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Variation of oxygen lines in magnetic Ap stars^{*}

J.-F. Gonzalez¹ and M.-C. Artru^{1,2}

¹ Ecole Normale Supérieure de Lyon, Laboratoire de Physique (CNRS-URA 1325), 46 allée d'Italie, F-69364 Lyon Cédex 07, France

² Observatoire de Lyon (CNRS-URA 300), 9 avenue Charles André, F-69561 Saint-Genis Laval Cédex, France

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Abstract. The red lines of the O I multiplet at λ 7773 Å are observed at high resolution and their rotational variation is recorded for a sample of nine magnetic Ap stars. These lines are found to be weaker than for normal A stars. The irregular distribution of oxygen on the stellar surface is connected to the magnetic geometry for the stars HD 25823 (41 Tau), HD 74521 (49 Cnc), HD 112185 (ϵ UMa), HD 112413 (α^2 CVn), and HD 125248 (CS Vir). For four of these stars, it is clearly established that oxygen is concentrated around a magnetic polar region.

The interpretation of the observed trends adds new constraints to the theory of radiative diffusion of oxygen in Ap stars.

Key words: stars: chemically peculiar – stars: magnetic fields – stars: rotation – diffusion

1. Introduction

The oxygen underabundance is a general feature observed over the different classes of peculiar stars and its depletion is roughly explained by the mechanism of radiative diffusion (Michaud et al. 1976). Since oxygen is one of the most abundant elements in stellar atmospheres, it is important to understand the process which produces its chemical anomalies. Babel & Michaud (1991a,b,c) have achieved a theoretical study of the diffusion of atoms and ions in the atmospheres of Ap stars and they pointed out that oxygen is a sensitive element for testing the diffusion process, since it is partially ionized in the line forming region. Especially they predicted a strong effect of the ambipolar diffusion, yielding a possible superficial accumulation of oxygen, connected to the partial ionization of hydrogen. In presence of a magnetic field, different effects occur together, mainly a desaturation of the line absorption, through Zeeman splitting, and

Send offprint requests to: M.-C. Artru (first address)

^{*} Based on observations collected at the Observatoire de Haute Provence, France and at the European Southern Observatory, La Silla, Chile

changes in the ion migration, depending on the field direction. Michaud & Babel (1991) and Babel & Michaud (1991a) show the complexity of a relevant theoretical interpretation which could account for the surface inhomogeneities connected to the magnetic geometry.

The present work is devoted to the variations of oxygen lines over the rotational period of several bright magnetic stars, with known variations of the longitudinal magnetic field. We have observed the red multiplet of O I at λ 7773 Å in order to study the abundance and the surface localization of oxygen in chemically peculiar stars. The three absorption lines appear strong enough, even when oxygen is underabundant; they are free from blending, in a spectral range that allows high resolution and high signal-to-noise ratio by using modern detectors.

Previous observations of the O I multiplet by van't Veer et al. (1989) for 15 Am stars and Gerbaldi et al. (1989) for 74 Ap stars provide oxygen abundances for a large sample of peculiar stars, to be compared with the similar data on 67 normal stars (Faraggiana et al. 1988). These abundances are corrected for the non-LTE effects, by means of an empirical factor derived from the model of Baschek et al. (1977). The work of Roby & Lambert (1990) concerning the three elements C, N and O, has provided additional data for a set of 37 peculiar stars. For the fifteen stars which are in common in the above studies, they determined LTE oxygen abundances which are generally larger (by an average factor of 2) than the previous results, but still smaller than the solar value ($\log(O/H)=-3.09$) and found a deficiency of oxygen by an average factor of 1/2 and 1/6, for the Hg-Mn and the magnetic Ap stars respectively.

Therefore the general underabundance of oxygen is well established for all classes of chemically peculiar stars, with large differences from star to star. It also appears from the previous extensive results that the oxygen depletion tends to be favoured in cooler stars as well as in magnetic stars, by comparison with the corresponding Am or Hg-Mn stars. Moreover Roby & Lambert (1990) have studied the variations of the oxygen abundances of α^2 CVn along its rotational period to connect the oxygen depletion with the magnetic geometry of this star. Apart from this study and the one of CS Vir by Mathys (1992), little is known about the maps of oxygen in magnetic Ap stars.

Table 1. General characteristics of the observed stars

HD	Name	Spectral Type	V	Period	$v \sin i$	v_{rad}	T_{eff}	Reference for T_{eff}
<i>Ap stars</i>								
25823	41 Tau	B9pSi	5.20	7.227424	20	-2	12 900	Lanz et al. 1993
74521	49 Cnc	A1pEuCr	5.66	7.769	20	+24	11 000	Lanz et al. 1993
112185	ϵ UMa	A0pCr	1.77	5.0887	38	-9	8 920	Shallis & Blackwell 1979
112413	α^2 CVn	A0pSiEuHg	2.90	5.46939	29	-3	11 040	Mégessier 1988
118022	78 Vir	A1pSrCrEu	4.94	3.7220	15	-12	8 410	Roby & Lambert 1990
125248	CS Vir	A0pCrEu	5.90	9.2954	9	-9	9 400	Stępień & Dominiczak 1989
133652	HR 5619	A0pSi	5.96	2.3040	69		13 300	Lanz 1993
137509		B8pSiCrFe	6.87	4.4912	50		14 100	Lanz 1993
176232	10 Aql	F0pSrEu	5.89	unknown	≤ 6	+15	7 700	Shallis et al. 1985
<i>Normal stars</i>								
91375	HR 4138	A1V	4.74		20	+8	9 100	Lanz 1993
99803	HR 4423	B9V	5.08		0	+3	10 750	Lanz 1993
107259	η Vir	A2IV	3.89		34	+2	9 160	Mégessier 1988
172167	α Lyr	A0Va	0.03		15	-14	9 500	Smalley & Dworetzky 1993

For cooler F-type stars, García López et al. (1993) recently determined oxygen abundances with the O I multiplet at λ 7773 Å. Their work provides an interesting test on the different mechanisms which can modify the oxygen concentration below the superficial convection zone of these stars, by comparison with the lithium case. The mean oxygen abundance in the F-type stars is close to the solar one, underabundances appearing with the Am anomalies, at effective temperatures larger than about 7000 K. Therefore if the diffusion in the internal layers below the convection zone seems unable to deplete the superficial oxygen, a different effect must be efficient above 7000 K which may involve the external layers and possible departure from LTE. Theoretical models should answer this question and require accurate observational data as a first step.

In this paper we present new high-resolution spectroscopic observations of the O I multiplet at λ 7773 Å that we have recorded for nine bright magnetic Ap stars. For most of them, the rotational period and the magnetic structure can be safely deduced from previous photometric and polarimetric observations, which are reviewed here. We display variation curves of equivalent widths for these red lines, and we analyze the observed variation within the frame of the oblique-rotator model, which assumes that the star is in rigid rotation, with its magnetic axis inclined with respect to the rotation axis and that its non-uniform surface properties are related to the magnetic geometry (Stibbs 1950; Deutsch 1958). The inclination of the rotation axis to the line of sight and the obliquity of the magnetic axis to the rotation axis are usually noted i and β , respectively. The variations are caused by the changing aspect of the star as it rotates. They are attributed to a real inhomogeneity of the surface abundance rather than changes in excitation conditions (see for example the review on magnetic Ap stars by Khokhlova 1985). When possible, we propose a model of the large-scale surface localization of oxygen, in comparison with previous maps of the star which may be available for other elements. Finally we discuss the common features and exceptions, that should constrain the theoretical interpretation.

