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Measurements of multi-component magnetic fields in Herbig Ae/Be stars with FORS1 at 8m-VLT

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Abstract. We have investigated the magnetic fields of several Herbig Ae/Be stars separately for the stellar and circumstellar (CS) field components. The investigation is based on the low-resolution spectropolarimetric data collected in 2003–2005 at the ESO (Chile) with the multi-mode instrument FORS1 installed at the 8m-VLT. We have shown that the results of spectropolarimetry depend heavily on the level of CS contribution to stellar spectra. Stellar magnetic fields of about 100 G have been found in some programme objects at an accuracy level of 7 σ, when they were at a low-state stage of their CS activity. We have established that at high state of this activity all polarization indications of magnetic field relate mainly to the CS media. An analysis of the CS field component has confirmed that the magnetic field centrifuge is likely to be a principle mechanism of the stellar wind acceleration in Herbig Ae/Be stars.

1 Introduction

The Herbig Ae/Be stars (Herbig 1960) are now recognized to be pre-main sequence objects of intermediate mass (from 2 to 10 $M_{\odot}$). According to common views they are surrounded by CS envelopes of a complex structure. The envelopes contain an equatorial gaseous/dusty disk and a stellar wind zone at higher latitudes. The matter outflow from the Herbig Ae/Be stars is time-variable and spatially inhomogeneous, and signatures of a non-stable matter infall onto the star are frequently observed. Presently, our knowledge of the relation between these different processes is clearly lacking.

Numerous theoretical works predict the existence of a global magnetic field of a complex configuration formed as a result of interaction between the star and the accretion disk. Namely, such a field is very likely to be responsible for all observational peculiarities of the Herbig Ae/Be stars. For this reason, an investigation of the strength and the topology of the magnetic field can provide important information on the origin of activity in these objects.

Over an extended period all attempts to measure directly the magnetic field in the Herbig Ae/Be stars have been rather unsuccessful. On the one hand, this could be explained by the weakness of the magnetic field in these objects with strengths considerably lower than those in magnetic A-type stars or low-mass young T Tau-type stars. The accuracy of all previous measurements was not high enough to measure such weak fields. On the other hand, the observational strategy allowed determination of only the average value of magnetic field using a number of different spectral lines. Due to the complex spatial structure of the field, the measured value must depend strongly on individual lines used for the field determination, which are formed in different spatial regions from the stellar surface to remote CS regions. Undoubtedly, any attempt to detect and to study fields in the Herbig Ae/Be stars must aim at: a) considerably better accuracy of measurements, and b) applying a specific observational strategy.

The first direct recording of the magnetic field in the Herbig star HD 104237 (A4–A7e) was carried out by Donati at al. (1997) ten yeas ago. Using high-resolution spectropolarimetry with the AAT/UCLES they found in metal lines of the object spectrum a marginal circular polarization signature indicating the existence of a weak longitudinal magnetic field of about 50 G. But somewhat later it was shown that HD 104237 is a multiple system containing a Herbig Ae star and additionally four T Tau-type components (Feigelson et al., 2003; Böhm et al., (2004). The most massive T Tau-type companion has a bolometric luminosity that is only a factor of 10 less than a Herbig Ae primary. It is well-known that T Tau-type G-M stars can possess their own magnetic fields of order of 1 kG. Therefore, the possibility that the detected field is actually related to the T Tau-type components cannot be ruled out.

2 Observations and data analysis

Spectropolarimetric low-resolution observations of 7 Herbig Ae stars were carried out in 2003–2005 with the spectropolarimeter FORS1 installed at the 8m-VLT in Chile. Observational data were obtained with the spectral resolving power R = 2000 and 4000 in the spectral regions $\lambda\lambda$ 3700–5900 Å and $\lambda\lambda$ 3900–5000 Å respectively. The technique applied for measuring stellar magnetic fields was developed by Angel and Landstreet (1970). Exclusively Balmer lines were used for the field determination. A detailed description of the programme is given by Hubrig et al. (2004, 2006).

