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Discovery of a very large magnetic field in three Ap stars*

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Abstract. We report the discovery of magnetic fields larger than 11 kG in the three Ap SrCrEu stars BD +40° 175, HD 63843 and HD 86592. In addition, we give new results for the star HD 47103, where the correlation peak is resolved into magnetically split components.

The average (quadratic) surface field measured by correlation methods in the three newly measured stars is 16, 12 and 16 kG respectively. Their effective temperatures, estimated from the profile of the Balmer lines, are 7100, 7500 and 7600 K. The projected rotational velocities are 17, <5 and 16 km s^{-1} respectively, so that two of these objects are not extremely slow rotators. One object, BD +40° 175, is particularly interesting as it undergoes a strong variation of the magnetic field on a timescale of days with extreme values at 12.8 and 22 kG, together with a large variation of the radial velocity measured in Hα and Hβ indicating a probable close SB1 system. For HD 86592, a period P = 2.887 days is also determined from Geneva photometry.

Our new measurements of HD 47103 do not show any relative variation of $<H>$ larger than 1% compared with those of April 1995, suggesting that the rotational period of this star might be very long, of the order of years. It shows, however, a significant shift in v_{rad} indicating a membership in a binary system

Key words: stars: individual: HD 47103, HD 63843, HD 86592 – stars: chemically peculiar – stars: magnetic fields – line: profiles

1. Introduction

Among the main sequence stars, strong magnetic fields are found essentially among the cool stars, where they are intermittent like in the sun, and among the Bp and Ap stars, where they have a simpler and roughly dipolar geometry. In the case of cool stars, the magnetic fields originate at the basis of the outer convective zone and migrate towards the surface through magnetic buoyancy. In the case of hotter stars, whose envelope is radiative, the field must have a different origin and is generally thought to be fossil, i.e. a remainder of the magnetic flux which reigned in the interstellar matter from which the stars formed. See e.g. Moss (1994) for a recent theoretical review of the magnetic fields in A and B stars.

On the observational side, many measurements have been made of the longitudinal (i.e. parallel to the line of sight) field averaged over the visible hemisphere of the star – the so-called *effective* field – by observing the circularly polarised light. Even fast rotators (with $V \sin i$ as high as ~ 200 km s^{-1}) could be observed, using the Balmer lines of hydrogen (Borra & Landstreet 1980; see also the review by Landstreet 1992). However, the *surface* field, i.e. the modulus of the field vector averaged on the visible hemisphere, can only be measured in slow rotators. Indeed, it is measured through the Zeeman splitting of the lines, which is completely smoothed out as soon as $V \sin i$ exceeds only 10 km s^{-1} or so. The most recent surface field measurements made in this way are those of Mathys (1990), Mathys & Lanz (1992) and Mathys et al. (1996). In the very best cases, fields as small as 2.2 kG can be measured (Wade et al. 1996), but generally they exceed 3 kG.

When the Zeeman components can not be resolved, it is no longer possible to measure the surface field proper, but the surface average of the square of the magnetic field modulus, can be measured through the differential broadening of the lines which are sensitive to the magnetic field and those which are not. Preston (1971) was the first to apply this method to a relatively large sample of 28 stars. He listed values as small as 0.5 kG, but without any error estimate, so that it is difficult to judge what his detection threshold was and we suspect that his detection threshold was closer to 1.5-2.0 kG than 0.5 kG for stars with $V \sin i \leq 10$ km s^{-1}. Mathys (1995) showed that while the contributions of $< H^2 >$, the mean square magnetic field modulus, and $< H_z^2 >$, the mean square longitudinal magnetic field, can hardly be diagnosed separately by differential broadening measurements, the sum of the two has the advantage that it is almost independent of the magnetic field geometry.

In this paper, we present four interesting stars discovered as strongly magnetic in the course of a systematic survey of

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* Based on observations collected at the Observatoire de Haute-Provence (OHP), France

mean quadratic fields among cool Ap stars, i.e. those of the type SrCrEu. The fields are estimated using a new technique applied to spectra obtained with the ELODIE spectrograph at OHP. A first discovery, that of a 17.5 kG field in the Ap SrEu star HD 47103, has already been published (Babel et al. 1995). Here three further strongly magnetic stars are presented, as well as additional measurements of HD 47103.

2. Observations and method

The observations have been done on April 6-12, 1995, on February 3-9, 1996 and on September 22-23, 1996 with the ELODIE echelle spectrograph attached to the 1.93m telescope at Observatoire de Haute-Provence, France (Baranne et al. 1996). The average resolving power of ELODIE is R = 42000, and the wavelength coverage is 3900 – 6800Å. The spectrograph lies in a thermally stable coudé room and is fed by fiber optics. An advanced software developed at Geneva Observatory reduces the spectra on-line and cross-correlates the spectrum with digital template(s) which can be provided by the user.

