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Spectropolarimetric measurements of the mean longitudinal magnetic field of chemically peculiar stars*

On the light, spectral and magnetic variability

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Abstract. We have equipped the spectrograph of the *Catania Astrophysical Observatory* with a polarimetric module which gives simultaneous circularly right and left polarised radiation spectra.

This facility has been used to perform time-resolved spectropolarimetric (Stokes V) measurements of the mean longitudinal (effective) magnetic field for seven chemically peculiar stars. Since this class of stars is characterised by a periodically variable magnetic field, the monitoring of the Stokes V parameter is a fundamental step to recover the magnetic field topology.

To better define the variation of the effective magnetic field, we have combined our observations with data from the literature. Variability periods given in the literature have been verified using Hipparcos photometric data and, if necessary, we have redetermined them.

From Hipparcos absolute magnitudes, we have determined the stellar radii and then, on the hypothesis of a rigid rotator, the inclination of the rotational axes with respect to the line of sight. On the hypothesis that the magnetic field presents a dominant dipolar component (that is, where the Stokes Q and U parameters are not necessary to recover the magnetic configuration) we have determined the angle between the rotational and dipole axes and the polar strength of the magnetic field.

Chemically peculiar stars show periodic anti-phase light variations short-ward and long-ward of a constant wavelength, the *null wavelength*. We have performed numerical computations of the expected flux distribution for metal-enhanced atmospheres with different effective temperature and gravity. From the behaviour of the *null wavelength*, we confirm the importance of the non-homogeneous distribution of elements on the stellar surface as origin of the light variability. However to explain the photometric variability of some stars, we suggest that the flux distribution is also influenced by the contribution of the magnetic field to the hydrostatic equilibrium.

Key words: instrumentation: polarimeters – stars: chemically peculiar – stars: magnetic fields

1. Introduction

All aspects which characterise Magnetic Chemically Peculiar (MCP) stars, such as: slow stellar rotation, anomalous abundances, light and spectral variability, are commonly ascribed to the presence of large-scale organised magnetic fields. To explain these phenomena, Stibbs (1950) proposed the Oblique Rotator Model (ORM), where a MCP star presents a magnetic dipole, whose axis differs from the rotational axis, and a non-homogeneous distribution of chemical elements on its surface. In the ORM, the observed variations are simply due to the stellar rotation. The anomalous abundances are caused by diffusion processes (Michaud 1970). Magnetic fields are suspected of influencing the diffusion by suppressing mass-motions and changing the path of ionised species (Michaud et al. 1981), so that diffusion in MCP stars results in a non-homogeneous distribution of elements on the stellar surface.

It has been known for a long time that the magnetic field of a MCP star is not purely dipolar. De-centered dipoles must often be invoked to explain the magnetic field variations (Stift 1975). Bagnulo et al. (1999) have shown that a quadrupolar component is often necessary to account for the variations of cross-over and quadratic field. Bagnulo et al. (1995) have pointed out that the broad-band linear polarisation (Q and U Stokes parameters) is not enough to recover the magnetic configuration, and that more precise results can be achieved only by combining all the Stokes parameters.

With the aim to increase the number of MCP stars with known effective magnetic field (Stokes V) variation, we have obtained time-resolved spectropolarimetric measurements of the effective magnetic field for seven of these stars.

2. Observations and data reduction

The fibre-fed REOSC spectrograph (see a description in Frasca & Catalano 1994) of the *Catania Astrophysical Observatory*

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* Based on observations collected at the Catania Astrophysical Observatory, Italy

has been equipped with a polarimetric module consisting of *a*) an achromatic quarter-wave plate converting from circular to linear polarisation, *b*) a calcite block, which spatially separates the two orthogonally polarised radiation beams and *c*) a couple of 200 μm fibers to feed the spectrograph. The quartz and MgF_2 retarder works in the 4300 - 6800 Å range with a 3% accuracy of the path difference. This module is located along the $f/15$ beam of the 90 cm telescope. Since the foci of the two beams emerging from a calcite block are at different distances, fiber input ends have been placed at the appropriate positions avoiding, with respect to a directly fed spectrograph, out-of-focus images on the spectrograph slit, or the use of additional optics for positioning the foci at the same distance. Moreover, fibers work as a depolariser and it is not necessary to use further depolarising optics to avoid dependence of the spectrograph efficiency on polarisation. Lens systems focus the linearly polarised beams at $f/4$ onto the fibers.

Spectra were recorded on a thinned, back-illuminated (SITE) CCD with 1024×1024 pixels of 24μm size. To take advantage of the maximum CCD efficiency and of the quadratic increase of the separation of Zeeman σ components with wavelength in contrast with the linear decrease of the echelle spectrograph resolution with wavelength, the 5700-6500 Å range was selected. At these wavelengths, orders are 7 pixels wide and the inter-order distance is 500 pixels. Fibre output ends have been separated to give any order splitted in two 10-pixel separated orders. The spectra have a linear dispersion of 6.3 Å mm^{-1} and the instrumental profile can be represented by a FHWM = 0.38 Å gaussian.

An incandescent lamp was used for flat-fielding the CCD frames and a thorium-argon lamp was used for the wavelength calibration. The light of both lamps have the same stellar light path inside the polarimetric module. Bias, flat-fielding and wavelength calibration lamp frames were recorded at the beginning and end of each observing night.

Left and right circularly polarised spectra were reduced separately using IRAF 2.11 routines with the steps: 1) over-scan and bias subtraction, 2) tracing of stellar orders, 3) scattered light subtraction, 4) order extraction for stars and calibration lamps, 5) flat-fielding and wavelength calibration of stellar spectra. As the flat-field spectra are as large as the stellar spectra, to avoid giving the same weight to the noisy edges as to the center of the order, we preferred to divide the extracted stellar spectrum by the extracted flat-field spectrum. The left and right circularly polarised spectra were then normalised to their respective continua with a quadratic polynomial, and more accurately redefined during line measurements using about 15 Å intervals. The coincidence of standard deviation (computed in intervals free of spectral lines of the normalised stellar spectra) with the photonic noise assures the accuracy of the data reduction. As to the wavelength calibration, we have independently calibrated the left and right polarised radiation thorium-argon spectra identifying more than one hundred lines. To evaluate the quality of the wave calibration, we have cross-correlated (using the FXCOR IRAF 2.11 routine) the opposite polarised Th-Ar lamp spectra and found that shifts are $\sim 0.2{\pm}2$ mÅ. No significant differences were found between calibration frames obtained at the beginning and at the end of the night. This is not surprising as the fibre-fed spectrograph is fixed in a thermally controlled room.

The magnetic chemically peculiar stars which are listed in Table 1 were observed between October 1998 and February 1999.

3. The measurement of the effective magnetic field

The mean longitudinal magnetic field or effective magnetic field ($H_{\rm eff}$) has been measured via the relation:

$$\lambda_R - \lambda_L = 2 \cdot 4.67 \times 10^{-13} g_{\rm eff} \lambda_0^2 \; H_{\rm eff}$$

where λ_R and λ_L, the barycentric wavelengths of the right and left circularly polarised lines, are computed from the integral:

$$\lambda_{R,L} = \frac{1}{EW} \int r_{R,L}(\lambda)\, \lambda \, \delta\lambda$$

Here $r_{R,L}$ is the residual, EW the equivalent width of the line and λ_0 is the wavelength of the unperturbed line. The effective Landé factors have been computed through the classical formula:

$$\begin{aligned} g_{\rm eff} \;=\; & 0.5(g_{\rm low} + g_{\rm high}) + \\ & 0.25(g_{\rm low} - g_{\rm high})(J_{\rm low}(J_{\rm low}+1) - J_{\rm up}(J_{\rm up}+1)) \end{aligned}$$

where $g_{\rm low}$ and $g_{\rm high}$ are the Landé factors of the lower and higher energy levels.