2. Observations and reduction

The observations presented here were performed during three runs at the Observatoire de Haute-Provence (OHP) in July 1992 (6 nights), December 1992 (8 nights), and May 1993 (7 nights) and one run at the European Southern Observatory (ESO) in April 1993 (6 nights). Our program contains 9 Ap stars, and 4 normal comparison stars for the study of the red lines of C, N, and O. In particular, we recorded spectra around the O I triplet at 7773 Å for each star. In the case of Ap stars, several spectra were obtained at different times of their rotational period. Due to weather conditions, the phase coverage is unequal from star to star. The general characteristics of the observed stars can be found in Table 1. The spectral type, V , $v \sin i$, and v_{rad} are taken from the Bright Star Catalogue (Hoffleit & Jaschek 1982). A journal of the observations is given in Table 2.

The OHP spectra were obtained with the 1.52 m telescope and the coudé spectrometer AURÉLIE. The detector was a one-dimensional Thomson TH 7832 CCD with 2048 pixels having a height of 750 μm and a width of 13 μm . The 1200 lines mm^{-1} grating was used in its first order with a dispersion of 7.5 Å mm^{-1} , which gave a wavelength range of 7730–7930 Å and a resolving power $R = \lambda/\Delta\lambda$ of approximately 30 000. We generally obtained signal-to-noise ratios of 200 to 300.

The ESO spectra were taken with the 1.4 m CAT telescope and the Coudé Echelle Spectrometer (CES). Its 79 lines mm^{-1} echelle grating was used in its 29th order, with the long camera and the CCD # 30. This configuration yielded a wavelength range of 7750–7810 Å, a dispersion of 2.3 Å mm^{-1} , and a resolving power of 80 000. The signal-to-noise ratios obtained were 300–400.

Before and after each long stellar exposure or each set of short stellar exposures, we recorded a series of 5 spectra of a tungsten lamp for the flat-field correction, 5 offset exposures and a spectrum of a thorium-argon hollow cathode lamp for the wavelength calibration. The reduction was performed with MIDAS procedures written by the authors. The flat-field and

Table 2. Journal of observations

HD	Name	JD (2440000+)	t_{exp} (min)	ϕ	Inst.
<i>Ap stars</i>					
25823	41 Tau	8 972.608	86	0.627	Aurélie
		8 973.609	104	0.765	Aurélie
		8 974.233	48	0.852	Aurélie
		8 975.324	38	0.003	Aurélie
		8 976.413	32	0.153	Aurélie
		8 977.296	26	0.275	Aurélie
		8 978.271	63	0.410	Aurélie
		8 979.288	128	0.551	Aurélie
74521	49 Cnc	8 973.692	104	0.984	Aurélie
		8 974.667	44	0.109	Aurélie
		8 975.667	52	0.238	Aurélie
		8 977.710	92	0.501	Aurélie
		8 978.640	110	0.621	Aurélie
112185	ϵ UMa	9 122.446	1	0.002	Aurélie
		9 123.537	3	0.217	Aurélie
		9 124.581	2	0.422	Aurélie
		9 125.408	3	0.584	Aurélie
		9 126.505	7	0.800	Aurélie
112413	α^2 CVn	9 122.424	4	0.440	Aurélie
		9 123.547	8	0.645	Aurélie
		9 124.571	10	0.833	Aurélie
		9 125.400	7	0.984	Aurélie
		9 122.409	22	0.501	Aurélie
118022	78 Vir	9 123.581	76	0.815	Aurélie
		9 124.549	38	0.075	Aurélie
		9 128.380	103	0.105	Aurélie
		9 084.745	50	0.747	CES
125248	CS Vir	9 086.775	60	0.966	CES
		9 122.470	45	0.806	Aurélie
		9 128.479	76	0.452	Aurélie
		9 084.700	55	0.201	CES
133652	HR 5619	9 085.767	60	0.664	CES
		9 086.673	90	0.058	CES
		9 087.774	70	0.536	CES
		9 088.777	60	0.971	CES
		9 089.795	50	0.413	CES
		9 084.801	100	0.817	CES
		9 085.833	120	0.047	CES
		9 086.868	150	0.277	CES
137509		9 087.860	160	0.498	CES
		9 088.858	160	0.720	CES
		9 089.872	160	0.946	CES
		8 829.579	180	0.625	Aurélie
		8 830.585	50	0.791	Aurélie
		8 831.486	70	0.940	Aurélie
		8 832.504	70	0.108	Aurélie
		8 833.500	70	0.273	Aurélie
176232	10 Aql	8 834.511	70	0.440	Aurélie
		9 086.616	35		CES
		9 089.768	20		CES
		9 125.433	60		Aurélie
		9 122.436	1		Aurélie
<i>Normal stars</i>					
91375	HR 4138	9 086.616	35		CES
99803	HR 4423	9 089.768	20		CES
107259	η Vir	9 125.433	60		Aurélie
172167	α Lyr	9 122.436	1		Aurélie

offset exposures were first averaged to improve their signal-to-noise ratio, and the mean offset was subtracted from the stellar spectrum and the mean flat-field. The net spectrum was obtained by dividing the resulting stellar exposure by the resulting flat-field and was then normalized by a third-order polynomial fitted to the continuum.

A fit of a third-order polynomial to the wavelengths of the thorium and argon lines gave the λ -pixel relation. The spectra was then computed into equal wavelength steps and smoothed by convolution with a gaussian curve of width 0.5 Å, in order to degrade all spectra to a similar final resolution. A correction was finally applied to the wavelength scale to convert it to the star's frame of reference.

The last step of the reduction was to derive the equivalent widths of the O I lines at $\lambda\lambda$ 7771.95, 7774.17, and 7775.39 Å. We used for this purpose the fitting package "fit/spectra" developed at the Observatoire de Lyon under the MIDAS environment (Rousset 1992). It allows us to fit the lines with three gaussian profiles whose separations were constrained to be 2.22 and 1.22 Å. The error bars of the equivalent widths were derived from the χ^2 given by the software.

3. Results

3.1. HD 25823 = 41 Tau

Photoelectric observations of this spectroscopic binary by Rakoš (1962) and Blanco & Catalano (1972), have shown a variation period of around 12 days. Subsequently, Wolff (1973) found a period of 7.227 days and Abt & Snowden (1973) made an independent analysis of the orbital parameters of 41 Tau and gave the ephemeris:

$$JD(\text{periastron}) = 2\,421\,944.74 + 7.227424E. \quad (1)$$

The data of Blanco and Catalano appears to be better represented by this more accurate period and all light curves show that the minimum of light occurs at phase 0.05.

Wolff (1973) also recorded Zeeman spectrograms of this star and determined the variations of the effective magnetic field, suggesting a maximum near phase 0.6 (Fig. 1a). However, the typical error is quite large (± 500 G) and it is difficult to see a sinusoidal variation as is expected in the oblique-rotator model. Nevertheless, as the field is predominantly positive, one can assume that the star only shows its positive magnetic pole.

