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Magnetic stars from a FEROS cool Ap star survey*

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ABSTRACT

New magnetic Ap stars with split Zeeman components are presented. These stars were discovered from observations with the Fibre-fed Extended Range Optical Spectrograph (FEROS) spectrograph at the European Southern Observatory (ESO) 2.2-m telescope. 15 new magnetic stars are analysed here. Several stars with very strong magnetic fields were found, including HD 70702 with a 15-kG magnetic field strength, and HD 168767 with a 16.5-kG magnetic field strength measured using split Zeeman components of spectral lines and by comparison with synthetic calculations. The physical parameters of the stars were estimated from photometric and spectroscopic data. Together with previously published results for stars with strong magnetic fields, the relationship between magnetic field strength and rotation period is discussed.

Key words: techniques: spectroscopic – stars: chemically peculiar – stars: magnetic field – stars: variables: general.

1 INTRODUCTION

Stars with strong global magnetic fields are found along the main sequence among chemically peculiar (CP or Bp/Ap/Fp) stars. They range over spectral type from mid-F to early B types up to the terminal-age main sequence. Magnetic fields produce significant effects in the atmospheres of peculiar stars. The interaction of the magnetic field with the plasma in stellar atmospheres is one of the most challenging problems in stellar astrophysics. The peculiarities of the CP stars are caused by unusual chemical abundances in their atmospheres. The strong magnetic field stabilizes their outer stellar layers and creates the conditions to support atomic diffusion separation of chemical elements (e.g. Michaud 1970, 1980). Radiative accelerations and gravitational settling in the magnetized atmosphere produce inhomogeneous surface distributions and vertical stratification (Babel & Michaud 1991; Babel 1994).

The magnetic field strength detected in magnetic stars varies from one star to another. The strongest magnetic field detected is 34 kG in HD 215441 (Babcock 1960; Preston 1969), which belongs to the hotter Si type of Ap/Bp stars, while for cooler Ap stars the magnetic field reaches 30 kG (Freyhammer et al. 2008; Elkin et al. 2010b). Observed magnetic fields in Ap/Bp stars vary with rotational period and are described by the oblique rotator model. In most magnetic stars, to first approximation, the magnetic field geometry may be considered as a simple dipole, while more precise observations and detailed analyses can reveal more complex configurations of magnetic field structure.

For a fraction of magnetic stars, high-resolution spectroscopic observations have allowed straightforward measurements of the magnetic field modulus. This happens when the star rotates slowly or is observed at low inclination angle, so has narrow spectral lines. Fortunately, peculiar stars show lower rotational velocities compared with normal stars of the same spectral class. Mathys et al. (1997) presented comprehensive analyses of stars with magnetic field moduli determined from resolved Zeeman components. Since that publication, more stars with strong magnetic fields and resolved components have been discovered.

In a high-resolution spectroscopic survey of cool peculiar stars compiled from a list by Martinez (1993) based on the Michigan Spectral Catalogues, we also have found stars with resolved Zeeman components. The results from our first observing set with Fibre-fed Extended Range Optical Spectrograph (FEROS) were presented in Freyhammer et al. (2008). Further observations of stars from our survey, and analyses of their spectra, reveal several more stars with strong magnetic fields. One of these, BD $+0^{\circ}4535$, has a strong magnetic field reaching 21 kG that was described by Elkin et al. (2010a). This paper presents 15 new magnetic Ap stars with sharp lines and with Zeeman splitting detected with FEROS observations.

2 OBSERVATIONS

The spectra analysed in this paper were obtained with the FEROS echelle spectrograph at the La Silla 2.2-m telescope of the European Southern Observatory (ESO). The FEROS spectra have a resolution of $R = 48\,000$ and a wavelength range from $\lambda\lambda$ 3500 to 9200 Å.

*Based on observations collected at the European Southern Observatory, La Silla, Chile, as part of programmes 078.D-0080(A), 080.D- 0191(A), 081.D-2002(A), 082.D-0061(A), 083.D-0034(A) and 084.D-0067(A).

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Some of the stars were also observed with the ESO Very Large Telescope (VLT) at Paranal Observatory using the Ultraviolet and Visual Echelle Spectrograph (UVES) installed at Unit Telescope 2 (UT2). UVES spectra covered the range λλ 4970–7010 Å, with a small gap near 6000 Å caused by the space between the two CCDs of the spectrograph.

For reduction of spectroscopic observations and extraction of 1D spectra, ESO-MIDAS pipelines were used and the 1D spectra were normalized to continuum. Some stars were observed two or more times, while most were observed only once.

3 ANALYSIS OF THE OBSERVATIONAL DATA

3.1 Magnetic field determination

Experimental determination of magnetic fields in Ap stars is based on measurement of the Zeeman effect in spectral lines. The line of Fe II 6149.258 Å with a convenient doublet Zeeman configuration (see e.g. Mathys et al. 1997) was used for magnetic determinations. The doublet structure of the Fe II 6149.258 Å line allowed us to select and directly measure magnetic field strengths greater than about 3 kG with the FEROS spectra. Only partial Zeeman splitting, or just a hint that it may be present in line broadening, is seen for smaller field strengths. The peculiarity level and type vary significantly from one star to another. The Fe II 6149.258 Å line is a blend with several other lines that can have significant strength for some stars. Other lines with large Landé factors are thus needed to test for magnetic splitting or broadening. Calculations of synthetic spectra using the SYNTHMAG code by Piskunov (1999) and comparison with observations are required to distinguish the blending effect from magnetic splitting and broadening. A further blending problem may occur for very strong fields when the splitting in the Fe II 6149.258 Å line is large and the Zeeman components are not clearly visible or may be blended.