We have adopted the Landé factors given by the Kurucz (1993) atomic line list, or computed them in the LS-coupling approximation from the formula:

$$g = 1 + \frac{J(J+1) - L(L+1) + S(S+1)}{2J(J+1)}$$

where S, L and J are the spin, orbital angular momentum and total angular momentum quantum numbers of the considered level.

To interpret the observed spectra and select the unblended lines necessary to measure $H_{\rm eff}$, for each star we:

- determined the effective temperature and gravity from (SIMBAD) Strömgren photometric data by using the Napiwotzki et al. (1993) relations as numerically coded by Dworetski (priv. comm.),
- computed the corresponding ATLAS9 (Kurucz 1993) atmosphere model, and
- solved the transfer equation in the observed wavelength range by using the SYNTHE (Kurucz & Avrett 1981) code together with the atomic line list provided by Kurucz (1993). Element abundances have been adjusted to match the observed spectra as closely as possible.

Since the measurement of the effective magnetic field is affected not only by the S/N and continuum determination but also by the selected lines through their number, strengths, precision of the Landé factors, it is not possible to obtain a general formula

Table 1. Observed magnetic chemically peculiar stars. Spectral types and peculiarity classes are from Renson et al. (1991). Magnitudes are from Hipparcos. Effective temperatures have been determined following Napiwotzki et al. (1993). Stellar radii have been measured from Hipparcos absolute magnitudes. The inclination (i) of the rotational axis with respect to the line of sight has been estimated, if possible, on the hypothesis of rigid rotator. r is the ratio between the minimum and the maximum values of the effective magnetic field. When the magnetic field shows a sinusoidal variation, on the hypothesis of a dominant dipolar component, we have determined the inclination of the dipole axis with respect to the rotational axis and the polar strength of the field.

Star	Spec.Type	V	T_{eff} K	R $R_\odot$	P days	$v_e \sin i$ km s^{-1}	i deg	r	β deg	H_p kG	References for $v_e \sin i$
4778	A1CrSrEu	6.12	10080	2.0	2.56171	33	57	−0.77	79	4.8	Abt & Morrell (1995)
24712	A9SrEuCr	5.99	7240	1.9	12.4572	5.6	46	0.31	27	4.9[1]	Ryabchikova et al. (1997)
								0.25	30	4.0[2]	
								−0.35	63	2.2[3]	
32633	B9SiCr	7.07	12270	2.4	6.43000	23		−2.04			Borra & Landstreet (1980)
62140	A8SrEu	6.47	8220	1.9	4.28679	18	53	−1.00	90	6.0	Abt & Morrell (1995)
196502	A2SrCrEu	5.19	8900	3.1	20.279	9		−1.10			Ryabchikova et al. (1999)
200311	B9SiCrHg	7.68	14600	2.9	52.0084	9		−1.15			Preston (1970)
201601	A9SrEu	4.71	7870	1.7	26890.6	∼ 0		−0.64			Ryabchikova et al. (1999)

Parameters of HD 24712 determined fitting separately the H_{eff} measurements obtained from
[1] photopolarimetry on H_β line by Ryabchikova et al. (1999)
[2] spectropolarimetry of Ti, Cr and Fe lines by Preston (1972)
[3] spectropolarimetry, mostly from Fe lines by Mathys (1994) and us

for the error. Mathys (1991) assumed the standard error to estimate the uncertainty affecting the measurement of the effective magnetic field. The effects of continuum and wavelength calibration errors on the H_{eff} measurements from right and left circularly polarised spectra have been evaluated by Mathys (1994). Applying this method to our measurements, we found that the uncertainties on H_{eff} are not different from the standard deviation. This is not unexpected as our observational conditions are very close to the ones of Mathys (1994), who revisited Mathys' (1991) measurements and determined errors almost equal to statistical errors. Numerical simulations have been performed to evaluate the effects on the H_{eff} measurement of the spectral resolution, line strength, stellar rotation, number of used lines and signal-to-noise ratio. The method described here has been applied to a series of synthetic left and right circularly polarised spectra in order to determine H_{eff} and its standard deviation ($\sigma(H_{eff})$). The RANDOMU routine of Interactive Data Language (IDL 5.1) has been used to include the photonic noise in our calculations. Because of the importance of the S/N, for any possible parameter-set the measurement of H_{eff} has been repeated one hundred times and the mean value of $\sigma(H_{eff})$ and its standard deviation have been computed. Table 2 reports how the accuracy of H_{eff} measurements increases with the S/N, the equivalent width of lines and the linear dispersion of the spectrograph. The accuracy is inversely dependent on the stellar rotational velocity: if $v \sin i$ is increased from zero to 30 km s^{-1}, errors are three times larger. A small dependence is found on the number of used lines: only the standard deviation of $\sigma(H_{eff})$ decreases with the number of lines.

Because of the previous considerations and results of numerical simulation, we assume as effective magnetic field the average, weighted from the line equivalent width, of the measurements from unblended lines whose equivalent width was larger than 80 mÅ. The standard deviation of the weighted average has been assumed as uncertainty of the measurement.

This procedure has been applied to the main sequence stars HR 7061 and HR 7534. As expected for non-magnetic stars, the effective magnetic field is null within statistical errors: we measured $H_{eff} = 83 \pm 147$ G for HR 7061 (V = 4.2 mag) from 19 unblended lines and $H_{eff} = 25 \pm 255$ G for HR 7534 (V = 5.0 mag) from 18 unblended lines. Measuring the effective magnetic field of the selected CP stars, we found no dependence of the measurement on the wavelength confirming that the chromatism is negligible. For the chosen wavelength region and effective temperature of the selected stars, we found that errors in the measurements of the effective magnetic field can be evaluated with a bi-linear relation in $(S/N)^2$ and number of used lines N: $\sigma = 700 - 5\,N - 0.02\,(S/N)^2$ G. This relation gives errors which are consistent with the values of the numerical simulation.

Spectral variability characterising CP stars is commonly explained assuming a non-homogeneous distribution of elements on the stellar surface. In principle, the measurement of the effective magnetic field is a line-intensity weighted average over the visible stellar disk and measurements from different elements should not be mixed. Our H_{eff} measurements are mostly based on iron lines and a possible dependence on different chemical elements cannot be statistically pointed out.

Table 3 reports the effective magnetic field, the standard deviation and the Julian dates of observations.

4. Individual stars

For each star, we have estimated:

Table 2. Our method for measuring H_{eff} has been applied to synthetic left and right spectra computed for different values of the equivalent width (EW), number of lines (N), spectrograph linear dispersion ($\Delta\lambda$), stellar rotation ($v_e \sin i$) and signal-to-noise ratio (S/N). Because of the importance of photon noise, for each possible combination of these parameters we have computed H_{eff} and its standard deviation ($\sigma(H_{eff})$) for one hundred times. The average value and the mean standard deviation of σ (H_{eff}) are here reported.

