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Abundance analysis of roAp stars

IV. HD 24712 *

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Abstract. We present the first abundance analysis of the rapidly oscillating chemically peculiar star HD 24712, and determine a $T_{\rm eff} = 7250$ K, $\log g = 4.3$, and $\xi_{\rm t} = 1\,{\rm km\,s^{-1}}$. Microturbulence seems to be entirely simulated by a magnetic field with a polar field strength of 4.4 kG and of dipolar structure, both of which are supported by our polarimetric observations.

Rotation of HD 24712 and a spotty surface distribution of the elements result in different mean abundances for different (magnetic) phases. Our results do not support the hypothesis of a monotonic correlation between the amplitude of abundance variations and the atomic number Z, and we present arguments in favour of one of the rotation periods ($P_{rot} = 12\overset{d}{.}4610$) discussed in the literature.

Rare earth elements are the most overabundant elements relative to the sun, and they have the largest abundance amplitude during a rotation cycle; only Mg has a larger amplitude. For HD 24712 we find a clear overabundance of Co while most of the other iron peak elements are underabundant. A comparison of the abundance pattern with the other three roAp stars analyzed so far by us concludes the paper.

A systematic difference between surface gravities obtained from spectroscopy and from both asteroseismology and evolutionary tracks is found for the roAp stars HD 24712, α Cir and γ Equ.

Key words: Stars: abundances – chemically peculiar – magnetic field – pulsation – individual: HD 24712

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1. Introduction

HD 24712, (HR 1217, DO Eri, mag(V) = 6.00) is a sharp-lined chemically peculiar star of spectral class near F0 V. Kurtz (1981) discovered oscillations with a period of 6.15 min and an amplitude of 14 mmag for this second member of the group of rapidly oscillating Ap (roAp) stars. Matthews et al. (1988) found RV variations with an amplitude of $400\pm50\,{\rm m\,s^{-1}}$, varying with the main frequency of photometric oscillations, giving strong support to a pulsational interpretation of these short time scale variations in roAp stars. The RV variations were confirmed by Belmonte et al. (1989), although with a slightly lower amplitude of $249\,{\rm m\,s^{-1}}$.

Early spectroscopic observations of HD 24712 (Preston, 1972) showed that this star is a spectral and magnetic variable with a rotation period P=$12\overset{d}{.}448$. The mean longitudinal magnetic field varies from +0.4 kG to +1.5 kG and its maximum nearly coincides with the maximum of the line intensity of rare-earth elements (REE). Compared to other elements, the REE show the greatest line intensity variations which occur in antiphase with the variations of Mg II lines. Preston found that the algebraic range of spectral variations systematically increases with Z, the atomic number. Bonsack (1979) confirmed the spectrum variability of HD 24712 and he claimed that the correlation between amplitudes and Z is *not* monotonic, but discontinuous. He also needed a slightly longer period of $12\overset{d}{.}46$ to phase his data with those of Preston (1972).

Photometric observations were first reported by Wolff & Morrison (1973) who found HD 24712 to be variable with the period proposed by Preston (1972). Kurtz & Marang (1987) used their high-speed photometry together with that of Wolff & Morrison to derive an improved rotation period for HD 24712 of $12\overset{d}{.}4572 \pm 0\overset{d}{.}0003$. With this period, extrema of the photometric and magnetic variations are separated in phase by 0.08. Catalano, Kroll & Leone (1991) obtained photometric observations in JHK bands and again found a phase shift of ≈ 0.1 between photometric and magnetic variations. They also noticed that IR light curves are shifted relative to UBV light curves.

The mean longitudinal magnetic field ("effective field"), B_ℓ, of HD 24712 has been measured by Preston (1972) and by Mathys (1991). Leroy et al. (1993), Bagnulo et al. (1995) and Leroy (1995) measured the linear polarization in broad spectral bands, which are sensitive to the mean transverse component of the magnetic field. Mathys combined his B_ℓ data and ours (see the following section) with those of Preston to revise the stellar rotation period. He concluded that the period adopted by Kurtz & Marang is probably not correct and derived a period $P = 12\overset{d}{.}4610 \pm 0\overset{d}{.}0025$ which was less precise but described better the magnetic variations of HD 24712. Based on Fourier analysis of both circular and linear polarization data, Bagnulo et al. (1995) derived a period $P = 12\overset{d}{.}4610 \pm 0\overset{d}{.}0011$, which confirms Mathys' value and has a smaller error. They also mentioned that Kurtz & Marang's period could not be ruled out by the analysis of the linear polarimetric data alone.

Combining linear and circular polarimetric data allows one to define an unambiguous (though undoubtedly simplified) model of the magnetic field geometry for HD 24712: a centered dipole with a polar field strength $B_{\rm p} = 3.9$ kG, an inclination angle between the line of sight and the stellar rotation axis of $i = 43°$, and an angle between the magnetic and rotation axes of $\beta = 30°$. Because of the constraints on both, the longitudinal and the transverse field components, these two angles are uncertain by less than 5°, apart from small additional inaccuracies introduced by the choice of which of the B_ℓ measurements (see Sec.2) to be used. These angles are very close to those obtained by Preston (1972), although his model, based purely on mean longitudinal field measurements, had much greater uncertainties. For a centered dipole, this geometry results in a mean field modulus ("surface field") of $B_{\rm s}$ between 2.5 kG and 3.0 kG which is also in a close agreement to 2.6 kG estimated by Preston (1971) from line broadening. This relatively weak magnetic field, in combination with the rotational velocity $v \cdot \sin i = 7\,{\rm km\,s^{-1}}$ (Preston 1972) prevents the direct observation of magnetic splitting of spectral lines even for those with appropriate Zeeman pattern (Mathys & Lanz 1992).

While a considerable amount of information is available for magnetic, photometric, and spectrum variations, not a lot is known about the atmospheric abundances of HD 24712. The light elements C, N, and O are found to be deficient in HD 24712 by -1.0, -0.4, and -0.7 dex, respectively (Roby & Lambert 1990). Faraggiana (1989) was unable to detect lines of the heavy elements Pb, Th, and U in the 2000-3000 Å spectral region.

