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Magnetic models of ε UMa and HD 147010

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Abstract. A magnetic field model for the CP star ε UMa has been constructed on the basis of the latest data on magnetic field variation with rotation phase. It has turned out that this is the central dipole providing a magnetic field of 480 G at the poles. A map of surface field intensity distribution has been made. A comparison of this map with the distribution of chemical elements taken from literature has confirmed the inference that O, Ti, Ca are concentrated in the region of the magnetic equator; Fe, Mn, Mg avoid the magnetic field equator and are concentrated about the north and south poles. The spot-like distribution of chemical elements is likely to suggest that the physical conditions of the surface are not uniform. A magnetic model has been constructed of one of the stars, HD 47010, which is unique in magnetic field intensity. It has turned out possible to work up models, assuming either a dipole-quadrupole magnetic field or a displaced dipole. In the former case the magnetic field intensity at the poles of the dipole, B_p, is 19750 G and 9800 G, while in the latter B_p = 103000 G and 7000 G with a dipole displacement, Δa = 0.45. It has been concluded that the dipole-quadrupole model describes the magnetic field structure of the star more correctly.

Key words: stars: magnetic fields – stars: individual: ε UMa – stars: individual: HD 147010

1. Introduction

Applying the method described by Gerth et al. (1997), we pursue the investigation of magnetic models of chemically peculiar stars from the relationship between effective magnetic field, B_e, variation and rotation phase, P. If one has not only $B_e(P)$ but also a similar relation for the average surface magnetic field, $B_s(P)$, for the star under investigation, the problem of modeling is then substantially simpler because in this case one can reliably determine two important parameters such as the star's inclination angle i and the angle between the dipole axis and the rotation axis χ. Otherwise angle i has to be estimated from $v\sin i$, which is sometimes not quite reliable.

In the present paper we are concerned with the models of two stars, ε UMa and HD 147010, being remarkable because the former is an old main sequence star and the latter has just settled on it. Given a sufficient body of data, such stars can be used to study the evolutionary path of magnetic CP stars.

2. The magnetic model of ε UMa

The star ε UMa is well studied from the point of view of surface distribution of chemical elements (Wehlau et al., 1982; Hatzes, 1991; Rice and Wehlau, 1990; Rice et al., 1997). By the present time a reliable magnetic field variation curve displayed in Fig. 1 has been derived from literature data and from hydrogen line measurements made with the 6 m telescope (Shtol' et al., 1997). This curve has been used to construct a model with the aid of the procedure described by Gerth et al. (1997), to compute the magnetic field intensity distribution over the surface and compare it with that of chemical elements.

2.1. Basic parameters

One of the basic parameters for the modeling is $v\sin i$. In the catalogue of Boyarchuk and Kopylov (1964) $v\sin i$=35 km/s, Abt et al. (1972) provide a value of 49 km/s, in the paper by Goncharsky et al. (1982) it is 34 km/s, Hatzes (1991) gives $v\sin i$=35(±0.5) km/s. $v\sin i$=35 km/s seems to be the most likely because it was derived from the greatest number of high dispersion measurements. T_e of the star is 9800 K (Glagolevskij, 1994). Rice et al. (1997) have reported T_e=9500 K.

Based on the investigation of Ursa Major, Levato and Abt (1978) have found that ε UMa is by 1.7 stellar magnitudes above the ZAMS line, which corresponds to $\lg g \approx 3.5$. From hydrogen lines we (Glagolevskij et al., 1982a) have estimated $T_e = 9500$ and $\lg g = 3.5$, using Kurucz models. From the model atmospheres Engin (1975) has obtained similar re-

