A rival for Babcock’s star: the extreme 30-kG variable magnetic field in the Ap star HD 75049

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ABSTRACT
The extraordinary magnetic Ap star HD 75049 has been studied with data obtained with the ESO VLTI and 2.2-m telescopes. Direct measurements reveal that the magnetic field modulus at maximum reaches 30 kG. The star shows photometric, spectral and magnetic variability with a rotation period of 4.049 d. Variations of the mean longitudinal magnetic field can be described to first order by a centered dipole model with an inclination $i = 25^\circ$, an obliquity $\beta = 60^\circ$ and a polar field $B_p = 42$ kG. The combination of the longitudinal and surface magnetic field measurements imply a radius of $R = 1.7 R_\sun$, suggesting the star is close to the zero-age main sequence. HD 75049 displays moderate overabundances of Si, Ti, Cr, Fe and large overabundances of rare earth elements. This star has the second strongest magnetic field of any main sequence star after Babcock’s star, HD 215441, which it rivals.

Key words: Stars: magnetic – stars: variables – stars: individual (HD 75049).

1 INTRODUCTION
The complex processes of atomic diffusion – radiative levitation and gravitational settling – occur in upper main sequence stars, and are particularly evident in chemically peculiar A, B and F-type stars, collectively known as Ap stars. Accordingly, these stars are good targets to place observational constraints on atomic diffusion, which is crucial for deepening our understanding of these processes within the framework of studies of the structure and evolution of stars, and for more global analysis of galactic chemical evolution. The Ap stars rotate considerably more slowly than spectroscopically normal main sequence stars with similar effective temperatures. A fraction of Ap stars have extremely long rotation periods from tens of days to tens of years, and even of the order of a century in the case of $\gamma$ Equ. There is no clear picture of the braking mechanism leading to such slow rotation, but the observational evidence strongly suggests that it is related to magnetic field (Mathys et al. 1997, Abt 2009).

Many Ap stars possess strong, predominantly dipolar magnetic fields. The first magnetic star, 78 Vir, was found by Babcock (1947). Eleven years later Babcock (1958) published the first catalogue of magnetic stars, and two years following that he discovered a huge 34 kG magnetic field in the star HD 215441 (Babcock 1960), known since then as “Babcock’s star”. Despite success in the years that followed in increasing the number known magnetic stars – especially in last several years (for example Hubrig et al. 2006, Kudryavtsev et al. 2006) – HD 215441 remains the record-holder for the main sequence star with the strongest magnetic field. The second strongest magnetic star, HD 154708, was discovered by Hubrig et al. (2005). Around the same time Kochukhov (2006) found HD 137509 to have magnetic field modulus of 29 kG. His result was in agreement with Mathys (1991) who discovered a very strong quadratic magnetic field up to 37 kG in this star and mentioned that it has one of the strongest magnetic fields. Surprisingly, the longitudinal magnetic field in HD 137509 is not very large and varies just from $-1.25$ to $+2.35$ kG (Mathys 1991). HD 154708 still has the strongest magnetic field known among the cooler rapidly oscillating (roAp) stars (Kurtz et al. 2006).

The origin of the magnetic fields in Ap stars and details of their peculiar properties are still mysteries, despite large efforts in the study of these stars. As usual in physics, analysis of extreme cases may provide key information, hence there is great interest in the stars with the strongest magnetic fields to help solve many problems in Ap stars. Recently, Freyhammer et al. (2008) discovered an extremely
strong magnetic field in the Ap star HD 75049. Many lines in the high resolution spectra are split into clear Zeeman patterns. From the value of splitting \( R = \frac{\lambda}{\Delta \lambda} \) estimated by Freyhammer et al. (2008), we deduced the photospheric magnetic field modulus to be about 30 kG. These observations also revealed a possibly short rotation period, and large variability both of the magnetic field and the spectral line intensities. Because of these interesting characteristics of this rare object, we obtained a series of high resolution spectra and carried out circular spectropolarimetric observations with the VLT. We present in this paper the results of our analysis.

2 OBSERVATIONS AND DATA REDUCTION

To characterise the magnetic field of an Ap star, it is necessary to have magnetic measurements that cover the rotational phases of the star well. While we had a preliminary estimate for the rotation period of 4.05 d determined by Freyhammer et al. (2008) from All Sky Automatic Survey (ASAS) photometric survey data (Pojmanski 2002), we were uncertain about this, so decided to spread new observations over half a year to be sure to determine the correct rotational period. There is also a possible 5.28 yr period in the ASAS data that was noted by Freyhammer et al. (2008). The nature of this long period is not clear, but it is certainly not a rotational period; the \( \sin i = 8.5 \text{ km s}^{-1} \) of HD 75049 does not allow that. Further understanding of this period will require long-term observations.