The present paper continues a series on the abundance analysis of roAp stars, with the goal of providing accurate fundamental parameters for this group of pulsating stars, especially $T_{\rm eff}$, log g and abundances.

2. Observations

Spectra of HD 24712 were obtained with the Coudé spectrograph of the Canada-France-Hawaii telescope in 1984 on eight consecutive nights, covering about 2/3 of one rotation.

The f/7.4 camera and 830 lines mm^{-1} grating were used with the 1872 diode Reticon detector (Campbell et al. 1981) giving a spectral range ≈ 65 Å long with 0.10 Å resolution. Spectra were obtained in the 4460-4525 Å spectral region, which includes many lines of the most important atoms and ions, including the Mg II doublet and numerous lines of REE.

Table 1 shows a journal of our spectroscopic observations. It gives mid-time of the exposures, the corresponding phases derived from

$$JD(B_{\ell,max}) = 2440576.8 + 12\overset{d}{.}4610 \cdot E$$

(see discussion in Sec. 4), and signal-to-noise ratios for typical continuum pixels. The two last columns contain information on the spectrum variability.

Table 1. Log of our HD 24712 spectroscopic observations. We number the spectrograms for reference in this paper, and tabulate times of mid-exposure, phases relative to the maximum magnetic field, signal-to-noise ratios for representative continuum pixels, equivalent width ratios determined for Nd II lines and for the Mg II 4481Å line, relative to the line widths at phase 0.793 (spectrum No. 6).

No.	Mid exposure JD 2440000+	Phase	S/N	W_λ/W_λ^6 Nd II	Mg II
1	5566.131	0.396	175	0.77±0.06	1.22
2	5567.126	0.476	215	0.67±0.03	1.26
3	5568.066	0.551	300	0.66±0.03	1.25
4	5569.082	0.633	200	0.71±0.03	1.24
5	5570.067	0.712	150	0.81±0.02	1.15
6	5571.076	0.793	150	1.00	1.00
7	5572.077	0.873	150	1.22±0.06	0.85
8	5573.060	0.952	160	1.40±0.09	0.75

We also have obtained a series of longitudinal field measurements for HD 24712 (see Tab. 2). These data were obtained in July 1983 with the University of Western Ontario photoelectric cassegrain polarimeter as a Zeeman analyzer attached to the 2.5-m Dupont telescope at the Las Campanas Observatory. Observations were obtained through a tilt-tuned Hβ filter of 5 Å FWHM (e.g., Bohlender et al. 1993). The circular polarization data were converted to the longitudinal field strength, B_ℓ, using a Hβ scan, which yielded a mean conversion constant of 13 600 G per % polarization. The quoted errors are calculated from photon statistics.

Table 2. Hβ-line polarimetric longitudinal magnetic field measurements for HD 24712. Time of mid-integration, phases relative to the maximum magnetic field, longitudinal magnetic field strength, B_ℓ, and estimated errors are given.

Mid exposure JD 2440000+	Phase	B_ℓ (G)	σ_B (G)
5534.926	0.892	1440	170
5535.921	0.971	1620	170
5537.910	0.131	810	240
5540.930	0.373	590	190
5541.913	0.452	500	140
5543.917	0.613	690	260
5544.909	0.693	1000	150

These data were already discussed by Mathys (1991) who noted that our data are about 250 G more positive than his own and Preston's measurements, based on metal lines. Such a modest discrepancy between magnetic data obtained from Hβ polarimetry and those obtained from metal lines are common, but unfortunately do not follow a simple pattern. It may be related with the difficult modelling of Zeeman broadened Balmer lines. Our data are plotted in Fig. 1 in panel (c) with filled diamonds, without any shifts to force an agreement with Preston's and Mathys' observations.

3. Reduction of spectra

All spectra were reduced as is described by Landstreet (1988) for the Ap star 53 Cam. We have slightly modified the original continuum fitting using the pcIPS package (Smirnov & Piskunov 1993), and synthetic spectra served as a guide line to place properly the continuum. Based on preliminary abundances (Kupka et al. 1995) we determined spectral regions with continuum windows, identified them in the observed spectrum and made a polynomial fit of typically 2nd order which was used for renormalizing the spectra. Wavelengths, half widths (FWHM) and equivalent widths were measured with the MultiProfile program (Smirnov & Ryabchikova 1995) which simultaneously fits Gaussian profiles to metal lines. A comparison of our measurements with the literature can be based only on mean equivalent widths of two spectral lines, Ti II λ4468 and Mg II λ4481 (Bonsack 1979). Within the errors typical for photographic measurements, equivalent widths of both lines are in good agreement with our values. Therefore we used part of the data published by Bonsack for abundance determination of elements which could not be obtained in the spectral regions observed by us.

With a typical signal-to-noise ratio of 150 in the continuum and a line width of FWHM = 0.15Å we obtained a formal 3σ error of about 2 mÅ for our equivalent width measurements of individual lines.

The Vienna Atomic Line Database (VALD, Piskunov et al. 1995) was extensively used for line identifications, based on preliminary abundances obtained by Kupka et al. (1995) as initial parameters for the line selection procedure. Only those lines from VALD which reduce unwidened by rotation the continuum level by at least 1 % were used for our synthesis. A more detailed description of the identification of various ions will be given in Sec. 7.

4. The period of the magnetic, spectrum and light variations

As previously discussed, several slightly different periods have been proposed for the rotation of HD 24712. Preston's (1972) original period has been modified by Kurtz & Marang (1987) based on photometric and line strength variations data, by Mathys (1991) and Bagnulo et al. (1995) based on magnetic and polarimetric data. The period of Kurtz & Marang leads to a phase shift between the magnetic curve (Preston 1972) and the light curve by 0.08 (or 1 day). In the following we investigate whether our data can shed any light on the question of which period to be prefered.