The distance between shifted Zeeman σ components is proportional to the value of the mean magnetic field modulus over visible stellar hemisphere $\langle B \rangle$ (e.g. Landstreet 1980; Mathys 1990):

$$\Delta\lambda = 9.34 \times 10^{-13} g_{\mathrm{eff}} \langle B \rangle \lambda_0^2, \quad (1)$$

where wavelength is in angstrom and magnetic field strength is in gauss. Throughout this paper, it is this modulus that is meant when we simply refer to the magnetic field strength. When the field is strong and the components were resolved, each component was fitted with a Gaussian. The distance between the central positions of the Gaussians was used for the magnetic field determination. Synthetic spectra were calculated with the SYNTHMAG code for different abundances and magnetic field strengths to obtain a best fit with the observed spectra. For these calculations, model atmospheres were obtained from the Vienna New Model Grid of Stellar Atmospheres (NEMO) data base (Heiter et al. 2002) and a spectral line list from the Vienna Atomic Line Database (VALD; Kupka et al. 1999), which includes lines of rare earth elements from the Database on Rare Earths at Mons University (DREAM) data base (Biémont, Palmeri & Quinet 1999). Stellar parameters were estimated for a selection of model atmospheres in the ranges of T_{eff} and $\log g$ for these stars. Strömgren photometric indices (Martinez 1993) and the calibration by Moon & Dworetsky (1985) were then used for initial estimates of T_{eff} and $\log g$. Synthetic spectra for the Hα region were then calculated with the SYNTH code (Piskunov 1992) for different effective temperatures and gravity. Finally, synthetic profiles of Hα were compared with the observed spectra for a best fit and a final determination of T_{eff} and $\log g$. The Hα profile is not very sensitive to the latter; therefore, the $\log g$ estimates were based on photometric calibration and are not precise, but are still suitable for our purposes.

3.2 Comments for individual stars

In this section, we present details of further analysis for newly discovered magnetic stars. By the standards of stellar magnetic field studies, all of these stars are relatively faint and poorly studied. Some limited information about them is present in different stellar catalogues, but most physical parameters are unknown. The stars from our list were observed photometrically with the All Sky Automatic Survey (ASAS; Pojmanski 2002). We used this photometry to check for rotational variability of each star. For some stars, we found a probable rotation period using the PERIOD04 package (Lenz & Breger 2005) and discrete Fourier transform of Kurtz (1985).

3.2.1 HD 3988

This is a spectroscopic binary system for which speckle interferometry by White et al. (1991) does not show any multiplicity. The lower and narrow part of the profiles of the Balmer lines, especially Hα, shows binary structure with strong and weak components in the double core. The sodium doublet, Na I 5889.951 and 5895.924 Å, also shows the spectra of both stars. The lines of the two stars show wavelength variability, changing from 1.14 to 1.29 Å on different nights of observation. There are insufficient data to derive an orbital period. By fitting Hα with synthetic spectra, we estimate the effective temperatures of the primary and secondary components to be 7200 and 6600 K, respectively, with an estimated precision of 200–300 K.

The spectrum is not extremely peculiar and has rather weak lines of rare earth elements that belong to one component. The Fe II 6149.258 Å line does not show splitting, but only some broadening that may be connected with a magnetic field. Partial splitting is seen in some lines with larger Landé factors, e.g. the line Fe I 6336.823 Å. Synthetic calculations give good agreement with observations for a magnetic field strength of 2.7 kG, as seen in Fig. 1.

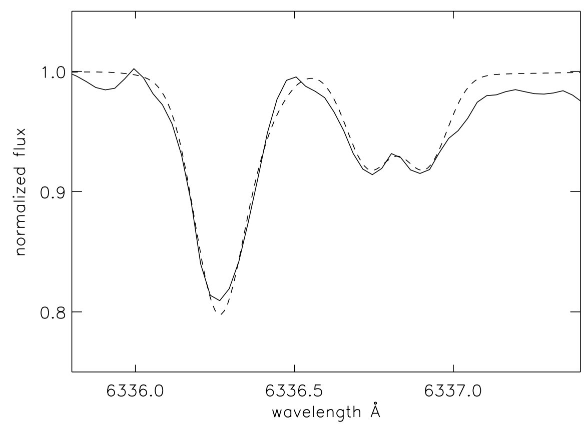

Figure 1. A spectral region with a magnetically sensitive line for HD 3988. For this and other figures, the observed spectrum is shown by a solid line, while the synthetic spectrum is presented with a dashed line. The synthetic spectrum was calculated for a magnetic field strength of 2.7 kG. The strongest line is Cr II 6336.263 Å, while the line with a doublet structure of partially split Zeeman components is Fe I 6336.823 Å.

3.2.2 HD 57040

This star has a peculiar spectrum with a strong magnetic field. Our FEROS spectrum shows only a hint of magnetic splitting for the Fe II 6149.258 Å line, whereas another spectrum obtained with UVES and the VLT shows Zeeman splitting. The spectrum has strong lines of Nd II, Nd III, Eu II and Ce II. With $T_{\rm eff} = 7500$ K, the star is a promising candidate to be an roAp star. In Fig. 2, part of a UVES spectrum of HD 57040 is shown with magnetic splitting in the Fe II 6149.258 Å line. A nearby spectral range with an example of Zeeman patterns is shown in fig. 1 of Mathys et al. (1997).

Spectral lines in HD 57040 also show rotational broadening. ASAS photometry reveals for this star a probable rotational period of 13.474 d. Fig. 3 illustrates the amplitude spectrum of the ASAS photometry with a significant peak corresponding to this period.

While two photometric attempts to detect pulsation in this star by Martinez & Kurtz (1994) were unsuccessful, pulsations with small amplitude may still exist. For example, low pulsation amplitude may be found using satellite photometry (e.g. Kurtz et al. 2011). We obtained 34 UVES spectra to test the star for rapid radial velocity variations. The analysis of these spectra will be presented in a separate paper.

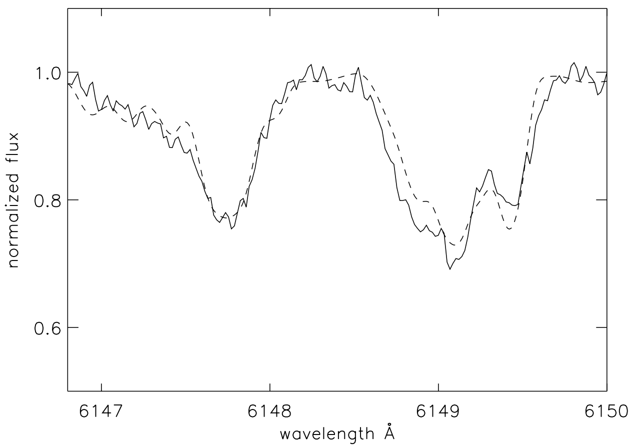

Figure 2. Observed (solid) and synthetic (dashed) spectral region for HD 57040. The synthetic spectrum was calculated for a magnetic field of 7.8 kG. The two strongest lines belong to Fe II 6147.741 Å and 6149.258 Å. The partially split line at 6149.258 Å is blended with weaker lines of Sm II and Ce II.