Definite evidence for the presence of magnetic field ($\sim$100$\pm$30 G) was presented for four Herbig Ae stars of 7 observed. But just after the publication, these results became a matter of discussion. Wade et al. (2005) made a re-analysis of the observational data for the programme object HD 139614 (A7Ve) obtained by Hubrig at al. in 2003. They confirmed the detection of a mean longitudinal field in Balmer lines B_z equal to -320 ± 75 G, which is similar to our former estimation $B_z = -450\pm93$ G. But the magnetic field was not detected when they included numerous metal lines in their analysis. The presence of the weak magnetic field in HD 139614 was confirmed by our more recent observations in 2005 ($B_z = -116\pm34$ G, Hubrig et al. 2006). But 3 weeks after our observations were made, Wade et al. (2005) used ESPaDOnS at the CFHT to obtain two additional high-resolution spectropolarimetric observations of this object and found no significant magnetic fields.

We tried to clarify this situation and assumed that an important factor having a strong effect on the results of the field measurement could be the CS contribution to the stellar spectrum. The CS influence can differ for different spectral lines and be time-dependent. Starting from this assumption, we re-analyzed our spectropolarimetric data for 7 programme stars separating all atmospheric and CS components of spectral lines. After that, we re-measured the stellar magnetic fields for the programme objects using the entire spectrum with the local wavelength regions affected by the CS matter excluded.

Separation of CS line components was carried out by comparison of observational and synthetic spectra which were calculated using the computer code SYNTH+ROTATE (Piskunov 1992). Because of the rather low resolution of our spectra, the fitting was applied only to the slopes of wide Stark broadened wings of the Balmer lines. We carried out numerical detections of B_z only for the stellar component of the field. Standard Landstreet's technique for measuring magnetic fields in stellar atmospheres can hardly be applied to the CS fields for the following reasons: a) topology of CS fields may be strongly dissimilar to that of stellar surface fields, b) profiles of CS lines may be asymmetric and contain absorption as well as emission components, and c) spatial regions where CS lines form may be rather extended, and the magnetic field may be significantly varying in such large volumes. Nevertheless, CS polarization signatures observed at wavelengths corresponding to clearly

Table 1: Measurements of magnetic field in HD 139614 in 2003 and in 2005 using different methods: $B_z(old)$ – Hubrig et al. (2006), only hydrogen lines are used; $B_z(new)$ – this paper, regions of CS Balmer lines components are excluded

Season	2003	2005
MJD	52904.04	53405.37
R	2000	4000
$B_z(old)$	-450±93 G	-116±34 G
$B_z(new)$	-112±36 G	-93±14 G
Group	II-III	I
Magnetic field	CS	Stellar

identified CS components allow some conclusions concerning the properties of magnetic fields in the line formation region to be made.

3 Results

According to our analysis, all the observations can be divided into three groups.

The first group contains the objects with the spectra demonstrating small CS contribution. The stellar magnetic fields of these objects can be measured numerically with rather high accuracy if spectral regions distorted by the CS influence are excluded from calculations.

The objects of group II exhibit polarization features in numerous lines. But these features are likely to result from different combinations of the atmospheric and CS components of the magnetic field. We have no possibility of separating the stellar wind component of these objects.

Objects with clear circular polarization signatures mainly of CS origin can be distinguished as a third group. We can analyze the CS magnetic field component of these objects only qualitatively, and can conclude nothing about their atmospheric field component.

3.1 HD 139614

Fig.1 displays the low-resolution normalized (I/Ic) spectra of HD 139614 in the region of the CaII doublet observed in 2003 and 2005 in comparison with the synthetic spectrum; the corresponding polarization (V/I) spectra are also presented.

In the season of 2005 the resolution was higher, and we could see that the CS contribution to the stellar spectrum was rather small. Polarization features typical of stellar surface magnetic fields are clearly seen in both K and H components of the CaII doublet and in the FeI blend also (Fig.1, bottom).