Our method of magnetic field estimation is based on the principle of cross-correlation and makes use of two CORAVEL-like templates. The first reason to use such technique is that the spectrum of Ap SrCrEu is heavily line-crowded in the visible, hampering reliable analysis of individual line-shapes. The first template is built to match only the lines with a small magnetic sensitivity ("low g_{eff}" maskhereafter), while the other selects those with a large sensitivity ("high $g_{\rm eff}$" maskhereafter). The individual magnetic sensitivities of each line, S_2 and D_2 or $g_{\rm eff}$ (see Mathys 1989, 1995), are computed from the g_u, g_l, J_u and J_l values from the *GFIRON* tape from Kurucz (1993). The average magnetic sensitivities of the masks, $\overline{S_2}$ and $\overline{D_2}$, are obtained by multiplying the magnetic sensitivities of individual lines by the square of the wavelength of the lines and weighting by the relative importance d_i of each line. The line depths d_i have been obtained by a synthetic spectrum made with the SYNTHE code from Kurucz & Avrett (1981) and fitted to the typical cool Ap star 73 Dra (HD 196502).

When the surface field is weak (i.e. smaller than about 6 kG), the cross-correlation profile remains mostly gaussian for both templates but that corresponding to lines with large magnetic sensitivity will have a larger "width" than the other, the quadratic difference of the "widths" of the two profiles, being proportional to the quadratic mean of the field modulus over the visible hemisphere of the star. From our two masks, which both have 590 lines, we obtain that $(\overline{S_2})^{1/2}$ = 0.840 for the "low-$g_{\rm eff}$" mask and 1.163 for the "high-$g_{\rm eff}$" template. We finally have that $(\Delta\overline{D_2})/(\Delta\overline{S_2})$ = 0.76, where the Δ-symbol means a difference between the average values of the two masks. Similarly to Mathys (1995), we make the weak-line approximation and define now, $M_I^{(2)}$, as the second-order moment of the correlation peak, with respect to the star radial velocity v_o. We obtain then that the difference of the second-order moment of the correlation peak between the two masks, $\Delta M_I^{(2)}$, is related independently of the magnetic field geometry and rotational broadening to the magnetic field by (see Eq. 12 of Mathys (1995)

$$\Delta M_I^{(2)} = (\Delta M_I^{(2)})_{H=0} + 0.31(< H^2 > +0.76 < H_z^2 >). \qquad (1)$$

The first right-hand side term is related to the difference in the nonmagnetic case of the second-order moment of the correlation peak between the two masks. This can be caused by global differences in intrinsic line widths between the two set of lines. This term was found here to be very small (see below). We also define

$$H_i \equiv (< H^2 > +0.76 < H_z^2 >)^{1/2}. \qquad (2)$$

If instead, we make the assumption of a random distribution of the magnetic field orientation over the stellar surface (e.g. Saar 1990, Mathys 1995), we obtain a value, $(< H^2 >_s)^{1/2}$, related to H_i by

$$(< H^2 >_s)^{1/2} = 0.897 H_i. \qquad (3)$$

The value of $(< H^2 >_s)^{1/2}$, which is more directly comparable to $< H >$, will be used throughout this paper. Finally, we use a deconvolution procedure to improve the quality of the correlation peak and continuum position. Indeed, cross-correlation methods produce some auto- or anti-correlation features, which prevent a very good placement of the continuum and a precise estimate of $M_I^{(2)}$. The procedure adopted is the following: From the spectral fit obtained for 73 Dra, we compute a synthetic spectrum containing no rotational broadening or instrumental broadening. We then build a response function by correlating our masks with this synthetic spectrum. Even though we obtain a narrow response function, it contains at this stage only low-frequency information, so that FFT deconvolution would require the use of noise filtering (Press et al. 1989) of the cross-correlation function (CCF) prior to deconvolution, a procedure which might be uncertain. To avoid this, we deconvolve the response function by a gaussian having a σ = 2.3 km s^{-1}(i.e. of the order of the Doppler thermal broadening of iron peak elements). This procedure increases substantially the high-frequency content of the response function and makes unnecessary the noise-filtering procedure. We finally obtain that deconvolution improves significantly the quality of the CCF for stars with a temperature between 7500 and 9000 K and thus for spectra not much different than from our prototype star 73 Dra. A somewhat similar method was used by Donati et al. (1997) and applied to spectropolarimetric observations.

Numerous tests were performed to check the mask properties. In particular, we controlled the presence of any intrinsic differential broadening, $(\Delta M_I^{(2)})_{H=0}$, due for instance to global variation of intrinsic line widths between the two set of lines. This test was performed both on observed and synthetic spectra. We obtained that $[(\Delta M_I^{(2)})_{H=0}]^{1/2}$, is of the order of 0.5 km s^{-1} (This corresponds to a difference of 30 m s^{-1} in the width of the CCF of the two masks for $(M_I^{(2)})^{1/2}_{H=0}$ = 4.5 km s^{-1}.). A subtle bias was also identified and suppressed. This effect arises if the wavelength distributions of the lines in the two masks differ.