A series high resolution spectra were obtained in service mode using UVES (Ultraviolet and Visual Echelle Spectrograph) on the ESO VLT (Very Large Telescope). Twelve spectra were collected between 2007 October 10 and 2008 April 1. Two previous observations of this star with FEROS and UVES obtained in 2007 February and March were also used for this analysis. These observations were made with echelle spectrographs over long spectral regions. For FEROS the spectral range is 3500–9220 Å with a resolution \( R = \frac{\lambda}{\Delta \lambda} = 48,000 \); for UVES the range is 4970–7010 Å with a resolution of \( R = 110,000 \). A journal of high resolution spectroscopic observations with UVES at the VLT and FEROS at the ESO 2.2-m telescope. The columns give the Barycentric Julian Date (BJD) of the middle of each exposure, the exposure time, the signal-to-noise ratio that was measured in sections of the continuum free of spectral lines.

Table 1. A journal of high resolution spectroscopic observations with UVES at the VLT and FEROS at the ESO 2.2-m telescope. The columns give the Barycentric Julian Date (BJD) of the middle of each exposure, the exposure time, the signal-to-noise ratio that was measured in sections of the continuum free of spectral lines.

| BJD       | exposure time | S/N ratio | Instrument |
|-----------|---------------|-----------|------------|
| 2454141.66963 | 1500         | 190       | FEROS      |
| 2454171.50422 | 900          | 180       | UVES       |
| 2454387.81593 | 1800         | 250       | UVES       |
| 2454432.82489 | 1800         | 240       | UVES       |
| 2454451.83366 | 1800         | 250       | UVES       |
| 2454555.70226 | 1800         | 260       | UVES       |
| 2454468.84589 | 1800         | 230       | UVES       |
| 2454481.81465 | 1800         | 230       | UVES       |
| 2454513.78892 | 1800         | 80        | UVES       |
| 2454516.88904 | 1800         | 240       | UVES       |
| 2454524.64641 | 1800         | 240       | UVES       |
| 2454544.51608 | 1800         | 260       | UVES       |
| 2454547.51127 | 1800         | 300       | UVES       |
| 2454557.59095 | 1800         | 240       | UVES       |

3 ROTATION PERIOD

The rotation period is an important parameter for the analysis of magnetic stars, which normally show photometric, spectral and magnetic variability with this period. In HD 75049 we found a clear picture of variability in all three cases. As mentioned above, photometric variability was detected in ASAS data, and spectral and magnetic variability were found from high resolution spectra (Freyhammer et al. 2008). Our new longitudinal field measurements have allowed us to determine the rotation period with confidence and higher accuracy.

Using a Discrete Fourier Transform (Kurtz 1985) and the programme PERIOD04 (Lenz & Breger 2005), we found a highest peak in the amplitude spectrum of the FORS 1 \( B_z \) data (comprising 13 measurements) at \( f = 0.2477 \text{ d}^{-1} \); using least squares fitting of a sinusoid we found \( f = 0.2470 \text{ d}^{-1} \), as is seen in Fig. We refined the fitted frequency and calculated uncertainties using nonlinear least-squares fitting, fitting the function

\[
B_z = A_0 + A \cos[2\pi f (t - t_0) + \phi]
\]

which gives our final values:

\[
f = 0.246975 \pm 0.000005 \text{ d}^{-1}
\]

\[
P_{rot} = 4.04899 \pm 0.00008 \text{ d}
\]

\[
A_0 = -5127 \pm 34 \text{ G}
\]

\[
A = 4824 \pm 40 \text{ G}
\]

\[
\phi = 0.00 \pm 0.01 \text{ rad}, \text{ where}
\]

\[
t_0 = \text{BJD} 245 4509.550 \pm 0.006
\]

\[
\sigma = 121 \text{ G}
\]

The standard deviation \( \sigma \) is per measurement with respect to the fit. The error on \( A_0 \) is thus \( \frac{\sigma}{\sqrt{N}} \), where \( N = 13 \) data points. The error on \( t_0 \) is the error in phase divided by \( 2\pi f \). We thus get an ephemeris of

\[
B_z^{max} = \text{BJD} 245 4509.550 \pm 0.006 + 4.04899 \pm 0.00008 E.
\]

The value of the rotation period is consistent with that deduced from ASAS data, and the error in the rotation period is within the limits of the photometric determination.
This yields an upper limit to the colour excess of only 0.05 ˚A for any in-
involving any interstellar component in the Na D1 and D2 lines, which show doublet splitting and belong to the star; any in-

denosing is negligible for this star. There is no clear eviden-
e in Table 2. Observations of HD 75049 with FORS 1. The columns give the Barycentric Julian Date (BJD) of the middle of each exposure, the rotational phase according to the ephemeris in eq. 2, and the longitudinal magnetic field for two wavelength ranges of the spectrum and for the hydrogen lines with the error of measurement.