$v_e \sin i = 0\,\mathrm{km\,s^{-1}}$, EW = 100 mÅ, N = 10			
$\Delta\lambda$ Åmm^{-1}	4.2	6.3	8.4
S/N			
50	340 ± 70	530 ± 120	930 ± 240
100	170 ± 40	270 ± 80	460 ± 110
200	80 ± 20	130 ± 30	230 ± 50
300	60 ± 15	90 ± 20	160 ± 35
$v_e \sin i = 0\,\mathrm{km\,s^{-1}}$, $\Delta\lambda = 6.3$Åmm^{-1}, N = 10			
EW mÅ	50	100	200
S/N			
50	1070 ± 210	530 ± 120	380 ± 90
100	540 ± 120	270 ± 80	180 ± 50
200	270 ± 60	130 ± 30	90 ± 20
300	180 ± 40	90 ± 20	60 ± 15
$\Delta\lambda = 6.3$Åmm^{-1}, EW = 100 mÅ, N = 10			
$v_e \sin i$ $\mathrm{km\,s^{-1}}$	0	15	30
S/N			
50	530 ± 110	770 ± 170	1300 ± 280
100	270 ± 70	360 ± 90	610 ± 140
200	140 ± 30	190 ± 40	310 ± 80
300	90 ± 20	120 ± 30	240 ± 50
$v_e \sin i = 0\,\mathrm{km\,s^{-1}}$, $\Delta\lambda = 6.3$Åmm^{-1}, EW = 100 mÅ			
N	5	10	20
S/N			
50	520 ± 170	530 ± 120	540 ± 100
100	250 ± 90	270 ± 70	260 ± 40
200	130 ± 40	130 ± 30	140 ± 25
300	85 ± 30	90 ± 20	90 ± 15

– the stellar radius, following North (1998), by adopting the Hipparcos absolute visual magnitudes given by Gómez et al. (1998). As to HD 196502, which was not considered by Gómez and co-workers, we have computed the absolute visual magnitude from Hipparcos database and applied the Lutz & Kelker (1973) correction,
– the inclination (i) of the rotational axis with respect to the line of sight on the hypothesis of a rigid rotator from the relation:

$$v_e \sin\, i = 50.6 \frac{R \sin\, i}{P_{\rm rot}}$$

where $v_e \sin\, i$ is the projected rotational velocity of the star.

Moreover, on the hypothesis of a dipolar field, we have obtained:

– the angle (β) between the rotational axis and the dipole axis from the relation (Preston 1971):

$$\tan\beta \tan i = \frac{1-r}{1+r}$$

where r is the ratio of the minimum and maximum observed values of the effective magnetic field,
– the polar strength of the magnetic field (H_p) from Schwarzschild (1950) relation:

$$H_{\rm eff}(min, max) = 0.316 H_p \cos(\beta \pm i)$$

The stellar and ORM parameters determined are summarised in Table 1.

4.1. *HD 4778 = HR 234 = GO And*

HD 4778 is classified as an A1CrSrEu star in the *General Catalogue of Ap and Am stars* by Renson et al. (1991). By means of photometric and spectroscopic observations available in the literature, Hensberge (1986) determined several possible variability periods, ranging from 1.6 to 2.6 days. Bohlender (1989) performed photopolarimetric measurements of the effective magnetic field and concluded that the period of the spectroscopic, photometric and magnetic variability is 2.5616±0.0001 days.

We have identified five FeI and one SiI unblended lines in the spectra of HD 4778. Our measurements of the effective magnetic field (Table 3) show that this period is slightly too short. Following Bohlender (1989), we performed a least-squares fit of all magnetic data with the function

$$H(t) = H_0 + H_1 \times \sin 2\pi \left(\frac{t-t_0}{P} + \phi\right)$$

determining the variability period: $P = 2.56171 \pm 0.00004$ days. The other parameters are $H_0 = 0.18 \pm 0.07$ kG and $H_1 = -1.21 \pm 0.10$ kG. From the error (= 0.018) on ϕ we get an uncertainty in time of 0.046 days. Errors are computed as the variation in a parameter changing the χ^2 by a unit.

Figs. 1 and 2 show the magnetic and photometric variability according to the ephemeris:

$$JD(H_{\rm eff}(min)) = 2\,446\,674.006 \pm 0.046 + 2.56171\ E$$

Winzer's (1974) photometry on the Johnson system shows double-wave light variations for HD 4778 with the U light maxima at the same phase of the V light minima, and an almost constant luminosity in the B filter. Because of the very large passband of the Hipparcos filter, which includes the B and V filter (ESA SP-1200), a direct comparison with Winzer's photometry is not possible. As expected, because of the small amplitude variation in the B filter, the Hipparcos light curve resembles and is in phase with the V light curve, confirming the validity of the determined period.

We note that HD 4778 presents a reversing sign magnetic field and that magnetic poles are brighter than the magnetic equatorial region in the V filter. According to Bohlender (1989), calcium and strontium are mainly concentrated at the positive magnetic pole.

Table 3. Measures of the effective magnetic field

JD 2,451,000+	H_{eff} $gauss$	σ $gauss$												
HD 4778			HD 24712			HD 32633			HD 62140			HD 196502		
115.431	−65	210	115.553	540	335	115.643	−1200	130	115.676	65	180	116.283	−480	250
116.417	−130	680	117.535	530	125	116.590	−1570	320	116.675	1080	150	117.285	−510	340
117.383	1315	385	118.523	780	210	118.576	−4030	1170	118.677	−1130	460	118.255	−740	550
119.415	825	690	119.517	400	360	119.567	−990	520	119.664	−1240	290	119.237	−630	440
120.408	630	310	120.509	−180	120	120.568	1520	550	120.668	690	490	120.244	−775	350
121.414	−960	630	121.515	−225	220	121.562	95	730	121.666	1450	570	121.271	−420	410
122.291	1010	570	215.300	355	530	122.565	−1470	650	122.677	−940	460	122.234	0	280
			238.258	550	460	213.331	−610	300	213.447	−1520	170			
HD 200311						214.391	−2840	120	214.452	−420	390	HD 201601		
116.325	510	370				215.358	−2850	670	217.422	−1460	460	115.296	−1050	290
119.277	480	350				217.380	1060	100				122.255	−1010	180
122.289	770	300												

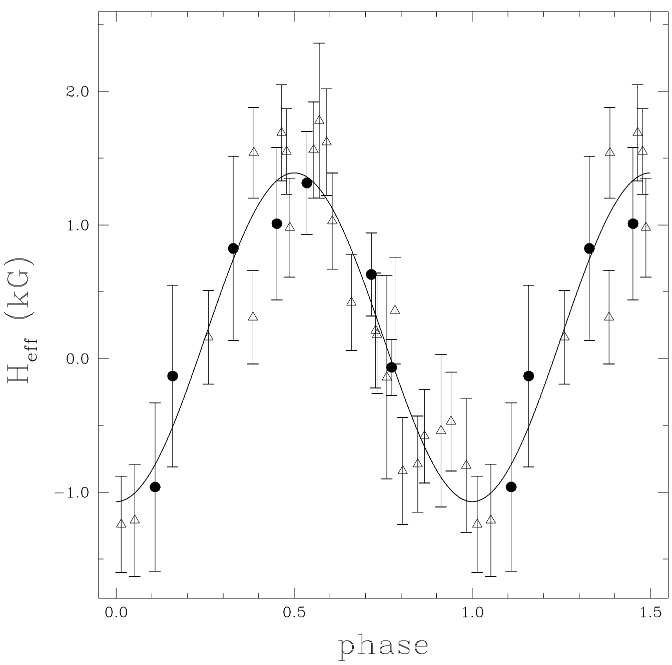

Fig. 1. Effective magnetic field of HD 4778 measured photometrically by Bohlender (1989) (triangles) and by us (filled circles). Error bars are two times the standard deviation. The solid line represents a least-squares fit by a sine curve.

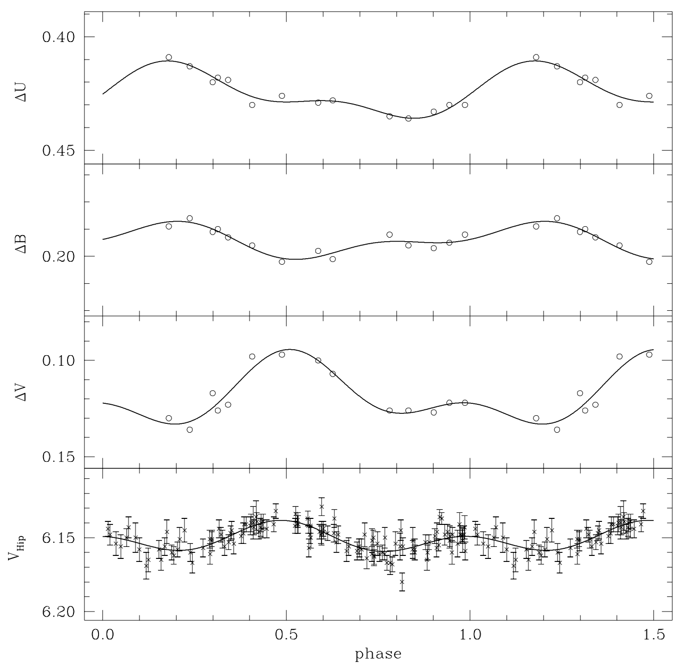

Fig. 2. Winzer (1974) and Hipparcos light curves of HD 4778. The solid line represents a least-squares fit by a sine curve and its first harmonic.

