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Ca isotopic anomaly in the atmospheres of Ap stars

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Abstract. We present results of the Ca stratification analysis in the atmospheres of 21 magnetic chemically peculiar (Ap) stars. This analysis was based on the spectral observations carried out with the UVES spectrograph attached to the 8-m VLT telescope. Ca was found to be strongly stratified in all stars with different effective temperatures and magnetic field strengths. This element is overabundant by 1–1.5 dex below $\log\tau_{5000} \approx -1$ and strongly depleted above $\log\tau_{5000} = -1.5$. Based on the overall Ca abundance distributions, we modelled a profile of the IR-triplet Ca II λ 8498 line. It shows a significant contribution of the heavy isotopes ^{46}Ca and ^{48}Ca, which represent less than 1% of the solar Ca isotopic mixture. In Ap stars with the relatively small surface magnetic fields ($\leq 4-5$ kG) the light ^{40}Ca isotope is concentrated close to the photosphere, while the heavy isotopes are pushed towards the outer layers. Isotopic separation disappears in the atmospheres of stars with magnetic fields above 6–7 kG. The observed overall Ca stratification and isotopic anomalies may be explained by a combined action of the radiatively-driven diffusion and the light-induced drift.

Key words: stars:atmospheres – stars: chemically peculiar – stars: magnetic fields – stars: abundances – process: diffusion – process: light-induced drift

1 Introduction

After the pioneering work by Michaud (1970) particle diffusion in stellar envelopes and atmospheres is considered as the main process responsible for the atmospheric abundance anomalies in the peculiar stars of the Upper Main Sequence. Detailed diffusion calculations performed for a set of chemical elements in the atmospheres of magnetic peculiar stars predicted an existence of abundance stratification. For a small number of elements, including Ca, an effect of the stratified element distribution on the spectral line profiles was demonstrated in early studies (Borsenberger at al. 1981), but the absence of high-resolution, high signal-to-noise spectroscopic observations did not allow the direct comparison between the observations and diffusion calculations. This step was carried out by Babel (1992), who calculated the Ca abundance distribution in the atmosphere of the magnetic star 53 Cam and showed that the unusual shape of Ca II K line – a sharp transition between the wide wings and extremely narrow core – is a result of a step-like Ca distribution with abundance decrease at $\log\tau_{5000} \approx -1$. Following Babel, the step-function approximation of the abundance distribution was commonly employed in many stratification studies based on the

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observed profiles of spectral lines (Wade et al. 2003; Ryabchikova et al. 2002; Ryabchikova et al. 2005; Ryabchikova et al. 2006).

Ca was found to be stratified the same way as in 53 Cam (enhanced concentration of Ca below $\log\tau_{5000} \approx -1$ and its depletion above this level) in all stars for which stratification analysis have been performed: β CrB (Wade et al. 2003), γ Equ (Ryabchikova et al. 2002), HD 204411 (Ryabchikova et al. 2005), HD 133792 (Kochukhov et al. 2006) and HD 144897 (Ryabchikova et al. 2006). Recently another Ca anomaly was detected, first in the spectra of HgMn stars by Castelli & Hubrig (2004) and then in Ap stars by Cowley & Hubrig (2005 - CH). These authors found a displacement of the lines of Ca II IR triplet due to significant contribution of the heavy Ca isotopes. CH merely noted the fact of the presence of heavy isotopes, but they did not perform any quantitative analysis. This was done by Ryabchikova, Kochukhov & Bagnulo, and the preliminary results were published in a review paper by Ryabchikova (2005). It was shown that the contribution of Ca heavy isotopes decreases with the increase of magnetic field strengths, and disappears when the field exceeds 3 kG.

In present study we give a detailed analysis of the Ca stratification in the atmospheres of magnetic Ap stars of different temperatures and magnetic field strengths with the application to a modelling of the IR triplet Ca II λ 8498 line.