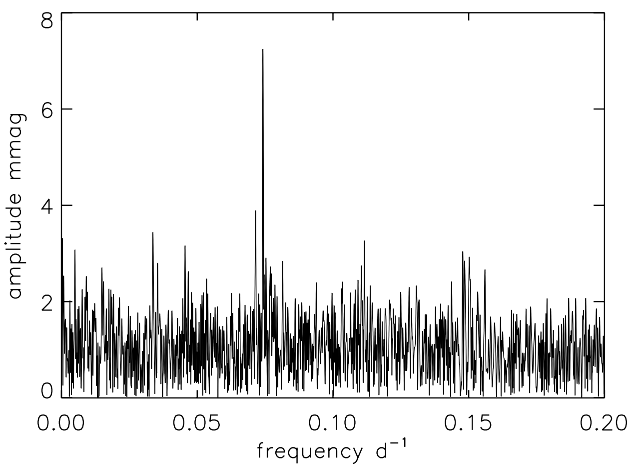

Figure 3. An amplitude spectrum of ASAS photometry for HD 57040 with a peak corresponding to the rotational period of 13.474 d.

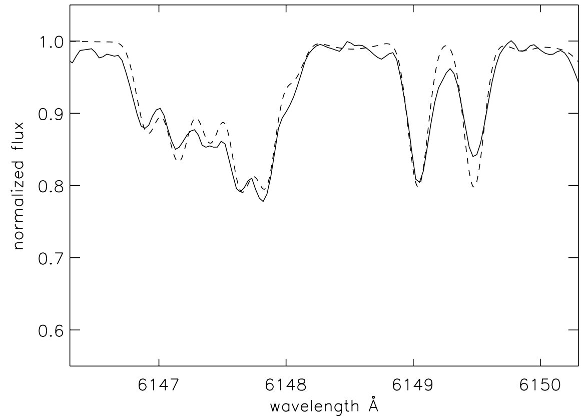

Figure 4. Observed (solid) and synthetic (dashed) spectra for HD 61513. The synthetic spectrum was calculated for a magnetic field strength of 9.2 kG. The profile of the Fe II 6149.258 Å line shows doublet splitting.

3.2.3 HD 61513

This star is among the faintest ($V = 10.15$) and hottest ($T_{\rm eff} = 10\,000$ K) stars we observed with FEROS. Lines of Nd III, Eu II, Ce II and some other rare earth elements are present in the spectrum at moderate strength for an Ap star. Some rotational broadening is present corresponding to $v \sin i = 7.0 \pm 1.5$ km s^{-1}. The magnetic field is strong, and many lines show Zeeman splitting. Components of the Fe II 6149.258 Å line are clearly resolved, as seen in Fig. 4. Direct measurements of the magnetic field from this line and by fitting with synthetic spectrum calculated with SYNTHMAG give similar results, 9.2 kG.

3.2.4 HD 70702

This is another hot star ($T_{\rm eff} = 9800$ K) in our target list. The spectrum is peculiar with rare earth element lines present, including Nd III and Eu II, but many lines are rather shallow.

The star shows a very strong magnetic field of 15 kG, which was not easy to recognize because of significant rotational broadening, $v \sin i = 17.0 \pm 1.5$ km s^{-1}. The rotational period should be no longer than several days. A comparison of the observed and synthetic profiles allowed us to distinguish between blending and Zeeman splitting in the Fe II 6149.258 Å line and determine a significant magnetic field in this star.

Zeeman splitting in the Fe II 6149.258 Å line is presented in Fig. 5. The split components show a complex doublet structure. This may be explained by high noise level or blending. A non-uniform distribution of iron in the line formation region combined with different field strengths also may be responsible for the asymmetry of the Zeeman patterns.

Some other spectral lines also show Zeeman structure, as is confirmed by synthetic calculations for magnetic field strengths in the range 14–16 kG. Zeeman splitting is visible, for example, in Cr II 5046.940 Å, Fe II 6238.392 Å and Eu II 6437.640 Å. Most other lines demonstrate just magnetic broadening.

With such a strong magnetic field, this star is an important target for further observations and magnetic field analysis.

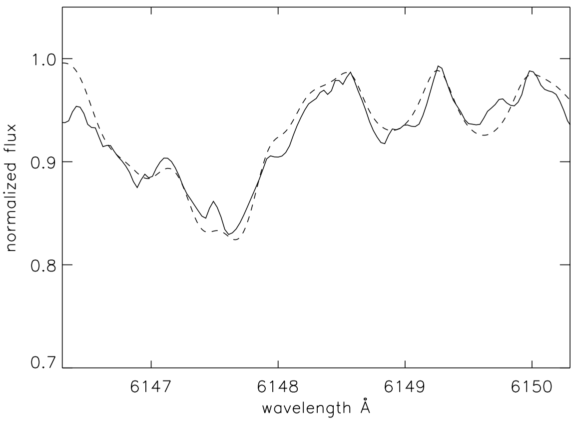

Figure 5. Observed (solid) and synthetic (dashed) spectra for HD 70702. The profile of the Fe II 6149.258 Å line shows huge Zeeman splitting. The synthetic spectrum was calculated for a magnetic field of 15 kG.

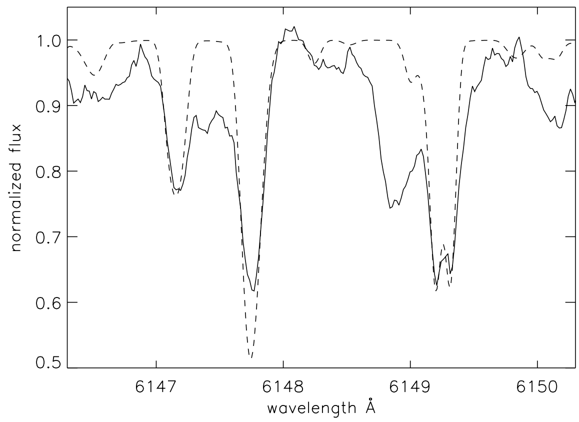

Figure 7. Observed (solid) and synthetic (dashed) spectra for HD 81588. The profile of the Fe II 6149.258 Å line shows partial Zeeman splitting. The synthetic spectrum was calculated for a magnetic field of 2.4 kG.