Since the H_{eff} variations are well represented by a sine function, we can suppose that the dipolar component of the magnetic field is the dominant one. Thus we have determined the inclination of the dipole axis with respect to the rotational axis ($\beta = 79°$) and the polar strength ($H_p = 4.8$ kG) of HD 4778 (Table 1).

4.2. HD 24712 = HR 1217 = $DO\ Eri$

The effective magnetic field of the A9SrEuCr star HD 24712 has been recently measured by Mathys & Hubrig (1997). Combining their measurements with data from the literature, these authors concluded that the variability period of HD 24712 is 12.4610 days and not 12.4572 days as suggested by Kurtz & Marang (1987) from photometry.

We have measured the effective magnetic field of HD 24712 from two silicon lines, two calcium lines, six iron lines and a barium line. Our measurements of the effective magnetic field do not confirm the period proposed by Mathys & Hubrig. We note that Kurtz & Marang's period phases well with the single-wave photometric variations by Wolff & Morrison (1973) and Hipparcos (Fig. 3), while Mathys & Hubrig's (1997) period gives a 0.15 phase shift.

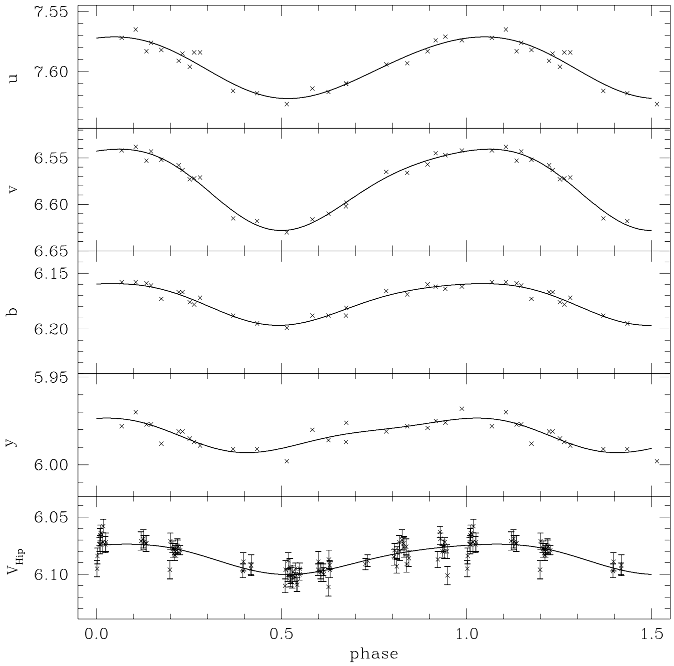

Fig. 3. Hipparcos and Wolff & Morrison (1973) light curves of HD 24712. The solid line represents a least-squares fit by a sine curve and its first harmonic.

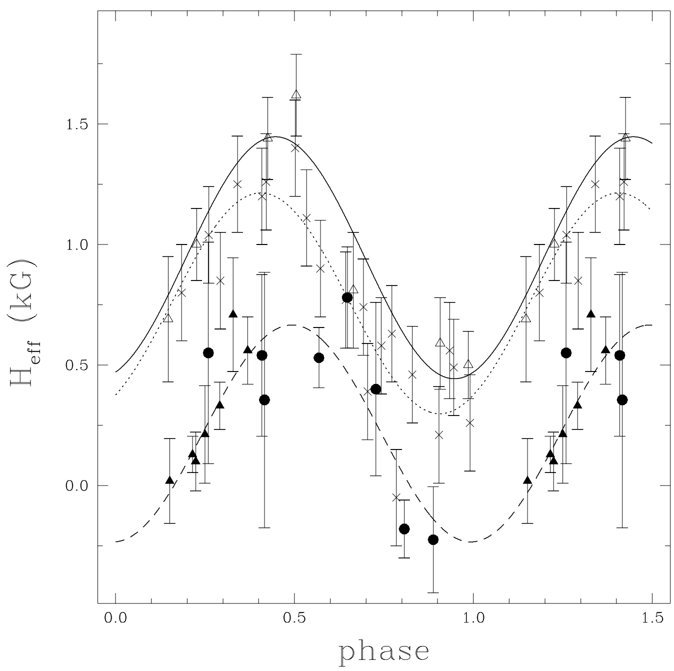

Fig. 4. Effective magnetic field of HD 24712 measured by Preston (1972) (crosses), Ryabchikova et al. (1997) (empty triangles), Mathys & Hubrig (1997) (filled triangles) and by us (filled circles). Error bars are two times the standard deviation. A sinusoidal fit shows that Mathys & Hubrig and our measurements (dashed line), from neutral iron lines, are smaller than the Preston measurements from Ti, Cr and Fe lines (dotted line) and also smaller than Ryabchikova et al. measurements from H_β line (solid line).

Adopting the ephemeris:

$$JD(v_{min}) = 2\,448\,506.9 + 12.4572\ E$$

we phased our measurements of the effective magnetic field together with the measurements by Preston (1972), Ryabchikova et al. (1997) and Mathys & Hubrig (1997) and found a large scatter of data (Fig. 4).

If we consider that: *a*) Preston (1972) measured the effective magnetic field from lines of different elements and found that Eu, Mg and Ti+Cr+Fe lines give decreasing values, *b*) the photopolarimetric measurements from the H_β line published by Ryabchikova et al. (1997) are also systematically larger than Preston's measurements[1], and *c*) Mathys' and our measurements, mostly, from neutral Fe lines, appear to be -0.75 kG shifted with respect to Preston's measurements, it appears that the measured effective magnetic field depends on the adopted method, as shown in Fig. 4.

HD 24712 is an MCP star where out-of-phase spectral variations are observed, for example europium lines are stronger when magnesium lines are weaker. Iron lines present small equivalent width variations which are in phase with magnesium line variations. Since we observe a predominantly positive magnetic field, some elements appear to be mainly concentrated in a region around the positive magnetic pole and others along a magnetic equatorial belt. Since the effective magnetic field is the average over the visible stellar disk of the longitudinal components of the magnetic field, weighted by the local element abundances, we conclude that the observed shifts between different data sets could be due to the different lines selected for measuring the effective magnetic field. We have determined the dipole geometric parameters for Preston's (1972) measurements, for Ryabchikova et al.'s (1997) measurements, and by combining Mathys' and our measurements (Table 1). These very different magnetic configurations illustrate the difficulty to recover the magnetic field topology if the non-homogeneous distribution of elements on the stellar surface is neglected.

Fig. 4 shows that the sine functions that fit the three different data sets are not in phase, with the most recent (our) data at largest phase with respect to the oldest data of Preston. We conclude that the variability period of HD 24712 is probably slightly longer than the value adopted here.

4.3. HD 32633 = *HZ Aur*

The rotational period of the B9SiCr star HD 32633 has been determined by Adelman (1997a) (P = 6.43000±0.00002 days) by combining his *uvby* photometry with Rakosch's (1962) *uv* photometry. This value of the variability period is confirmed by Hipparcos photometric data (Fig. 5).

[1] These measurements were quoted by Mathys (1994) who applied a -0.25 kG shift to let them to coincide with Preston's (1972) measurements.