| BJD          | rotation phase | longitudinal magnetic field $B_z$ (G) | hydrogen lines |
|--------------|----------------|--------------------------------------|----------------|
| 2454482.76787 | 0.3978         | −8894 ± 68                           | −9744 ± 132    |
| 2454483.69947 | 0.6057         | −9071 ± 39                           | −9938 ± 74     |
| 2454493.70464 | 0.0989         | −905 ± 32                            | −1475 ± 61     |
| 2454516.73363 | 0.7865         | −4471 ± 35                           | −5064 ± 65     |
| 2454526.56586 | 0.2148         | −3538 ± 40                           | −3970 ± 74     |
| 2454527.58159 | 0.4657         | −9832 ± 36                           | −10529 ± 72    |
| 2454532.72343 | 0.7356         | −5811 ± 49                           | −6367 ± 91     |
| 2454539.77171 | 0.4764         | −9639 ± 46                           | −10334 ± 94    |
| 2454543.57545 | 0.4158         | −9237 ± 39                           | −9941 ± 75     |
| 2454546.52195 | 0.1435         | −1821 ± 44                           | −2364 ± 86     |
| 2454555.53106 | 0.3685         | −8139 ± 33                           | −8528 ± 64     |
| 2454557.61944 | 0.8843         | −1785 ± 34                           | −2397 ± 62     |
| 2454464.85968 | 0.9749         | −640 ± 36                            | −1415 ± 68     |

4 THE STELLAR PARAMETERS

As an initial step to determine the fundamental stellar parameters we employed previous photometric observations. We used the uvbyβ photometry by [Martinez, 1993] and the UVBYBETA program written by T.T. Moon and modified by [Napiwotzki et al., 1993] based on the grid published in [Moon & Dworetsky, 1985]. We derived an effective temperature, $T_{\text{eff}} = 9600$ K, and a gravity of log $g = 4.47$ (cgs). The surface gravity is an issue, since it is known that photometric calibrations of the c1 index, which are useful for determination of luminosity (hence surface gravity) for normal stars, are not entirely suitable for Ap stars, where they tend to underestimate luminosity because of heavy line blanketing in the v filter. The effective temperature estimate, on the other hand, usually needs only a small correction (e.g. [Hubrig, North, & Mathys, 2003]). The reliability of the gravity estimate from Strömgren photometry is discussed by [North & Kroll, 1989]. From Geneva photometry ([Mermilliod, Mermilliod, & Hauck, 1997] and using different calibrations [Cramer & Maudet, 1979; North & Nicolo, 1994]), we obtained effective temperature estimates from 9300 K to 9900 K. These, together with the estimate from uvbyβ, give an average photometrically-determined value of $T_{\text{eff}} = 9600 ± 300$ K. Interstellar reddening is negligible for this star. There is no clear evidence of any interstellar component in the Na D1 and D2 lines, which show doublet splitting and belong to the star; any interstellar component is below 0.05 Å in equivalent width. This yields an upper limit to the colour excess of only $E_{B-V} < 0.02$ ([Munari & Zwitter, 1997]).

The Balmer lines profiles are sensitive to effective tem-

erature and gravity. Reliable determination of the right

continuum for them – especially for echelle spectra – is not an easy task and may be a source of scatter and errors.

In the case of HD 75049 magnetic broadening is large and

needs to be taken into account in the Balmer lines, too. That

small variations of Balmer lines may occur has long been

known, as discussed recently by, e.g., [Valyavin et al., 2007]

and [Elkin et al., 2008]. Balmer lines profiles of Hα, Hβ and

Hγ in the FEROS spectrum, Hβ in the FORS 1 spectra, and Hα in the UVES spectra were compared with

synthetic profiles for best fits as a function of $T_{\text{eff}}$ and log $g$. An average gives $T_{\text{eff}} = 9700 ± 170$ K and log $g = 4.07 ± 0.28$. The comparison between the observed and synthetic profiles of the Balmer lines gives acceptable agreement for a model with $T_{\text{eff}} = 9600$ K and log $g = 4.0$. Synthetic calculations of the Balmer lines were done with the SYNTH code of [Piskunov, 1992]. Model atmospheres by [Kurucz, 1974], and from the NEMO database ([Heiter et al., 2002]) were used.