These spectrograms also yielded variations of Si II, Sr II, and Ti II lines and showed that the Si II minimum, near phase 0.4, coincides approximately with the maximum of light whereas Sr II and Ti II minima occur near phase 0.0. More recently, visible observations of Lanz et al. (1993) confirmed the results of Artru & Freire-Ferrero (1988) who observed 41 Tau with the IUE satellite and showed that the minimum of silicon absorption occurs at phase 0.47, just before the gallium maximum at phase 0.59. C II and Ti III lines also vary in phase with the gallium ones. Gonzalez & Artru (1993) used the same UV spectra to derive variations of C I, C II, and O I lines and found that

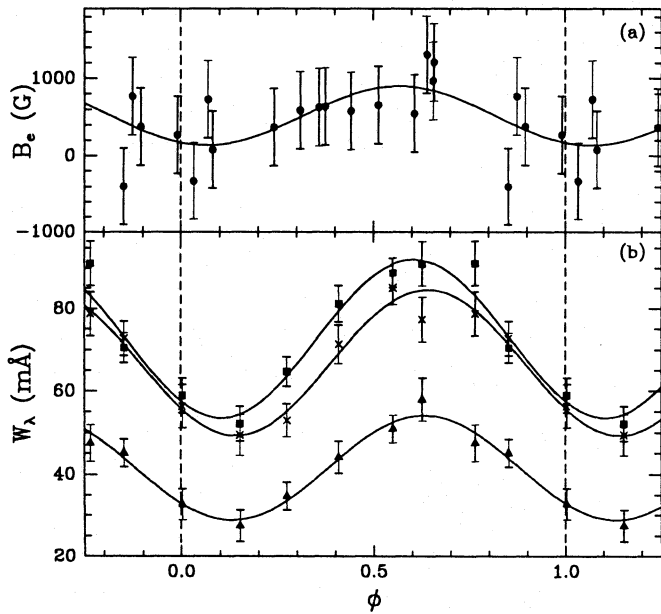


Fig. 1a and b. Variations of 41 Tau. **a** Effective magnetic field measurements from Wolff (1973) together with the best fit sine wave. **b** Equivalent widths of the O I lines at $\lambda\lambda$ 7771.95 (squares), 7774.17 (crosses), and 7775.39 Å (triangles). The solid lines are least-square fits by a sine wave whose parameters are given in Table 3

all carbon lines had their maximum equivalent width between phases 0.5 and 0.6, and that oxygen was maximum at phase 0.7.

We recorded eight spectra of the O I triplet at λ 7773 Å, well spaced in phase. The equivalent widths of the three lines are plotted against phase in Fig. 1b. We performed a least-square fit of the form:

$$W_{\lambda} = W_{\lambda}^0 + W_{\lambda}^1 \cos(2\pi(\phi - \phi_0)) \quad (2)$$

to the data. The resulting parameters are given in Table 3, and the corresponding sine wave is displayed in Fig. 1b. Each line shows variations of the order of 60%, with a maximum around $\phi = 0.6$, in phase with the effective field maximum. These new results, confirming the previous UV observations, show that there must be an accumulation of oxygen around the positive magnetic pole of 41 Tau.

3.2. HD 74521 = 49 Cnc

Photometric observations of this star showed that its light variations are very small. Therefore the determination of a period is very uncertain: Stępień (1968) reported a period of 5.43 d whereas Rakoš & Fiedler (1978) found 4.24 d. The more recent and intensive study by Lanz & Mathys (1991a) confirms the existence of low amplitude variations and gives possible periods of 7.576 or 7.769 days.

Magnetic observations of 49 Cnc were performed by Babcock (1958), Mathys (1991) and Bohlender et al. (1993), giving effective field values ranging respectively from -180 to $+1450$ G, from $+360$ to $+885$ G and from $+200$ to $+770$ G. Lanz

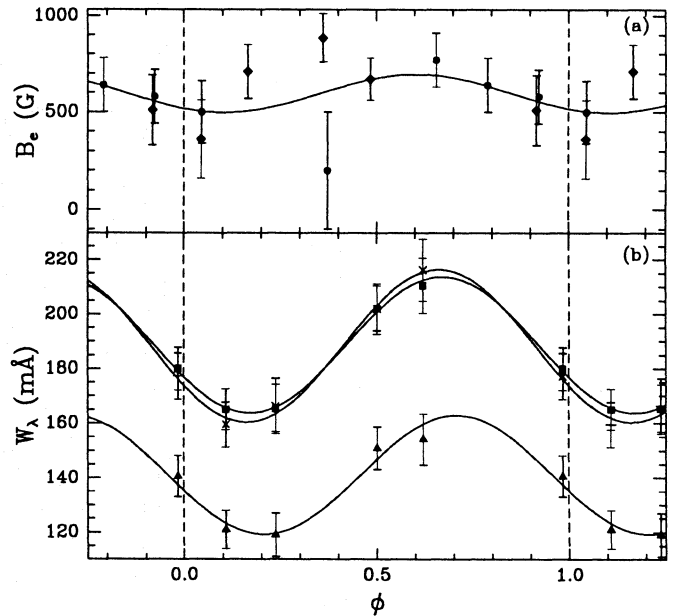


Fig. 2a and b. Variations of 49 Cnc. **a** Magnetic field as measured by Mathys (1991, diamonds) and by Bohlender et al. (1993, circles). The sine wave is fitted to both sets of observations. **b** Same as Fig. 1b

& Mathys (1991a) analysed their photometric data together with the last two sets of magnetic measurements to give additional constraints to the period and derived the following ephemeris:

$$JD(\max U \text{ light}) = 2\,447\,194.717 + 7.769E, \quad (3)$$

the effective magnetic field being maximum at phase 0.6 (Fig. 2a). The variations of B_e detected by Mathys (1991) and Bohlender et al. (1993) have a rather low amplitude, which implies that, within the assumption of the oblique-rotator model, either the inclination i of the rotation axis to the line of sight or the obliquity β of the magnetic axis to the rotation axis is quite small. The values of $v \sin i$ and of the period suggest that $i \gtrsim 30^\circ$, causing β to be equal to a few degrees or less (Bohlender et al. 1993). The star then only shows its positive magnetic pole.

Five spectra have been obtained for 49 Cnc. The equivalent widths of the O I lines vary within $\pm 30\%$ and are maximum around phase 0.7 (Fig. 2b and Table 3), near the maximum of the effective magnetic field, which suggests that oxygen is located near the positive magnetic pole.

3.3. HD 112185 = ϵ UMa

ϵ UMa is the brightest Ap star, and has been intensively studied. Guthnick (1934) was the first to derive an accurate value of the rotation period (5.0887 days) from the variations of the absorption lines intensity, which was confirmed later by Swensson (1944) and Deutsch (1947). Provin (1953) achieved a photometric study of this star and measured a double-wave light variation with the same period, the maximum coinciding with the mini-

imum of the Ca II K line intensity at $JD = 2434\,131.124$. We will then use the following ephemeris:

$$JD(\text{Ca II K min}) = 2434\,131.124 + 5.0887E. \quad (4)$$

An interesting feature is the doubling of some lines, essentially of Fe II and Cr II, reported by Struve & Hiltner (1943) around the phases 0.29 and 0.72, which they related to the rotation of the star.