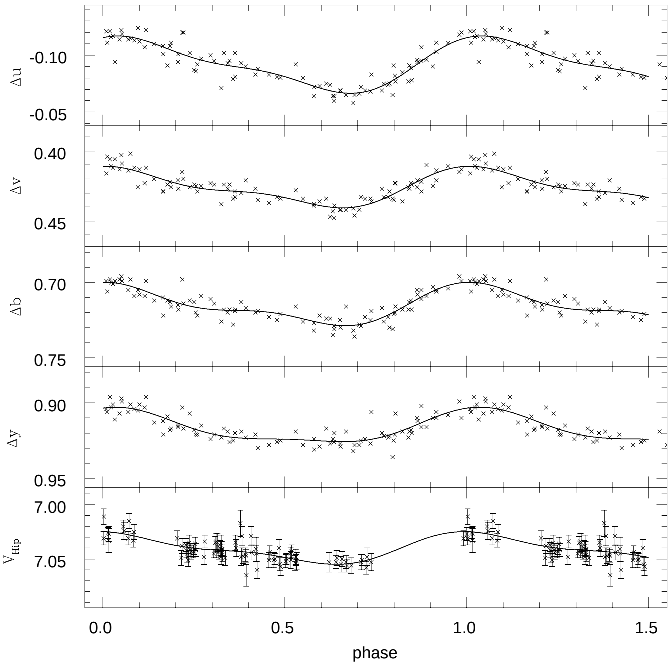

Fig. 5. Hipparcos and Adelman (1997a) light curves of HD 32633. The solid line represents a least-squares fit by a sine curve and its first harmonic.

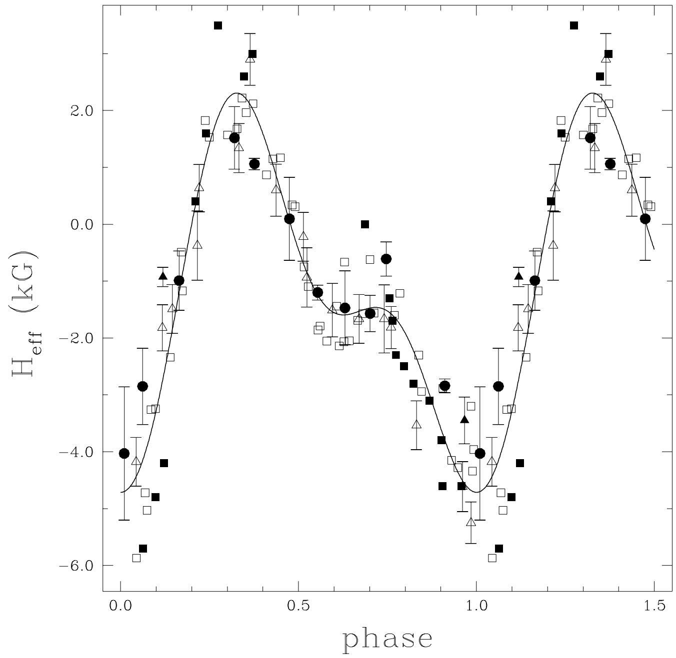

Fig. 6. Measures of the effective magnetic field of HD 32633 by Babcock (as listed by Renson 1984) (empty squares), Preston & Stepien (1968) (filled squares), Borra & Landstreet (1980) (empty triangles), Mathys (1994) (filled triangles) and by us (filled circles). Error bars are two times the standard deviation. The solid line represents a least-squares fit by a sine curve and its first harmonic.

In our spectra of HD 32633 we have identified three SiII and six FeII unblended lines useful for measuring the magnetic field. Adopting the ephemeris

$$JD(H_{\rm eff}(min)) = 2\,437\,634.8 + 6.43000\ E$$

we have phased our measurements of the effective magnetic field, the spectropolarimetric measurements on photographic plates by Babcock (as listed by Renson 1984) and Preston & Stepien (1968), the photopolarimetric measurements by Borra & Landstreet (1980) and the CCD spectropolarimetric data by Mathys (1994) (Fig. 6).

We note that this star is brighter when the magnetic field is stronger. Unfortunately no paper in the literature reports the spectroscopic behaviour of HD 32633. From our spectra, it appears that this star does not present large spectral variations. For the SiII 637.1359 nm line we measured an equivalent width of 307±28 mÅ and for the FeII 596.1705 nm line we obtained 146±17 mÅ. Even if the equivalent width variations are not very large, we found that silicon and iron lines are stronger when the absolute value of $H_{\rm eff}$ is larger.

The value of the projected rotational velocity $v \sin i = 23$ km s^{-1} given by Borra & Landstreet (1980) is not compatible with the stellar radius deduced from the Hipparcos absolute magnitude ($R = 2.4 R_\odot$). If Borra & Landstreet's value is correct the stellar radius should be $R > 2.9 R_\odot$. If $R = 2.4 R_\odot$, then $v_{\rm e} \sin i < 19$ km s^{-1}. An accurate measure of $v \sin i$ is then necessary to determine the inclination of the rotational axis.

Since the variation of the effective magnetic field is largely different from a sinusoidal function, the dipolar component is clearly not dominant, and no parameters have been determined for the magnetic field of HD 32633.

4.4. HD 62140 = HR 2977 = 49 *Cam*

The A8SrEu star HD 62140 is a photometric variable with a 4.28679 day period (Adelman 1997b). We note that with Adelman's ephemeris:

$$JD(v_{\rm max}) = 2\,441\,254.08 + 4.28679\ E$$

the $V_{\rm Hip}$ photometric variation is in phase with the vby light curves (Fig. 7).

We have measured the effective magnetic field from two SiI lines, two CaI lines and seven FeI lines. Fig. 8 shows that our measurements are in good agreement with the data by van den Heuvel (1971), Bonsack et al. (1974) and Leroy et al. (1994a).

From the phase relations between light and magnetic variations, it appears that this star is brighter when the effective magnetic field is null. Since the effective magnetic field modulation can be well represented by a sinusoidal function, we can assume a magnetic dipole and conclude that the brightest region of HD 62140 is a magnetic equatorial belt.

If the magnetic field is assumed to be simply dipolar, elements are mainly concentrated on the positive magnetic pole (Bonsack et al. 1974). Our measurements of equivalent widths confirm the concentration of iron around the positive magnetic pole and show, differently, that silicon is mainly concentrated around both magnetic poles.

We note that the light and line strength variations are not in phase and that light maxima coincide with the nulls of the effective magnetic field.

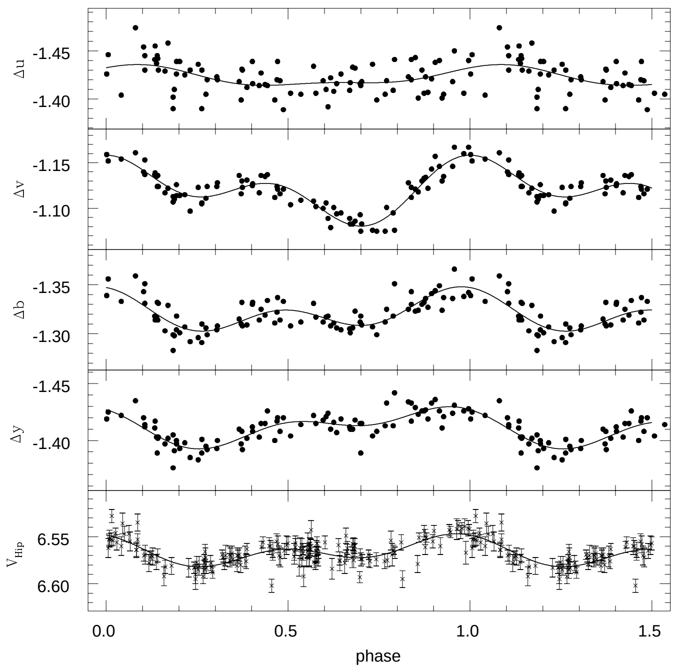

Fig. 7. Hipparcos and Adelman (1997b) light curves of HD 62140. The solid line represents a least-squares fit by a sine curve and its first harmonic.