Numerical simulations show that different line distributions together with the variation of the number of blends between the red and blue part of the spectra could lead to spurious magnetic field detections in rotators with $v \sin i \geq 10$ km s^{-1}. We thus build our masks in such a way that we have completely identical wavelength distributions of spectral lines over bins of 200 Å and performed numerical simulations which confirmed the disappearance of the bias. Finally our masks do not contain strongly saturated lines and we did not observe any magnetic amplification in the high-sensitive mask relative to the low-sensitive mask, indicating that the correlation dip behaves mostly like a weak-line. For slow rotators, numerical simulations show that the uncertainty in the width of the CCF caused by limited photon statistics is of the order of 30 m s^{-1} for $S/N \simeq 30$. Using Eq. 1 and including other sources of errors, we obtain a detection limit of $H_i \gtrsim 1 - 1.5$ kG for slow rotators. Our method has thus a competive sensitivity and is also very appropriate for large surveys. A more detailed description of the method including comparisons with measurements obtained with other methods will be given in a forthcoming paper.

For very large magnetic fields the σ-component and π-component of the CCF are in some cases resolved (see Babel et al. 1995). In this case, the mean field modulus $< H >$ is obtained through the relation

$$\Delta v = 1.40 \times 10^{-7} \lambda_{norm} \overline{g_{\rm eff}} < H > . \quad (4)$$

Δv, expressed in km s^{-1}, is the radial-velocity shift between the centre of gravity of the σ_+-component and the π-component. λ_{norm} is a normalisation wavelength in Å, and the term $\overline{g_{\rm eff}}$ defines an average effective Landé factor (see Eq. 3 of Babel et al. 1995). For the present templates, and for λ_{norm} = 5000 Å, we get that $\overline{g_{\rm eff}}$ = 0.980 for the low sensitive template and $\overline{g_{\rm eff}}$ = 1.459 for the high sensitive template [1].

The journal of the observations is given in Table 1. The published measurements of HD 47103 made in April 1995 are included for completeness (Babel et al. 1995).

3. Results

3.1. BD +40°175 A

This star has been classified SrCrEu by Bidelman (1985). There is no other bibliographical reference to this object in the SIMBAD database. It is a visual double (ADS 693, IDS 00456+4039) with a 3″.7 separation and 0.5 magnitude difference. The duplicity is a real problem for nights with bad seeing, where both stars are impossible to distinguish. In such cases, we obtained that the surface of the cross-correlation peaks seems to be slightly larger than in the case where the companion is excluded from the fiber's entrance of the spectrograph. Due to the low effective temperature of this star (see Sect. 3.1.2), the deconvolution procedure described in Sect. 2 did not cause any improvement of the continuum placement.

[1] Note that in Babel et al. (1995), the $\overline{g_{\rm eff}}$ were incorrectly given as being respectively 0.999 and 1.411 though the same values as here were used.

Table 1. Journal of the observations of the three new stars, and of HD 47103. The epochs are heliocentric julian dates corresponding to the middle of the exposure. t_{exp} is the exposure time and S/N is the signal-to noise at 5000 Å. The abbreviation "Rns" refers to Renson (1991). $(< H^2 >_s)^{1/2}$ is the magnetic field obtained using the assumption of a random distribution of the magnetic field orientation over the stellar surface (see Eq. 3).

Star HD/BD...	V	HJD −2400000	$t_{\rm exp}$ [s]	S/N	$(< H^2 >_s)^{1/2}$ [kG]
+40°175 A,	9.4	50118.248	936	14	12.8[1] ± 1.5
[Rns 1290,		50118.318	1164	9.4	12.7[1] ± 1.5
SAO 36713]		50119.251	1837	28	16.1 ± 1.5
		50122.252	2401	8.0	15.7[1] ± 1.5
		50349.459	3005	38	22.3 ± 2.5
63843,	10.24	50117.547	1301	19	11.5 ± 0.6
[Rns 17630]					
86592,	7.867	49815.366	501	53	15.5 ± 1.0
[Rns 24760]		50118.554	1800	38	16.1 ± 1.0
Star	V		$t_{\rm exp}$	S/N	$< H >$
47103,	9.1	49816.352	1800	30	17.67
[Rns 12630,		49817.367	1500	30	17.33
+20°1508]		49818.318	470	27	17.65
		49818.330	580	36	17.48
		49819.388	1800	29	17.42
		50119.485	1865	41	17.37
		50349.643	2401	43	17.16

[1]: uncertain due to the presence of the companion in the fiber's entrance of the spectrograph.

Table 2. Radial velocity measurements of BD +40°175, obtained from fit of the core of $H\alpha$ and $H\beta$, v^c_{rad}, and estimated from the first-order moment of the "low g_{eff}" mask, v^l_{rad}, and "high $g_{\rm eff}$" mask, v^h_{rad}.