The strong spectrum variations of ε UMa suggested an important magnetic field, but Babcock (1958) was unable to detect such a field. Subsequent observations by Landstreet et al. (1975) and Borra & Landstreet (1980) reported B_e values smaller than a few hundred gauss whereas Glagolevsky et al. (1982) and Hubrig (1988) found a reversing field exceeding several hundred gauss. All these measurements have large uncertainties. The first reliable determinations of a magnetic field were achieved independently by Donati et al. (1990) and Bohlender & Landstreet (1990), showing a variation from approximately -100 G to $+100$ G, with a maximum at phase 0.95. With an inclination $i = 65^\circ$, Bohlender & Landstreet (1990) give a value of $\beta = 54^\circ \pm 30^\circ$ for the obliquity, measured between the visible rotation pole and the positive magnetic pole, of a dipolar field of polar strength on the order of 400 G, whereas Donati et al. (1990) assume a decentered dipolar structure with $\beta = 74^\circ \pm 6^\circ$, $B_p = 186 \pm 6$ G (value of the polar field if the dipole was centered), and a decentering $a = 0.10 \pm 0.02 R_*$ towards the negative pole.

Several Doppler imaging methods have been used to determine abundance maps of several iron peak elements on the surface of ε UMa (Wehlau et al. 1982; Hatzes 1988; Rice et al. 1989; Rice & Wehlau 1990, 1991). Hatzes (1988) found for Cr II a large underabundant arc and 3 overabundant spots located in a circle of radius 50° . Rice & Wehlau (1990, 1991) derived more detailed maps for Fe and Cr, showing a symmetry around an axis with an inclination of 45° to the rotation axis. Both elements are found to be underabundant on the equator associated with this axis, and accumulated on two rings located 50° away from the “poles”. The passage of the northern pole near the line of sight coincides with the maximum of B_e , suggesting that this axis of symmetry may be the magnetic axis and that $\beta = 45^\circ$.

We have recorded five spectra of the O I triplet for ε UMa, which are displayed in Fig. 3. The most striking feature in this picture is the profile variations of the lines, which change from almost inexistent to very strong and clearly exhibit a doubling at phase 0.422. In the oblique-rotator model, this can be interpreted as the presence of two spots of oxygen on the surface of the star. In Fig. 3, we have labelled 1 and 2 the contribution of each spot to the line at 7771.95 \AA , each contribution moving towards redder wavelengths as the star rotates. At phases 0.217 and 0.800, the lines are quite sharp, suggesting that there is only one spot of oxygen on the visible surface of the star.

Figure 4 shows the visible hemisphere of ε UMa at the five phases of observation. We have chosen the intermediate value $\beta = 54^\circ$ of Bohlender & Landstreet (1990) to draw the magnetic poles and equator (heavy spots and line). From the comparison

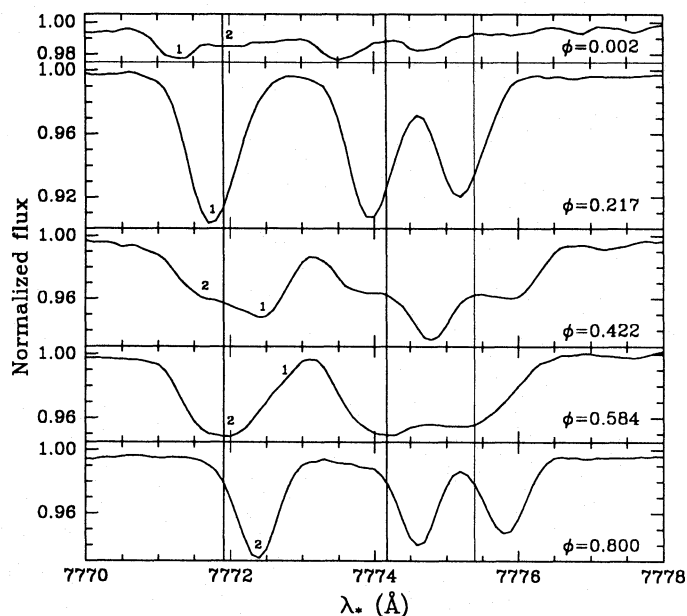


Fig. 3. The O I multiplet observed along the rotational period of ε UMa. The labels 1 and 2 refer to the features discussed in the text

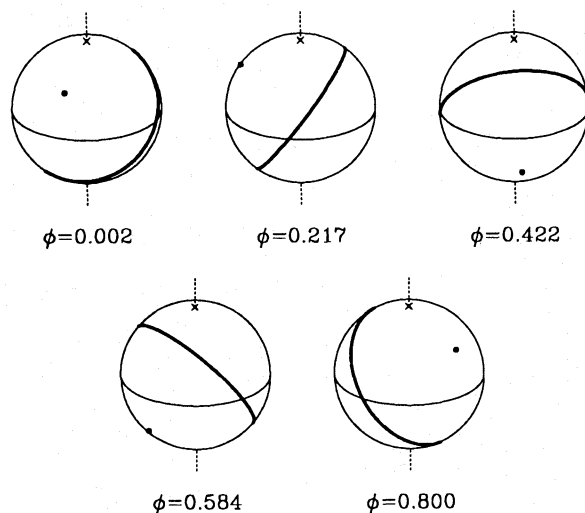


Fig. 4. Visible hemisphere of ε UMa at the phases of observation. The heavy spots and lines represent the magnetic poles and equator. The positive pole is in the upper hemisphere

of Figs. 3 and 4, it appears that oxygen lines are very weak when the positive magnetic pole is near the line of sight ($\phi = 0.002$) and very strong when the magnetic equator crosses the line of sight ($\phi = 0.217$), thus suggesting that the “spots” 1 and 2 are located on the magnetic equator and more precisely that they represent its two crossings with the line of sight. At phase 0.422, we see two parts of the equator: the first one receding from the center of the stellar disk and the second one coming into view, which is translated into the two Doppler-shifted contributions in the spectrum. At phases 0.584 and 0.800, we see essentially the second appearance of the equator on the visible hemisphere.

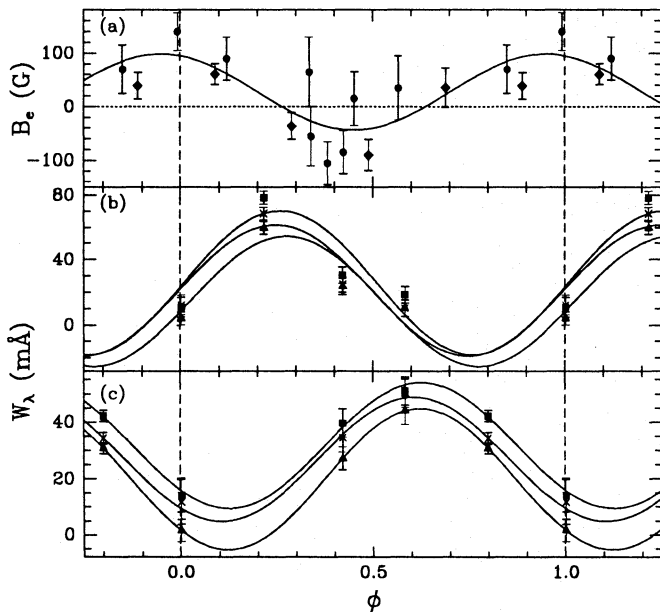


Fig. 5a–c. Variations of ε UMa. **a** Magnetic observations of Donati et al. (1990, diamonds) and of Bohlender & Landstreet (1990, circles). The sine wave is fitted to both sets of data. **b** Same as Fig. 1b for system 1. **c** Same as Fig. 1b for system 2 (see text)

In order to confirm this interpretation, we have fitted two systems of three lines to the spectra at phases 0.002, 0.422, and 0.584 and one system at phases 0.217 and 0.800, and computed the equivalent widths of the corresponding lines. The results are given in Table 3 and shown in Fig. 5b for the system labelled 1 in Fig. 3, and in Fig. 5c for system 2. The accuracy is lower for each system since they are not completely separated, and the minimum of the fitted sine wave is negative for 4 of the 6 lines. Nevertheless, the results are quite significant: the lines of systems 1 and 2 show maxima at phases 0.27 and 0.62, exactly when the effective field goes through zero (Fig. 5a), that is when the magnetic equator crosses the line of sight.