Our spectroscopic observations cover slightly less than two thirds of a rotation cycle. We applied both ephemerides to our equivalent width data and selected for this purpose five unblended lines of Nd II ($\lambda\lambda$ 4462.979, 4467.839, 4501.812, 4506.583, and 4516.346 ÅÅ), an element which shows the strongest spectral line variations. The average equivalent widths per spectrum were normalized to spectrum No. 6 and are listed in Tab. 1 in column five with the respective errors. Due to the higher quality of our spectra, the errors are smaller than those, e.g., of Preston (1972). Furthermore, we can use weaker spectral lines which are less influenced by possible magnetic intensification and hyperfine-structure effect. Relative intensities of the Mg II λ 4481Å line are given in the sixth column of Tab. 1.

For a discussion of the published rotation periods we used measurements of the effective magnetic field derived from Ti-Cr-Fe lines by Preston (1972), magnetic field measurements obtained by Mathys (1991), Δ B photometric data from Kurtz (1982), Kurtz & Seeman (1983) and Kurtz & Marang (1987), as well as our equivalent width measurements. A plot of all these data based on the ephemeris from Kurtz & Marang (1987) results in phase = 0.4 for the magnetic minimum, phase = 0.5 for the light maximum, and phase = 0.6 for the REE minimum.

With the ephemeris from Bagnulo et al. (1995), on the other hand, we obtain coincidence in phase for the extrema of magnetic, light and spectral variations. A plot of all data is shown in Fig. 1. Our spectroscopy alone is not sufficient to yield a definite conclusion about the rotation period of HD 24712, but it supports the value which removes the phase shifts between spectroscopic, photometric and magnetic variations. Because this solution provides a simpler model for the star's geometry than is implied by a period which results in various phase shifts for different stellar phenomena, we adopt in the following discussions the ephemeris used for Fig. 1.

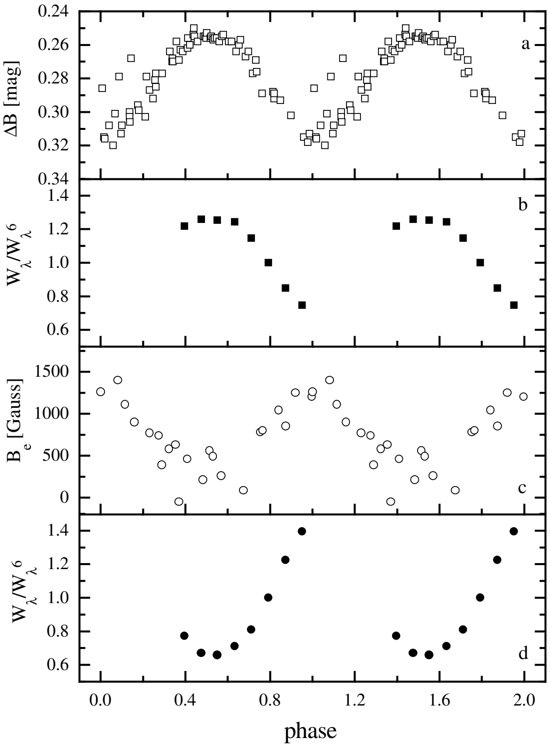

Fig. 1. ΔB variations (a, top), relative intensity variations of the Mg II λ 4481 line (b), mean longitudinal magnetic field variations (c), and relative intensity variations of Nd II lines (d, bottom) with the ephemeris JD(magn.max) = 2440576.$^{\rm d}$8 + 12.$^{\rm d}$4610 · E

5. The magnetic field of HD 24712

The absence of resolved Zeeman splitting (Mathys 1991) for the Fe II λ 6149 line which has doublet Zeeman configuration with a Landé factor $g_{\rm eff} = 1.33$ indicates a weak surface magnetic field. According to Bagnulo et al. (1995), id the choice is made to renormalize our magnetic data by -250 G to bring them into agreement with those of Mathys and Preston, all circular and linear polarization measurements can be modelled with a pure dipole and a polar magnetic field strength $B_{\rm p} = 3.9$ kG, $i = 43°$, and $\beta = 30°$. Note that these angles imply that, as the star rotates, the sub-solar point shifts from an angular distance of about 13° from the magnetic pole to about 73°, which explains why the observed effective magnetic field does not reverse. The relation between both the surface ($B_{\rm s}$) and longitudinal (B_ℓ) magnetic fields and the polar field for a pure dipolar configuration (Hensberge et al. 1977) is:

$$B_{\rm s} = B_{\rm p}\frac{3}{(3-u)}((0.77778(1-u)+0.55165u)\cos^2\alpha$$
$$+(0.64775(1-u)+0.41426u)\sin^2\alpha), \qquad (1)$$

and:

$$B_\ell = B_{\rm p}\frac{15+u}{20(3-u)}\cos\alpha, \qquad (2)$$

with u being the limb-darkening coefficient (0.616 in our case), and α the angle between the magnetic axis and the line of sight. Using this relation and the dipole parameters from Bagnulo et al. (1995) we estimate the $B_{\rm s}$ variation between 2.5 and 3.1 kG, which is in good agreement with Preston's (1971) value of 2.6 kG. B_ℓ varies between 0.4 and 1.3 kG. With the parameters of the magnetic dipole $B_{\rm p} = 4.4$ kG, $i = 40°$, $\beta = 30°$ derived by Preston (1972) we obtain $B_{\rm s}$ variation between 2.9 and 3.5 kG and that of B_ℓ between 0.5 and 1.4 kG. A combination of Preston's value for the polar field with the angles from Bagnulo et al. provides slightly larger amplitude of B_ℓ variations between 0.4 and 1.4 kG which is more consistent with the observations. The corresponding limits for surface field variations lie between 2.8 and 3.5 kG.

To test the adopted simple magnetic model, we tried to estimate the mean field modulus directly from our HD 24712 spectra with two methods. The major line broadening effects are due to stellar rotation, instrumental broadening, rotation and the magnetic splitting. Both methods described in the following are based on line width measurements, but different sets of lines were chosen according to different selection criteria.