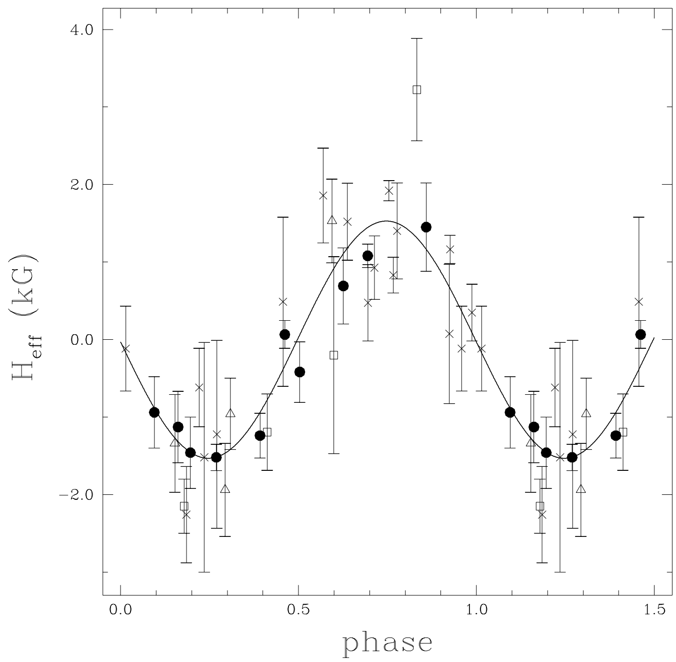

Fig. 8. Measures of the effective magnetic field of HD 62140 by van den Heuvel (1971) (squares), Bonsack et al. (1974) (crosses), Leroy et al. (1994a) (triangles) and us (filled circles). Error bars are two times the standard deviation. The solid line represents a least-squares fit by a sine.

A sinusoidal fit of the magnetic data gives a ratio between minimum and maximum $r = 1$, indicating that the dipole axis is exactly orthogonal to the rotational axis (Table 1).

4.5. HD 196502 = HR 7879 = 73 Dra

The spectroscopic and magnetic behaviour of the A2SrCrEu star HD 196502 was studied by Preston (1967), who found that this star is variable with a 20.2754 day period. The effective magnetic field changes its sign during the stellar rotation, the strength of chromium and iron lines shows two maxima of equal intensity at the phases of the magnetic extrema, magnesium lines are stronger only at the phase of the magnetic positive extremum, while lines of titanium, manganese, barium and europium are stronger during the minimum of the magnetic field.

We have used one NaI line, one SiII line, eleven FeI and seventeen FeII lines to measure the effective magnetic field of HD 196502. These measurements have been combined with the ones by Preston (1967) and Wolff & Bonsack (1972) to determine the variability period by performing a least-squares fit with the function:

$$H(t) = H_0 \ +H_1 \times \sin 2\pi \left(\frac{t-t_0}{P} + \phi_1\right)$$
$$+H_2 \times \sin 2\pi \left(\frac{t-t_0}{2P} + \phi_2\right)$$

We found $P = 20.279 \pm 0.001$ days, $H_0 = 0.12 \pm 0.03$, $H_1 = -0.77 \pm 0.04$ and $H_2 = -0.16 \pm 0.04$ kG.

Fig. 9 shows the variation of the effective magnetic field according to the ephemeris:

$$JD(H_{\rm eff}(min)) = 2\,426\,904.071 \pm 0.122 + 20.279 \ E$$

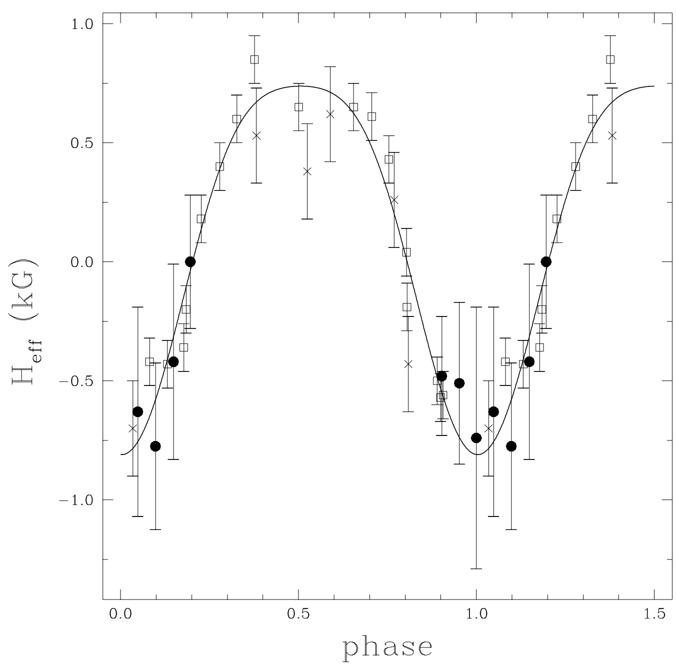

Fig. 9. Measures of the effective magnetic field of HD 196502 by Wolff & Bonsack (1972) (squares), Preston (1967) (crosses) and by us (filled circles). Error bars are two times the standard deviation. The solid line represents a least-squares fit by a sine curve and its first harmonic.

The $U\,B\,V$ photometric data of Stepien (1968) and Hildebrandt et al. (1985) confirm the validity of the variability period determined here (Fig. 10) and show double-wave light varia-

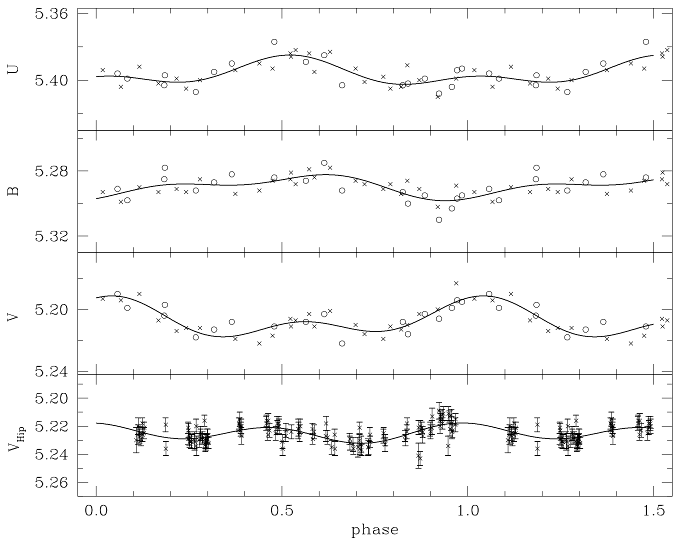

Fig. 10. UBV photometry of HD 196502 by Stepien (1968) (crosses) and Hildebrandt et al. (1985) (circles). The solid line represents a least-squares fit by a sine curve and its first harmonic.

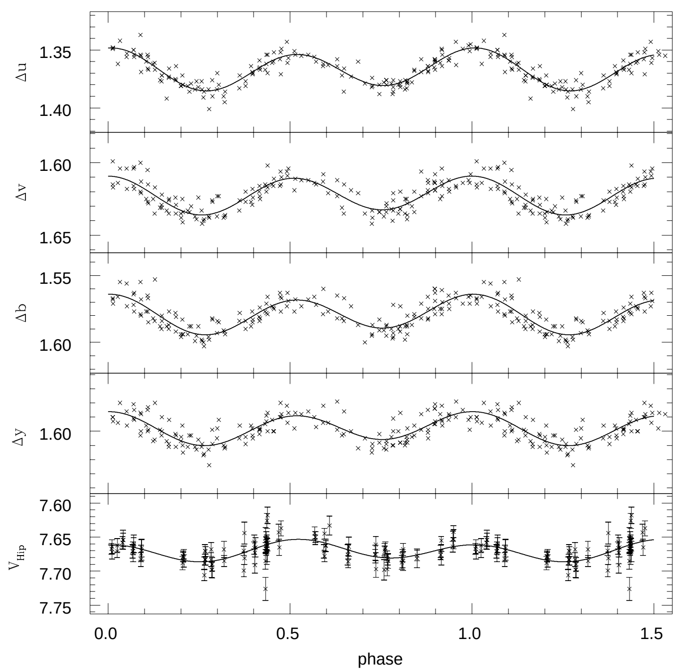

Fig. 11. Adelman's (1997a) Strömgren photometry and Hipparcos data of HD 200311 phased with the 52.024 day period. The solid line represents a least-squares fit by a sine curve and its first harmonic.