HJD -240000	v^c_{rad} km s^{-1}	v^l_{rad} km s^{-1}	v^h_{rad} km s^{-1}
50118.248	−5.4 ± 0.5	−6.5	−6.8
50118.318	−5.4 ± 1.0	−7.5	−7.8
50119.251	−4.9 ± 0.5	−4.1	−5.5
50122.252	−8.6 ± 1.5	−6.2	−8.8
50349.459	−11.9 ± 0.5	−9.1	−8.0

3.1.1. Magnetic field

In Fig. 1 are shown the five cross-correlation functions, for the template corresponding to high $g_{\rm eff}$ values. One sees a cross-correlation peak which is much larger than the one corresponding to low $g_{\rm eff}$ values (Fig. 2), with marginal indications of a resolved triplet. In both figures, the small vertical bars indicate the radial velocity of the star, obtained through a fit of the core of Hα and Hβ. The radial velocity was found to vary between −5.4 and −11.9 km s^{-1}. These values were found to be in good agreement with the first-order moment of the correlation peak, though this latter might be affected by abundance spots or other surface inhomogeneities (see Table 2). The variability of the radial velocity can not be attributed to the presence of the companion in the fiber's entrance, as it is also clearly present in the two observations where the companion could be excluded from the fiber's entrance of the spectrograph.

The correlation peak of BD +40°175 A is in an intermediary regime, halfway between resolved and unresolved components. We estimate thus both the mean surface field and the mean quadratic field.

1. Applying Eq. 4 to the π- and σ_+-components which are the best defined in the first two nights of observations, we obtain respectively a field $< H >$ of 14.0 $\pm$ 2 and 15.8 $\pm$ 2 kG, values only slightly smaller than that of HD 47103. No estimate can be obtained for the two last observations.
2. The mean quadratic field, $< H_s^2 >^{1/2}$, we obtain from the quadratic difference of the 2nd-order moments of the CCF (see Eqs. 1 to 3) is given in Table 1 for every measurement. The 2nd-order moments were obtained by direct integration over the correlation peak, using for the velocity reference, v_o, the velocity, v^c_{rad}, obtained from the core of Hα and Hβ. While the method is more reliable than the previous one due to the marginal separation of the triplet components, it is sensitive to the presence of the companion.
   In the two cases where comparison could be achieved, we obtain a good agreement with the estimate of the mean surface field $< H >$. Finally, we observe in Fig. 1 for the last observation a very broad correlation peak. For this observation, we obtain a quadratic field $< H_s^2 >^{1/2}$= 22 $\pm$ 2.5 indicating that BD +40°175 A is one of the most magnetic Ap stars. The relatively large error quoted on the field measurement for this observation is due to the small depth of the CCF in the "high $g_{\rm eff}$" maskwhich makes the estimate of the magnetic field quite uncertain.

3.1.2. Effective temperature

Using the same procedure as described in Babel et al. (1995), the Hγ and Hβ lines have been fitted to theoretical profiles, for ATLAS9 model atmospheres of Kurucz (1979, 1992), with various effective temperatures, for log g = 4.0 and for $[M/H]$ = +1.0. For $T_{\rm eff} >$ 8000 K we used a mixing length parameter α = 1.0, while for temperatures lower than 8000 K and according to Fuhrmann et al. (1993) we used α = 0.5. A determination of the effective temperature through this method remains for Ap SrCrEu quite uncertain due to the unknown status of the HII convection zone in presence of magnetic field or due to the possible compression of the atmosphere by the interaction of ambipolar diffusion of hydrogen with the magnetic field (Babel & Michaud 1991, LeBlanc et al. 1994).

A satisfactory fit to the wings of both lines is obtained for

$T_{\rm eff}$ = 7100 $\pm$ 400 K.

The overall fit quality is, however, quite poor due to the peculiar shape of the two hydrogen lines. This effective temperature is consistent with the spectral peculiarity SrCrEu. Unfortunately, there is as yet no published photometry of BD +40°175 A, not even in the UBV system, so an independent check of the effective temperature can not be made here.