2 Observations and data reduction.

Twenty-one slowly rotating Ap stars were chosen for the Ca stratification analysis. For all but two stars, HD 24712 and HD 66318, high-resolution, high signal-to-noise-ratio spectra were obtained with the UVES instrument at the ESO VLT in the context of program 68.D-0254. The UVES instrument is described by Dekker et al. (2000). The observations were carried out using both available dichroic modes. In both the blue arm and the red arm the slit width was set to $0.5''$, for a spectral resolution of about 80 000. The slit was oriented along the parallactic angle, in order to minimize losses due to atmospheric dispersion. Almost the full wavelength interval from 3030 to 10400 Å was observed except for a few gaps, the largest of which was at 5760-5835 Å and 8550-8650 Å. In addition, there are several small gaps, about 1 nm each, due to the lack of overlapping between the échelle orders in the 860U setting. Spectra of HD 24712, HD 66318 and HD 61421 (Procyon) were obtained with the same setting and were extracted from ESO archive. Due to the gaps in spectral coverage, only one line of the Ca II IR triplet, λ 8498.023 Å, could be observed in this UVES setting and is accessible for modelling.

The Ca IR triplet line studied overlaps with the hydrogen lines from the Paschen series. Due to the difficulties of continuum normalization at the edge of observed spectral region, we have employed theoretical spectrum synthesis to establish the correct continuum level. In this procedure observations around Ca II λ 8498.023 Å were adjusted, so that the pseudo-continuum of the Paschen line wings matches predictions of the theoretical spectrum synthesis.

The list of the program stars is given in Table 1. In addition, two stars, HD 27411 (A3m) and Procyon (HD 61421), were used as standards for the Ca isotopic study.

3 Model atmosphere parameters

Fundamental parameters of the program stars are given in Table 1. For most stars effective temperatures T_{eff} and surface gravities $\log g$ were taken from the literature (last column of Table 1). For HD 965, HD 47103, HD 118022, and HD 134214 atmospheric parameters were derived using Strömgren photometric indices (Hauck & Mermilliod 1998) with the calibrations by Moon & Dworetsky (1985) and by Napiwotzki et al. (1993) implemented in the `TEMPLOGG` code (Rogers 1995). For HD 75445, HD 176232, and HD 203932 effective temperatures were slightly corrected by fitting Hα

Table 1: Fundamental parameters of target stars.

HD number	$T_{\rm eff}$ (K)	$\log g$	$v_{\rm e}\sin i$ (km s^{-1})	$\langle B_{\rm s}\rangle$ (kG)	Reference
			Program stars		
217522	6750	4.30	2.5	$\leq$1.5	Gelbmann (1998)
122970	6930	4.10	5.5	2.5	Ryabchikova et al. (2000)
24712	7250	4.30	5.6	2.3	Ryabchikova et al. (1997)
134214	7315	4.45	2.0	3.1	this paper
965	7500	4.00	3.0	4.4	this paper
203932	7550	4.34	5.3	$\leq$1	Gelbmann et al (1997)
137949	7550	4.30	1.0	5.0	Ryabchikova et al. (2004b)
176232	7650	4.00	2.0	1.5	Ryabchikova et al. (2000)
75445	7650	4.00	3.0	3.0	Ryabchikova et al. (2004b)
166473	7700	4.20	0.0	8.6	Gelbmann et al. (2000)
29578	7800	4.20	2.5	5.6	Ryabchikova et al. (2004b)
128898	7900	4.20	12.5	1.5	Kupka et al. (1996)
116114	8000	4.10	2.5	6.2	Ryabchikova et al. (2004b)
137909	8000	4.30	2.5	5.4	Ryabchikova et al. (2004b)
47103	8180	3.50	0.0	16.3	this paper
188041	8800	4.00	0.0	3.6	Ryabchikova et al. (2004a)
66318	9200	4.25	0.0	15.5	Bagnulo et al. (2003)
133792	9400	3.70	0.0	1.1	Kochukhov et al. (2006)
118022	9500	4.00	10.0	3.0	this paper
170973	10750	3.50	8.0	0.0	Kato (2003)
144897	11250	3.70	3.0	8.8	Ryabchikova et al. (2006)
			Reference stars		
27411	7650	4.00	18.5	0.0	this paper
61421	6510	3.96	3.5	0.0	Allende Prieto et al. (2002)

profile. The mean surface magnetic fields $\langle B_{\rm s}\rangle$ were derived from the resolved and partially resolved Zeeman patterns. In all stars rotational velocities were estimated by fitting line profiles of the magnetically insensitive Fe I 5434.5 and 5576.1 Å lines. Model atmospheres were calculated with the ATLAS9 code (Kurucz 1993).

