

A high-precision search for magnetic field oscillations in the roAp star HD 24712[★] (Research Note)

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ABSTRACT

We have obtained a time series of 81 high-cadence circular polarization observations of the rapidly oscillating Ap star HD 24712 with the new ESPaDOs spectropolarimeter at CFHT. We used the high-S/N, high-resolution Stokes I and V spectra to investigate possible variation of the mean longitudinal field over the pulsation cycle in this roAp star. Our multiline magnetic field and radial velocity measurements utilized 143 spectral lines of rare-earth elements, attaining precision better than 13 G and 19 m s^{-1} , respectively. A multiperiodic radial velocity variation with an amplitude of 40–136 m s^{-1} is clearly detected at the known pulsation frequencies of HD 24712. At the same time, no evidence for pulsational changes of the magnetic field can be found. We derive a 3σ upper limit of 10 G, or about 1% of the mean longitudinal field strength, for magnetic field oscillations in the upper atmosphere of HD 24712. The absence of detectable pulsational variability of the magnetic field provides a valuable constraint for the interaction between pulsations and magnetic field in roAp stars and is compatible with the recent predictions of detailed theoretical models of stellar magnetoacoustic oscillations.

Key words. stars: atmospheres – stars: chemically peculiar – stars: individual: HD 24712 – stars: magnetic fields – stars: oscillations

1. Introduction

Rapidly oscillating magnetic Ap (roAp) stars are cool magnetic chemically peculiar stars exhibiting a remarkable combination of unusual surface properties. These objects have strong, organised magnetic fields, most likely of fossil nature, and show photospheric chemistry deviating far from that of the Sun and other cool, non-magnetic A-type stars. They show non-uniform distributions of chemical elements, both laterally across their surfaces, as well as vertically with height in their atmospheres. Most remarkably, they exhibit high-overtone, low-degree, non-radial p -mode pulsations with periods ranging from 6 to 21 min.

Their strong magnetic fields play a central role in the mechanisms responsible for pulsation mode excitation and selection (Balmforth 2001; Saio 2005) and in shaping the frequency spectra of roAp stars (Cunha 2006). Pulsational perturbations observed in roAp stars occur in the magnetically-controlled outer stellar layers, which is why pulsations are aligned with the oblique quasi-dipolar magnetic field (Kochukhov 2004; Saio 2005) instead of the stellar rotation axis as in all other types of non-radially pulsating stars.

Recent time-resolved spectroscopic observations of pulsations in roAp stars (Kochukhov & Ryabchikova 2001a, 2001b; Mkrtichian et al. 2003; Elkin et al. 2005; Kochukhov 2006) demonstrate that, in addition to the remarkable horizontal

geometry, the magnetoacoustic p -modes show outstanding vertical structure due to the combination of the rapid increase of pulsation amplitude with height in the atmosphere and the short vertical wavelength of the pulsational fluctuations. The general picture of the atmospheric pulsational behaviour of roAp stars is determined by the propagation of magnetoacoustic waves through the distinct layers of the chemically stratified atmosphere (Ryabchikova et al. 2002). Pulsations are weak or non-detectable in the lower atmosphere probed by lines of light and iron-peak elements. On the other hand, rare-earth elements (REE) are concentrated in clouds located high above the photosphere, in the layers where pulsation amplitudes reach up to several km s^{-1} .

An important new insight into the complex physics of pulsations in roAp stars can be achieved by the analysis of interaction between the p -modes and the magnetic field. The first search for variations of the mean longitudinal magnetic field, $\langle B_z \rangle$, over the pulsation cycle was conducted by Hubrig et al. (2004). These authors used low-resolution time-resolved circular polarization observations of six roAp stars, and measured $\langle B_z \rangle$ using hydrogen lines and unresolved blends of metal lines. Hubrig et al. (2004) failed to detect magnetic field variation above the noise level of their analysis, which was 40–100 G.