In Balmer lines Hβ - Hδ the centers of wide photospheric lines are overlapped by CS emission, and no traces of polarization are observed. We used the entire spectrum for the stellar magnetic field determination excluding 3 local spectral regions distorted by CS emission in Balmer lines. As a result, in 2005 we obtained the value of B_z with an accuracy of $\pm 7\sigma$ instead of our previous estimation, $\pm 3\sigma$ (see Table 1).

In 2003 the spectral resolution was twice lower comparing to that in 2005, and we cannot exactly estimate the CS contribution to the stellar spectrum. But the polarization spectrum demonstrate features in both K and H CaII lines, which are not similar to those observed in 2005 (Fig.1, top). They have a complex two-component profile. We believe that they are formed by composition of the stellar and CS field components. In our opinion, the CS contribution to the stellar spectrum

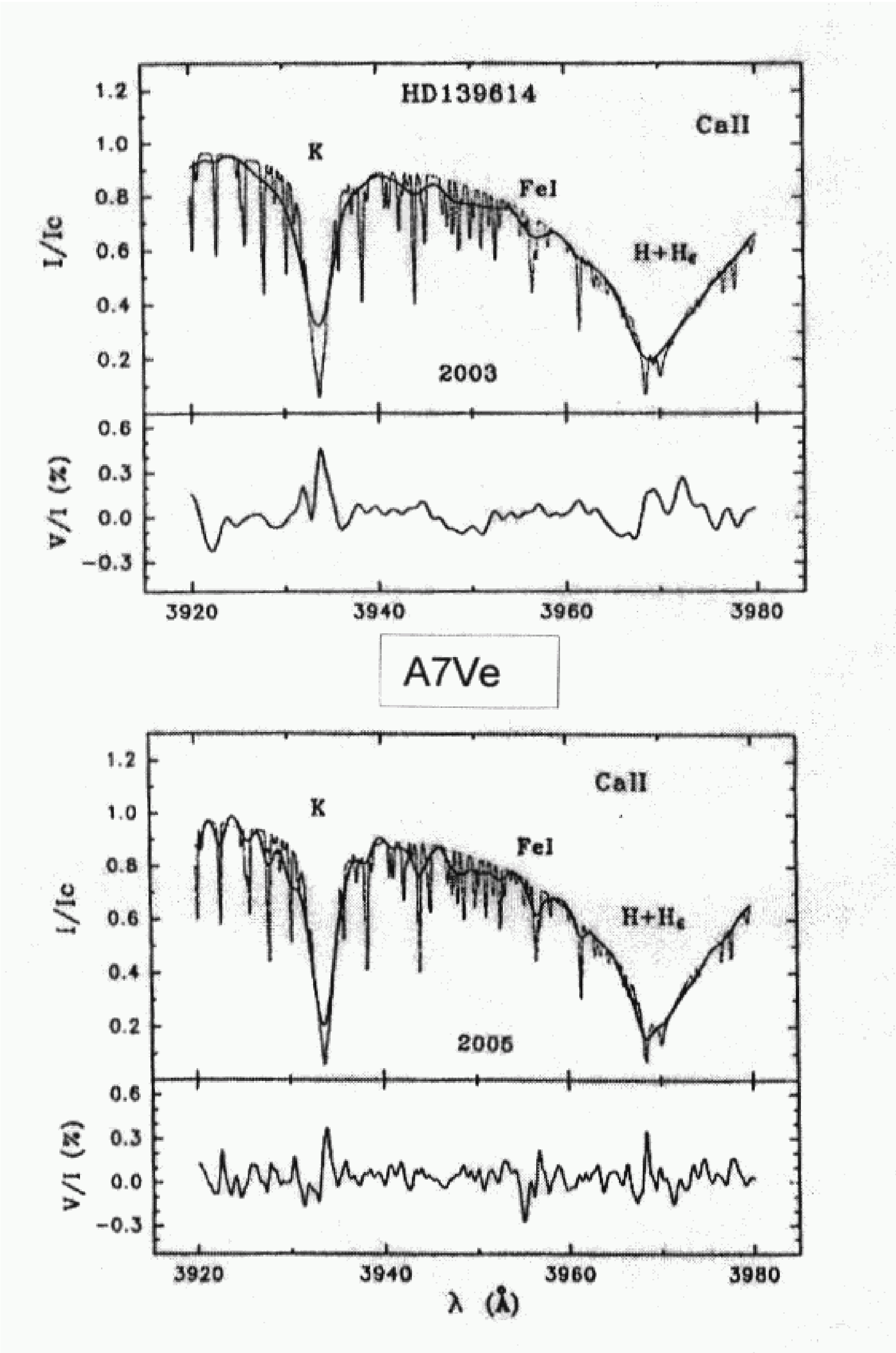

Figure 1: Normalized and polarization spectra of HD 139614 near the CaII doublet observed in 2003 (top) and 2005 (bottom). The synthetic spectrum is given for comparison by thin line.

Table 2: Measurements of magnetic field in HD 144432 in 2003 and in 2005 using different methods: $B_z(old)$ – Hubrig et al. (2006), only hydrogen lines are used; $B_z(new)$ – this paper, regions of CS Balmer and CaII K and H lines components are excluded

Season	2003	2005
MJD	52900.99	53447.35
R	2000	4000
$B_z(old)$	-94±60 G	-119±38 G
$B_z(new)$	-32±37 G	-111±16 G
Group	II-III	I
Magnetic field	CS	Stellar

was much higher in 2003 than in 2005. And a high value of B_z (of order of 400 G) obtained using Balmer lines relates exclusively to CS magnetic field and is only nominal (see Table 1).

3.2 HD 144432