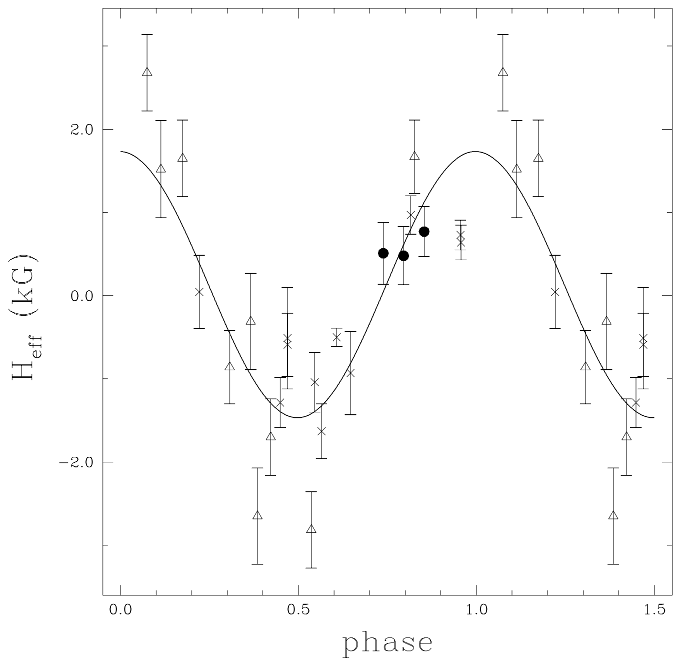

Fig. 12. Effective magnetic field measurements of HD 200311 from: photopolarimetry of the H$_\beta$ line (triangles), spectropolarimetry with photographic plates (crosses) by Wade et al. (1997) and spectropolarimetry with CCD (filled circles) by us. Error bars are two times the standard deviation. The solid line represents a least-squares fit by a sine curve.

tions whose extrema have the phases of $H_{\rm eff}$ and line strength extrema. In details, the U photometric primary maximum coincides with the V photometric secondary maximum and the secondary U maximum has the same phase of the primary V maximum. HD 196502 is almost constant in the B filter.

From $v_{\rm e}\sin i = 9$ km s^{-1} (Ryabchikova et al. 1999) and $P = 20.279$ days, we get a stellar radius for HD 196502 larger than 3.6 $R_\odot$. Since the stellar radius determined from the Hipparcos absolute magnitude is 3.1 $R_\odot$, it is not possible to determine the inclination of the rotational axis. Probably a much more accurate rotational velocity is necessary to infer the inclination of the rotational axis.

4.6. HD 200311

From $uvby$ photometry, Adelman (1997a) determined the photometric variability period of the B9SiCrHg star HD 200311 as equal to 26.0042 days. Mathys et al. (1997) measured the mean magnetic modulus and found that their measurements were variable with a 51.75±0.13 day period. Wade et al. (1997) measured the effective magnetic field of HD 200311 by photopolarimetric observations on the H$_\beta$ line wings and with spectropolarimetric observations on photographic plates and CCD. These authors concluded that the magnetic field is variable with a period equal to 26.0042 × 2 = 52.0084 days.

We noted that for the ephemeris

$$JD(v(max)) = 2\,445\,409.0 + 52.0084\,E$$

Adelman's and Hipparcos data are in phase (Fig. 11).

We have identified three SiII and four FeII unblended lines in our spectra of HD 200311. Our measurements of the effective magnetic field are more in agreement with the spectropolarimetric than with photopolarimetric measurements by Wade et al. (1997) (Fig. 12), suggesting a smaller amplitude variation.

Spectroscopic variations are unknown for HD 200311, so no conclusion can be drawn on the relations among the light, spectra and magnetic variabilities. We observe that visible light maxima have the same phases as the magnetic field extrema.

The $v_e \sin i = 9$ km s^{-1} determined by Preston (1970) and the 52.0084 day period give a stellar radius ($> 9.2R_\odot$) very different from the value deduced from Hipparcos data ($2.9R_\odot$). The rotational velocity should then be better measured to establish whether HD 200311 is a main sequence star.

4.7. HD 201601 = HR 8097 = γ Equ

The effective magnetic field of the A9SrCr peculiar star HD 201601, was measured by Babcock (1958), Bonsack & Pilachowski (1974), Scholz (1979), Borra & Landstreet (1980), Mathys (1994), Mathys & Hubrig (1997), Scholz et al. (1997) and Bychkov & Shtol' (1997).

In spite of so many measurements, the variability period of HD 201601 is still uncertain. Leroy et al. (1994b) concluded that this star is variable with a 77 year period. According to Scholz et al. (1997) the magnetic field is variable with a period slightly longer than 70 years. Bychkov & Shtol' (1997) suggested a variability period of 26890.6 days $\sim$ 73.6 years.

Our measurements of the effective magnetic field, based on ten iron unblended lines, when phased with the ephemeris

$$JD(H_{\rm eff}(min)) = 2\,421\,577.1 + 26890.6\,E$$

give an effective magnetic field more negative than expected assuming Bychkov & Shtol' (1997) period, and suggest a longer variability period (Fig. 13).

It is worthy to note that Bychkov & Shtol's (1997) measurements of the effective magnetic field obtained some few minutes apart show a spread larger than expected from statistical errors. It could be that the rapid pulsating star HD 201601 may also show variations of the magnetic field on a short time scale, thus producing a very large scatter of the observational data.

Because of the very long period of HD 201601, there are no data in the literature to establish any relation among the light, spectral and magnetic variations.

The projected rotational velocity is very close to zero (Ryabchikova et al. 1997), and it is not possible to determine the inclination angle of the rotational axis.

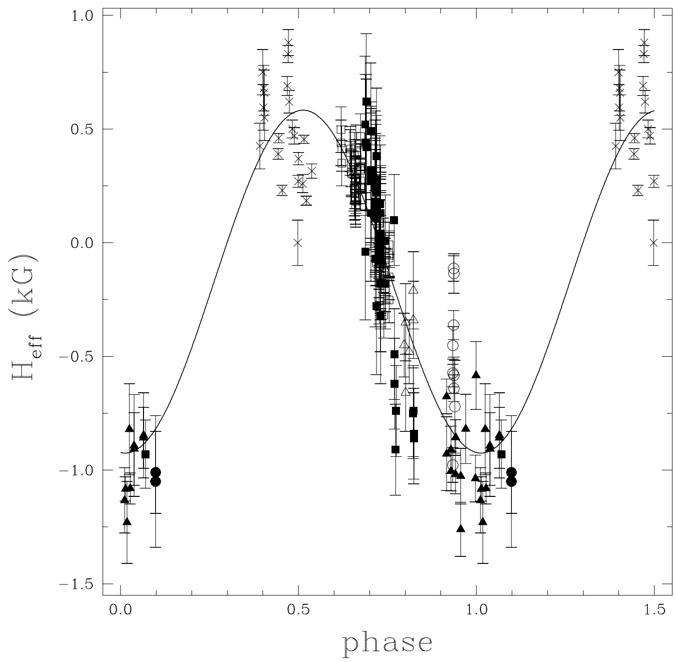

Fig. 13. HD 201601 measurements of the effective magnetic field. Crosses are by Babcock (1958), empty squares by Bonsack & Pilachowski (1974), full squares by Scholz (1979) and Scholz et al. (1997), empty triangles by Borra & Landstreet (1980), filled triangles by Mathys (1994) and Mathys & Hubrig (1997), empty circles by Bychkov & Shtol' (1997). Dots represent our measurements. Error bars are two times the standard deviation. The solid line represents a least-squares fit by a sine curve with a 73.6 year period.