3.2.5 HD 76460

This star has a peculiar spectrum with narrow lines. Those of Ba II are very strong, while rare earth element lines, including Nd III and Eu II, have moderate intensities. The doublet line of Li II 6708 Å is also present in the spectrum. The magnetic field is strong enough for partial splitting of the Fe II 6149.258 Å line as can be seen in Fig. 6. The line of Fe I 6336.823 Å also shows partial doublet splitting. We measure the field strength to be 3.7 kG.

3.2.6 HD 81588

The star was first observed with FEROS and showed a highly peculiar spectrum with strong rare earth element lines of Nd III and Pr III. The doublet Li II 6708 Å line was also detected, but it is a blend with lines of Ce II and Sm II. The spectral lines are sharp and narrow, but the FEROS resolution was not sufficient to see magnetic splitting in the Fe II 6149.258 Å line. A UVES spectrum showed small partial splitting, as seen in Fig. 7. The line of Fe I 6336.823 Å also demonstrates partial doublet splitting for the UVES spectrum. In the FEROS spectrum, this line has only magnetic broadening.

The fundamental parameters of HD 81588 determined from photometry and spectroscopy are similar to some known roAp stars. Martinez & Kurtz (1994) observed this star five times photometrically searching for rapid oscillations and did not detect any.

3.2.7 HD 88241

The spectrum of this magnetic star has very strong lines of Ba II and good lines of Nd III. Other rare earth element lines such as Eu II and Gd II are also present. This star has a strong Li I 6708 Å doublet. The Fe II 6149.258 Å line shows partial Zeeman splitting, as seen in Fig. 8. The line of Fe I 6336.823 Å also demonstrates partial doublet splitting. The synthetic calculations and fitting yield a magnetic field 3.6 kG. Other lines with large Landé factors also show magnetic broadening.

3.2.8 HD 158450

Two spectra of this peculiar and strongly magnetic star were obtained with FEROS. The spectral lines show magnetic Zeeman splitting or broadening and rotational broadening. Rare earth element lines found in the spectra include Nd III and Eu II, among others. These lines are relatively weak in comparison with most peculiar stars.

Direct measurements of the field from split Zeeman components of the Fe II 6149.258 Å line reveal a magnetic field modulus of

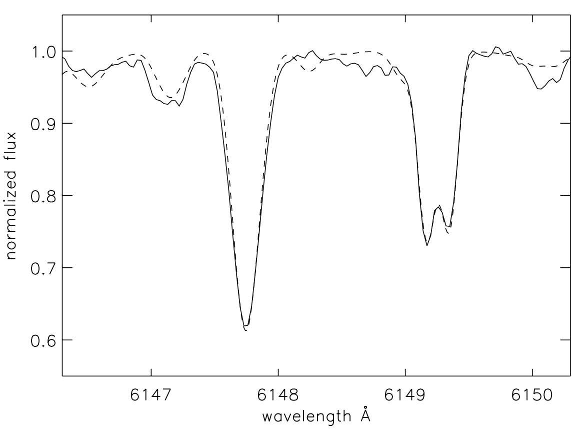

Figure 6. Observed (solid) and synthetic (dashed) spectra for HD 76460. The profile of the Fe II 6149.258 Å line shows partial Zeeman splitting. The synthetic spectrum was calculated for a magnetic field of 3.7 kG.

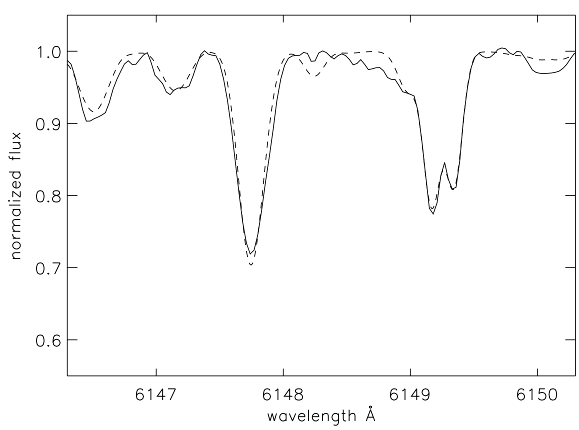

Figure 8. Observed (solid) and synthetic (dashed) spectra for HD 88241. The profile of the Fe II 6149.258 Å line shows partial Zeeman splitting. The synthetic spectrum was calculated for a magnetic field of 3.6 kG.

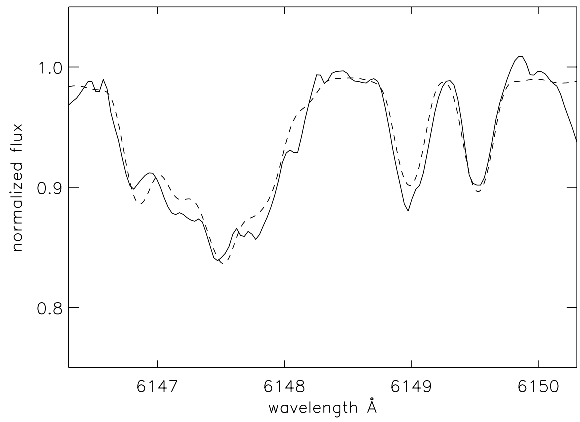

Figure 9. Observed (solid) and synthetic (dashed) spectra of the second FEROS spectrum obtained for HD 158450. The profile of the Fe II 6149.258 Å line shows Zeeman splitting. The synthetic spectrum was calculated for a magnetic field of 11.2 kG.

11.9 kG for one spectrum and 11.2 kG for a second observation. In Fig. 9, the spectral region with the Fe II 6149.258 Å line is shown together with a synthetic spectrum calculated for an 11.2-kG field. Despite the strong field, only a small number of lines demonstrate Zeeman splitting. The main reason is rotational broadening. The Fe II 6238.392 Å line has doublet splitting corresponding to a magnetic field of 9.9 kG. The longitudinal magnetic field was found to vary between −2.92 and +0.81 kG over several days (Kudryavtsev et al. 2006). Only four observations of this star have been published, and they are consistent with the rotational period found from the photometry. Fig. 10 presents an amplitude spectrum of the ASAS photometry, while Fig. 11 shows the longitudinal magnetic field phased with the photometric 8.524-d period.