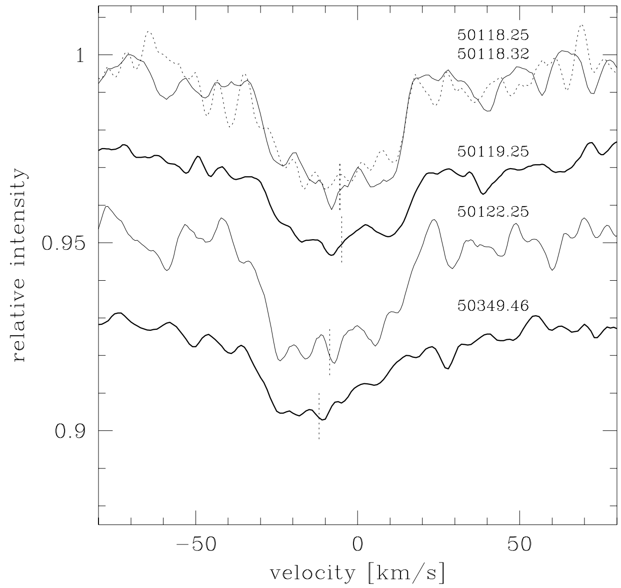

Fig. 1. Observed cross-correlation functions of BD +40°175 A, for the "high $g_{\rm eff}$" template and for the observations from Table 1. Heavy curves are for the observations for which the companion could be excluded from the fiber's entrance to the spectrograph. Successive profiles are shifted downwards for graphics purposes. The dotted line is for the low signal-to-noise observations at 50118.32. The dotted bars indicate the radial velocity deduced from the core of Hα and Hβ.

3.1.3. V sin i

The large magnetic field, and large rotational broadening does not permit to use individual lines for the determination of V sin i for BD +40°175 A. We can use instead the correlation dip. Indeed, from the 2^{nd}-order moment of the "low-$g_{\rm eff}$" and "high-$g_{\rm eff}$" dips, we can extrapolate to $g_{\rm eff}$ = 0 and obtain the 2^{nd}-order moment, $(M_I^{(2)})_{H=0}$, the dip would have, when not affected by a magnetic field. $(M_I^{(2)})_{H=0}$ includes in general several broadening effects like: instrumental, thermal, micro- and macroturbulence, Stark and rotational broadening. For magnetic Ap stars, microturbulence and macroturbulence are both expected to be inhibited by the magnetic field. The relation between $(M_I^{(2)})_{H=0}$ and V sin i has thus to be calibrated. This was done by computing synthetic spectra for our prototype star 73 Dra for various rotation velocities and computing $(M_I^{(2)})_{H=0}$ as a function of v_{rot} from the theoretical CCFs. We obtain then values for V sin i between 16 and 19 km s^{-1} for the first four measurements. For the last measurement, magnetic broadening dominates too much over rotational broadening so that no relevant rotational velocity can be derived. The mean value is:

$V \sin i$ = 17 $\pm$ 2 km s^{-1}.

Such a rotational velocity translates to a rotational period, $P_{rot} \simeq$ 7.5 sin i days according to the oblique rotator model and assuming a radius $R \sim$ 2.5 $R_\odot$. The large variation of the CCF on a timescale of days suggests that the period might be significantly smaller than 7.5 days. Photometric or further spec-

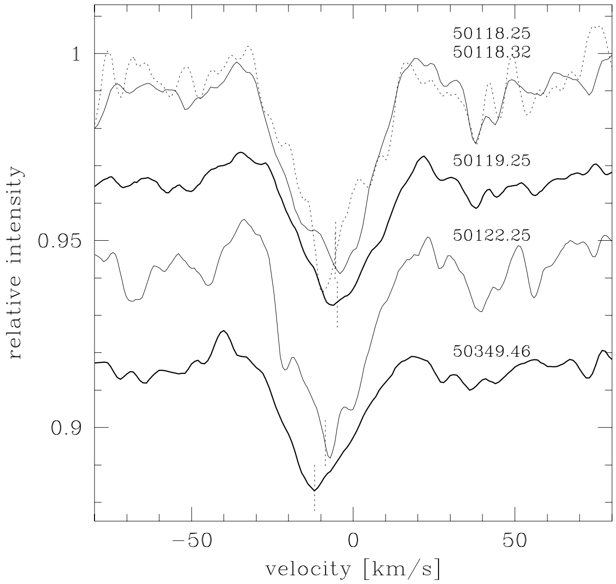

Fig. 2. Same as in Fig. 1, but for the "low g_{eff}" template.

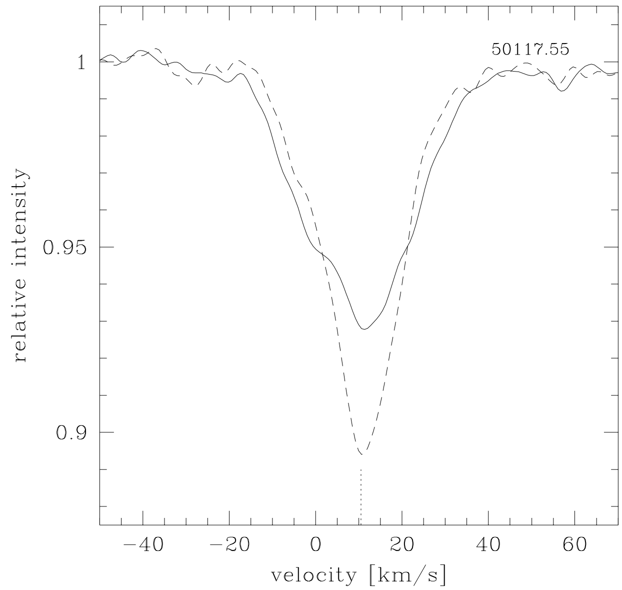

Fig. 3. Observed cross-correlation functions of HD 68343, for the "high g_{eff}" template (solid curve) and for the "low g_{eff}" (dashed curve). The dotted bar indicate the radial velocity deduced from the core of Hα and Hβ.

troscopic measurements should be made to determine the period exactly.