A similar situation takes place in the case of the Herbig A9Ve star HD 144432. The normalized and polarization spectra of the object near the Hβ, Hδ and CaII K and H lines observed in 2005 are presented in Fig.2 (bottom). These spectra show the presence of a dense stellar wind. Blueshifted absorption components are clearly seen in these lines. Sufficient polarization features at the wavelengths of these components indicate that outflowing gas is magnetized.

As in the case of HD 139614, we determined the stellar surface magnetic field of HD 144432 in 2005 with an accuracy of 7σ, using the entire spectrum but excluding the local regions of the hydrogen and CaII CS components. Our former estimation was made at a level of only 3σ (Table 2).

The upper panel of Fig.2 shows a notable difference in the Hβ profiles observed in 2003 and 2005. In 2003 the CS blueshifted absorption was significantly deeper. We believe that in this season the CS contribution to the stellar spectrum was much larger. It is possible that a larger amount of dense outflowing gas was accumulated close to the line-of-sight. As a consequence, the polarization signatures of the stellar magnetic field, which were clearly visible in 2005, were likely distorted by CS matter. And no magnetic field has been found in this period.

3.3 Objects of group II

The polarization spectra of two programme objects HD 38238 (A7IIIe) and HD 144668 (A7IVe) from group II are presented in Fig.3.

The most significant polarization features are observed in the regions where CS components are clearly seen. But the majority of these features probably represent a combination of the stellar atmospheric and CS magnetic field signatures. No significant stellar magnetic field has been revealed in these objects.

3.4 Objects of group III

Three objects of group III: HD 163296 (A1Ve), HD 31648 (A3pesh) and HD 190073 (A2IIIe) are the most early-type targets of our programme. Also, they demonstrate the most prominent CS line components in comparison with other programme stars. All our attempts to determine the stellar magnetic field component of these objects, excluding different spectral bands containing CS line components, were unsuccessful.

