is insured by the Doppler distribution of atomic velocities (Thomas, 1957).

With the RE stellar atmosphere model used, a small shoulder appears in the profiles computed without rotation; it is situated 0.12 A from the center, but it disappears completely in the profile convoluted with $v \sin i \neq 0$ (Fig. 7, inset diagram). The inner core of the line is formed in a quasi isothermal medium, i.e. in the region of the RE temperature plateau (see the run of $S_c = B_\nu(T_e)$ on Figure 9 for that model). One notices on Figure 9, where τ_L denotes the line central optical depth, that the line source function S_L joins S_c at $\log \tau_L \simeq 2$, and that S_L and S_c are within the temperature plateau from log $\tau_L \simeq 2$ to $\log \tau_L \simeq 3$; it is this region which forms the shoulder in the theoretical profile, and as it is little extended, the shoulder is rather shallow.

3. *The* Ca *Abundance*

We now discuss briefly the abundance values found in the literature, and our value of Ca/H, obtained with the Schild et al. model (Table 3). The nLTE calculation gives an abundance which is higher than our LTE one, which was chosen to fit the line wings (and not the core) of the K line; it follows that our LTE abundance is lower than that determined by other authors, which adjusted the equivalent widths, and not the line wings, as here.

The departure coefficients (Fig. 10a) verify $b_1 < 1$ and $b_1/b_3 > 1$ in the formation region of the K line central part, a case where one cannot unambiguously predict a priori how the nLTE abundance differs from the LTE value (Freire, Praderie, 1974). The same discussion as in Paper I applies to the uncertainties affecting the Ca abundance derived in nLTE; mainly the photoionization rates depend on lines modifying the radiation field in the far UV.

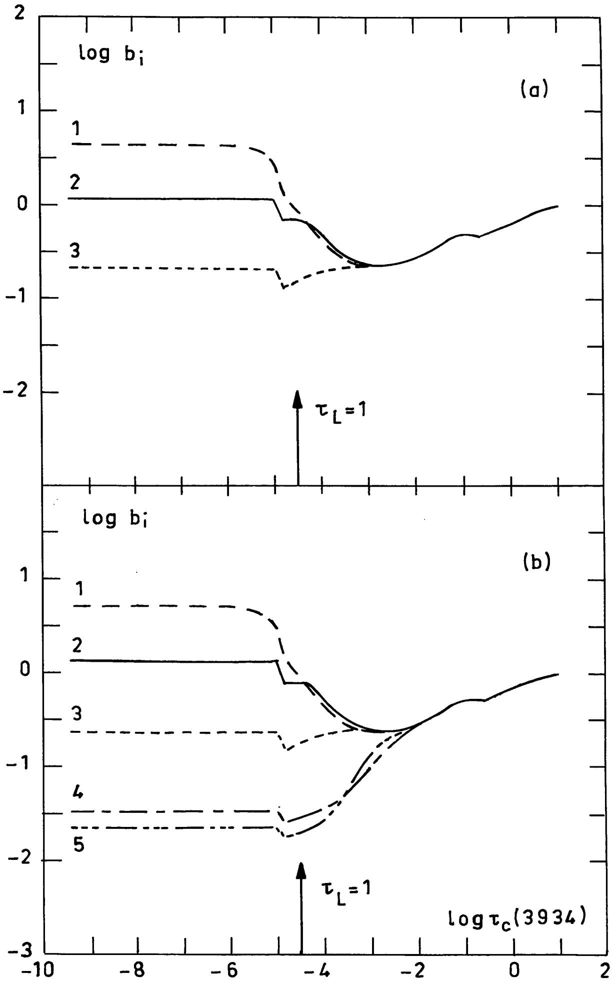

Fig. 10a and b. Departure coefficients for the population of levels in Ca II. τ_c is computed for $\lambda = 3934$ Å. **a** 3 level atom; **b** 5 level atom