Kochukhov et al. (2004b) and Savanov et al. (2006) obtained high-precision measurements of the mean magnetic field modulus over the 12-min pulsation period of the bright roAp star γ Equ. The resolved, Zeeman-split profile of the Fe II 6149.25 Å line was used in both studies. Neither of the authors detected any pulsational fluctuation of the field strength, deriving an upper limit of 10 G for the possible field variation.

[★] Based on observations obtained at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawaii.

The low-resolution spectropolarimetry and the field modulus measurements using Fe II lines have limited diagnostic capabilities because both types of magnetic field monitoring techniques probe low atmospheric layers where pulsation amplitudes are small. Taking guidance from the highly successful radial velocity analyses, an investigation of the magnetic field oscillations in roAp stars should focus on individual REE lines which show conspicuous pulsational variations. The first study of this kind has been carried out by Leone & Kurtz (2003). They observed several Nd III lines in γ Equ using a circular polarization analyzer and a high-resolution spectrometer. Based on only 18 time-resolved spectra, Leone & Kurtz (2003) announced the discovery of the pulsational variation of $\langle B_z \rangle$ with amplitudes 110–240 G although curiously with discrepant phases of magnetic maximum for different Nd III lines. Subsequently, Kochukhov et al. (2004a) obtained independent high-resolution polarimetric observations of γ Equ. Their analysis combined magnetic signatures of 13 Nd III lines and was based on more than 200 spectra collected over three nights. Kochukhov et al. (2004a) were unable to detect longitudinal field variability over the pulsation cycle in γ Equ exceeding 40 G. They suggested that the field variation claimed by Leone & Kurtz (2003) is spurious and likely results from the neglect of blending of the few REE spectral features employed in their magnetic measurements.

The contradictory results obtained in the previous searches for rapid magnetic field oscillations in γ Equ call for an extension of time-resolved spectropolarimetric studies of REE lines to other roAp stars. We have therefore obtained a new set of time-resolved, wide wavelength coverage Stokes I and V spectra for the well-known roAp star HD 24712 (HR 1217, HIP 18339, DO Eri).

HD 24712 was identified as a roAp star by Kurtz (1982). The recent extensive Whole Earth Telescope photometric campaign revealed eight pulsation modes with frequencies in the range of 2.6–2.8 mHz (Kurtz et al. 2005). Ryabchikova et al. (1997) performed detailed model atmosphere and chemical abundance analysis of HD 24712. They inferred $T_{\text{eff}} = 7250$ K and $\log g = 4.3$, and found that the atmosphere of this roAp star is rich in REEs but relatively poor in the iron-peak elements. In their study of the evolutionary state of magnetic chemically peculiar stars Kochukhov & Bagnulo (2006) derived the following fundamental characteristics of HD 24712: mass $M = 1.55 M_{\odot}$, luminosity $L = 7.4 L_{\odot}$ and an age $\approx 10^9$ yr, corresponding to about 50% of the main sequence lifetime. Bagnulo et al. (1995) demonstrated that a dipolar magnetic field topology with the polar strength $B_p = 3.9$ kG and the angle $\beta = 150^\circ$ between the rotation and magnetic axes provides a good fit to both the longitudinal field curve of HD 24712 and to the broad-band linear polarization measurements. Combining magnetic field and line strength observations of HD 24712 obtained over more than three decades, Ryabchikova et al. (2005) determined a rotation period of 12.45877 d.

2. Observations and data reduction

Eighty-one new Stokes V spectra of HD 24712 were obtained on 9 January 2006 UT using the ESPaDOnS spectropolarimeter at the Canada-France-Hawaii Telescope. Observations covered roughly 3 h, starting at HJD = 2453 744.70540. According to the ephemeris of Ryabchikova et al. (2005), our time-resolved monitoring of HD 24712 corresponds to the rotation phase 0.9, which is close to the positive extremum of the longitudinal magnetic field variation and to the phase of maximum non-radial oscillation amplitude. Observations were obtained in

polarimetric mode, with a nominal resolving power $\lambda/\Delta\lambda = 65\,000$, and cover the spectral region 3700–10 500 Å. The details of the ESPaDOnS are reported by Donati et al. (in preparation)¹. In particular, both results of the commissioning tests and our own velocity measurements using telluric absorption lines in the spectra of HD 24712 indicate that the typical relative spectral stability of the instrument is better than 10–15 m s⁻¹ for the frequency range corresponding to roAp pulsations.