We can therefore state that, for ε UMa, oxygen is located around the magnetic equator.

3.4. HD 112413 = α^2 CVn

This very bright star was one of the first in which Ap peculiarities were noted (Maury 1897) and one of the first found to show spectrum variability (Ludendorff 1906). It is the prototype of periodic Ap stars and has pronounced variations in spectral-line intensities, magnetic field strength, and light. Farnsworth (1932) obtained an accurate period for the spectral variations given by:

$$JD(\text{Eu II max}) = 2419\,869.720 + 5.46939E. \quad (5)$$

Provin (1953) found that the star's brightness varies with the same period and that the light maximum occurs at the maximum of Eu II absorption.

α^2 CVn was discovered to be magnetic by Babcock & Burd (1952) who found a strong reversing field. Subsequently, Borra

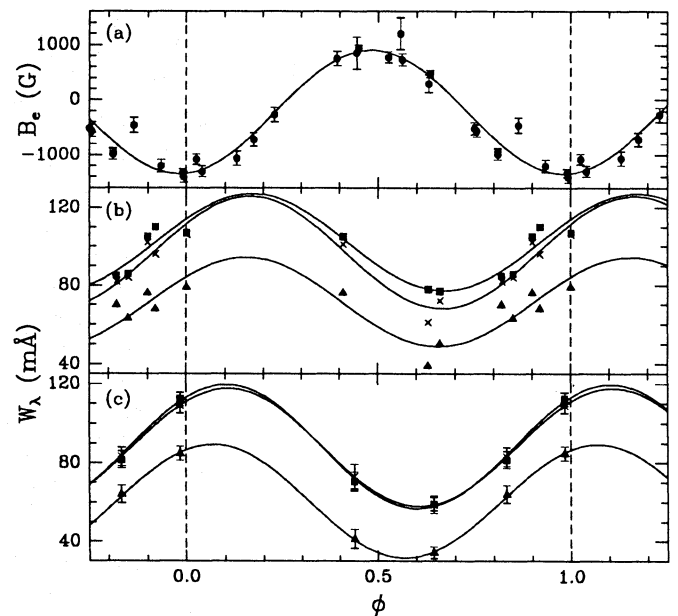


Fig. 6a–c. Variations of α^2 CVn. **a** Magnetic measurements of Borra & Landstreet (1977) with the least-square fit by a sine wave. **b** Equivalent widths of the O I multiplet at λ 7773 Å recorded by Roby & Lambert (1990). The symbols have the same meaning as in Fig. 1b. **c** Same as Fig. 1b

& Landstreet (1977) and Borra & Vaughan (1978) reported variations from -1400 to $+1000$ G, the negative extremum occurring around phase 0.0 (Fig. 6a). Landstreet (1980) proposes a decentered dipole model with the parameters $i = 65^\circ$, $\beta = 115^\circ$ (from the visible rotation pole to the positive magnetic pole), $a = 0.2R_*$ towards the positive pole, and $B_p = 5.1$ kG.

Burbidge & Burbidge (1955) and Pyper (1969) made an analysis of the line variations and reported that the rare-earth elements have a maximum strength at phase 0.0, whereas the iron peak elements have at least two maxima near phases 0.2–0.4 and 0.6–0.9. More recently, Goncharkii et al. (1983) derived a map of the Eu distribution over the stellar surface, showing an accumulation near the magnetic poles of Landstreet (1980). Khokhlova & Pavlova (1984) then obtained maps of Fe, Cr and Ti, showing that Cr is clearly most abundant along the magnetic equator, whereas Fe and Ti show deficient regions near the magnetic poles and 3 to 4 overabundant spots at intermediate latitudes. Roby & Lambert (1990) recorded the variations of C II, N I, and O I lines, which all show a minimum near phase 0.7, corresponding approximately with one of the Fe peak lines maxima. Figure 6b shows the variations of their equivalent widths for the O I multiplet at λ 7773 Å.

We have obtained four spectra for α^2 CVn. The equivalent widths of the O I lines are displayed in Fig. 6c and Table 3 gives their fit parameters. A common maximum appears around $\phi = 0.1$, close to the maximum found by Roby & Lambert (1990), and near the negative extremum of B_e , suggesting an accumulation of oxygen on the negative magnetic pole. However, these results may be uncertain since both sets of data are

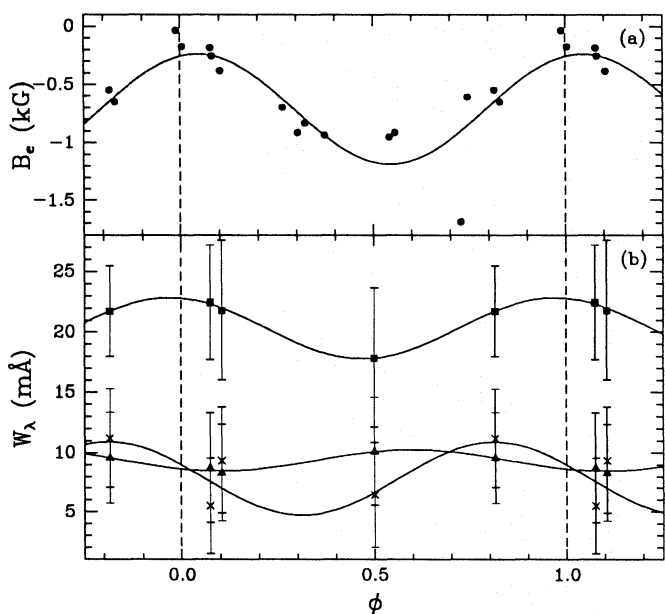


Fig. 7a and b. Variations of 78 Vir. **a** Effective magnetic field from Borra (1980a) together with the least-square fit by a sine wave. **b** Same as Fig. 1b

located in the second half of the rotation cycle. The opposite behaviour that is generally found in Ap stars for oxygen and iron lines (see Sect. 4) would lead to think that the O I lines may have a second minimum around phase 0.3, corresponding to the first maximum of the Fe lines. Oxygen would then be depleted on the magnetic equator and accumulated on both magnetic poles, as europium is. This is still speculative, additional observations being necessary to draw a reliable conclusion.