Table 3

Ca/H[a]	Ion	Method[b]	Reference
2. (−6)	Ca I-II	W_{LTE}, CG	Hunger (1960)
0.5 (−6)	Ca I-II	W_{LTE}, CG	Strom, Gingerich, Strom (1968)
0.35 (−6)	Ca II	W_{LTE}, CG	Gehlich (1969)
0.2 (−6)	Ca II	LTE profile, wings adjusted	this work
1. (−6)	Ca II	nLTE profile	this work

[a] The notation 2. (−6) means 2 10^{-6}. In this work, C/H = 2 10^{-4}, Si/H = 3 10^{-5} for the computation of UV continuous opacity
[b] W_{LTE} = equivalent width computed in LTE; CG = use of curve of growth method

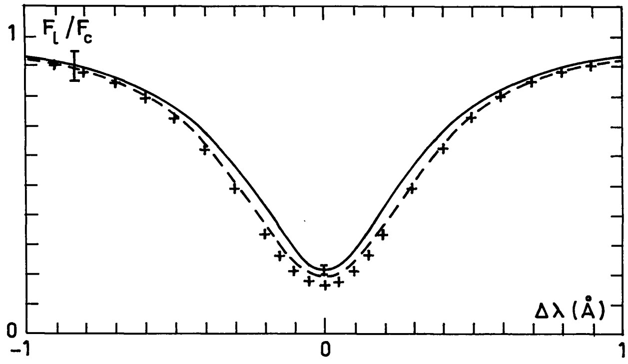

Fig. 11. Same as 7. The model used is due to Frandsen (1974)

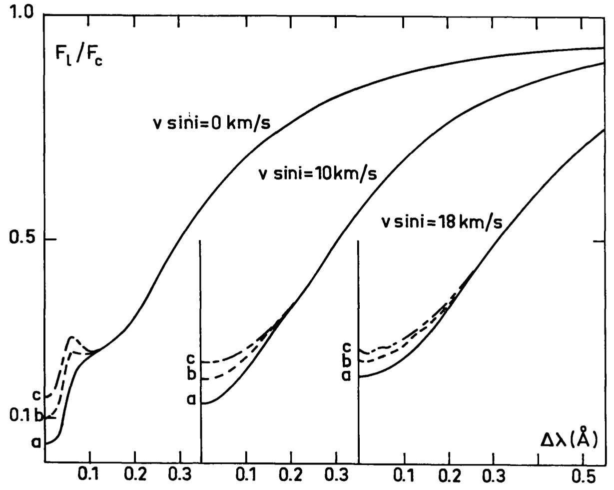

Fig. 12. Theoretical profiles of the K line for simulated chromospheres of type Chr 2. Ca/H=1 10^{-6}; $\xi=1$ km s^{-1}. Curves labelled *a, b, c* refer to temperature plateaux at respectively 10000 K, 15000 K, 20000 K

4. On the Sensivity of the Profiles to Temperature Rises in the Outer Layers

When using model (ii), i.e. a RE, nLTE atmosphere, one obtains theoretical K line profiles shown on Figure 11, for $\xi=0$ and $\xi=3$ km s^{-1}, Ca/H$=1.10^{-6}$. Recalling that Frandsen's model is not fitted to α Lyr, but has only about the same T_{eff}, one shall not look for a close agreement between the observations and those theoretical profiles in this case. What is noticeable is that the radiatively induced temperature rise is not "felt" by the profile while the depth for formation of the K line center is only slightly larger than in Schild et al. model ($\tau_c(3934)=3.6\ 10^{-5}$ instead of $2.8\ 10^{-5}$, in any case at smaller depth than T_{min}).

Simulated chromospheres of type Chr 1 (i.e. where T_e rises at $\tau_{5000}<4.10^{-4}$) all produce K line profiles nearly identical with those of Figure 11, which implies that if such a temperature structure exists in the outer layers of α Lyr, the K line does not allow to detect it.