First, we repeated slightly modified Preston's procedure. Instead of two groups of lines with small and large effective Landé factors $g_{\rm eff}$ we considered line widths in the whole range of $g_{\rm eff}$-values (0.3 to 1.7). In the case of unresolved Zeeman lines, when the magnetic splitting is less than the Doppler and instrumental broadening, the full width at half maximum (FWHM) of a spectral line may be written approximately as:

$$FWHM^2 = FWHM_0^2 + K^2\cdot\lambda^4\cdot g_{\rm eff}^2, \qquad (3)$$

where K is a constant proportional to the magnetic field, $B_{\rm s}$, with a calibration according to Preston (1971):

$$B_{\rm s}(kG) = 0.5 + 7.9\cdot K \qquad (4)$$

For a set of 25 lines with measured FWHM-values we calculated a least-squares linear fit of FWHM^2 and $\lambda^4 g_{\rm eff}^2$. This solution gives us the Doppler plus instrumental width

FWHM$_0$ (excluding magnetic effects) and the constant K. Note that the error in FWHM measurements of our line sample is about 0.006 Å. Hence, the expected magnetic broadening due to a 2.5 kG field exceeds eight times the error. Our surface magnetic field estimates are given in Tab. 3 for the phase of magnetic minimum (spectrum No. 3), magnetic maximum (spectrum No. 8) and for the FWHM values averaged from all our spectra.

The second method is based on a different approximation for the magnetic splitting of spectral lines. While rotational and instrumental broadening result in an approximately Gaussian spectral line profile, the stellar magnetic field splits the lines into groups of π and σ components. The simplest case of a Zeeman splitting (the anomalouse Zeeman effect) can be described by one π component at the unshifted wavelength (λ_0) – i.e. the wavelength without magnetic field –, and two symmetrically shifted σ components, where the shift ($\Delta\lambda_m$) is proportional to the magnetic field strength (Babcock 1958).

$$\Delta\lambda_m = \pm 4.67 \cdot 10^{-10} \cdot g_{\rm eff} \cdot \lambda_0^2 \cdot B_{\rm s}, \quad (5)$$

With the magnetic field $B_{\rm s}$ in kG, λ_0 in Å, and the effective Landé factor, $g_{\rm eff}$. The intensity ratio of the components π/σ depends on the orientation of the stellar magnetic field relative to the line of sight and is described by Seares equations (Seares 1913). This ratio changes from 0 to 2.0, corresponding to an angle between the magnetic field vector and the line of sight changing from 0° to 90°. For most spectral lines the Zeeman splitting is more complex, but a simple Zeeman triplet with an individual effective Landé factor, $g_{\rm eff}$, is a reasonable approximation.

The sum of the squares of rotational broadening, $V_{\rm rot}$, and instrumental broadening, $V_{\rm inst}$, gives the total non-magnetic broadening:

$$\Delta\lambda = \frac{\lambda_0}{c}\sqrt{V_{\rm rot}^2 + V_{\rm inst}^2}, \quad (6)$$

where c is the speed of light, λ_0 is the unshifted wavelength in Å, and all velocities are given in km s^{-1}. Figure 2 shows the scheme for a magnetically split spectral line with the typical π (at λ_0) and σ (shifted by $\pm\lambda_m$) Zeeman components. Each of them has a FWHM, corresponding to the total non-magnetic broadening $\Delta\lambda$.

The observed spectral line is the sum of three Zeeman components, as is illustrated in Fig. 2, and is always smaller than the sum of the total non-magnetic broadening and the magnetic splitting.

$$FWHM \lesssim 2 \cdot \frac{\Delta\lambda}{2} + 2 \cdot \Delta\lambda_{\rm m} \quad (7)$$

The stellar surface magnetic field can therefore be estimated with

$$B_{\rm s} \lesssim \frac{FWHM - \Delta\lambda}{2 \cdot 4.67 \cdot 10^{-10} \cdot g_{\rm eff} \cdot \lambda_0^2}. \quad (8)$$

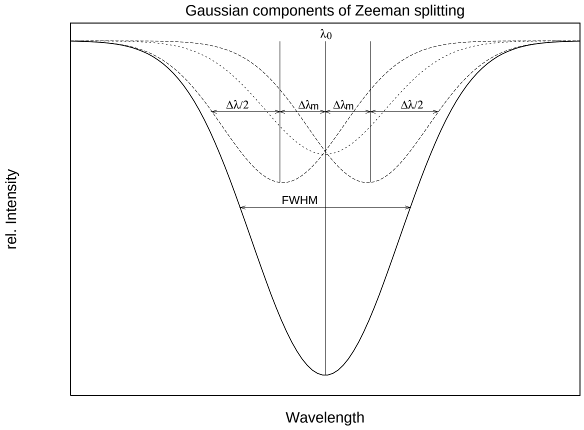

Fig. 2. Schematic Zeeman splitting with an intensity ratio for the components $\sigma_\pm/\pi = 1.2$ which corresponds to an angle between the magnetic field and the line of sight of 50°.

This equation gives only an upper limit for the magnetic field, but since we are using effective Landé factors the magnetic splitting is rather underestimated. Furthermore, weak and unresolved blends in most of the suitable lines tend to increase the measured FWHM. In summary, these uncertainties tend to compensate each other.

Finally, 19 unblended lines with equivalent widths of less than 100 mÅ were used to estimate the maximum and minimum surface magnetic field of HD 24712 (Tab. 3).

Table 3. Surface magnetic field of HD 24712 derived with two methods described in the text. Spectrum No. 3 was obtained at magnetic minimum, No. 8 at magnetic maximum.