5 MAGNETIC FIELD

5.1 Longitudinal field

From observations with FORS1 the variable mean longitudinal magnetic field $B_z$ was determined. Table 2 gives the results obtained for three methods of calculation when various lists of spectral lines and spectral regions are used. There are no differences between $B_z$ obtained from all spectral lines in two spectral regions, 3212 – 6215 Å and the shorter 3705 – 6215 Å. But there are shifts of around 600 G between the latter and measurements from the hydrogen lines. These differences most likely reflect the uncertainties involved in the interpretation of the observed circular polarization signal in terms of a magnetic field, which arise from the statistical nature of the measurement (the considered spectral ranges include many lines of different elements, which have different magnetic sensitivities) or from the complexity of the physical foundations of the treatment of the formation of hydrogen lines in A-type star atmospheres in the presence of a magnetic field ([Mathys et al., 2004]). Differences in the non-uniform distribution of chemical elements in the stellar atmosphere may also contribute, but seem unlikely to repre-

sent the dominant effect. The phase curves for all three

methods are similar and show sine curves. The distribution

\[ http://obswww.unige.ch/gcgp/gcgp.html \]
of hydrogen in the stellar atmosphere is more homogeneous than for other chemical species. Therefore we used results from hydrogen (last column in Table 2) for further analysis.

Figure 1. Frequency analysis of 13 FORS1 measurements of $B_z$ with times in BJD. The top panel shows the amplitude spectrum with the highest peak at $f = 0.2477 \, \text{d}^{-1}$. The middle panel shows the residuals on the same scale after the highest peak has been refined by linear and nonlinear least squares fitting, and prewhitened from the data. It is clear that all of the apparent “noise” in the top panel is spectral window pattern. The bottom panel shows a least-squares fit of a sinusoid to the same data where the best-fitting frequency, $f = 0.2470 \, \text{d}^{-1}$, is clear.

Figure 2. Top panel: The variation of the longitudinal magnetic field $B_z$ with rotational period for HD 75049. Filled circles are observations with FORS1 using the hydrogen lines. The curve is a centered dipole model for $B_p = 42 \, \text{kG}$, $i = 25^\circ$ and $\beta = 60^\circ$. Bottom panel: The variation of the magnetic field modulus $\langle B \rangle$ with rotational period for HD 75049 from our UVES and FEROS data. Different symbols are used to represent measurements performed using lines of different ions: filled circles for Fe ii $\lambda\lambda 5018 \, \text{Å}, 6160 \, \text{Å}$, open squares for Nd iii using four lines at $\lambda\lambda 5050 \, \text{Å}, 5845 \, \text{Å}, 6145 \, \text{Å}$ and 6323 Å, and diamonds for Eu ii using two lines at $\lambda\lambda 6049 \, \text{Å}$ and 6437 Å. The solid line is the same model as for upper panel. The dashed curve is a least-squares fit of a sinusoid plus first harmonic to the Fe ii data.

5.2 Mean magnetic field modulus

The mean magnetic field modulus $\langle B \rangle$ was determined from high resolution spectra using resolved Zeeman components of several spectral lines. Using Gaussian fitting we determined the centres of shifted Zeeman $\sigma$ components. The distance between these two components in a spectral line is proportional to value of magnetic field modulus $\langle B \rangle$ (Mathys et al. 1997):

$$\Delta \lambda = 9.34 \times 10^{-13} g_{\text{eff}} \langle B \rangle \lambda^2$$

(3)

where wavelength is measured in Å and $g_{\text{eff}}$ is an effective Landé factor. This relation is valid in fairly general con-
Table 3. The magnetic field modulus \( \langle B \rangle \) (kG) in HD 75049 determined from resolved Zeeman components in some selected spectral lines. Because of the non-uniform surface abundance distributions of various ions, some of the differences in field strength at specific rotation phases may be attributable to the distribution of elements. Less reliable results are identified by question marks.

| BJD       | phase | Fe ii 5018 Å | Nd iii 5050 Å | Cr ii 5237 Å | Nd iii 6145 Å | Nd iii 6327 Å | Eu ii 6437 Å |
|-----------|-------|--------------|---------------|-------------|---------------|---------------|--------------|
| 2454141.66963 | 0.1550 | 26.08 | 26.58 | 26.83 | 26.67 | 26.34 | 29.49 |
| 2454171.50422 | 0.5234 | 29.54 | 28.76 | 28.23 | 26.98 | 28.44 | 30.10 |
| 2454387.81593 | 0.9470 | 25.66 | 26.58 | 25.91 | 28.32 | 28.09 | 28.78 |
| 2454432.82489 | 0.0631 | 24.65 | 25.19 | 25.14 | 25.72 | 26.08 | 29.05 |
| 2454451.83366 | 0.7578 | 27.99 | 27.98 | 27.68 | 29.12 | 28.01 | 29.62 |
| 245455.70226 | 0.7133 | 28.46 | 28.29 | 27.91 | 29.12 | 28.38 | 29.87 |
| 245468.84589 | 0.9594 | 25.24 | 25.82 | 25.64 | 28.10 | 26.08 | 28.67 |
| 245481.81465 | 0.1624 | 26.83 | 26.64 | 27.97 | 27.13 | 28.73 | 29.64 |
| 245513.78992 | 0.0593 | 24.25 | 24.74 | 24.84 | 23.27 | 24.25 | 24.74 |
| 245516.68904 | 0.7755 | 27.73 | 27.69 | 27.48 | 29.20 | 27.60 | 29.52 |
| 245524.66461 | 0.7453 | 28.04 | 27.98 | 27.83 | 29.26 | 28.21 | 29.62 |
| 245544.51608 | 0.6481 | 28.96 | 28.60 | 28.18 | 29.40 | 28.38 | 30.06 |
| 245547.51127 | 0.3878 | 29.51 | 28.44 | 28.57 | 29.63 | 29.10 | 30.04 |
| 245557.59095 | 0.8773 | 26.45 | 26.49 | 26.71 | 28.77 | 26.77 | 29.98 |