In the Catalogue of Components of Double and Multiple stars (Dommanget & Nys 2002), this star is noted to be a binary star with a faint 10.2-mag component at distance of 0.6 arcsec.

Martinez & Kurtz (1994) observed HD 158450 photometrically for about 2 h to search for rapid variations. This result was uncertain and further similar observations would be useful.

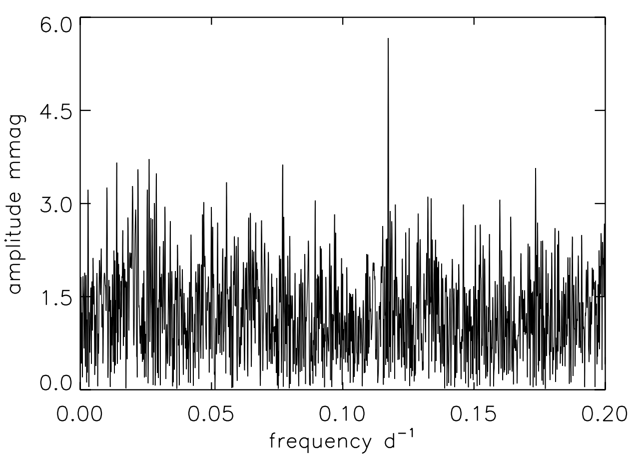

Figure 10. An amplitude spectrum of the ASAS photometry for HD 158450 with a peak corresponding to a rotational period of 8.524 d.

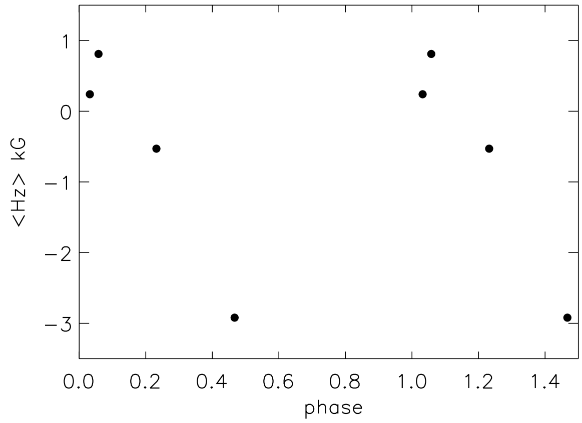

Figure 11. The longitudinal magnetic field of HD 158450 from Kudryavtsev et al. (2006) with phase of 8.524-d period.

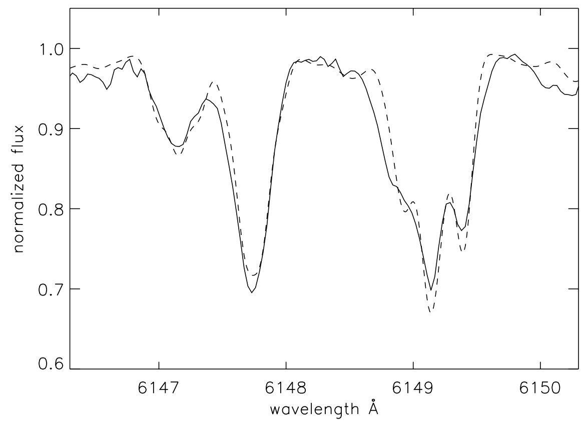

Figure 12. Observed (solid) and synthetic (dashed) spectra for HD 162316. The synthetic spectrum was calculated for a magnetic field of 6.0 kG. It can be seen that the Fe II 6149.258 Å line shows partial Zeeman splitting. This line is a blend with a strong line of Sm II 6149.060 Å.

3.2.9 HD 162316

This star has very strong lines of Nd III while other lines of rare earth elements such as Eu II are also present. Zeeman splitting is visible in the Fe II 6149.258 Å line as shown in Fig. 12. This line is a blend, but comparison with a synthetic spectrum proves the presence of a magnetic field. The Fe I 6336.823 Å line also shows a doublet structure of Zeeman components. Lines with low Landé factors are narrower than other lines. ASAS photometry shows variability with a probable rotation period of 9.304 d. A clear peak is visible in the amplitude spectrum shown in Fig. 13.

3.2.10 HD 168767

This star shows a peculiar spectrum, but most of the metal lines are weak and shallow with rotational and magnetic broadening. The spectrum has rather weak lines of Nd III, Pr III and Eu II. The magnetic field can be recognized from splitting of the Fe II 6149.258 Å line, although it was not obvious and required a synthetic spectrum for comparison, as shown in Fig. 14.

The Fe II 6238.392 Å line also shows doublet Zeeman splitting, which fits well when compared to a synthetic spectrum calculated for a magnetic field of 16.5 kG. Despite this strong field, most other lines do not show splitting because of relatively rapid rotation with

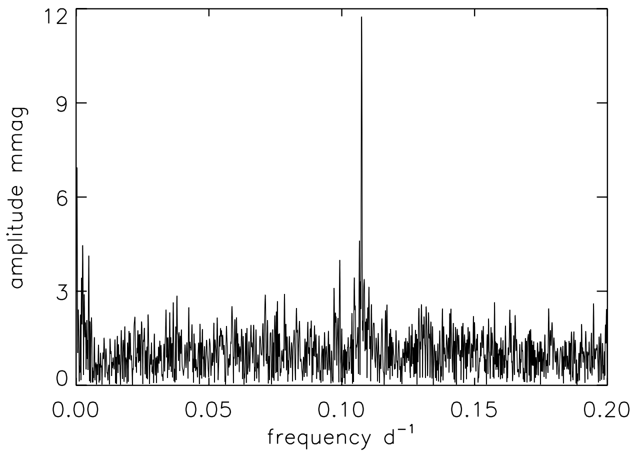

Figure 13. Fourier transform of ASAS photometry for HD 162316 with a peak corresponding to a rotational period of 9.304 d.