3.2. HD 63843

This star has been classified CrEu by Bidelman & MacConnell (1973). There are three good photometric measurements in the Geneva photometric system, which indicate a significant variability in the V magnitude; it should then be relatively easy to find a photometric (hence rotational) period for this star. The visual average magnitude and photometric indices are given in Table 3.

3.2.1. Magnetic field

There is unfortunately only one spectrum of this star, with a relatively low S/N ratio. The deconvolved correlation dip is shown in Fig. 3. It is deep and very well defined and indicate a quite large field of $< H_s^2 >^{1/2}$= 11.6$\pm$0.8 kG. The narrow lines of this star make also possible an estimation of $< H >$ through the Zeeman doublet λ6149.246 (Mathys 1990), from which we obtain a separation $\Delta\lambda$ = 0.45 $\pm$ 0.05 Å giving $< H >$= 9.4 $\pm$ 1 kG.

3.2.2. Effective temperature

The colours measured in the Geneva photometric system (Table 3) allow a preliminary estimate of the effective temperature or, more precisely, of a lower limit to it. The $B2 - G$ index is -0.432, implying $T_{\rm eff}$ = 7910 $\pm$ 300 K through the calibration of Hauck & North (1993). Adopting an approximate distance of 370 pcs, we get from the $E(B-V)$ (Lucke 1978) and N_H maps (Fruscione et al. 1994), that $E(B-V) \simeq 0.03$. We obtain then $T_{\rm eff}$ = 8120 $\pm$ 300 K after correction for reddening. Fitting the Hβ line profile, we obtain a somewhat lower temperature

$T_{\rm eff}$ = 7500 $\pm$ 250 K.

3.2.3. $V \sin i$

Both an extrapolation to the 2^{nd}-order moment of the correlation peak for the nonmagnetic case (see Sect. 3.1.3) and the width of the blue component of the Fe II λ6149.246 line indicate a $V \sin i$ definitely lower than 5 km s^{-1}. Therefore, unless the inclination is very small, the rotational period must be rather long, i.e. more than about 25 days.

3.3. HD 86592

This star has been classified SrEu by Bidelman (1981). It has 24 photometric measurements in the Geneva system (Table 4), allowing to determine a period of 2.8867 days, with the following ephemeris

$$\text{HJD(min. B mag.)} = 2446896.801 + (2.886669 \pm 0.000030)E. \quad (5)$$

The epoch of zero phase corresponds to maximum light intensity. The lightcurves are shown in Fig. 4 and indicate a peak-to-peak variation of 0.08 in magnitude $[B]$. The coefficients of the fitted Fourier series can be obtained on request from the authors.

The rms scatter of the residuals is 0.0101 in $[U]$, 0.0056 in $[B]$ and 0.0062 in $[V]$, i.e. slightly larger than expected; additional photometric measurements would be welcome between

Table 3. Average visual magnitude and colour indices in the Geneva photometric system for some of our programme stars. The quantities Q and P are the weights of Rufener (1988) on the visual magnitude and on the colours respectively.

HD/BD	V	σ_V	Q	[U-B]	[V-B]	[B1-B]	[B2-B]	[V1-B]	[G-B]	$\Delta(V1-G)$	σ_c	P
47103	9.144	0.002	2	1.507	0.696	0.968	1.401	1.413	1.816	0.019	0.006	3
63843	10.244	0.013	3	1.627	0.716	0.954	1.415	1.435	1.847	0.015	0.005	3
86592	7.866	0.007	24	1.388	0.657	0.977	1.401	1.372	1.788	-0.002	0.017	25

Table 4. Photometric measurements of HD 86592. Q and P are the qualities of the visual magnitude and of the colours respectively, on a scale going from 0 (very bad) to 4 (excellent).