5.3 Dipole model

From Harmanec (1988) we estimate for a main sequence A star with \( T_{\text{eff}} = 9600 \) K that the stellar radius will be around 2.1 \( R_\odot \). This value agrees well with other published estimations of stellar radii. While main sequence stars with a similar temperature may range in radius between 1.7 \( R_\odot \) and 5 \( R_\odot \) from the zero-age main sequence to the terminal-age main sequence, a radius more than 2.4 \( R_\odot \) is ruled out for HD 75049, as it requires an implausibly high polar magnetic field in comparison with the observed magnetic field modulus for the dipole model discussed in the next section. The range of possible radius for HD 75049 is therefore between 1.7 \( R_\odot \) and 2.4 \( R_\odot \).

The spectral lines with zero Landé factor, and resolved Zeeman components of lines with large Landé factors, give \( \nu \sin i = 8.5 \pm 1.0 \) km s\(^{-1}\). From the relation: \( B_{\text{eq}} = \frac{2 \mu B}{\sin i} \), where \( P \) is measured in days, we derive a rotational inclination of \( i = 23.6^\circ \pm 3^\circ \) and an equatorial velocity \( \nu_{\text{eq}} = 21.2 \) km s\(^{-1}\) for 1.7 \( R_\odot \), and \( i = 16.5^\circ \pm 2^\circ \) and \( \nu_{\text{eq}} = 30.0 \) km s\(^{-1}\) for 2.4 \( R_\odot \).

From least squares fitting with the Period04 program (Lenz & Breger 2003), for the hydrogen lines we have an average \( B_{\text{eq}} = -5.76 \) kG which varies with an amplitude of 4.89 \pm 0.06 kG. From expressions for an oblique rotator (e.g., Preston 1967) we find a magnetic obliquity in the range \( \beta = 63^\circ \pm 3^\circ \) for star with radius 1.7 \( R_\odot \) to \( \beta = 71^\circ \pm 3^\circ \) for 2.4 \( R_\odot \). Following the approach of Stibbs (1954) and Preston (1974) we calculated a grid of models using the above parameter range and found a best fit for \( B_p = 42 \pm 2 \) kG, \( i = 25^\circ \pm 3^\circ \) and \( \beta = 60^\circ \pm 3^\circ \), values that are suitable for a stellar radius of 1.7 \( R_\odot \). The variation of the longitudinal magnetic field \( B_p \) with the rotational period and selected model fitting is shown in the top panel of Fig. 2. We can get an equally good fit to the top panel of Fig. 2 with the parameters, \( R = 2.4 \) \( R_\odot \), \( i = 16.5^\circ \), \( \beta = 71^\circ \), \( B_p = 60 \) kG, but then the model curve for \( \langle B \rangle \) in the bottom panel has a minimum of 38 kG, which is clearly wrong. Under the assumption that the field geometry is dipolar, the implication of this is that HD 75049 is close to the zero-age main sequence.

Variations of \( \langle B \rangle \) show less symmetric curves than that for \( B_p \). To fit the \( \langle B \rangle \) curve for Fe ii 5018 Å we had to employ a sine curve with its first harmonic. Our centred dipole model does not fit the variation of this Fe ii line but is acceptable for lines of Nd iii and Eu ii, considering the errors of measurement and nonuniform distribution of chemical elements. Otherwise the magnetic field geometry is more com-
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Figure 3. Variation with rotation phase of the equivalent width (left) and the radial velocity (right) of the lines Cr\textsc{\textit{II}} λ5334 Å, Fe\textsc{\textit{II}} λ5432 Å, and Nd\textsc{\textit{III}} λ6145 Å.