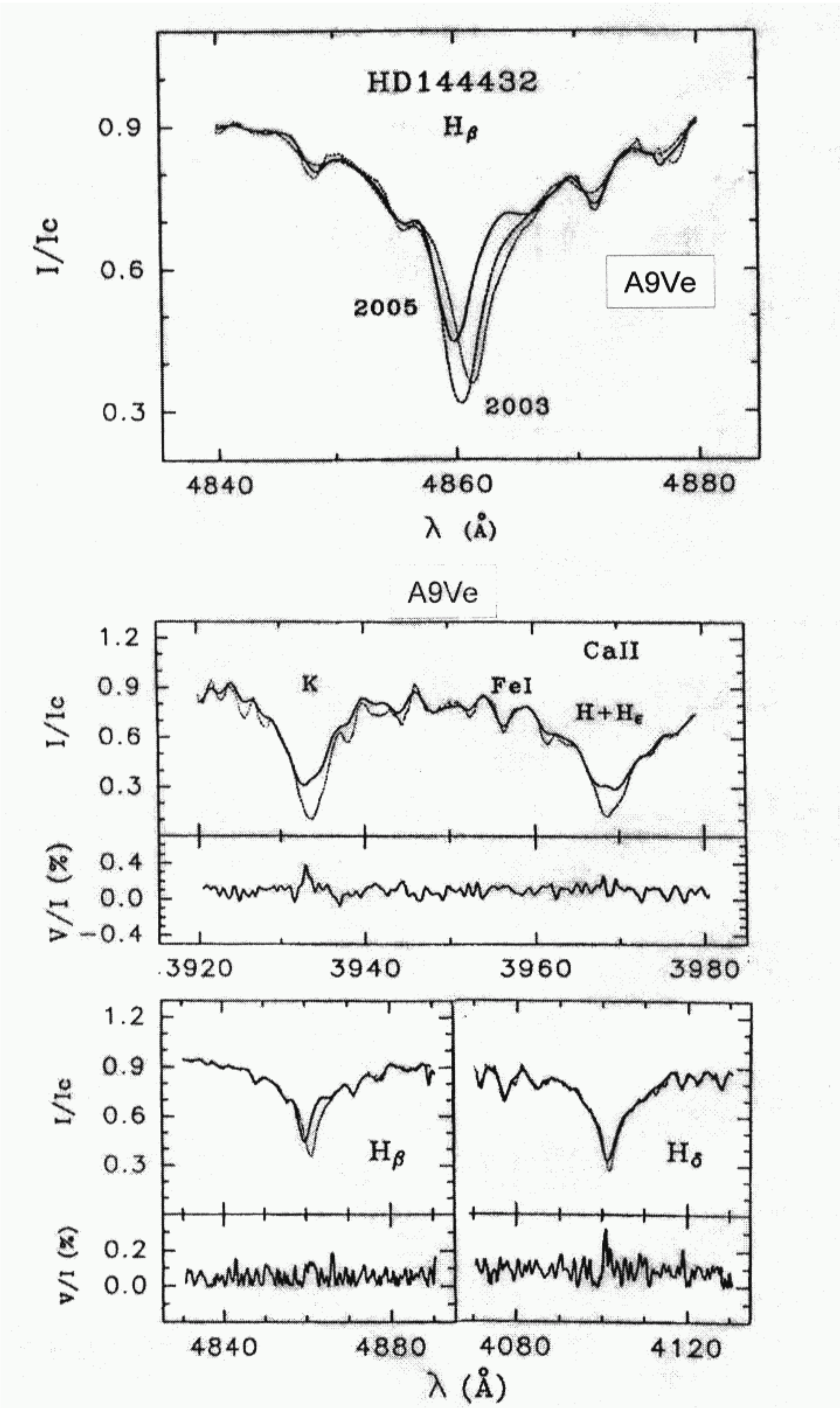

Figure 2: Normalized spectra of HD 144432 near Hβ observed in 2003 and in 2005 (top) and normalized and polarization spectra of the object near Hβ, Hδ and CaII doublet observed in 2005 (bottom). The synthetic spectra are given for comparison by thin lines.