The 81 Stokes V spectra of HD 24712 were computed from 162 individual circular polarization exposures. Between subsequent exposures, the Fresnel rhomb quarter-wave retarder was rotated by 90° (i.e. alternately to position angles of +45° and -45°) in order to interchange the positions of the ordinary and extraordinary beams on the CCD. The data were reduced using the Libre-ESpRIT package; each subsequent pair of CCD frames was combined into a single Stokes V spectrum with typical peak S/N of 115. Examination of the diagnostic null spectrum (Donati et al. 1997) indicates that the beam-switching technique has removed all spurious contributions to the Stokes V spectrum to below the noise level. We emphasize that this is the first time that this high-precision spectropolarimetric observing method has been applied to monitor rapid magnetic field variations of a roAp star.

Individual circularly polarized exposures were of 20 s duration, and the readout using the CCD's fast readout mode required 25 s. Taking into account time required for repositioning of the waveplate between exposures, the average time required for acquisition of a single Stokes V spectrum was typically 1.25 min. This effective time resolution of the time series is significant in comparison with the $P = 6.0$ – 6.4 min pulsational variation of HD 24712. Our numerical modelling shows that the pulsational amplitude inferred from such a time series is underestimated by 12% relative to observations with a much higher time resolution. The treatment of this effect must be included in the time-series analysis.

3. Time-series analysis of radial velocity and magnetic field

Ryabchikova et al. (2007) have recently presented a detailed study of the spectroscopic pulsational behaviour of HD 24712 using high-resolution échelle spectra acquired at several large telescopes. This analysis demonstrated that, similar to other roAp stars, the pulsational radial velocity (RV) variation can be clearly detected only for REE lines and, marginally, for the cores of a few very strong lines of light elements (hydrogen Balmer lines, Ca II 3933 Å). Taking these results into account, we have investigated the pulsational variation of the Stokes I and V profiles for REE lines. An initial list of the central wavelengths and Zeeman splitting parameters was compiled for more than 200 lines based on the information from Ryabchikova et al. (2006, 2007), and the VALD (Kupka et al. 1999) and DREAM (Biémont et al. 1999) databases. This list is dominated by Pr III, Nd II and Nd III lines, but also includes Y II, La II, Ce II, Pr II, Sm II, Eu II, Gd II, Tb III, Dy II, Dy III, and Er III spectral features. The Stokes I and V profile of each line was examined to remove lines affected by blending. Radial velocities were determined for the remaining lines with the center-of-gravity method:

$$\langle v \rangle = \frac{c}{\lambda_0} \left(\frac{\int \lambda(I_c - I) d\lambda}{\int (I_c - I) d\lambda} - \lambda_0 \right), \quad (1)$$

¹ For up-to-date information, visit <http://www.ast.obs-mip.fr/projets/espados/espados.html>