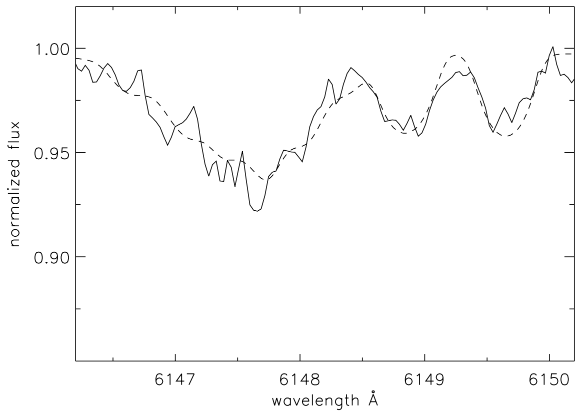

Figure 14. Observed (solid) and synthetic (dashed) spectra for HD 168767. Zeeman splitting is visible for the Fe II 6149.258 Å line when compared with a synthetic spectrum calculated for a magnetic field of 16.5 kG.

$v \sin i = 14.0 \pm 1.5\,\mathrm{km\,s^{-1}}$. With a strong magnetic field and relatively short rotational period (not more than several days given the relatively high $v \sin i$), this star is one of the most interesting targets for future observations. We have only one spectrum; observations at other rotational phases may reveal an even stronger magnetic field.

3.2.11 HD 177268

This star was observed with FEROS three times as it was not clear whether it shows magnetic splitting. Moderate-intensity spectral lines of rare earth elements are present in the spectrum. The partial Zeeman splitting of the Fe II 6149.258 Å line is visible for two spectra and shows some hint of splitting for the third. This means that the magnetic field is variable with an unknown rotation period. ASAS photometry did not give a clue to a possible period. Fig. 15 demonstrates a portion of one of the spectra together with a synthetic spectrum. Another Fe I 6336.823 Å line also shows partial Zeeman splitting, thus supporting the discovery of a magnetic field in this star. The star has physical parameters similar to known roAp stars, which led Martinez & Kurtz (1994) to search photometrically for rapid oscillations, but no evidence for pulsation was found.

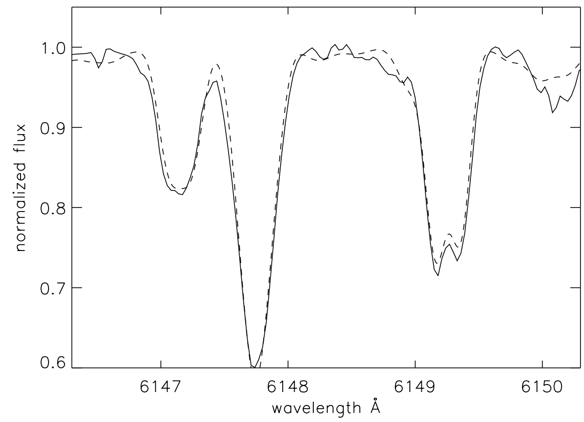

Figure 15. Observed (solid) and synthetic (dashed) spectra for HD 177268. The partial Zeeman splitting is visible for the Fe II 6149.258 Å line. The synthetic spectrum was calculated for a magnetic field of 4.1 kG

3.2.12 HD 179902

This is another star with very strong lines of Nd III. Other strong rare earth element lines are also found in the spectrum, including Pr III and Eu II. The spectrum is reminiscent of HD 162316 with similar peculiarities. Even the lines of Fe II 6149.258 Å, which are heavily blended in both stars, show similar blending and splitting. The splitting in this line is partial, so it requires a SYNTHMAG synthetic calculation to estimate the magnetic field strength. Fig. 16 shows the profile of this iron line in comparison with a synthetic spectrum. The magnetic field also is confirmed by partial doublet splitting of the Fe I 6336.823 Å line. This star was observed twice with FEROS with a 6-d gap, but no significant spectral variability was detected. The magnetic field also did not change within the errors for these two spectra. In contrast to HD 162316, we did not find any significant variability for HD 179902 using ASAS photometry.

3.2.13 HD 184120

This peculiar star shows rather moderate or weak lines of Nd III, Eu II and some other rare earth elements in the spectrum. The magnetic field is strong and Zeeman components of the Fe II 6149.258 Å line are split, as can be seen in Fig. 17. Some other lines with large Landé factors also show Zeeman splitting, mostly partially. Many

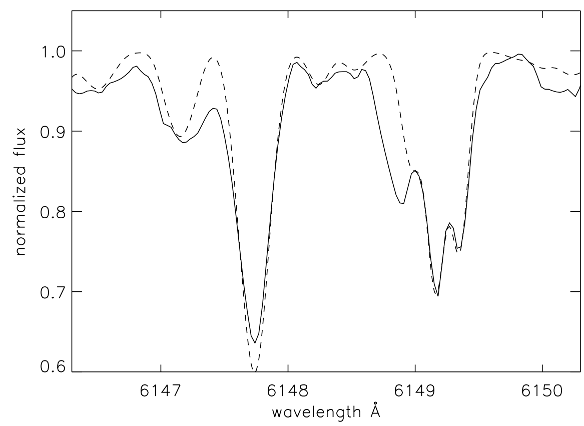

Figure 16. Observed (solid) and synthetic (dashed) spectra for HD 179902. The synthetic spectrum was calculated for a magnetic field 3.9 kG. Partial Zeeman splitting is visible for the Fe II 6149.258 Å line.

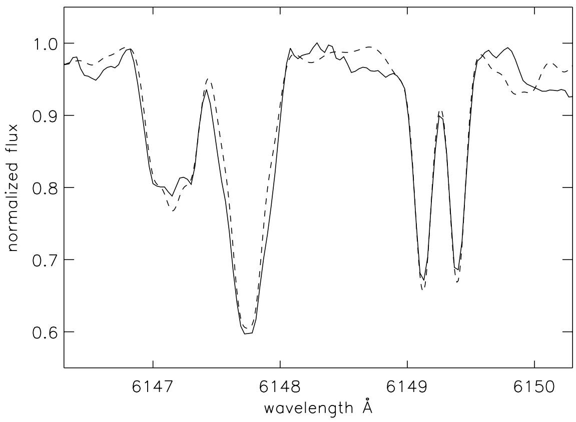

Figure 17. Observed (solid) and synthetic (dashed) spectra for HD 184120. The synthetic spectrum was calculated for a magnetic field 5.7 kG. Zeeman splitting is clearly visible for the Fe II 6149.258 Å line.