HJD -2440000	Q	V	P	[U-B]	[V-B]	[B1-B]	[B2-B]	[V1-B]	[G-B]
5753.728	3	7.879	3	1.411	0.715	0.965	1.411	1.422	1.853
5805.591	3	7.874	3	1.403	0.713	0.963	1.412	1.427	1.851
6481.743	3	7.862	3	1.367	0.641	0.979	1.389	1.358	1.769
6549.511	3	7.873	3	1.407	0.676	0.974	1.400	1.381	1.801
7166.816	3	7.857	3	1.379	0.631	0.983	1.403	1.345	1.755
7167.836	3	7.873	3	1.409	0.699	0.965	1.401	1.408	1.831
7204.714	3	7.861	3	1.392	0.670	0.974	1.406	1.378	1.799
7213.712	3	7.861	3	1.407	0.671	0.967	1.404	1.387	1.810
7251.554	3	7.870	3	1.410	0.695	0.971	1.408	1.414	1.832
7253.581	3	7.863	3	1.389	0.642	0.977	1.407	1.377	1.791
7265.581	2	7.858	3	1.393	0.680	0.974	1.406	1.394	1.814
7267.550	2	7.851	3	1.345	0.602	0.989	1.382	1.323	1.727
7273.591	3	7.877	3	1.369	0.633	0.975	1.393	1.345	1.758
10416.819	3	7.867	3	1.339	0.603	0.998	1.391	1.315	1.721
10417.821	3	7.871	3	1.412	0.678	0.970	1.396	1.378	1.806
10419.826	3	7.857	4	1.368	0.604	0.994	1.376	1.327	1.724
10420.827	3	7.862	4	1.409	0.679	0.975	1.422	1.399	1.814
10421.829	3	7.859	4	1.386	0.668	0.981	1.400	1.385	1.809
10422.802	4	7.866	3	1.372	0.610	0.991	1.395	1.327	1.738
10423.831	3	7.874	3	1.411	0.688	0.966	1.414	1.399	1.816
10424.830	3	7.866	3	1.376	0.655	0.979	1.402	1.364	1.783
10425.825	3	7.861	3	1.376	0.625	0.986	1.399	1.340	1.749
10426.829	3	7.871	3	1.406	0.691	0.971	1.403	1.404	1.825
10427.831	3	7.855	3	1.372	0.631	0.983	1.395	1.350	1.769

phases 0.0 and 0.4 but we think the period we propose is fairly unambiguous.

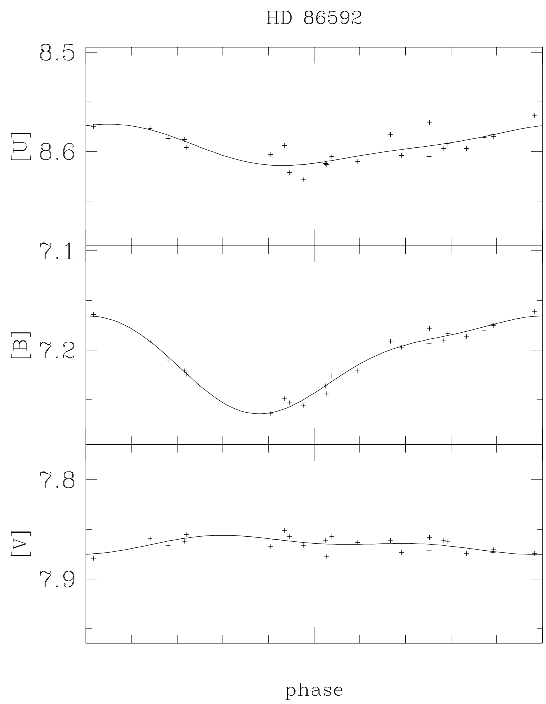

Fig. 4. Geneva lightcurves of HD 86592 in filters [U], [B] and [V] according to the ephemeris given by Eq. 5. The crosses are for the observations given in Table 4. The curves are for fits with Fourier series truncated at the first harmonic.

3.3.1. Magnetic field

The deconvolved correlation functions displayed in Fig. 5 for the two observations show that in spite of the relatively large rotational velocity, a differential magnetic broadening is clearly present and indicates in both cases a quadratic field, $< H^2 >$, of $15 - 16$ kG. A variation of the magnetic field can not be assessed. We also obtain no sign of variation larger than 2% in the correlation peak surface. According to the photometric period derived above the two observations are very close in phase with ϕ = 0.05 and 0.08 respectively. This could explain the absence of variability noticed here. The radial velocity deduced from the first-order moment of the correlation peak is v_{rad} = 12.7 ± 0.3 km s^{-1}, while a fit of the cores of Hα and Hβ gives v_{rad} = 13.0 ± 0.6 km s^{-1}. Due to the large rotational broadening, the line at λ6149.246 does not show any resolved component [2].

[2] Nevertheless, we observed, after co-adding both spectra, a weak and rather uncertain indication of Zeeman splitting in the FeII line λ6147.735 (Mathys 1990). In both spectra, the two major components of λ6147.735 are separated by $0.25 - 0.3$ Å with a mean position at λ6147.92. This translate into $< H >= 13 - 16$ kG and $v_{rad} \simeq 10$ km s^{-1}. These values are very uncertain but seem roughly consistent with the determinations obtained through the correlation peak.

3.3.2. Effective temperature

The Geneva photometric indices yield $T_{\rm eff}$ = 7660 ± 300 K (according to the calibration of Hauck & North 1993). Adopting an approximate distance of 130 pcs, we get from Lucke (1978) and Fruscione et al. (1994) that $E(B-V) \lesssim 0.01$ so that reddening effects are negligible in comparison to the uncertainty in the photometric determination. Fitting theoretical profiles to the Balmer lines provides the following estimate:

$T_{\rm eff}$ = 7600 ± 200 K.