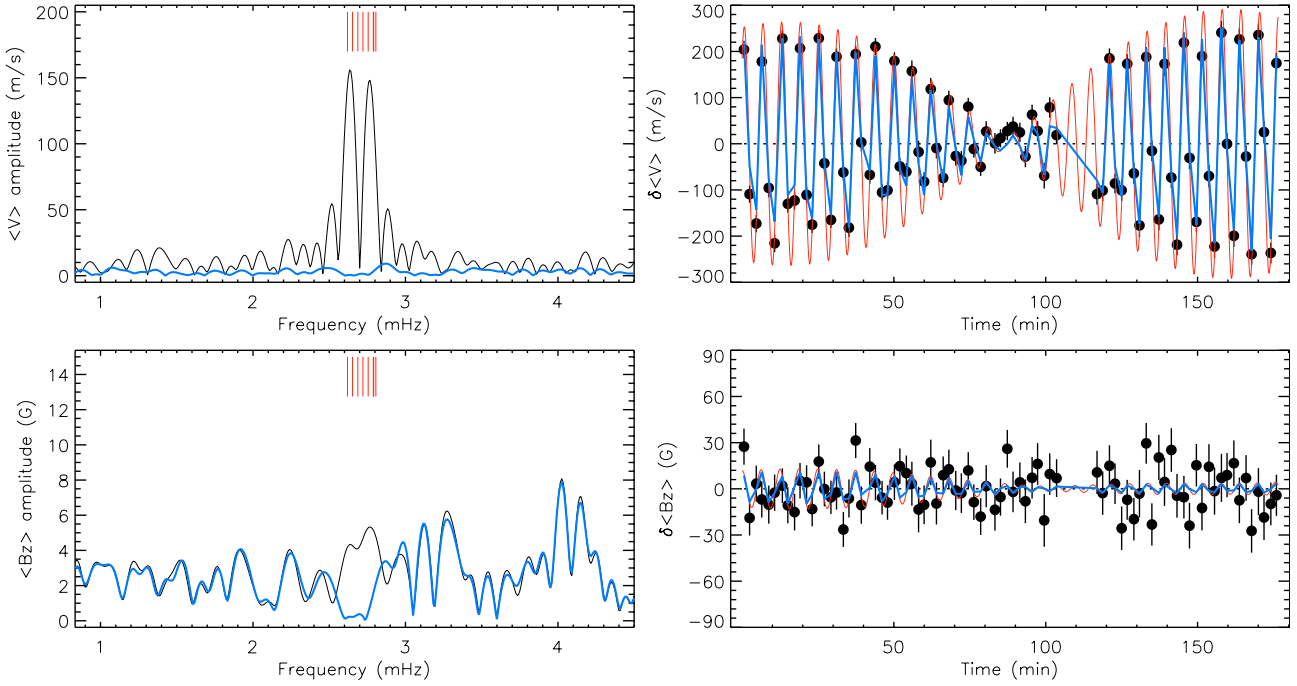


Fig. 1. Pulsational variation of radial velocity (*upper panels*) and longitudinal field (*lower panels*) for the REE lines in HD 24712. The left panels show the amplitude spectra of RV and $\langle B_z \rangle$ (*thin line*) as well as Fourier transforms of the residual variation (*thick line*) obtained by subtracting least-squares sinusoidal fit from the original time series. The vertical bars show pulsation frequencies of HD 24712 determined in the photometric study by Kurtz et al. (2005). The right panels illustrate velocity and magnetic field variation in the time domain. Individual $\delta\langle v \rangle$ and $\delta\langle B_z \rangle$ measurements (*symbols*) are compared with the best fit three-frequency model (*thick line*), which takes into account data sampling and phase smearing (see text). The thin line shows the same oscillation model neglecting these effects.

where λ_0 is the laboratory wavelength, I and I_c correspond to the line and continuum intensity, respectively, and c is the speed of light.

The mean longitudinal magnetic field was estimated by integrating the Stokes V profiles of REE lines:

$$\langle B_z \rangle = -\frac{4\pi m_e c}{e} \frac{\int (v - \langle v \rangle) V dv}{\lambda_0 z \int (I_c - I) dv}, \quad (2)$$

where z is the effective Landé factor, m_e is the electron mass, e is the electron charge, and v is the velocity coordinate. The errors of $\langle v \rangle$ and $\langle B_z \rangle$ were derived applying the standard error propagation rules to Eqs. (1) and (2), and using the formal uncertainties of the Stokes I and V spectra provided by the Libre-ESPRIT spectral extraction package.

Preliminary time-series analysis was carried out for each measured transition to exclude lines showing no RV oscillation signal above 2σ in the 2.4–3.0 mHz frequency interval to which all known pulsation frequencies of HD 24712 are confined (Kurtz et al. 2005). Four Tb III were also excluded from consideration because their pulsational radial velocity curves show a large phase shift with respect to the variation of other REE ions (Ryabchikova et al. 2007). This left us with 139 REE lines. Due to overlap of the blue échelle orders in the ESPaDOnS spectra, many lines could be measured twice, increasing the total number of spectral features included in the final sample to 168.