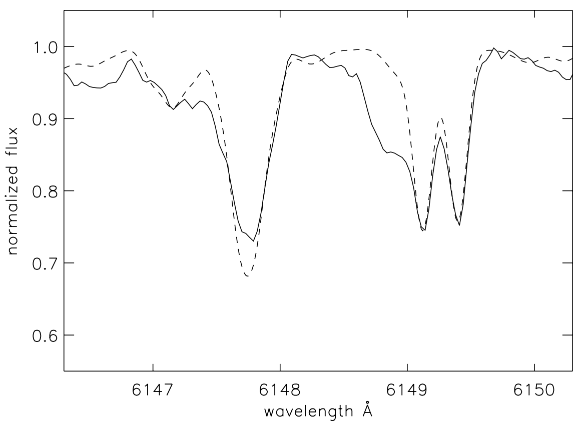

Figure 18. Observed (solid) and synthetic (dashed) spectra for HD 185204. The synthetic spectrum was calculated for a magnetic field of 5.9 kG. Zeeman splitting is clearly visible for the Fe II 6149.258 Å line, which is a blend with an unknown line.

lines demonstrate magnetic broadening. This star was observed with FEROS twice and both spectra are similar with no significant spectral variability. Martinez & Kurtz (1994) did not find any rapid photometric variability, even though the spectrum and physical parameters of this star are similar to roAp stars.

3.2.14 HD 185204

This magnetic star has a peculiar spectrum with very strong lines of Nd III and good lines of Pr III, Eu II and some other rare earth elements. This peculiar star was observed twice; both spectra are similar. Zeeman splitting is visible in the Fe II 6149.258 Å line, as can be seen in Fig. 18. The line of Fe I 6336.823 Å also shows partial doublet splitting, and partial splitting is also visible for many other lines across the spectrum.

This star is a promising target for searching for rapid oscillations. Martinez & Kurtz (1994) observed it twice photometrically, but pulsations were not found. Additional precise high time resolution observations will be useful to test further if the star pulsates with low amplitude.

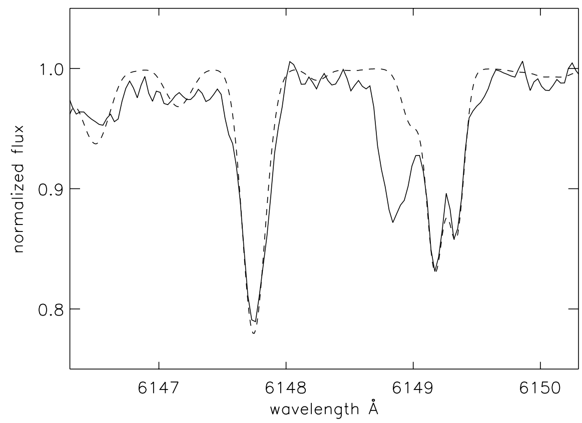

Figure 19. Observed (solid) and synthetic (dashed) spectra for HD 191695. The synthetic spectrum was calculated for a magnetic field of 3.4 kG. Zeeman splitting is clearly visible for the Fe II 6149.258 Å line, which is a blend with Sm II 6149.060 Å and with another unknown line.

3.2.15 HD 191695

This peculiar star shows very strong lines of Nd III, Pr III and Ba II, but lines of Eu II are rather weak. The magnetic field is not very strong and only partial Zeeman splitting is present in the Fe II 6149.258 Å line, as can be seen in Fig. 19. The presence of a magnetic field is also supported by partial doublet splitting of the Fe I 6336.823 Å line. Nelson & Kreidl (1993) did not find rapid oscillations in HD 191695 above a noise level of 1 mmag, but this cool Ap star is still a good target to search for low amplitude pulsation with high precision, using both spectroscopic and photometric high time resolution observations.

4 DISCUSSION AND CONCLUSIONS

Measured magnetic fields in Ap stars show significant variability with rotation period. The magnetic oblique rotator model explains this variability as an aspect effect of the observed star. Most stars presented here were observed in just one or two rotation phases and require more observations over their rotation periods to establish how strong their magnetic fields are and to determine their geometries. It is especially interesting to observe stars with strong magnetic fields like those of HD 70702 and HD 168767. The extreme values of the fields in these and other stars we have presented here may be higher in other rotational phases.

Table 1 shows the results of magnetic field measurements together with other determined parameters of the stars. The standard deviation for magnetic field measurements for well-resolved Zeeman components with high signal-to-noise ratios in the spectra is about 100 G, while for partially split lines, blended lines and for spectra with high noise it is in the range 200–500 G. The effective temperatures in this table are based mostly on fitting the observed Hα profiles with synthetic profiles. At best, we estimate the error on $T_{\rm eff}$ to be 200–300 K. For most of the stars studied, the difference between photometric and spectroscopic effective temperatures is less than 500 K, although for a few cases, especially for hotter stars, this difference is larger.

Our v sin i parameter determination has a precision of about 1–1.5 km s^{-1}. While for some stars a v sin i value of 3 km s^{-1} was obtained, this is just the lower limit for the FEROS resolution. Considering that the magnetic field stabilizes the stellar atmosphere, we used a value of zero for the microturbulence and macroturbulence

Table 1. List of detected magnetic stars. The columns give the star name, magnitude, the Modified Julian Date (MJD) of the start of each exposure, exposure time, the magnetic field modulus, effective temperature and projected rotational velocity. The error estimates for the determined parameters are described in the text.

Star	V	MJD	Exposure time (s)	Magnetic field modulus (kG)	$T_{\rm eff}$	$v \sin i$ (km s^{-1})
HD 3988	8.4	54686.37371	321	2.7 ± 0.2	7200	3.0
		54687.37890	540	2.5 ± 0.2		
		54690.29598	600	2.7 ± 0.2		
		54691.29863	700	2.7 ± 0.2		
HD 57040	9.2	54444.28124	3480	7.5 ± 0.4	7600	5.5
HD 61513	10.1	54870.15212	1200	9.2 ± 0.1	10 000	7.0
HD 70702	8.5	54141.10660	420	15.0 ± 0.6	9800	17.0
HD 76460	9.8	55227.20701	1100	3.6 ± 0.2	7200	3.0
HD 81588	8.5	54515.21196	3340	2.4 ± 0.2	7400	3.0
HD 88241	8.6	55228.15571	500	3.6 ± 0.2	7000	3.5
HD 158450	8.5	54686.01386	371	11.9 ± 0.3	8000	7.5
		55022.27403	900	11.2 ± 0.3		
HD 162316	9.4	55029.17408	1100	6.0 ± 0.2	7600	3.0
HD 168767	8.7	54686.11474	480	16.5 ± 0.6	7600	14.0
HD 177268	9.1	54689.24174	950	3.7 ± 0.2	7800	3.5
		55023.27249	1100	3.9 ± 0.2		
		55029.18944	1100	4.0 ± 0.2		
HD 179902	10.0	55023.30541	1200	3.7 ± 0.2	7200	3.0
		55029.26619	2400	3.9 ± 0.2		
HD 184120	10.2	55023.33752	1200	5.8 ± 0.1	7400	4.0
		55030.31810	2400	5.7 ± 0.1		
HD 185204	9.6	54690.24203	1200	5.7 ± 0.2	7400	4.0
		54688.25639	1023	5.7 ± 0.2		
HD 191695	9.9	55023.36940	1200	3.4 ± 0.2	7000	2.7
		55028.36782	1200	3.0 ± 0.2		