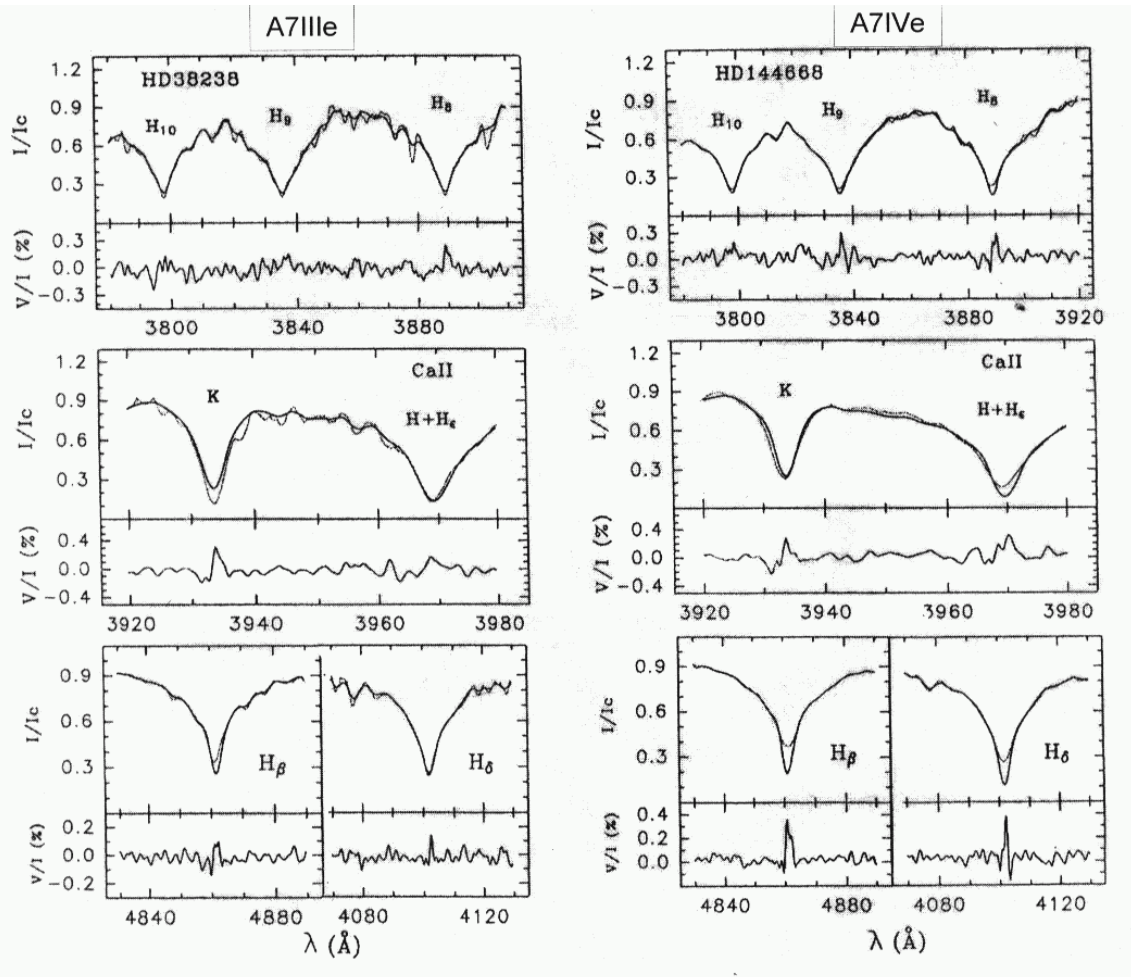

Figure 3: Normalized and polarization spectra of objects of group II.

Therefore, different polarization features, clearly observed in spectra of these stars, are exclusively of CS origin (Fig.4). In our last paper (Hubrig et al. 2006) the values of magnetic fields are given for HD 31648 and HD 190073 determined with an accuracy of 3σ. Now we conclude that these estimations are only nominal and are not related to the stellar surface magnetic field.