Spec. No.	FWHM$_0$ Å	K	B$_s$, kG method 1	B$_s$, kG method 2
3	0.147±0.038	0.29±0.15	2.8±1.7	2.5±1.0
8	0.149±0.038	0.32±0.15	3.0±1.7	3.3±1.3
all	0.147±0.033	0.28±0.13	2.7±1.5	

Both methods give similar values for the surface magnetic field. The relatively high errors can be explained primarily by the line variability connected with the spotty surface distribution of different chemical elements. The limited spectral range of our data does not allow us to estimate the magnetic field with lines of individual chemical elements or groups of similar elements, like for example the iron-peak or REE. However, when increasing the polar field to 4.4 kG, a value which is favoured by Bagnulo et al. (1995), our results – including B_ℓ measurements – are in even better agreement with the simple dipolar magnetic field model.

The non-magnetic part of the total line half-width (FWHM$_0$) may be used to derive a more accurate value for the rotational velocity. With the instrumental resolution of 0.1 Å we obtain $v \cdot \sin i = 5.6 \pm 2.3$ km s^{-1}. This value is consistent with 6±2 km s^{-1}, recently determined by Wade (1997).

6. The model atmosphere

For HD 24712 both Strömgren and Geneva photometry give a very similar effective temperature (see Renson et al. 1991: $T_{\rm eff} = 7230$ K (Strömgren) and $T_{\rm eff} = 7200$ K (Geneva)). The Geneva photometric indices are not sensitive in this temperature region to the surface gravity, while $\log g = 4.26$ is given by the Strömgren calibration. The determination of stellar temperature and surface gravity with Strömgren photometry yields good estimates for the normal B, A, and F-type stars. Enhanced line blanketing in the spectra of chemically peculiar stars, however, leads to a redistribution of the flux which affects the calibration and makes their application to CP stars problematic. Fortunately, our preliminary abundance analysis (Kupka et al. 1995) indicates no significant deviation for the iron-peak element abundances, which mainly define the line opacities, from the solar values. This justifies our use of the atmospheric model with solar composition.

All model atmospheres are based on the ATLAS9 code (Kurucz 1993). For the final analysis we used a model with $T_{\rm eff} = 7250$ K, $\log g = 4.3$, and $\xi_{\rm t} = 1.0$ km s^{-1}. The microturbulence value was derived from Fe I and Fe II lines. Recent model calculations with a new treatment of convection (Smalley & Kupka 1997) confirm our choice for the atmospheric parameters of HD 24712. Most likely, the non-zero microturbulence is only due to magnetic effects. If we treat the magnetic intensification in terms of adding microturbulence (see, e.g., Paper I and III), than each spectral line will have its own microturbulent velocity depending on $g_{\rm eff}$. Kurucz's original program WIDTH9 was modified by V. Tsymbal to take into account magnetic effects through the magnetic pseudo-microturbulence. We used this version, called WIDTH9mf, for all abundance calculations except for the blended lines which were synthesized with SYNTH and ROTATE codes (Piskunov 1991). A magnetic field of about 2 kG is sufficient to remove a trend of individual line abundances versus their equivalent widths. This is equivalent to a mean magnetic pseudo-microturbulence of 1.0 km s^{-1} for a line with $g_{eff} = 1.0$ and 4500 Å.

Our effective temperature is very close to the recently derived $T_{\rm eff} = 7330 \pm 140$ K (Wade 1997). His estimates of the mass, radius and luminosity give $\log g = 3.97 \pm 0.35$. Our spectroscopicially determined $\log g$, although still being within Wade's $1-\sigma$ error limits, is clearly larger. The difference between the evolutionary and the spectroscopically determined surface gravity will be discussed in Sec. 8.

7. Abundance analysis

All atomic parameters needed for abundance calculations were extracted from VALD (Piskunov et al. 1995) which was supplemented by the experimental data for Fe I from Bard, Kock & Kock (1991), Bard & Kock (1994), and Johansson et al. (1994). More accurate wavelengths for Fe I were taken from Nave et al. (1994). For Dy I, Gd I, and Er I we also used *gf*-data from Komarovskij & Smirnov (1992, 1993, 1994), for Gd II from Bergston et al. (1988), and the new intensity calibration of La II lines from Bord, Barisciano & Cowley (1996) which are now included in VALD.

Mean atmospheric abundances of HD 24712 for the phases of magnetic minimum (dominant magnetic equator, spectrum No. 3), and magnetic maximum (dominant magnetic pole, spectrum No. 8), are summarized in Tab. 4. Due to the specific orientation of magnetic and rotation axes of HD 24712 relative to the observer, no information about abundances near the hidden negative magnetic pole is available. The abundances are compared in this table with those of the roAp stars α Cir (Paper I), HD 203932 (Paper II) and γ Equ (Paper III). The last column of Tab. 4 contains solar atmospheric abundances (Anders & Grevesse 1989), complemented by recent data on C,N,O (Biemont et al. 1993), S (Biemont, Quinet & Zeippen 1993), Ti (Bizzarri et al. 1993), Cr (Pinnington et al 1993), Fe (Biemont et al. 1991, Holweger et al.1991), and Dy (Biemont & Lowe 1993). Those elements for which the HD 24712 abundances were determined by spectrum synthesis are marked with an asterisk, those for which abundances are estimated from the mean equivalent widths given in Bonsack (1979) are marked with two asterisks.

Our analysis confirms Bonsack's conclusion about the lack of a monotonic correlation between the amplitude of abundance variations and the atomic number Z. According to Bonsack's (1979) and the present results only Mg has a strong antiphase variation with the REE, whereas the variations of Al to Ni are very small. The only exception from the iron-peak elements is Co, for which the variations are *in phase* and as strong as for the REE.

7.1. Light elements: C to Ca

Roby & Lambert (1990) found CNO elements to be deficient in HD 24712 by -1.0, -0.4, and -0.7 dex, respectively. Similar deficiencies were found in HD 203932 (Paper II) while in α Cir (Paper I) the most deficient element seems to be oxygen. C is only slightly deficient, and no data for N and O are available for γ Equ. At phases of Mg maximum Mg, Al, Si, and Ca show practically solar abundances for all four roAp stars including HD 24712 , while these elements are deficient by 1.0 dex in the minimum phases.