We have constructed a high-precision measure of the pulsational changes of RV and magnetic field by calculating the weighted average of the deviation of $\langle v \rangle$ and $\langle B_z \rangle$ from their mean values:

$$\overline{\delta S} = \frac{\sum_{i=1}^N [S_i - (a_i + b_i t)] / \sigma_i^2(S)}{\sum_{i=1}^N 1 / \sigma_i^2(S)}, \quad (3)$$

where $N = 168$, S corresponds to $\langle v \rangle$ or $\langle B_z \rangle$, $\sigma_i(S)$ are the respective errors and a_i , b_i represent coefficients of a linear least-squares fit to the full timeseries describing the mean and linear drift of each quantity.

The amplitude spectrum and time dependence of the resulting average $\delta\langle v \rangle$ and $\delta\langle B_z \rangle$ are illustrated in Fig. 1. We have unambiguously detected pulsational variation of RV at the level of $\approx 150 \text{ m s}^{-1}$. Pronounced modulation of the RV amplitude due to beating of the oscillations with $P \approx 6.05$ and 6.30 min is evident in our data. The first period coincides with the frequency ν_5 (2755 μHz , 6.049 min) of Kurtz et al. (2005), whereas the second one lies between ν_1 (2620 μHz , 6.362 min) and ν_2 (2653 μHz , 6.282 min). Given that the frequency spectrum of HD 24712 is well known and remains constant over many years, we assume that the p -mode oscillations detected in our CFHT spectra are caused by the superposition of the three pulsation periods corresponding to ν_1 , ν_2 and ν_5 of Kurtz et al. (2005). We keep these periods fixed in the following time-series analysis.

Figure 1 shows that there is no evidence of the $\langle B_z \rangle$ variation with any of the known pulsation frequencies of HD 24712, nor any other frequency up to the Nyquist limit of our data. The highest $\delta\langle B_z \rangle$ peaks reach 6–8 G, but none is statistically significant.

We have used a least-squares analysis in the time domain to determine RV amplitudes and to infer accurate upper limits for the magnetic field variation. For high-cadence data in which the time sampling is much shorter than the pulsation period, the expression

$$\overline{\delta S} = \sum_{i=1}^3 A_i \cos\left(\frac{2\pi t}{P_i} + 2\pi\varphi_i\right) \quad (4)$$

Table 1. Results of the multifrequency least-squares analysis of the variation of radial velocity and longitudinal magnetic field for REE lines in HD 24712. For each group of lines we list the number of measured spectral features, followed by the number of unique lines. Amplitudes are given in m s^{-1} and G for $\langle v \rangle$ and $\langle B_z \rangle$, respectively, while phases are measured in fractions of pulsation period.

P (min)	Radial velocity		Magnetic field	
	A (m s^{-1})	φ	A (G)	φ
168(139) REE lines				
6.049	138.7 ± 3.9	0.850 ± 0.005	4.9 ± 2.4	0.857 ± 0.076
6.282	113.9 ± 6.2	0.861 ± 0.009	6.6 ± 3.8	0.143 ± 0.098
6.362	40.9 ± 6.3	0.120 ± 0.024	5.1 ± 3.9	0.944 ± 0.118
56(47) Nd II lines				
6.049	189.6 ± 6.0	0.936 ± 0.005	5.2 ± 5.6	0.399 ± 0.174
6.282	132.0 ± 9.5	0.971 ± 0.012	19.9 ± 9.0	0.317 ± 0.072
6.362	41.3 ± 9.7	0.139 ± 0.037	8.0 ± 9.1	0.808 ± 0.184
44(34) Nd III lines				
6.049	152.0 ± 4.3	0.842 ± 0.005	4.8 ± 3.2	0.944 ± 0.106
6.282	138.6 ± 6.9	0.851 ± 0.008	7.4 ± 5.1	0.196 ± 0.108
6.362	43.7 ± 7.1	0.148 ± 0.026	10.3 ± 5.2	0.037 ± 0.079
17(16) Pr III lines				
6.049	179.5 ± 8.6	0.662 ± 0.007	16.5 ± 7.6	0.859 ± 0.075
6.282	173.7 ± 13.5	0.663 ± 0.012	18.4 ± 12.1	0.902 ± 0.105
6.362	73.8 ± 13.8	0.975 ± 0.030	8.7 ± 12.2	0.754 ± 0.227
15(12) Sm II lines				
6.049	213.5 ± 10.5	0.923 ± 0.008	10.5 ± 9.2	0.829 ± 0.143
6.282	191.4 ± 16.9	0.966 ± 0.014	30.0 ± 14.9	0.678 ± 0.078
6.362	26.3 ± 17.2	0.419 ± 0.104	18.4 ± 15.1	0.474 ± 0.130