4 Ca stratification analysis

Before performing careful study of the IR Ca II λ 8498 line profile, we have to investigate Ca abundance distribution in Ap atmospheres. In all program stars Ca stratification was derived using a set of spectral lines in the optical region, for which no indication of the significant isotopic shifts exists. Atomic parameters of these lines, as well as the Ca II λ 8498 line, are given in Table 2. Stratification analysis requires high accuracy not only for the oscillator strengths but also for the damping parameters, because Ca has a tendency to be concentrated close to the photospheric layers where the electron density is high. In particular, it is important for Ca II lines. For Ca II $\lambda\lambda$ 3158, 3933, 8248, 8254, 8498 lines the Stark damping constants were taken from the paper by Dimitrijević & Sahal-Bréchot (1993), where semi-classical calculations as well as a compilation of the experimental data were presented. For the rest of the Ca lines the Stark damping constants calculated by Kurucz

(1993) were used. The oscillator strengths were taken mostly from the laboratory experiments, and they are verified by the recent NLTE analysis of calcium in late-type stars (Mashonkina et al. 2007). Because of the large range in effective temperatures and magnetic field strengths, we could not use the same set of lines for all stars.

Table 2: A list of spectral lines used for the stratification calculations. The columns give the ion identification, central wavelength, the excitation potential (in eV) of the lower level, oscillator strength (log gf), the Stark damping constant, and the reference for the oscillator strength.

Ion	Wavelength	E_i (eV)	log gf	log γ_{St}	Ref.
Ca II	3158.869	3.123	0.241	-4.90	Teodosiou 1989
Ca II	3933.655	0.000	0.105	-5.73	Teodosiou 1989
Ca I	4226.728	0.000	0.244	-6.03	Smith & Gallagher 1966
Ca II	5021.138	7.515	-1.207	-4.61	Seaton et al. 1994
Ca II	5339.188	8.438	-0.079	-3.70	Seaton et al. 1994
Ca I	5857.451	2.933	0.240	-5.42	Smith 1988
Ca I	5867.562	2.933	-1.57	-4.70	Smith 1988
Ca I	6122.217	1.896	-0.316	-5.32	Smith & O'Neil 1975
Ca I	6162.173	1.899	-0.090	-5.32	Smith & O'Neil 1975
Ca I	6163.755	2.521	-1.286	-5.00	Smith & Raggett 1981
Ca I	6166.439	2.521	-1.142	-5.00	Smith & Raggett 1981
Ca I	6169.042	2.253	-0.797	-5.00	Smith & Raggett 1981
Ca I	6169.563	2.256	-0.478	-4.99	Smith & Raggett 1981
Ca I	6449.808	2.521	-0.502	-6.07	Smith & Raggett 1981
Ca I	6455.598	2.523	-1.340	-6.07	Smith 1988
Ca II	6456.875	8.438	0.410	-3.70	Seaton et al. 1994
Ca I	6462.567	2.523	0.262	-6.07	Smith & Raggett 1981
Ca I	6471.662	2.526	-0.686	-6.07	Smith & Raggett 1981
Ca II	8248.796	7.515	0.556	-4.60	Seaton et al. 1994
Ca II	8254.721	7.515	-0.398	-4.60	Seaton et al. 1994
Ca II	8498.023	1.692	-1.416	-5.70	Teodosiou 1989

The Ca stratification analysis was performed using the step-function approximation of the abundance distribution (for details see Ryabchikova et al. 2005). In a few cases the step-function approximation can not provide an adequate description of the full set of spectral lines. The obvious reasons are the use of normal non-magnetic star atmosphere with homogeneous element distribution for a star with known abundance stratification, and a deviation of the abundance distribution from the simple step-function. In cooler stars the range of formation depth of the optical lines is different from the IR-triplet lines of interest, therefore Ca abundance in the upper atmospheric layers derived from the optical lines may be not accurate enough for the description of cores of IR lines. Also, continuum normalization in the IR lines region is indirectly based on the adopted effective temperatures, which may introduce significant uncertainty and sometimes lead to a poor fit in the line wings.