3.5. HD 118022 = 78 Vir

78 Vir is the first star in which a magnetic field was discovered (Babcock 1947). The field was found to be variable and always negative. Preston (1969) measured variations of B_e between -500 and -1500 G, and gave the following ephemeris:

$$JD(B_e \text{ max}) = 2\,434\,816.9 + 3.7220E. \quad (6)$$

He also reported that the light shows weak variations suggesting a maximum at phase 0.5, and that the radial velocities exhibit small range variations roughly in quadrature with the magnetic variation.

Borra & Landstreet (1980) and Borra (1980a) reported observations of the effective magnetic field of 78 Vir, which was found to vary between -100 G around phase 0.0 and -1000 G near phase 0.5 (Fig. 7a). Borra (1980b) attempted to determine the magnetic geometry, and found that the observations were equally fitted by two geometries: the first one is a dipole-quadrupole combination with the parameters $i = 22^\circ$, $\beta = 115^\circ$ (to the positive pole), $B_p^+ = +6000$ G (field at the strongest pole), and $Q = 0.5$ (parameter that expresses the strength of the quadrupolar component, defined in such a way that the field is

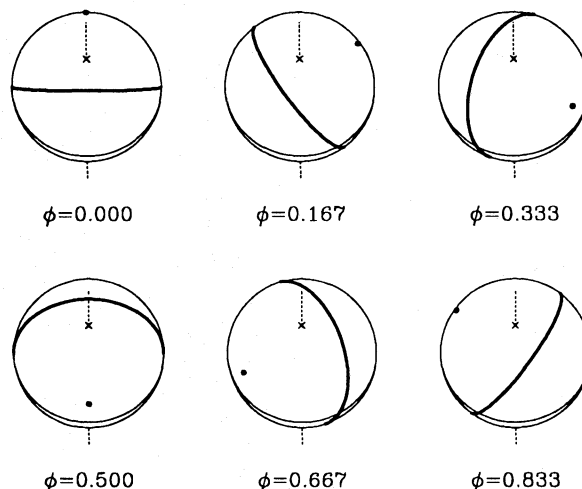


Fig. 8. Visible hemisphere of 78 Vir at six phases equally spaced over the rotation period. The heavy dots and lines represent the magnetic negative pole and the magnetic equator

given by B_p at the strongest pole and by $[(Q - 1)/(Q + 1)]B_p$ at the weakest pole); the second possibility is a decentered dipole geometry with the same angles i and β , and with $a = 0.2R_*$ towards the positive pole and $B_p = 4.1$ kG.

Deutsch (1947) noted that the Ca II K line is variable and reaches its maximum strength at the negative extremum of the magnetic field. According to Preston (1969), the Eu II variation is marginal at most, but the comparison of spectrograms at phases near 0.0 and 0.5 suggests that the rare-earth lines probably vary in phase with Ca II K.

Four spectra have been recorded for 78 Vir. The results are given in Table 3 and displayed in Fig. 7b. The O I lines in this star are the weakest that we have measured. Especially the lines at $\lambda\lambda 7774.17$ and 7775.39 \AA have the lowest measured equivalent widths ($< 10 \text{ m\AA}$) and their uncorrelated variations are probably not significant. The strongest line of the triplet, $\lambda 7771.95$, varies in phase with the effective magnetic field, but with an amplitude only slightly larger than the error bars. This uncertain result suggests that oxygen is depleted around the negative pole.

The weak line variations may be explained by the small value of the inclination angle i : the visible hemisphere of 78 Vir, which is shown at six phases in Fig. 8, always contains the magnetic equator and the negative pole in almost the same configuration, except around phase 0.0 where the pole is near the star's limb. Despite the quite large variation of B_e , the line variations are very weak because the "landscape" on the star does not change enough. This reveals the determinant effect of the geometry (i and β angles) on the amplitude of the observed variations. The inverse situation occurs in ϵ UMa, which has a weak magnetic field, but exhibits large changes in the visible magnetic features during its rotation period ($i = 65^\circ$), causing a spectacular variation in the line profiles.

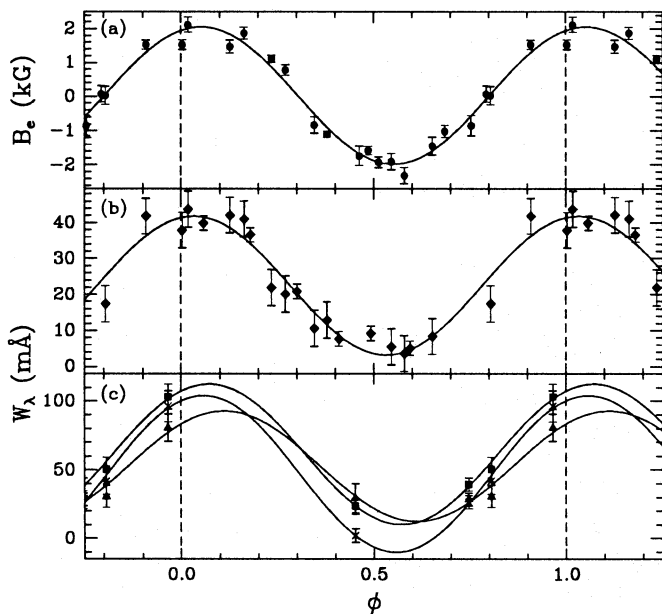


Fig. 9a–c. Variations of CS Vir. **a** Magnetic observations of Mathys (1991) with the least-square fit by a sine wave. **b** Equivalent widths of the O I line at $\lambda 6156.8 \text{ \AA}$ measured by Mathys (1992). **c** Same as Fig. 1b

3.6. HD 125248 = CS Vir

Morgan (1931) discovered that this star is a strong spectrum variable, exhibiting large changes of intensity for the lines of Eu II, Cr I, and Cr II. These two elements were found to vary in opposite phase. Deutsch (1947) derived a period of 9.295 d, with a maximum Eu II intensity at $JD = 2430\,143.07$. Stibbs (1950) made photometric observations of CS Vir and obtained a well-defined light curve with the same period. The light maximum occurs at phase 0.55, coinciding approximately with the maximum intensity of the chromium lines.

The magnetic observations of Babcock (1951, 1960) showed a large reversing magnetic field and allowed to refine the period value, giving the ephemeris:

$$JD(\text{Eu II max}) = 2430\,143.07 + 9.2954E. \quad (7)$$

Borra & Landstreet (1980) and Mathys (1991) made new magnetic measurements and obtained values of B_e ranging approximately from -2.2 to $+2.3$ kG. The positive extremum occurs near phase 0.0 (Fig. 9a). Borra & Landstreet (1980) modeled the variations of the field with a centered dipole of inclination $i = 79^\circ$, obliquity $\beta = 74^\circ$, and polar field $B_p = 9$ kG, but Mathys (1993) concludes that the magnetic field is not cylindrically symmetric about an axis going through the center of the star.

Deutsch (1947, 1958), Hockey (1969) and Bonsack (1974) studied the spectral variability of CS Vir and found that the rare-earths show strong variations and have their maximum line intensity near phase 0.0. Fe and Ti lines also reach their maximum near phase 0.0, but exhibit much smaller variations. Finally, the absorption of Cr, Sr, Ca, and Mg is maximum around phase 0.5.