5.4 Correlation between magnetic and spectral variability

One sees in Fig. 2 that the field modulus measurements obtained from the three sets of analysed lines show different amplitudes of variation. The Fe-based measurements vary with the largest amplitude, while the lowest variation amplitude is observed for \( B \) values derived from consideration of the Eu lines. These differences may find their origin in part in differences in the non-uniform distribution of the various elements of interest over the stellar surface. In order to test this interpretation, we have checked the dependence on rotation phase of the equivalent widths and radial velocities of lines of the considered elements. The examples in Fig. 3 illustrate the observed behaviours. The spectral lines that are shown, Cr\textsc{\textit{II}} λ5334 Å, Fe\textsc{\textit{II}} λ5432 Å and Nd\textsc{\textit{III}} λ6145 Å, are representative of all the reasonably unblended lines of the elements from which they arise. Equivalent width variations are definitely observed for Cr and Nd, but they are not definitely detected for Fe. The Nd lines also show radial velocity variations, while our data show no clear indications of such variations for Cr and Fe. Even after averaging the radial velocity measurements of several lines of these elements, no convincing evidence for variability was found.

For Nd, maximum equivalent width occurs close to phase 0.5, hence to the negative extremum of the longitudinal field, and to the maximum of the field modulus. The radial velocities of the Nd lines vary in phase quadrature with their equivalent widths; the lines are blueshifted between phases 0 and 0.5, and redshifted between phases 0.5 and 1.0. This is consistent with the presence of a region of enhanced abundance ("spot") of Nd around the negative magnetic pole. The same conclusion applies to Eu, whose lines show similar variability to those of Nd.

The equivalent widths of the Cr lines show the opposite variation, reaching their minimum close to phase 0.5, and being largest close to phase 0. Any radial velocity variations that they may show do not clearly stand out of the measurement noise, so that their amplitude is definitely much lower (by a factor of 5 or more) than for Nd lines. Yet, this may not be inconsistent with equivalent width variations being due to a non-uniform distribution of Cr over the stellar surface such that the abundance of this element is minimum around the
negative pole, and increases away from it. Possible configurations include a band of enhanced Cr abundance along the magnetic equator. With a distribution of this type, one can simultaneously observe on the visible stellar hemisphere approaching and receding Cr-rich regions, whose contributions to the radial velocity of Cr spectral lines mostly averages out in disk-integrated observations.

Finally, Fe lines do not show any definite variability of their equivalent widths or radial velocities, indicating that any abundance inhomogeneity in the distribution of this element on the visible part of the star must be moderate at most. Si behaves like Fe.

Thus we are left with the qualitative picture of a star showing a concentration of Nd and Eu and a (relative) depletion of Cr around its negative magnetic pole, with a comparatively uniform distribution of Fe and Si over its surface. One should keep in mind, though, that due to the low inclination of the rotation axis on the line of sight, a large fraction of the stellar surface is never observed.

The non-uniform distribution of Nd over the stellar surface may account for part of the differences between the values of \( \langle B \rangle \) that are derived from measurements of its lines, and from those of Fe, whose abundance appears much more constant across the star. However, it is unlikely to be the only factor, or even the main one. If it were, one would, for instance, expect greater values of the field modulus to be determined from Nd lines than from Fe lines close to phase 0.5; the opposite is observed in Fig. 4. Most likely, the origin of the difference should be sought elsewhere. In particular, one should bear in mind that Nd lines are subject to hyperfine structure. This introduces severe complications in the treatment of their formation in the presence of a strong magnetic field, as illustrated, e.g., in Landi Degl’Innocenti (1973). Accordingly, the physical meaning of the value of \( \langle B \rangle \) that is obtained by application of Eq. 3 to the observed splitting of Nd lines is not fully clear. In particular, one cannot a priori expect it to provide a measurement of the mean magnetic field modulus that is consistent with its determinations from analysis of Fe lines, which rests on a firmer physical basis. The same applies to the usage of Eu lines to measure \( \langle B \rangle \). The differences seen in Fig. 2 between the variation curves of this field moment resulting from measurements of the Nd \( \text{III} \) and Eu \( \text{II} \) lines would actually be very difficult to understand in terms of abundance inhomogeneities since the equivalent width and radial velocity behaviours indicate that, to first order, the distribution of both elements over the stellar surface is similar. On the other hand, around phase 0, the lines Eu \( \text{II} \) \( \lambda \lambda 6049 \text{Å} \) and 6437 Å become very weak and shallow, so that the uncertainties of the \( \langle B \rangle \) determinations based on them become very large, and the values obtained for this field moment between phases ~0.9 and ~0.2 should be considered with appropriate caution.