5. Light, spectral and magnetic variability

Preston (1970) suggested that the light variability of chemically peculiar stars is directly linked to the spectrum variations. He supposed that changes in the continuous opacity in the ultraviolet region, particularly due to silicon, are the origin of the light variations. From Copernicus observations of the CP prototype α^2CVn, Molnar (1973) confirmed Preston's conclusion. This star shows out-of-phase light variations short-ward and long-ward of 298.5 nm where it is constant, the so called *null wavelength*. The same behaviour has also been discovered for several other CP stars (Leckrone 1974, Molnar et al. 1976, Mallama & Molnar 1977, Molnar & Wu 1978).

To test the hypothesis that the observed light variations are due to photospheric regions with an enhanced line blocking of a rotating star, we have compared the flux distribution of ATLAS9 atmosphere models computed for several values of effective temperature, gravity and metallicity. The ATLAS9 code provides the most realistic atmosphere models through the inclusion of 5.8×10^7 lines for calculating the line-blanketing. In doing this, it uses Opacity Distribution Functions which are tabulated for multiples of the solar metallicity.

Our computations show that for a given effective temperature, metal-rich regions are fainter in the ultraviolet and brighter in the visible. The *null wavelength* occurs where two ATLAS9 models with equal effective temperature and different metallicity show the same flux. This *null wavelength* decreases when the effective temperature increases and it moves from the visible to the ultraviolet as the effective temperature only goes from 7000 to 9000 K (top panel of Fig. 14).

From the stars considered here, and larger samples (see for example Mathys & Manfroid 1985), we note that generally the *null wavelength* really decreases for increasing temperatures. Our hottest stars, i.e. HD 32633 and HD 200311, do not present the *null wavelength* in the visible region and we can suppose that it is in the ultraviolet. HD 4778 (T_{eff} = 10080 K) and HD 196502 (T_{eff} = 8900 K) present the *null wavelength* in the B region. HD 62140 (T_{eff} = 8220 K) presents the *null wavelength* in the u region. We conclude that our computations confirm Preston's (1970) explanation of the MCP star light variability.

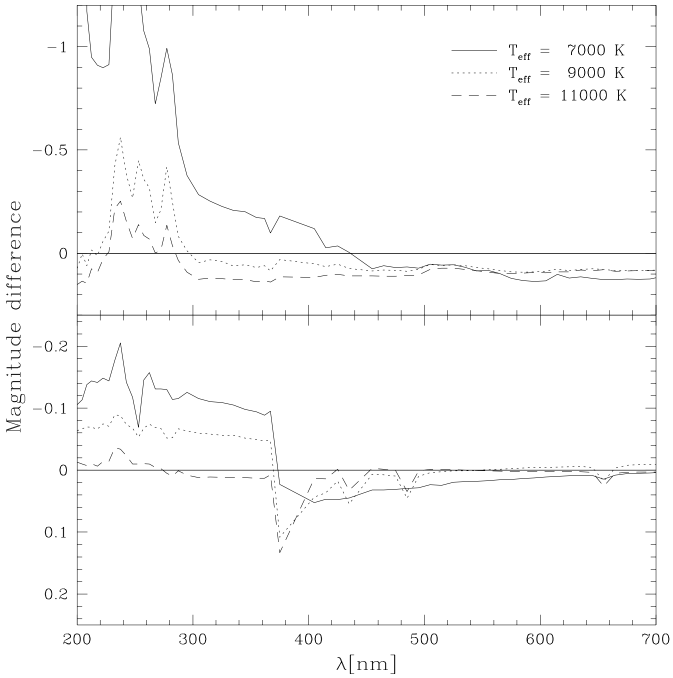

Fig. 14. Magnitude difference between atmosphere models with the *solar metal composition* and *ten times the solar composition* (top panel), and for *solar composition* atmospheres with $\log\ g = 4.0$ and $\log\ g = 3.5$ (bottom panel).

However, enhanced metallicity regions on the stellar surface cannot be the only origin of the light variability:

– HD 24712 (T_{eff} = 7240 K) does not show the *null wavelength* in the visible region as expected from its effective temperature,
– HD 62140 does not show the visible light curve in phase with the line strength variability, and it presents the light maxima at the phases of null effective field.

A possible additional source of photometric variability could be line blocking inside a given pass-band. However, Bonsack (1979) found that the measured line blocking in the v, b and y filters accounts only for one-half of the light variation observed in HD 24712.

A further source of photometric variability could be the contribution of the magnetic field to the hydrostatic equilibrium. For a main sequence star with T_{eff} = 8000 K whose gas pressure at the surface is expected to be $P_g = 10^4$ dyn cm^{-2}, a horizontal 354 gauss magnetic field produces a magnetic pressure equal to the photospheric gas pressure (Gray 1992). Thus photospheric regions with strong enough horizontal magnetic fields are expected to present a lower gas density. To evaluate the photometric behaviour of these regions with respect to regions where the magnetic field does not contribute to the hydrostatic equilibrium, we compared the flux distribution of ATLAS9 models with solar metallicity and gravities equal to $\log g = 3.5$ and $\log g = 4.0$. We found that the magnitude differences decrease with the effective temperature, disappearing for $T_{eff} > 11000$ K, and that the *null wavelength* is now always fixed at the Balmer jump value (bottom panel of Fig. 14). The contribution of the magnetic pressure to the hydrostatic equilibrium could be at the origin of the observed light variations of HD 62140. This star with T_{eff} = 8220 K has the *null wavelength* in the u filter region, out-of-phase visible-light and spectral variations and light maxima at the phase of null magnetic field. With a dominant dipolar component, nulls of the effective magnetic field occur when the line of sight lies in the magnetic equatorial plane, that is when magnetic field lines are parallel to the stellar surface and give the maximum contribution to the hydrostatic equilibrium. The light variability of HD 32633 could have the same origin ; it does not show important spectral variations (Wolff & Wolff 1971).

6. Conclusions

We have equipped the ECHELLE spectrograph of the *Catania Astrophysical Observatory* with a polarimetric module which gives simultaneous left and right-hand circularly polarised spectra. This instrument has been used to obtain time-resolved measurements of the effective magnetic field for seven chemically peculiar stars.

Our measurements have been combined with data from the literature to define the variability of the effective magnetic field. Particular attention has been paid to the accuracy of the variability period in order to define the phase relations between the magnetic, spectral and light variability.

From the observed phase relations between the light, spectral and effective magnetic variations, we conclude that photospheric regions where the magnetic field lines tend to be vertical (largest $H_{\rm eff}$ values) are usually metal-rich. This result is consistent with a study of diffusion in the presence of a magnetic field by Michaud et al. (1981), who concluded that diffusion stops where the magnetic field is horizontal.

Moreover, photospheric regions where the magnetic field lines tend to be vertical are also usually brighter in the visible and fainter in the violet than regions where the magnetic field is horizontal. From numerical simulations of stellar atmospheres with different effective temperature, metal composition and gravity, we found that metal-rich regions of the stellar surface are expected to be fainter in the ultraviolet and brighter in the visible giving rise to periodic light variations because of the stellar rotation. We also found that the wavelength of no light variation (*null wavelength*) moves towards the ultraviolet for increasing effective temperature. This being the observed behaviour of the *null wavelength*, and the light and spectral variabilities being in phase, we conclude that the enhanced line blocking is certainly important in explaining the light curves. However, the light, spectral and magnetic variability of stars like HD 62140 cannot be explained with only a non-homogeneous distribution of elements on the surface. The coincidence of the light maxima with the nulls of the effective magnetic field and the comparison of atmosphere models with equal effective temperature and different photospheric pressure suggest that the stellar regions with horizontal magnetic fields can be brighter than regions with vertical field if the magnetic field contributes to the hydrostatic equilibrium.

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