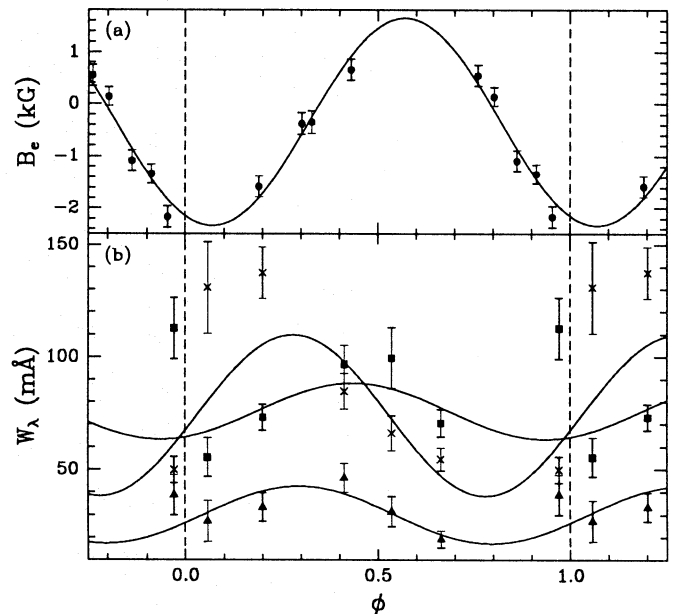


Fig. 10a and b. Attempt to detect variations in HD 133652 (see text). **a** Magnetic field observations by Bohlender et al. (1993) and the least-square fit by a sine wave. **b** Same as Fig. 1b

Mathys (1992) reported the first observation of an inhomogeneous surface distribution of oxygen in an Ap star. He measured on CS Vir the equivalent width of the O I $\lambda 6156.8$ line at 19 phases and showed that its variation is nearly sinusoidal (Fig. 9b). The maximum oxygen line strength occurs at phase 0.0, close to the effective field positive extremum.

We have obtained four spectra for CS Vir. Table 3 and Fig. 9c show the equivalent widths of the O I lines. They are well fitted by sine waves in phase with the one derived by Mathys (1992) and with the effective magnetic field. The agreement between both sets of data is excellent and allows to conclude that oxygen is accumulated near the positive magnetic pole of this star.

3.7. HD 133652 = HR 5619

This star was suspected to be magnetic by Babcock (1958). Recently, Bohlender et al. (1993) discovered a strong reversing magnetic field. Lanz et al. (1991) achieved Geneva photometry and, with the set of magnetic measurements, determined the following ephemeris:

$$JD(\text{max } U \text{ light}) = 2448\,344.652 + 2.3040E. \quad (8)$$

The effective magnetic field ranges from -2 to $+2$ kG and the negative extremum occurs around phase 0.0 (Fig. 10a). Within the assumption of the oblique rotator model, these observations suggest that the two magnetic poles are visible during the rotation period. Bohlender et al. (1993) constrain the inclination to $32^\circ \leq i \leq 90^\circ$ and the obliquity to $\beta < 86^\circ$.

Bonsack (1974) obtained spectrograms for HD 133652 which indicate a probable spectrum variation, but do not clearly establish its existence.

We have recorded six spectra of this star, which has the greatest value of $v \sin i$ in our sample, and attempted to detect variations of the broadened O I lines. The result is not satisfactory, as can be seen in Fig. 10b. The equivalent widths show quite large variations but are not fitted by sine waves and do not show any agreement between the three lines. This is probably due to the blending of these broadened lines with others and prevents us from deriving any conclusion regarding the regions where oxygen accumulates on HD 133652.

3.8. HD 137509

This star was first mentioned by Cowley & Houk (1975) to exhibit strong lines of Si II, Fe II, Cr II and Ti II and no lines of He I. Its light variability was reported by Lodén & Sundman (1989) and its period was determined by Lanz & Mathys (1991b) who combined their photometric data with the magnetic measurements of Mathys (1991) to derive the ephemeris:

$$JD(\max U \text{ light}) = 2\,448\,344.575 + 4.4912E. \quad (9)$$

The light curves show a secondary maximum at phase 0.5.

The magnetic field of HD 137509 was discovered by Mathys (1991), who measured large variations of B_e from -1.3 kG at phase 0.5 to $+2.4$ kG at phase 0.0, suggesting that the star shows its two magnetic poles during its rotation. Bohlender et al. (1993) made additional measurements of the effective field and gave a lower limit to i at 24° .

Mathys (1991) also reported that the spectrum of HD 137509 undergoes spectacular variations during the rotation, the line intensity of Fe II and Cr II being maximum around phase 0.0.

Six spectra have been obtained for this fairly rapidly rotating star, in which the O I multiplet is almost inexistent. We only derived an upper limit for the equivalent width of each line at $5 \text{ m}\text{\AA}$.

We noticed a fairly strong line at $\lambda 7782 \text{ \AA}$, absent from the spectra of comparison stars, which we identify as Pr III. Its intensity varies, with a maximum near phase 0.0, corresponding to the positive extremum of the effective magnetic field. This line confirms the presence of Pr III in the spectrum of this star, as suggested by Mathys & Cowley (1992).

3.9. HD 176232 = 10 Aql

Babcock (1958) measured a variable magnetic field for 10 Aql ranging from about -300 to $+400$ G over a period of years. Preston (1970) obtained a constant magnetic field on 10 consecutive nights and concluded that the variation period might be on the order of years. Several observers reported that the amplitude of the light variations was not greater than 0.015 magnitude, and different periods were found: 9.78 d (Stępień 1968), 6.05 d (Guerrero & Mantegazza 1973) and 6.5386 d (Winzer 1974). However, the photometric observations of Wolff & Morisson (1973) did not show any significant variation and Adelman (1981) indicates that if 10 Aql is variable, it is only weakly so. Hube & Anderson (1986) reexamined the previous observations together with

theirs and concluded that this star is probably variable on a short time scale with an amplitude of approximately 0.01 magnitude and an unknown period, none of the formerly proposed values satisfying all the data.

10 Aql was later discovered to be a rapidly oscillating Ap (roAp) star by Heller & Kramer (1988). They found a light variation of semi-amplitude 0.42 mmag with a period of approximately 11.5 minutes.

We have recorded six spectra of 10 Aql, showing little difference between each other, despite their well spaced phases. The equivalent widths of the O I lines exhibit very weak variations (smaller than 10%) and none of the periods cited above was able to fit our data. Our conclusion for the spectrum variations of this star confirms the previous ones concerning the magnetic and light variations: if this star is variable, it has a very small amplitude and its period is still unknown.

3.10. Comparison with normal stars

We observed four normal stars: HD 91375, HD 99803, HD 107259 (η Vir), and HD 172167 (α Lyr or Vega), and measured the equivalent width of the O I lines, which are given in Table 3. The total equivalent width of the triplet ranges from 371 to 700 mÅ. For Vega, our value of $675 \pm 25 \text{ m}\text{\AA}$ compares well with the value of 637 mÅ obtained by Roby & Lambert (1990) but is smaller than that of 870 mÅ measured by Gerbaldi et al. (1989).

The observed Ap stars have much smaller equivalent widths than the normal stars, except for 49 Cnc, for which W_λ is in the range of normal stars. This confirms the general underabundance of oxygen in peculiar stars (Gerbaldi et al. 1989; Roby & Lambert 1990).