We start the analysis with the best homogeneous Ca abundance derived from a chosen set of spectral lines, and then vary parameters of the step-function until the adequate fit to the observed line profiles is achieved. Magnetic spectral synthesis code `SYNTHMAG`(Piskunov 1999; Kochukhov 2006) was used in our calculations. Fig. 1 displays the results of the stratification analysis for HD 176232 (10 Aql), where synthetic profiles calculated with homogeneous Ca distribution $\log(Ca/N_{\rm tot}) = -5.14$ are shown by the dashed line while those calculated with the stratified Ca distribution are shown by the full line. The derived Ca distribution is given in Fig. 2 (right panel). The stratified Ca abundance yields two times smaller standard deviation compared to the homogeneous Ca distribution.

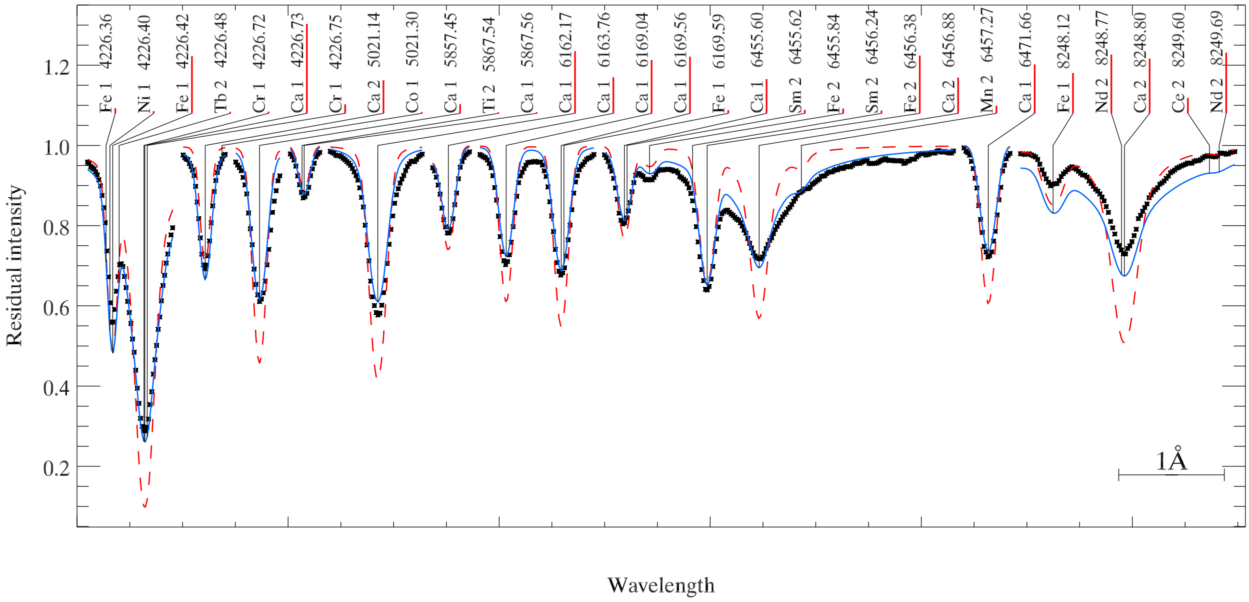

Figure 1: A comparison between the observed line profiles (dots) and calculations with the stratified Ca abundance distribution (full line) and with the homogeneous Ca abundance (dashed line) in HD 176232.

The same procedure was applied to all stars included in our sample. Ca distributions in the atmospheres of several stars are shown in Fig. 3. They are all characterized by an abundance jump in the region $-1.3 \geq \log \tau_{5000} \leq -0.5$, an 1–1.5 dex overabundance deep in the atmosphere and a strong Ca depletion above $log\tau_{5000} = -1.5$. It is difficult to say if there is any dependence on the effective temperature and/or on the magnetic field strength.

5 Ca isotopic anomaly

Ca has six stable isotopes, 40, 42, 43, 44, 46, 48, and in the solar-system matter Ca mixture consists mainly of ^{40}Ca (96.9 % — see Anders & Grevesse 1989). Table 3 gives wavelengths of all Ca isotopes following the isotopic shifts measured by Nörtershäuser et al. (1998) as well as the isotopic fractional oscillator strengths corresponding to the solar-system matter mixture.