Table 4. Abundances of the roAp star HD 24712 with error estimates in units of 0.01 dex based on n measured lines. An asterisk indicates that the spectrum synthesis technique was used for the abundance determination. Two asterisks indicate that abundances are based on the mean equivalent widths from Bonsack (1979). The abundances for HD 203932, α Cir and the Sun are published only for the elements and we quote therefore the same abundance for all ions of the same element.

Ion	HD 24712			HD 203932	γ Equ	α Cir	$\odot$
	minimum B_ℓ	maximum B_ℓ					
	$\log(N/N_{tot})$		n	$\log(N/N_{tot})$	$\log(N/N_{tot})$	$\log(N/N_{tot})$	$\log(N/N_{tot})$
Mg II*	-4.55	-5.60	1	-4.23	-4.50	-4.46	-4.46
Al I **	-5.53:		1	-5.34	-4.93		-5.57
Si II**	-4.43:		1	-4.39	-4.42	-4.20	-4.49
Ca I**	-5.69		1	-5.17	-5.40	-5.15	-5.68
Ca II	-5.22:	-4.88:	1	-5.17	-6.03:	...	-5.68
Ti I	-7.22±14	-7.29±20	2	-7.01	-6.95	-6.87	-7.00
Ti II	-7.08 04	-7.28 12	5	-7.01	-7.00	-6.87	-7.00
Cr I	-5.93 07	-5.80 06	6	-5.64	-5.43	-5.55	-6.30
Cr II	-5.58:	-5.33:	1	-5.64	-5.66	-5.55	-6.30
Mn I	-6.77 03	-7.01 03	3	-6.39	-6.01	-6.00	-6.49
Fe I	-4.77 14	-4.88 25	8	-4.42	-4.28	-4.50	-4.56
Fe II	-4.80 12	-5.11 19	5	-4.42	-4.42	-4.50	-4.56
Co I	-5.88 06	-5.57 19	4	-5.97	-5.98	-5.50	-7.12
Co II	-6.01 41	-5.53 50	2	-5.97	-6.18	-5.50	-7.12
Ni I	-6.18 24	-6.34 24	1	-5.88	-6.06	-6.15	-5.79
Sr II**	-8.20		1	-7.38	-7.43	-7.25	-9.14
Y I *	-7.80	-7.80	2	-8.29	-7.94		-9.80
Y II*	-8.30	-8.30	1	-8.29	-8.51	-8.50	-9.80
In I	-9.50	-9.00	1				-10.58
Ba II*	-9.12	-8.98	1	-9.33	-9.06	-10.30	-9.91
La II*	-9.40	-8.75	3	-10.10	-9.59	-10.32:	-10.82
Ce II	-9.18 06	-8.90 09	5	-9.27	-9.20	-9.40	-10.49
Pr II	-10.15	-9.60	1	-10.09	-9.98	-10.40	-11.33
Nd II	-9.13 19	-8.64 11	8	-9.50	-9.17	-9.30	-10.54
Sm II	-9.75 26	-9.16 15	4	-10.06	-9.53	-9.50	-11.04
Eu II*	-9.50	-9.00	2	-9.15	-10.24	-9.40	-11.53
Gd II	-9.11 10	-8.70 12	5	-9.90	-9.35	-9.45	-10.92
Dy II	-9.38 24	-8.94 21	3		-9.14	-10.00:	-10.84
Er II	-9.79	-9.53	1	-9.73	-10.04		-11.11
$T_{\rm eff}$	7250			7450	7700	7900	
log g	4.20			4.30	4.20	4.20	
B_s (kG)	2.5	3.0		<1.0	4.0	<3.0	

7.2. Iron peak elements: Sc to Ni

Chromium and iron abundances obtained from Bonsack's equivalent widths of three unblended lines agree with the present abundance determinations. We obtained the line-abundances $\log(\mathrm{Cr}/N_{tot})$ = -6.28 (Cr I λ 4274.8) and -5.75 (Cr II λ 4588.2), and $\log(\mathrm{Fe}/N_{tot})$ = -5.08 (Fe I λ 4271.8). Exept for Co, a comparison of the iron-peak abundances in four roAp stars shows a tendency for cooler stars to have lower abundances, perhaps even less than solar. Cobalt, on the other hand, has an overabundance of about 1.0 dex in HD 24712, HD 203932, γ Equ, and α Cir. For HD 24712 we obtained the ratio Cr:Co of about 1 and Co:Ni > 1 which seems to be a common feature for roAp stars (Paper I-III). It should be noted that atomic parameters for Co I and Co II lines were derived mainly theoretically by Kurucz (1994). Our analysis shows that plenty of Co lines can be detected even in the short spectral region of 4460-4526 Å and they could be used for abundance determinations. Unfortunately, no reliable atomic parameters yet are published for many Co as well as REE lines, what frequently makes their unambiguous identification difficult. Accurate experimental oscillator strengths for Co I and Co II lines are definitely needed, as well as hyperfine-structure data, which may lead to a reduced Co overabundance.

7.3. s-process elements: Sr, Y, In and Ba

The Sr abundance was obtained from the mean equivalent width of the Sr II λ 4215 line. We calculated a set