4. Discussion

For five over nine of the observed magnetic stars, the present results establish a definite rotational modulation of the oxygen lines at $\lambda 7773 \text{ \AA}$. Two stars, 41 Tau and 49 Cnc, have a maximum of oxygen absorption which is synchronous with the appearance of the visible magnetic pole. α^2 CVn shows an oxygen maximum near the negative pole and, because of the poor phase coverage, another maximum is not excluded near the other pole. For CS Vir (the two poles being seen) oxygen is maximum on one pole and minimum on the other, which suggests a strong disymmetry between the field modulus at the two poles. The remaining star, ϵ UMa, is an exception to this behaviour: the new observations suggest a concentration of oxygen around the magnetic equator.

For three stars of this group (41 Tau, α^2 CVn and CS Vir) variations of other abundant elements are known, as summarized in Sect. 3, and the following constant trends can be stressed: oxygen roughly varies in phase with carbon and titanium, but in antiphase with iron and chromium. The rare-earths are generally in phase with oxygen. We verified this trend from the behaviour of the $\lambda 7781.98 \text{ \AA}$ line of Pr III, close to the O I triplet. This line which is invisible for normal stars, appears with various

Table 3. Parameters of the fit $W_\lambda = W_\lambda^0 + W_\lambda^1 \cos(2\pi(\phi - \phi_0))$ for each line of the O I triplet

HD	Name	7771.95 Å			7774.17 Å			7775.39 Å			
		W_λ^0	W_λ^1	ϕ_0	W_λ^0	W_λ^1	ϕ_0	W_λ^0	W_λ^1	ϕ_0	
<i>Ap stars</i>											
25823	41 Tau	73 ± 1	19 ± 3	0.61 ± 0.02	67 ± 2	18 ± 3	0.64 ± 0.03	42 ± 1	13 ± 3	0.63 ± 0.03	
74521	49 Cnc	189 ± 4	25 ± 9	0.67 ± 0.05	188 ± 4	28 ± 10	0.66 ± 0.05	141 ± 4	21 ± 8	0.71 ± 0.05	
112185	ϵ UMa ^a	26 ± 3	44 ± 5	0.26 ± 0.01	21 ± 3	40 ± 4	0.25 ± 0.02	15 ± 3	40 ± 4	0.28 ± 0.01	
		32 ± 3	22 ± 5	0.63 ± 0.04	27 ± 3	22 ± 6	0.61 ± 0.05	20 ± 2	25 ± 4	0.62 ± 0.03	
112413	α^2 CVn	88 ± 3	31 ± 4	0.10 ± 0.02	88 ± 3	30 ± 5	0.11 ± 0.03	61 ± 3	29 ± 4	0.07 ± 0.03	
118022	78 Vir	20 ± 3	3 ± 4	0.97 ± 0.27	8 ± 2	3 ± 4	0.81 ± 0.21	9 ± 2	1 ± 4	0.60 ± 0.81	
125248	CS Vir	61 ± 5	51 ± 9	0.07 ± 0.03	47 ± 6	57 ± 10	0.06 ± 0.03	53 ± 7	40 ± 11	0.11 ± 0.04	
133652	HR 5619 ^b	77 ± 8			67 ± 7			29 ± 6			
137509	^b	< 5			< 5			< 5			
176232	10 Aql ^b	47 ± 2			39 ± 2			36 ± 2			
<i>Normal stars^c</i>											
91375	HR 4138	258 ± 9			238 ± 8			204 ± 8			
99803	HR 4423	136 ± 16			123 ± 15			111 ± 14			
107259	η Vir	158 ± 13			166 ± 13			131 ± 13			
172167	α Lyr	252 ± 9			229 ± 8			194 ± 8			

^a The parameters are given separately for systems 1 and 2 (see text)

^b For these stars, W_λ^0 is the mean of the measured equivalent widths

^c For the normal stars, W_λ^0 is the measured equivalent width

intensities in the spectra of the observed Ap stars. In most cases, this line varies in phase with oxygen ones.

Although the observed variations significantly differ from star to star and despite the small size of the sample, it appears significant that four stars show such a similar behaviour, that is a trend for oxygen to concentrate in the polar magnetic regions, as do carbon, titanium and the rare-earths, and opposite to iron and chromium trends.

The effective temperature of these four stars ranges from 8 410 to 12 900 K, and their projected rotational velocities $v \sin i$ are within 9–29 km s⁻¹. The exception of ϵ UMa appears quite striking and could add interesting constraints on the theoretical interpretation. This star has a medium effective temperature in the sample, a value of $v \sin i$ slightly larger (38 km s⁻¹), but its magnetic field is significantly smaller than in the other stars. We have little indication of the age of these stars: Leckrone & Snijders (1979) stated that α^2 CVn is rather evolved. Hubrig & Schwan (1991) confirmed this result and suggested that ϵ UMa is much more evolved than most magnetic Ap stars, which might explain its singular behaviour.

The measured equivalent widths are averages over the stellar disk and only give approximate maps of oxygen, but the general results obtained from these new observations extend the results of Mathys (1992) to other stars and confirm his conclusion regarding the existence of large inhomogeneities of oxygen abundances on the surface of Ap stars. In order to get an estimate of the abundance variation, we performed a LTE line synthesis for 41 Tau and CS Vir, using the code written by Hubeny et al. (1994), models with $T_{\text{eff}} = 13\,650$ K and 10 000 K respectively (Lanz 1993) and an homogeneous oxygen abundance at a given phase. We are able to reproduce the extreme values of the equivalent widths with an abundance variation of 0.8 dex and

1.5 dex respectively. The introduction of the Zeeman effect in the synthetic calculation indicates that the induced desaturation may contribute to the variations for stars having a strong surface field: the amplitudes of the abundance variations given above are reduced by about 0.3 dex for a magnetic field of 2 kG. The exact contribution cannot be computed as long as the precise field geometry is unknown and the observed small variations of oxygen in some stars could perhaps be explained by Zeeman desaturation. However, the observed variations in the five stars 41 Tau, 49 Cnc, ϵ UMa, α^2 CVn, and CS Vir are large enough to be clearly caused by abundance inhomogeneities of oxygen over the stellar surface.

The next step of such a study should make use of the Doppler-imaging technique to obtain detailed maps of oxygen, which requires better phase coverage, as well as more precise descriptions of the magnetic geometry.

The basic theoretical background to interpret the line variations versus the rotational phase has been described by Michaud et al. (1981). They predict curves of the equivalent width variation, for different simple schemes where the observed element is concentrated in rings around the magnetic axis. However, the complex nature of the geometry involved is not completely resolved, even for the brightest stars of our sample. A detailed mapping of a few elements exists only for ϵ UMa and α^2 CVn (see Sect. 3).

The explanation of the surface distribution of oxygen in the atmospheres of Ap stars would require a detailed computation of its diffusion, including the various effects caused by the magnetic field, as detailed by Babel & Michaud (1991b,c). Such a model is applicable only for a few well-studied stars, in order to reduce the number of unknown parameters, especially the hydrodynamical effects. The example of their detailed study

of 53 Cam (Babel & Michaud 1991a) demonstrates that the theory predicts correctly the mean abundances, but cannot reproduce the various inhomogeneities of all observed elements. Then many elements must be investigated simultaneously to build a consistent description of one star and the present observations add informations about an element which could give a clue to diffusion processes in Ap stars.

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