It is remarkable that in Balmer lines notable polarization features are observed only in one object of the three — HD 31648. This star demonstrates very deep blueshifted absorption components of Hβ and Hδ formed in the stellar wind along the line-of-sight between the star and the observer. In spectra of the other two stars such absorptions are also present, but they are not so deep. It indicates that the density of the outflowing gas crossing the line-of-sight in these stars is likely to be lower than in HD 31648. No polarization signatures are observed in Balmer lines of HD 163296, and only a weak feature is seen in the spectrum of HD 190073 near Hδ.

However in the CaII K and H lines polarization signatures are present very clearly in all three objects. The profile of the CaII K line in the spectra of HD 163296 and HD 31648 is much wider than that predicted by the synthetic spectra. They display a two-component structure containing blueshifted and redshifted absorptions. The CaII lines in the spectra of these stars are very likely to be formed at the base of the stellar wind and in the accretion gaseous flows. Therefore the polarization spectrum near the CaII resonance doublet allows the CS magnetic field in the region of interaction of the star with the accretion disk to be diagnosed.

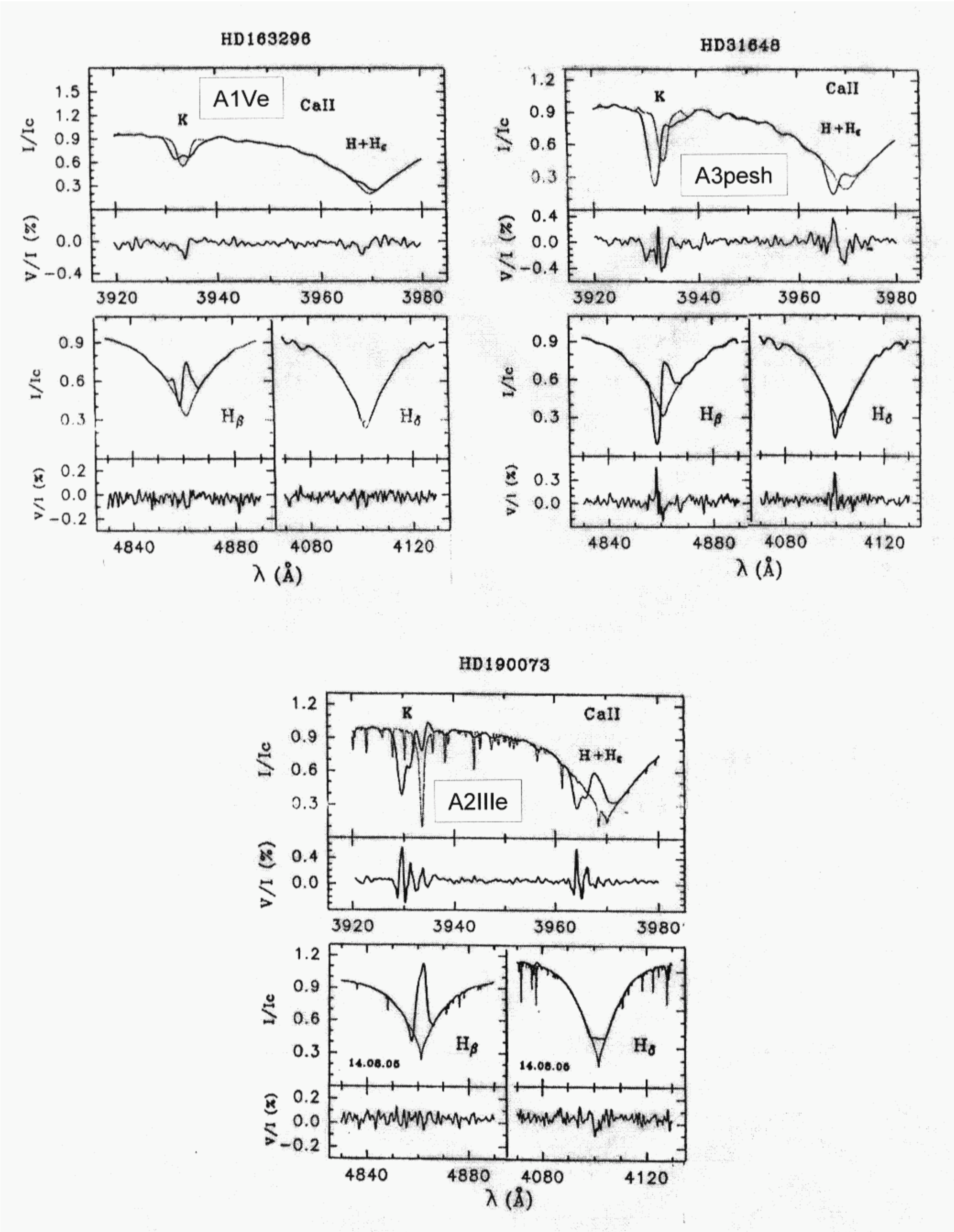

Figure 4: Normalized and polarization spectra of objects of group III.

3.5 HD 190073

The most interesting result has been obtained for the object of group III, HD 190073. Its very prominent peculiarity is a complex multi-component structure of the CaII K and H absorption profiles (Pogodin et al. 2005). Actually, it consists of about 20 blueshifted components of various width and depth, but our low-resolution spectropolarimetry allowed us to distinguish only three main components (Fig.4, bottom). It is remarkable, that three distinctive polarization signatures are clearly visible and their positions coincide with the positions of three blueshifted components of the K and H line profiles in the normalized spectrum.

This picture leads us to the conclusion that there is a direct relation between the specific structure of these line profiles and the CS magnetic field.

4 Conclusions

As a result of our magnetic field investigation of seven Herbig Ae stars, we made the following advances:

- We conclude that previous discrepancies in B_z estimations in some Herbig Ae/Be stars observed on different dates by different investigators are likely to be a result of a variable CS contribution to the stellar spectrum.
- The use of a specific method of data analysis allowed us to improve considerably the accuracy of the stellar magnetic field determination (for objects of group I), namely from the 3σ to 7σ level.
- We deduced that our formerly registered magnetic fields of HD 31648 ($B_z = +87\pm22$ G) and HD 190073 ($B_z = +84\pm30$ G), as it is reported by Hubrig et al. (2006), are of CS but not of atmospheric origin.
- We found that polarization signatures of the CS magnetic field in Balmer lines in the spectra of the Herbig Ae/Be stars are mainly observed in deep absorption components formed in the stellar wind.
- We also established that the most sensitive indicator for the CS magnetic field in Herbig Ae/Be stars in the region of the interaction between the star and the accretion disk is the resonance CaII (K & H) doublet.
- The results of our investigation evidence in favour of the hypothesis that the well-known puzzling multi-component structure of the absorption CaII lines in the spectrum of HD 190073 is caused by a complex topology of the CS magnetic field of the object (Pogodin et al. 2005).

We would like to emphasize that the most effective strategy for future studies of magnetic fields in the Herbig Ae/Be stars will be to carry out spectropolarimetric monitoring of these stars followed by close control over the state of their CS contribution to the stellar spectrum. In the state of minimum CS influence the stellar magnetic field can be relatively easy detected applying our method presented above. When the CS spectrum becomes the most prominent, one has a good chance for studying the field in the CS environment.

We also note that high-resolution spectropolarimetric observations would allow using for the field determination a considerably larger sample of spectral lines originating at different levels in the stellar atmosphere and the CS envelope. This should provide an opportunity to reconstruct the magnetic field topology from the stellar surface to the external CS regions. The first results of high-resolution spectropolarimetric investigations of several Herbig Ae/Be stars are presented in Wade et al. (these Proceedings).

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