Simulated chromospheres of type Chr 2 (i.e. where T_e rises at $\tau_{5000}<1.10^{-3}$), at the contrary, produce a self reversed K line core (Fig. 12); the emission in K_2 is larger when the temperature of the plateau increases from 10000 K to 20000 K. But one notes on the same Figure 12 that even a small $v \sin i$, like 10 km s^{-1}, suffices to mask these chromospheric emissions; with $v \sin i=18$ km s^{-1}, the central intensity when the chromospheric plateau is at $T_e=10000$ K has become the same as on Figure 11, and is equal to the observed value.

On the basis of the K line data above, we therefore cannot rule out the possible validity of "deep" chromospheric models. However, a comparison of the observed and predicted UV energy distribution and Balmer discontinuities shows that such models are unacceptable (Table 2). What occurs is that such models are more transparent in the Balmer continuum than models of type Chr 1; at the depth of formation of $\lambda\ 3647^-$ (violet side of Balmer discontinuity), the temperature is higher in Chr 2 than in Chr 1, for a same value of the plateau temperature. Therefore the Balmer continuum becomes a more sensitive criterium of the presence of a temperature reversal than is the K line, as already pointed in Paper I.

Therefore, from the present study, and mostly on the base of the UV energy distribution, we reject the possibility of deep chromospheres: but it is not excluded (see also Paper I) that chromospheres of type Chr 1 do exist in early A type stars.

5. Comparison of Profiles Obtained with Different Ca II *Model Atoms*

When one adds two more levels to the model atom, which now consists in $4s\ ^2S$, $3d\ ^2D$, $4p\ ^2P^0$, $5s\ ^2S$, $4d\ ^2D$, the change in the departure coefficients is as depicted by Figure 10: b_1, b_2, b_3 are slightly increased (by less than 10%), while the ratio b_3/b_1 is not changed in an appreciable way, nor the K line source function; therefore the effect on the theoretical profile (without rotation) is less than 1% of the continuum for $\Delta\lambda<0.1$ A, equal 3–5% of the continuum at larger $\Delta\lambda$.

IV. Summary and Conclusion

Very high spectral resolution profiles of H and K Ca II lines have been obtained for the single star Vega (AOV) with the Meudon Solar Tower.

The core of the K line does not show the presence of asymmetries: the differences between the profiles are always contained within the error bar; this establishes a difference between Vega and the stars Sirius, γ Gem and Altair (Freire et al., 1977).

The nLTE computation of the K line gives a new determination of the Ca abundance and of ξ: Ca/H $=1.10^{-6}$ and $\xi=1$ km s^{-1}. But, while we can assess that

ξ cannot be as great as 3 km s^{-1}, we cannot exclude that the atmosphere is fully stable in terms of small scale motions, and $\xi = 0$ km s^{-1} is as good a value for the microturbulence parameter, as is $\xi = 1$ km s^{-1}.

We confirm for Vega a result that has already been obtained in Paper I for two other early A-type stars: an increase in electronic temperature towards the exterior of the stellar atmosphere is compatible with the observations provided it begins at log $\tau_c(3934) < -4$. The K line provides no information on the possible existence of a chromosphere beginning above this height.

We shall recall here that rotation may suppress small chromospheric emission, an affect which constitutes an intrinsic difficulty in the detection of chromospheric phenomena in early type stars.

While early A-type stars may have a chromosphere, the present observations of the K line and of the UV continuum at $\lambda > 1350$ Å place an upper limit on its optical depth. As we shall show in a future paper (Freire, 1978), Copernicus observations of ultraviolet resonance lines (C II and Si II) that are formed further out in the atmosphere of Vega bring us to the same conclusion as that expressed above. Only the level of the continuum at $\lambda < 1200$ Å or a still stronger line than C II and Si II resonance lines (e. g. Ly α) may be indicators of chromosphere, and allow to separate chromospheres with different depths. It appears therefore to be very difficult at present to detect chromospheres in such stars.

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