(where A_i and φ_i are the amplitude and phase of oscillation with period P_i) is suitable to approximate the variability of pulsating stars. However, the phase smearing caused by the longer effective time sampling used in this study is non-negligible. We have explicitly taken the data sampling effects into account by integrating and averaging Eq. (4) for the time intervals corresponding to the individual polarimetric subexposures. Applying trivial trigonometric relations, one can obtain the following expression:

$$\overline{\delta S} = \sum_{i=1}^3 \frac{A_i P_i}{\pi \Delta t} \sin\left(\frac{\pi \Delta t}{P_i}\right) \cos\left(\frac{\pi t^{+45} + \pi t^{-45}}{P_i} + 2\pi \varphi_i\right) \times \cos\left(\frac{\pi t^{+45} - \pi t^{-45}}{P_i}\right), \quad (5)$$

where t^{+45} and t^{-45} are mid times of the subexposures with different retarder orientation and $\Delta t = 20$ s is the exposure time.

Results obtained by fitting Eq. (5) to the $\langle v \rangle$ and $\langle B_z \rangle$ variations are summarized in Table 1 and illustrated in Fig. 1. The RV pulsations have amplitudes 40–136 m s^{-1} and are detected at the 6–36 σ level. The rms deviation between observations and the least-squares fit indicates an uncertainty of 19 m s^{-1} for a single multiline RV measurement. The corresponding precision of the multiline magnetic measurements is 13 G. Figure 1 shows that the amplitude of the residual oscillations does not exceed 5–10 m s^{-1} after prewhitening observations with the three-frequency model. At the same time, the formal $\langle B_z \rangle$ amplitudes are 5–6 G, detected at the 2σ confidence level or less. Therefore, we conclude that HD 24712 exhibits no pulsational variation of the disk-averaged line of sight magnetic field component. The 3σ upper limit for pulsational field changes is 7–12 G, depending on the pulsation mode considered.

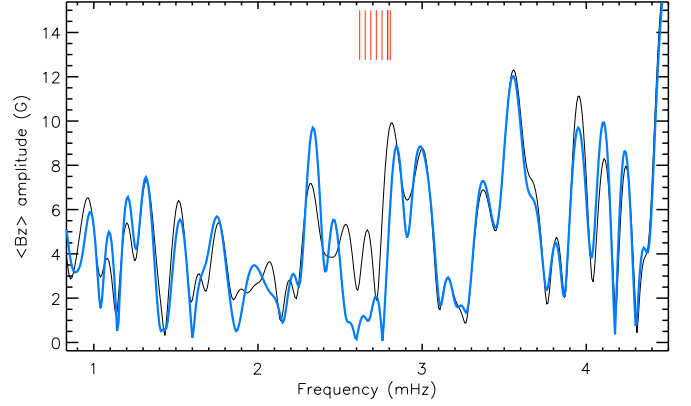


Fig. 2. Amplitude spectra of the LSD $\langle B_z \rangle$ measurements for HD 24712. Fourier transform of the original $\langle B_z \rangle$ time series (*thin line*) is compared with the residual amplitude spectrum (*thick line*). The vertical bars show photometric pulsation frequencies of HD 24712.