6 ASYMMETRY OF SPECTRAL LINES

Spectral lines in HD 75049 show significant variability with rotation period, and for many lines we also note asymmetry in the Zeeman patterns. Spectral line asymmetry is often visible in high resolution spectra of Ap stars. While non-uniform distribution of chemical species on the stellar surface contributes to this, the main source of line asymmetry more often is the variable combination of Zeeman and Doppler effects across the stellar surface. Indeed, due to the large-scale structure of the magnetic field, the Zeeman and Doppler shifts are correlated across the stellar disk, and this correlation is reflected in the shapes of the disk-integrated spectral lines.

The observed presence of this effect in HD 75049 is particularly plausible, considering that this star has a very strong magnetic field, and a large \( v \sin i \) for a star with magnetically resolved lines. That is the dominant effect for explanation of the origin of the line asymmetries can be inferred from consideration of Fig. 4. Representative lines of each of the three elements Fe, Cr, and Nd are seen to show qualitatively similar asymmetries: a red \( \sigma \) component (or red wing) shallower and broader than its blue counterpart at phases comprised between \( \sim -0.6 \) and \( \sim 0.9 \), and vice-versa in the phase range \( \sim 0.1 - 0.4 \). Since the distributions of Fe, Cr and Nd over the star differ considerably from each other, the similarity of the line asymmetries for all of them cannot arise primarily from their inhomogeneities. Also, because the magnetic field of HD 75049 is very strong, partial Paschen-Back effect may contribute to asymmetries of a significant number of lines (Mathys 1990), but it affects different transitions to a variable extent and in qualitatively different ways, so that it cannot account for the consistent behaviours illustrated in Fig. 4.

7 CHEMICAL ABUNDANCES

Large overabundances of some chemical elements, especially of rare earth elements, is one of the defining characteristics of Ap stars. Various chemical elements concentrate in different places on the surface of the star. There is a tendency for rare earth elements to concentrate around the magnetic poles in some sort of spots. The size and number of spots may vary (Kochukhov et al. 2004; Freyhammer et al. 2009). The situation is even more complex since the atmospheres of Ap stars also show vertical stratification (e.g., Babel & Landi Degl’Innocenti 1992; Wade et al. 2003; Kochukhov et al. 2004) where various elements accumulate in different layers in the atmosphere.

Because of the spotted structure of Ap stars, average abundances do not reflect the complexity of the physical conditions at the stellar surface, yet they are useful for statistical analysis and comparison of stars in the class (e.g., Adelman 1973; Ryabchikova et al. 2004). HD 75049 has a rich spectrum, but is not extraordinarily peculiar. In the spectrum many lines of rare earth elements are visible, but the majority of the strongest metal lines belong to Ti\( \text{II} \), Ti\( \text{II} \), Fe\( \text{II} \) and Cr\( \text{II} \). Lines of Sr\( \text{II} \) in the blue region of the FEROS spectrum are also rather strong.

We obtained the abundances of several elements using spectral synthesis where the observed spectra were compared with synthetic spectra until a best fit was obtained. An example for Fe\( \text{II} \) 55018 Å is shown in Fig. 5. The synthetic spectra were calculated with the software SYNTHE-MAG (Piskunov 1990). The spectral line list was taken from
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Figure 4. Variation with rotation phase of the observed profiles of the spectral lines $\text{Fe}^{\text{ii}} \lambda 5018$ Å, $\text{Nd}^{\text{iii}} \lambda 5050$ Å, and $\text{Cr}^{\text{ii}} \lambda 5334$ Å. Each spectrum is shifted vertically from the normalised continuum to a value corresponding to $(1 +$ rotation phase), hence the ordinate shows both continuum and rotation phase.

Table 4. Chemical abundances for HD 75049 for selected elements, and their corresponding solar abundances (Asplund, Grevesse, & Sauval 2005). The errors quoted are internal standard deviations for the set of lines measured. Only an upper limit could be placed on the abundance of $\text{Nd}^{\text{ii}}$. Columns 3 and 5 give the number of lines used, $N_{\text{lines}}$, in each case.