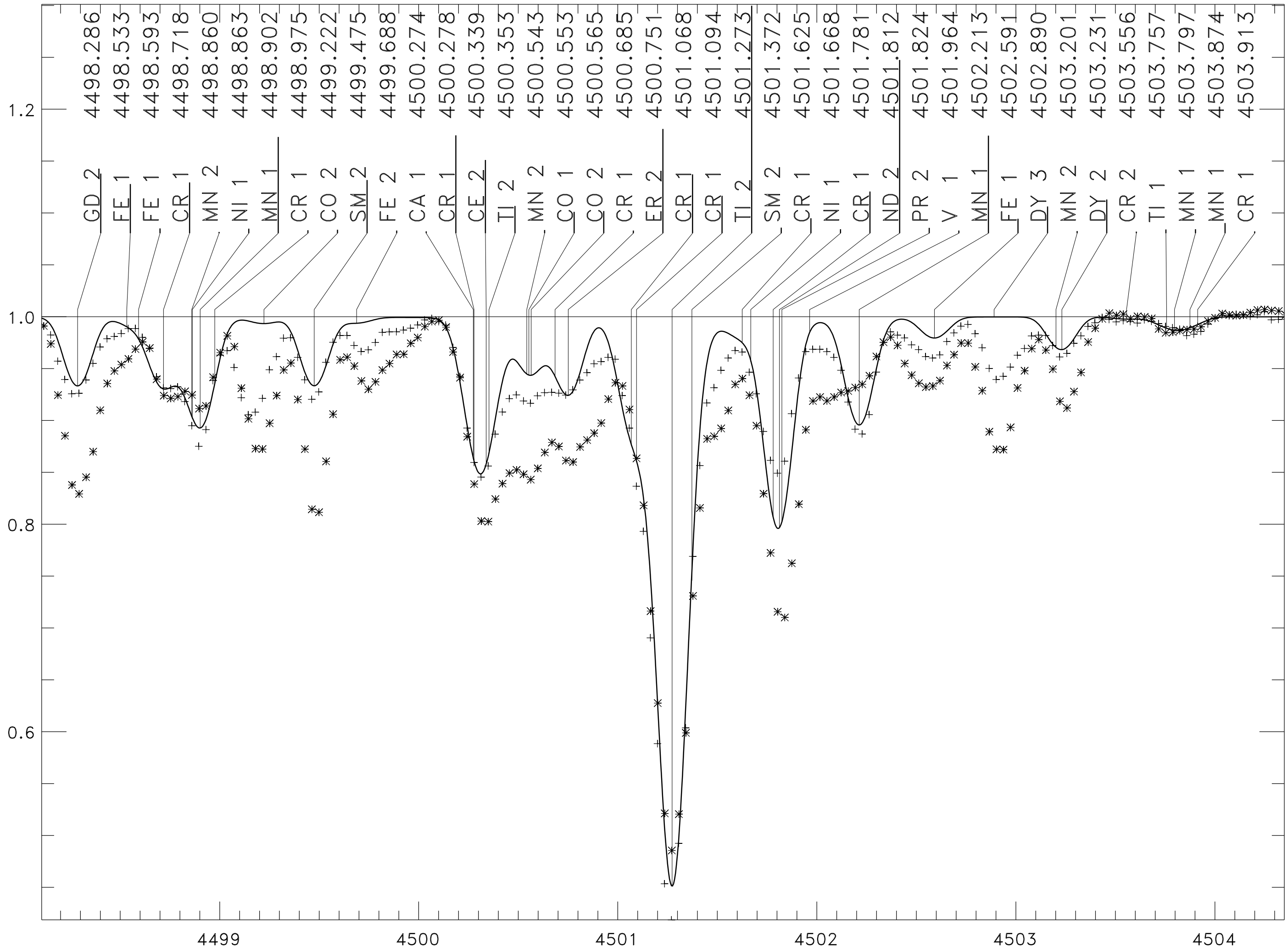

Fig. 3. Comparison of two spectra of HD 24712 taken at phase 0.551 (pluses, magnetic minimum) and at phase 0.952 (stars, magnetic maximum). The synthetic spectrum, calculated with the abundances obtained from spectrum No. 3 ($\Phi = 0.551$) is shown by the solid line.

of synthetic spectra in the region of this line taking into account hyperfine-structure as given by McWilliam et al. (1995). Sr is less abundant in HD 24712 than in the three other roAp stars, while Y has the same abundance in all four stars. Our Y abundance is confirmed by $\log(\mathrm{Y}/\mathrm{N}_{tot}) = -8.10$ obtained from the equivalent width of the Y II λ 3951 line measured by Bonsack (1979). The Ba abundance in HD 24712 changes slightly with rotation phase. With an equivalent width of the resonance Ba II λ 4554 line from Bonsack we deduce $\log(\mathrm{Ba}/\mathrm{N}_{tot}) = -8.70$ without taking possible blends into account, and which is in reasonable agreement with our result.

There are only two In I lines in the spectral region of 3800-5000Å. One In I λ 4511.307 line was clearly identified and the other one, at λ 4101.765, is close to the core of H_δ. The first line shows intensity variations with the same amplitude as the REE lines, and we therefore cannot exclude a wrong element identification due to the extremely poor knowledge of doubly ionized REE spectra. From this line we deduce an overabundance for In of 1.0 dex for the REE minimum and an overabundancy of 1.5 dex at REE maximum.

Usually, the elements in the fifth group of the periodic table of elements are represented in abundance analyses by Sr, Y, and Zr. Presently, anomalies of other elements of this group are found only for γ Equ in particular for Nb and Mo. The short spectral region we had at our disposal does not contain lines of either element. A careful investigation of elements in the fifth and sixth period is still needed for HD 24712.

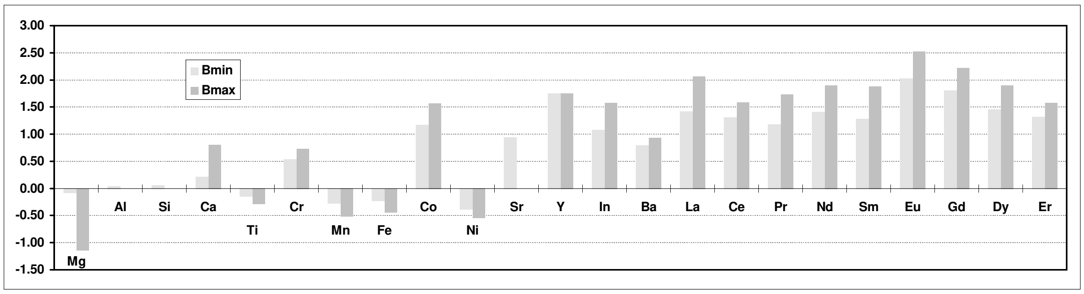

Fig. 4. Logarithm of abundances for HD 24712 relative to the sun for the phases of minimum (light grey bars) and maximum (dark grey bars) longitudinal magnetic field.