We have examined separately the average RV and $\langle B_z \rangle$ for several groups of REE ions. Table 1 presents results of this analysis for the four groups of REE species with >10 unique lines each (Pr III, Nd II, Nd III, Sm II). The time-series analysis is less precise for individual ions, but it generally confirms results obtained with all REE lines. In particular, none of the investigated REE species shows statistically significant pulsational changes of $\langle B_z \rangle$, although each of them shows RV pulsations at $>20\sigma$ level.

The REE line analysis was complemented by the study of $\langle B_z \rangle$ measured for the Least Squares Deconvolved Stokes I and V spectra (LSD profiles, see Donati et al. 1997). This diagnostic is based upon strong lines of light and iron-peak elements and, therefore, probes conditions in the lower part of HD 24712 atmosphere. The amplitude spectrum of the LSD $\langle B_z \rangle$ measurements is presented in Fig. 2. No variation above 13–21 G (3σ limits) is present at the frequencies detected in the REE line radial velocities. The average longitudinal field obtained with the LSD technique is 1022 ± 30 G, which is in good agreement with the known rotational modulation of $\langle B_z \rangle$ in HD 24712 (Ryabchikova et al. 2005, 2007).

4. Discussion

We have obtained the first time-resolved high-resolution circular polarization observations of the roAp star HD 24712. Our aim was to search for the variation of the stellar magnetic field with the pulsation cycle. Unlike all previous time-resolved spectropolarimetric studies of roAp stars (Hubrig et al. 2004; Leone & Kurtz 2003; Kochukhov et al. 2004a), we have employed the beam-switching technique to minimize spurious polarization. The resulting phase smearing was accounted for in the time-series analysis. To boost precision further, we have combined oscillation signal in 139 REE spectral lines, thus significantly improving the sensitivity to the magnetic field variation in comparison with previous studies. Variability with the known pulsation frequencies was found for the average RV obtained from all REE lines as well as for individual ions. However, no magnetic field variability above 7–12 G could be detected. Since our observations were obtained at the rotation phase of magnetic maximum of HD 24712, when $\langle B_z \rangle \approx 1$ kG, we infer the upper limit of the relative pulsational changes of the field strength: $\delta B/B \lesssim 10^{-2}$.

The null result of our search for the pulsational magnetic field variation in HD 24712 agrees with the 2–4% $\delta B/B$ upper limit obtained by Kochukhov et al. (2004a) for γ Equ. Our study thus strengthens the view that no significant field variability in roAp stars should be expected on pulsational timescales.

Hubrig et al. (2004) published a preliminary theoretical estimate of the expected pulsational modulation of $\langle B_z \rangle$ in roAp stars. These authors claimed that field variations at the level of 1% to 14% for different roAp stars may be expected. For the pulsation period and the radial velocity amplitude observed in the upper atmosphere of HD 24712, magnetic changes should be about 1% of $\langle B_z \rangle$ or 10 G. This level of the magnetic field variations is marginally inconsistent with our conservative upper limit of 7 G derived for the highest-amplitude pulsation mode. At the same time, Hubrig et al. (2004) predict that the rapid magnetic variations of γ Equ should reach 10% of the field strength, which is clearly ruled out by the observational results of Kochukhov et al. (2004a).

Saio (2005) has pointed out that in their estimate of the magnetic field variation Hubrig et al. (2004) have erroneously disregarded the effect of the horizontal component of the pulsational displacement. Based on the detailed non-adiabatic theoretical model of the magnetoacoustic oscillations in roAp stars, Saio (2005) suggested that the amplitude of the magnetic field variation should not exceed $\delta B/B \sim 10^{-5}$ or ~ 0.01 G for a star with a kG-strength magnetic field. This theoretical prediction is confirmed by our spectropolarimetric monitoring of HD 24712 and by the time-resolved magnetic observations of γ Equ presented by Kochukhov et al. (2004a).

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