3.3.3. $V \sin i$

Considering as before the widths of the correlation dips, the result is

$V \sin i = 16 \pm 2$ km s^{-1}.

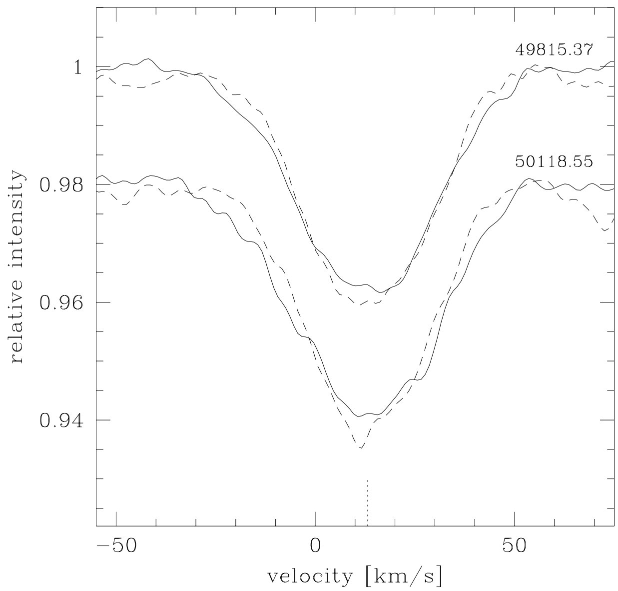

Fig. 5. Observed cross-correlation functions of HD 86592, for the "high g_{eff}" template (solid curves) and for the "low g_{eff}" (dashed curves). The dotted bar indicate the radial velocity deduced from the core of Hα and Hβ.

This large value shows that provided the S/N ratio is high enough (i.e. larger than 30-40), our method remains useful to detect large fields even for relatively fast rotators. We obtain also from the photometric period and $V \sin i$ that the inclination angle i is lower than 25°.

3.4. HD 47103

Since the observations were published (Babel et al. 1995), this star has been observed several times, with two new measurements with sufficient signal-to-noise. The old and new values of the magnetic field are listed in Table 1 and show no important variation, but a possible small decrease, at the 2σ level, by about 1% of the field intensity between 1995 and 1996, the field varying from $< H >= 17.51 \pm 0.06$ kG, to 17.26 ± 0.1 kG. All values listed have been determined through a gaussian fit to the resolved Zeeman σ_+- and σ_--components and applying Eq. 4. The relative intensity of the π- and σ-components has also remained constant within the errors, implying that the mean angle $< \psi >$ between the axis of the magnetic field and the line of sight has not changed much in 1.46 years. Apparently, this object has a very long spin period, unless it is seen nearly pole-on. The measurement of $< H >$ from the doublet at λ6149.246 does not help to conclude about any field variation and gives a value of $< H >= 17.6 \pm 0.4$ kG for the new measurements, while $< H >= 17.6 \pm 0.3$ kG was obtained for the 1995 measurements.

We nevertheless observe a small but definite variation of the radial velocity of the whole triplet, the velocity changing from a mean value of -13.9 ± 0.2 km s^{-1} for HJD=2449818 to -10.8 and -11.2 km s^{-1} for the two last measurements indicating a possible membership in a binary system.

Three photometric measurements of moderate quality could be made, yielding $B2 - G = -0.415$, which translates into $T_{\rm eff} \sim 7820 \pm 300$ K. Adopting an approximate distance of 300 pcs for HD 47103, we get from Lucke (1978) that $E(B-V) \simeq 0.07$, giving $T_{\rm eff} \sim 8310 \pm 300$ K after correction for reddening. Babel et al. (1995) obtained $T_{\rm eff} = 8900 \pm 300$ K from a fit of the Balmer lines. A more detailed analysis is however necessary to refine the determination of $T_{\rm eff}$.

4. Conclusion

We have presented the discovery of three Ap stars with very large surface magnetic fields (i.e. larger than 11 kG). In addition, new measurements of the field previously detected in HD 47103 have also been presented, showing no significant variability of the magnetic field on a timescale of one and a half years. The projected rotational velocities of all four stars are estimated, and it is interesting to mention that two of them have a relative fast rotation, with $V \sin i$ close to 20 km s^{-1}, while the other two rotate very slowly. In addition, the rotational period could be measured for one star of the sample using Geneva photometry, and its value is consistent with the rather large $V \sin i$ estimated from the spectra.

These results illustrate the efficiency of the cross-correlation technique for the detection of magnetic fields in cool Ap stars with low signal-to-noise observations. In particular, this technique seems also appropriate to detect surface magnetic fields in moderately fast rotators. It proves thus to be complementary to other methods which are currently biased towards very slow rotators (see e.g. Mathys et al. 1996).

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