7.4. Rare Earth elements: La to Er

The REE have with an amplitude of about 0.5 dex, the largest abundance changes compared to all other elements, except Mg, which has an even larger amplitude. Except for Eu, the REE abundance pattern is similar to that of the sun. For three out of four roAp stars studied so far (HD 24712, HD 203932, and α Cir) a violation of the odd-even effect in the Sm-Eu-Gd sequence is observed. The REE abundances of HD 24712 at minimum line intensity are similar to γ Equ, while at maximum the REE abundances are the highest of our sample of roAp stars. There are many as yet unidentified lines in the spectrum with intensity variations *in phase* with REE lines. Some of them could be associated with lines of double ionized REE, like a blend of Nd III λ 4483.43 and Dy III λ 4483.386, as well as Dy III $\lambda\lambda$ 4502.890 and 4510.004. Wavelengths for Nd III are taken from Cowley & Bord (1997), those for Dy III from Aikman, Cowley & Crosswhite (1979).

Fig. 3 displays a section of the HD 24712 spectrum for two extreme phases $\Phi = 0.551$ and 0.952. It is obvious that all unidentified features change their intensity in phase with REE. The positions of the Dy III λ 4502.890 line is also shown.

The Eu abundance is more uncertain because it is based only on two blended lines. The first one is the weak Eu II λ 4485.153 line which has to be shifted by -0.07 Å to fit our observed feature, and the second is λ 4522.58, and heavily blended. Bonsack (1979) published equivalent widths of Eu II $\lambda\lambda$ 4129 and 4205 lines for different rotation phases. Both lines suffer from strong hyperfine-structure (Hartoog, Cowley & Adelman 1974). We synthesized a small spectral region centered on λ 4205 and took hyperfine-structure into account through an additional pseudo-microturbulence of 4 km s^{-1} (see van't Veer-Menneret, Burkhart & Coupry 1988). Equivalent widths of this line can be fitted at Eu maximum and minimum with $\log(\mathrm{Eu}/\mathrm{N}_{tot}) =$ -9.0 and -9.8, respectively, which is not too different from our values in Tab. 4.

The mean enhancement of the REE abundances amounts to 1.48 and 1.93 dex for the phases of REE minimum and maximum, respectively. At REE minimum we find abundances for HD 24712 to be similar to those obtained for the Am star HR 178 (van't Veer-Menneret et al. 1988) which is further support for the claim of Magazzu & Cowley (1986) that the REE abundance pattern in cool Ap and in Am stars are quite similar.

8. Evolutionary status

Evolutionary estimates from the rigid rotator geometry (Wade 1997) as well as asteroseismology (Kurtz & Martinez 1993) indicate that HD 24712 has passed more than 50 % of its lifetime on the main sequence. Spectroscopic surface gravity suggests the star to be younger. If we were to decrease the model surface gravity, this would cause a smaller fraction of the iron to be ionized, an we would derive a larger abundance for Fe I than for Fe II. This discrepancy would not be resolved by NLTE effects for Fe I, since NLTE models usually also predict an increase in the iron abundance (relative to an LTE model) obtained from Fe I lines without changing that derived from Fe II lines

(Lemke 1989). Consequently, we have to expect for HD 24712 an even greater discrepancy in the the ionization equilibrium when taking NLTE into account.

For two other roAp stars, α Cir and γ Equ, we encounter a similar discrepancy between surface gravity values obtained from spectroscopy and from both evolutionary tracks and asteroseismology. Kurtz & Martinez (1993) give $M_{\rm v} = +1.9$ for both stars derived from parallaxes. This value is very close to $M_{\rm v} = +1.8$ obtained for γ Equ from asteroseismology. Using effective temperatures from Paper I and Paper II and bolometric corrections from Kurucz (1991) we obtain $\log(L/L_{\odot}) = 1.17$ for α Cir and 1.19 for γ Equ. From evolutionary tracks (Schaller et al. 1992) we obtain $M_{\star} \approx 1.85\,M_{\odot}$ for both stars. From luminosity and effective temperature we estimate a stellar radius of about $2.1 - 2.2\,R_{\odot}$, and with the estimated mass we obtain $\log g = 4.0$, which is again smaller than what we have obtained spectroscopically for α Cir and γ Equ (Tab. 4). Further observations as well as fully consistent model atmospheres with the magnetic field included are certainly needed.

9. Conclusion

Our abundance analysis of HD 24712 is the first one for this rapidly oscillating chemically peculiar star. To phase the spectroscopic and polarimetric observations we investigated the rotation periods discussed in the literature and conclude that $\rm P = 12\overset{d}{.}4610$ has to be preferred, mainly because this period results in the most plausible model for spectrum, light, and magnetic field variations.

Photometrically determined estimates for $T_{\rm eff} = 7230$ K and $\log g = 4.26$ agree well with what we derived from spectroscopy. A microturbulence of $\xi_{\rm t} = 1\,{\rm km\,s^{-1}}$ seems to be entirely simulated by a dipolar magnetic field with a polar field strength of 4.4 kG which is supported by our polarimetric observations. For such a model no microturbulent velocity is needed to synthesize spectral features, provided that blends and hyperfine-structure are taken properly into account.

A spotty distribution of the chemical elements on the surface of HD 24712 and rotation lead to different mean abundances for different (magnetic) phases as a consequence. Our results do not support the hypothesis of a monotonic correlation between the amplitudes of abundance variations and the atomic number Z.

Rare earth elements are the most overabundant elements relative to the sun, and they have the largest abundance amplitude within a rotation cycle; only Mg has a larger amplitude. For HD 24712 we find a clear overabundance of Co while most of the other iron peak elements are underabundant.

Finally we find disagreement for at least three roAp stars (α Cir γ Equ and HD 24712) between surface gravities obtained from spectroscopy on the one hand, and from both asteroseismology and evolutionary status on the other.

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