velocities in all calculations. With ASAS photometry (Pojmanski 2002) and using the PERIOD04 program by Lenz & Breger (2005), we tested stars from Table 1 and found rotation periods for three of them.

A correlation of the effective temperatures obtained by photometry and spectroscopy is shown in Fig. 20. The agreement between effective temperatures obtained with different methods is mostly acceptable, while in a few cases, further analysis is needed to resolve the discrepancy. We prefer to use the effective temperature obtained with spectroscopic analysis, since the photometric calibrations are known to be problematic for extremely peculiar stars, as a consequence of line blocking.

One of the fundamental questions of the physics of Ap stars concerns the relation between magnetic field strength and rotational period. The Ap stars rotate much more slowly than normal stars with the same effective temperature. Typically, the rotation periods of magnetic Ap stars range from several days to many years, and even decades. The magnetic field is responsible for braking Ap stars.

To examine this relationship further here, we collected more magnetic field and period values for Ap stars from the literature. A graph for rotational period as a function of extrema of magnetic field modulus for a sample of magnetic stars is presented in Fig. 21. Data for 30 stars in this figure were taken from Mathys et al. (1997). For other stars, the data were obtained from Elkin et al. (2010b),

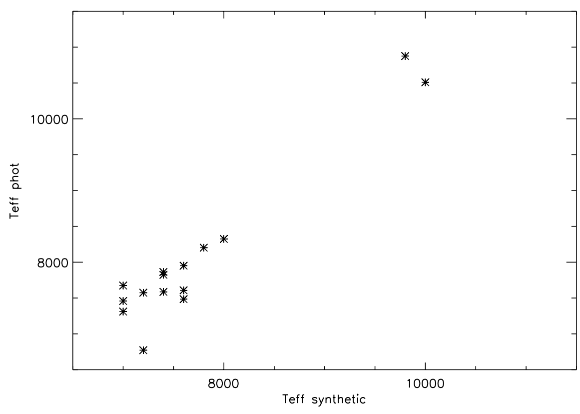

Figure 20. Correlation of effective temperatures determined from photometry and spectroscopy.

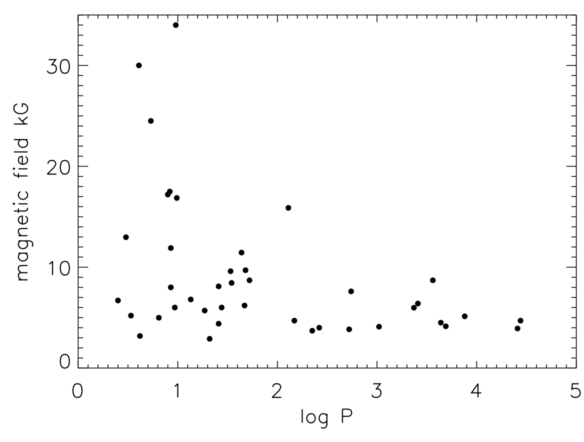

Figure 21. Logarithm of rotational period versus extrema of magnetic field modulus for magnetic stars.

Freyhammer et al. (2008), Hubrig et al. (2009), Mathys, Kurtz & Elkin (2007), Ryabchikova et al. (2006) and the current paper. This figure demonstrates that the stars with strongest magnetic fields typically have rotational periods between 5 and 10 d. This is also supported by our observations of two stars HD 70702 and HD 168767 presented in this paper. Both stars have a very strong field and relatively high projected rotational velocities, which suggests that rotational period should not be more than several days. The lack of stars with very strong fields and with periods less than 5 d may be at least partly explained by selection effects, as the fast rotators have wider spectral lines and even for fields more than 10 kG the Zeeman components are not resolved. Spectropolarimetric techniques would be useful for searching for longitudinal fields among the fast rotators. A good example is the star NGC 2244−334 (Bagnulo et al. 2004), which shows a very strong longitudinal field and has wide spectral lines with magnetic and rotational broadening. This star also should have a relatively short rotational period.

Mathys et al. (1997) suggested a possible anticorrelation between the mean magnetic field modulus and stellar rotation period. Fig. 50 from Mathys et al. (1997) differs from our Fig. 21 because we have included several stars with very strong fields that were found subsequent to Mathys et al. (1997). The rms longitudinal magnetic fields as a function of rotation period were studied by Hubrig, North & Schöller (2007) on a wider sample of Ap stars. They showed that the stars with strongest longitudinal field generally show periods less than 10 d.

Together with previous papers (Freyhammer et al. 2008; Elkin et al. 2010a; Elkin, Kurtz & Mathys 2011), we have found a total of 34 new magnetic stars with resolved and partly resolved Zeeman components using high-resolution spectra from our FEROS survey of cool Ap stars. Among them, we found several stars with a mean magnetic field modulus more than 10 kG. Considering the number of observed Ap stars in this survey, we can estimate that the proportion of stars with resolved Zeeman components is slightly less than 10 per cent. Mathys (2004) noted only 47 magnetic Ap/Bp stars with resolved Zeeman splitting. Our discovery of 34 stars with clear Zeeman splitting found among cool Ap stars is a significant contribution to further study of this type of star. This comes from our survey of more than 300 cool Ap stars from which we also found several stars with very strong magnetic fields. The strongest field of 30 kG was found in HD 75049. Most probably, this value is close to a physical limit for the observed magnetic field in cool Ap stars.

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