With the solar-matter isotopic mixture we calculated Ca II λ 8498 line profile in the spectra of our reference stars Procyon and HD 27411 and compared them with the observations. Fig. 4 shows the results of this comparison. Although in the Procyon spectrum our LTE calculations cannot provide a very good fit, however, no wavelength shift was detected in both stars. At the same time, the observed profile of this line in the spectrum of our program star HD 217522 presented in Fig.4 has a complex structure and is clearly redshifted with the strongest component being at the position of the heaviest Ca isotope.

The core of the IR Ca II λ 8498 line is formed higher than any of the optical lines, except Ca II λ 3933. For most stars the Ca II λ 3933 line were not accounted in the stratification calculations,

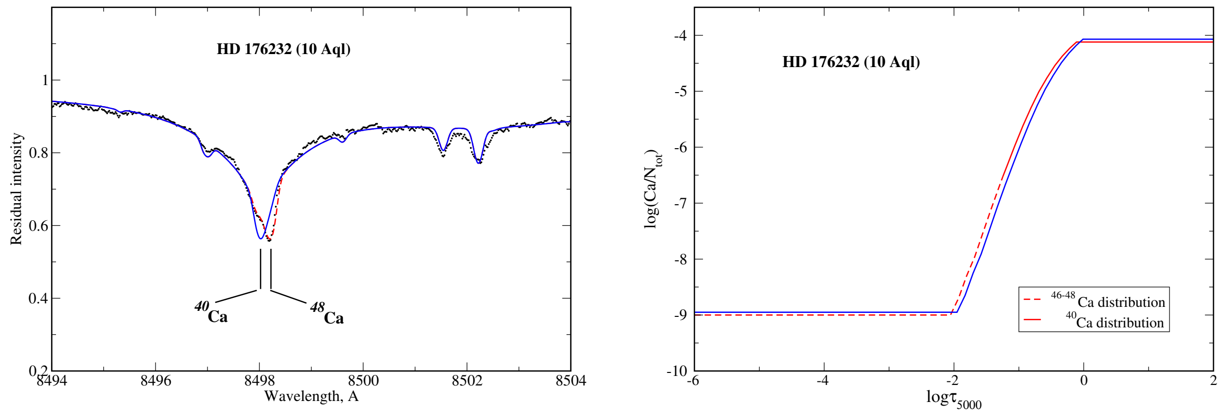

Figure 2: A comparison between the observed (filled circles) and synthetic line profiles of Ca II λ 8498 (left panel), calculated with Ca distribution shown in the right panel. Synthetic spectrum calculations with the solar-matter Ca isotopic mixture are shown by full line, and those with Ca isotopic separation as indicated in the right panel are shown by dashed line. Ca distribution derived from the optical lines is shown by the solid blue line in the right panel, while isotopic separation are shown by red line (dashed + solid). For illustration purpose two distributions are slightly shifted relative to each other.

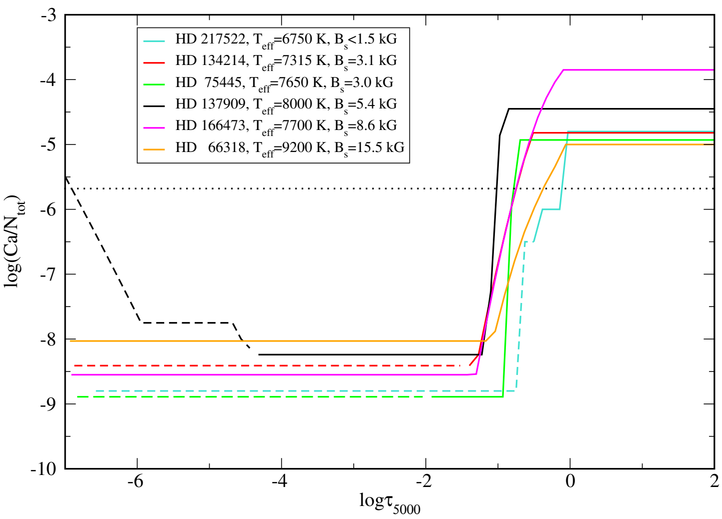

Figure 3: Ca abundance distributions in the atmospheres of a few stars with different effective temperatures and magnetic field strengths. Dashed line shows optical regions where ^{40}Ca is dominated, while the solid line indicates the regions of predominant ^{46}Ca and ^{48}Ca isotopes concentration. Solar Ca abundance is marked by dotted line.