| Ion     | $\log N/N_{\text{tot}}$ | $N_{\text{lines}}$ | $\phi = 0.388$ | $\log N/N_{\text{tot}}$ | $N_{\text{lines}}$ | $\phi = 0.063$ | $\log N/N_{\text{tot}}$ | $N_{\text{lines}}$ | Sun |
|---------|-------------------------|---------------------|----------------|-------------------------|---------------------|----------------|-------------------------|---------------------|-----|
| $\text{Si}^{\text{ii}}$ | $-3.70 \pm 0.05$ | 2 | $-3.55 \pm 0.05$ | 2 | $-4.49$ |
| $\text{Ti}^{\text{ii}}$ | $-6.04 \pm 0.10$ | 2 | $-5.85 \pm 0.15$ | 2 | $-7.10$ |
| $\text{Cr}^{\text{ii}}$ | $-4.73 \pm 0.15$ | 14 | $-4.53 \pm 0.13$ | 9 | $-6.36$ |
| $\text{Fe}^{\text{ii}}$ | $-3.93 \pm 0.17$ | 10 | $-4.10 \pm 0.29$ | 4 | $-4.55$ |
| $\text{Fe}^{\text{ii}}$ | $-3.89 \pm 0.15$ | 17 | $-3.98 \pm 0.15$ | 6 | $-4.55$ |
| $\text{La}^{\text{ii}}$ | $-7.15 \pm 0.21$ | 16 | $-7.23 \pm 0.18$ | 6 | $-10.87$ |
| $\text{Ce}^{\text{ii}}$ | $-7.48 \pm 0.16$ | 5 | $-7.95 \pm 0.05$ | 4 | $-10.42$ |
| $\text{Pr}^{\text{iii}}$ | $-8.07 \pm 0.15$ | 4 | $-8.10 \pm 0.16$ | 4 | $-11.29$ |
| $\text{Nd}^{\text{iii}}$ | $-7.27 \pm 0.05$ | 3 | $-7.57 \pm 0.12$ | 3 | $-10.55$ |
| $\text{Nd}^{\text{ii}}$ | $< -8.40$ | 3 | $< -7.98$ | 3 | $-10.55$ |
| $\text{Eu}^{\text{ii}}$ | $-7.71 \pm 0.19$ | 4 | $-8.10 \pm 0.29$ | 4 | $-11.48$ |

the Vienna Atomic Line Database (VALD, Kupka et al. 1999), which includes lines of rare earth elements from the DREAM database (Biémont, Palmeri, & Quinet 1999). A model atmosphere with $T_{\text{eff}} = 9600$ K and $\log g = 4.0$ with metallicity of 0.5 dex above solar from the NEMO database (Heiter et al. 2002) was used. The synthetic spectra provided a good match to many spectral lines with the field strength chosen, but some lines need further broadening to match the wings. Macroturbulence is possibly not the explanation for this, as magnetic fields suppress macroscopic motion in the stellar atmospheres. With the non-uniform distribution of abundances – both horizontally and vertically – in Ap star atmospheres, it may be that stronger magnetic field strengths in different line-forming regions could explain this extra broadening. Further study is needed to test this idea.

Two spectra at rotation phases near minimum and maximum longitudinal field strength (phase 0.063 and 0.388; see Fig. 2) were used for abundances determination. Magnetic field strengths of 26 kG and 30 kG, respectively, were used for calculation of the synthetic spectra at these two rotational phases. Synthetic line profiles for various abundances were compared with observed profiles for best fits. Many calculated line profiles do not fit the observed profiles perfectly as a result of blending and asymmetry, but the average value for a number of lines gives reliable results. It was more difficult to fit the spectrum observed at rotational phase 0.063 when the field strength is lower and some lines are not as sharp and more asymmetric. Table 4 presents the
8 CONCLUDING REMARKS

The strong magnetic field of HD 75049 is an exciting discovery. This star is a rival for the long-known strongest Ap magnetic field in Babcock’s star, HD 215441. Both stars have deep silicon lines, but are at opposite ends of the temperatures range of the ApSi stellar group. Babcock (1960) noted that HD 215441 does not have outstanding peculiarities in the spectrum. We have found the same in HD 75049, which has a rich peculiar spectrum, but with overabundances of number chemical elements similar to other Ap stars with much smaller field strengths.

HD 215441 has a magnetic field modulus that changes from 32 to 35 kG over the rotational period [Babcock (1964); Preston (1969)]. Preston (1964) suggested that the magnetic field of this star deviates from a centred dipole. Magnetic configurations with a combination of dipole and quadrupole components (Borra & Landstreet 1978) or dipole, quadrupole and octupole (Landstreet & Mathys 2001) components were required to model both observations of $B_z$ obtained by Borra & Landstreet (1978) and $\langle B \rangle$ by Preston (1969).

In contrast, for HD 75049 the centred dipole model is a suitable first approximation to fit both the longitudinal field and field modulus measurements. Some discrepancy with the second magnetic moment dipole model may be a result of nonuniform distribution of chemical elements at surface. More complex magnetic geometry may also be present in this star. An important result is that the star is probably young. Its estimated stellar radius places it close to the zero-age main sequence.

Landstreet & Mathys (2000) examined the inclination of rotation axis $i$ to line-of-sight and obliquity $\beta$ of the magnetic axis to the rotation axis for a sample of magnetic Ap stars. They found that the majority of the slow rotators with periods longer than 25 d have $\beta$ smaller than 20°, while stars with short rotation periods tend to have a large obliquity of the magnetic axis. Our estimation of $\beta = 60^\circ \pm 3^\circ$ for HD 75049 is consistent with this conclusion.

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