therefore Ca abundance in the upper atmosphere may be rather uncertain, because all other optical lines are not sensitive to abundance variations above $log\tau_{5000} = -2.0$ to -2.5. The abundance in the upper atmosphere is defined by the slope of the abundance gradient in the jump region. If the Ap atmosphere is close to the normal ATLAS9 one (Kurucz 1993) adopted in our analysis, then Ca II λ 8498 line should be fitted with the Ca abundance distribution derived from optical lines. Our calculations show that while it is correct for the observed total intensity, in part of program stars we cannot fit the line cores, which are often redshifted. Fig. 2 (left panel, dashed line) shows a fit of synthetic spectrum calculated with the solar-matter Ca isotopic mixture and Ca abundance

Table 3: Atomic data for the isotopic components of Ca II λ 8498. The fractional isotope abundances ϵ correspond to the composition solar-system matter.

$\lambda, \AA$	isotope	$\log gf\epsilon$
8498.023	40	−1.43
8498.079	42	−3.60
8498.106	43	−4.29
8498.131	44	−3.10
8498.179	46	−5.81
8498.223	48	−4.14

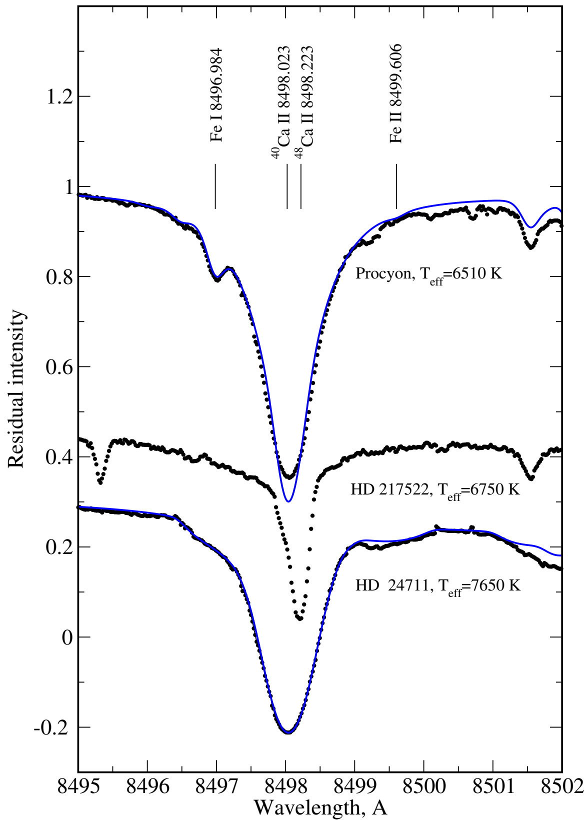

Figure 4: A comparison between the observed line profiles (dots) and the calculations with the solar-matter Ca isotopic mixture (full line) in the spectra of Procyon and Am star HD 27411. The observed spectrum of Ap star HD 217522 is in the middle.

distribution (right panel) to the observed spectrum of HD 176232. One immediately notices that while the line wings are fitted rather satisfactory, the line core cannot be fitted with the solar-matter Ca isotopic mixture. When we separate ^{40}Ca and ^{46}Ca, ^{48}Ca isotopes in the atmosphere as indicated in Fig. 2 (right panel), then we get a satisfactory agreement between the observed and calculated spectra (full line in the left panel of Fig. 2). Of course, it is a crude approximation, however it gives us direct evidence of the Ca isotopic separation in the atmospheres of Ap stars.

This procedure was applied to all stars of our program. Fig. 5 gives an example of our fitting

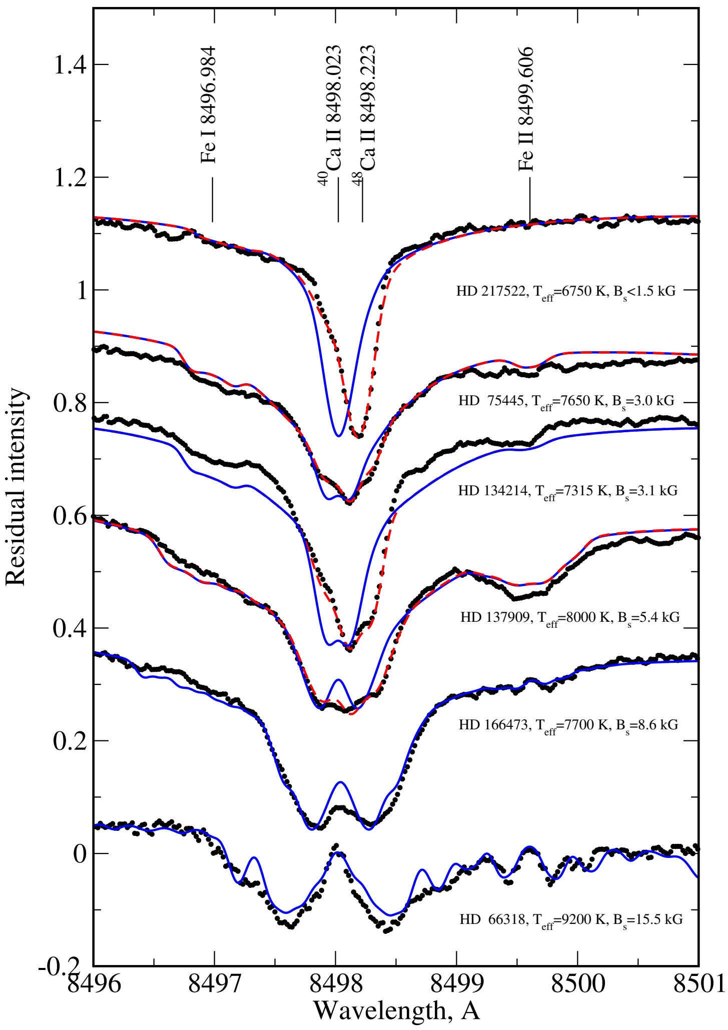

Figure 5: The same as in Fig. 2 (left panel) but for a set of program stars.

procedure for a subset of stars with different effective temperatures and different magnetic field strengths, and the corresponding Ca stratifications with the isotopic separation are shown in Fig. 3. In the stars with small to moderate magnetic fields we clearly see a significant contribution of the heavy isotopes ^{46}Ca and ^{48}Ca, and this contribution decreases with the increase of the magnetic field strength. Even in HD 137909 (β CrB) with the mean magnetic modulus $\langle B_{\rm s}\rangle$=5.4 kG one still needs a small contribution of ^{48}Ca, but under the assumption of very specific Ca distribution shown in Fig. 3. We have to introduce a rapid increase of Ca abundance in a thin upper atmospheric layer above $log\tau_{5000} = -5$. In principle, it does not contradict the theoretical Ca diffusion calculations. Both Borsenberger et al. (1981 — Fig. 6) and Babel (1992) obtained Ca abundance increase in the upper layers after the abundance jump. However, NLTE treatment of the Ca lines formation is needed to investigate the upper atmospheric layers.

The same results were obtained for other stars with similar magnetic field strengths: HD 965, HD 137949, HD 29578.

6 Discussion

If the overall distribution of Ca abundance in the atmospheres of Ap stars follows the predictions of the radiatively driven diffusion, our results on the isotopic separation favour the light-induced drift (LID) as the main process responsible for this separation. Indeed, according to Atutov & Shalagin (1988) LID arises when the radiation field is anisotropic inside the line profile. Such an anisotropy takes place for a line of the trace isotopes, ^{46}Ca, ^{48}Ca for instance, in the solar-matter mixture, which is sitting in the wing of a strong line of the main isotope ^{40}Ca, and the main isotope should induce the drift velocity for other isotopes. If we have a trace isotope's line in the red wing of the main isotope's line, then the drift velocity is directed from towards the upper atmosphere and the trace isotopes are pushed upwards. This is the case for the Ca isotopic structure. Zeeman splitting changes the line shape and decreases the flux anisotropy for a trace isotope's line. When magnetic field becomes strong enough, $\sim 4-5$ kG, then the flux anisotropy disappears and the isotopic separation is ceasing. Therefore, the observed Ca isotopic anomaly in magnetic stars may be qualitatively explained by the combined action of the radiatively-driven diffusion and light-induced drift.

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