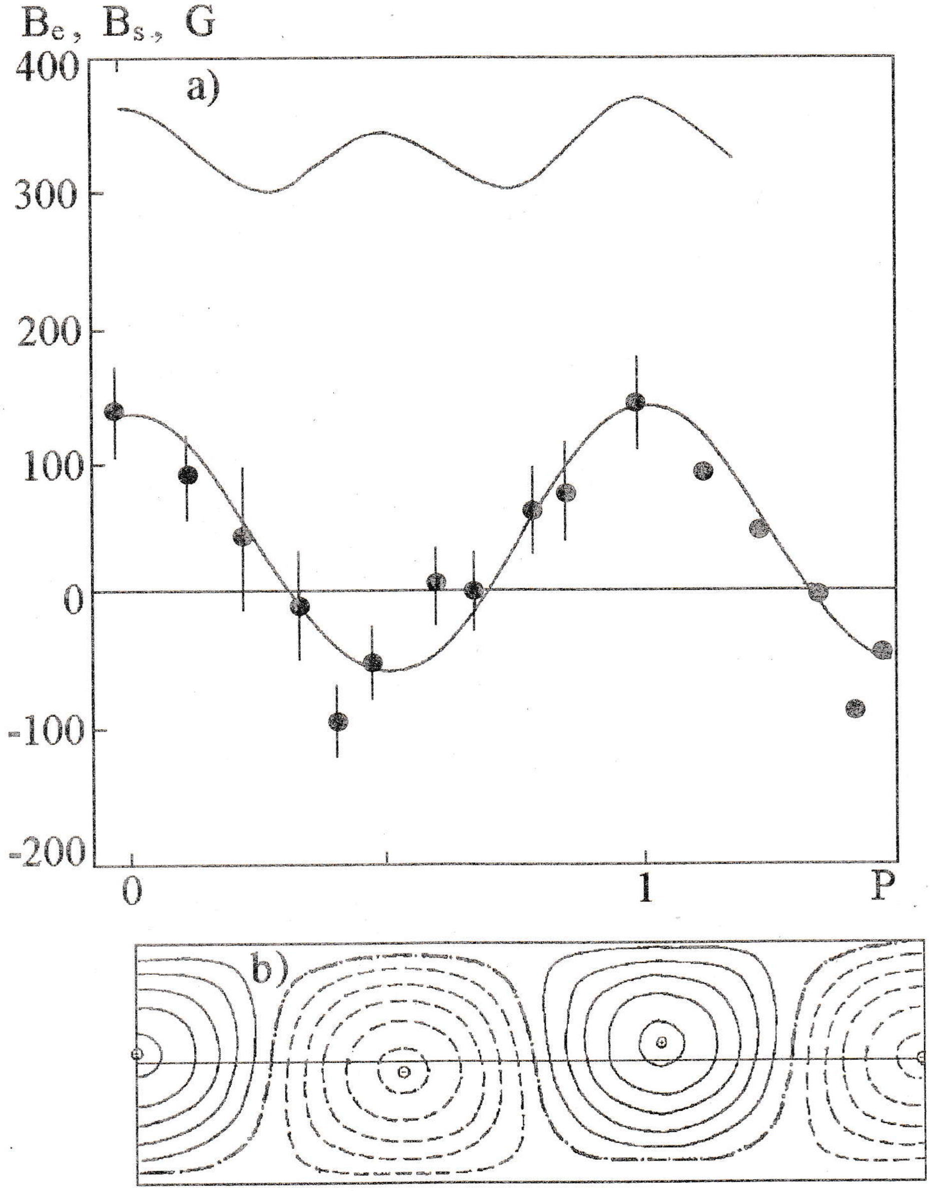

Figure 1: *Modeling of the magnetic field of the star ε UMa: a) the dots show the measured magnetic field, the lower curve is plotted from the model calculation, the upper curve is the computed curve of the mean surface magnetic field variation; b) the magnetic field strength distribution: the solid curves show the fields of positive sign, the dashed ones indicate the negative fields, the dash-and-dot line is for the magnetic equator.*

sults, $T_e = 9300\,K$ and $\lg g = 3.2$. Leushin (1965) has estimated $\lg g$ at 3.5. Thus all the estimates of T_e and $\lg g$ are in good agreement with one another. From all the data presented $T_e = 9525$ and $\lg g = 3.42$. By the formula

$$\lg(R/R_{ZAMS}) = 0.5(\lg g_{ZAMS} - \lg g)$$

and with the aid of the relations $\lg g_{ZAMS(T_e)}$ (Straizis and Kuriliene, 1981) obtain $R/R_{ZAMS} = 2.82$, $R = 4.5$, $M_b = -0.7$. By the formula

$$V = 50.6\,R/P$$

and from $v\sin i$=35 km/s, find $i = 51°$ (P=5.09 days), which is fairly close to $i = 55°$, the value adopted by Rice et al. (1997).

Based on the obtained value of M_b, ε UMa is seen to be located at the upper edge of the main sequence. The star is on the verge of "leaving" it, and by the example of this star we observe the last stage of evolution of a magnetic star on the main sequence. Proba-

Table 1: *Parameters of ε UMa*

Parameter	Value
T_e	9525 K
$\lg g$	3.42
$v\sin i$	35 km/s
angle i	51°
radius R	4.5
absol. mag.	−0.7
R/R_{ZAMS}	2.82

Table 2: *The parameters of the central dipole of the ε UMa magnetic field*

B_p, G	r	Longitude	Latitude
520±30	0.1	$0° \pm 10°$	$8° \pm 1°$
-520 ± 30	0.1	$180° \pm 10°$	$-8° \pm 1°$

bly the further increase in radius and the atmospheric instabilities diminish the field or it will be destroyed altogether.

The criterion "degree of peculiarity" shows the star to be of "moderate" peculiarity.

The star parameters that we have finally adopted are as listed in Table 1.

2.2. The model magnetic field

The modeling of the magnetic field with the aid of the $B_e(P)$ variation curve from (Shtol' et al., 1997) has been performed using the technique described by Gerth et al. (1997). The best fit of the computed and observed curve is attained under the assumption of a central dipole having the parameters presented in Table 2.

Here B_p is the magnetic field strength at the poles, r is the relative distance of the magnetic monopoles from the star centre. At an angle of star inclination to the line of sight $i = 50°$, the dipole axis is inclined to the axis of rotation at an angle $\chi = 82°$, i.e. the dipole lies practically in the equator plane. For the quantity r the mean value observed in CP stars with dipolar magnetic fields has been taken. This parameter can be determined accurately provided that the observed surface magnetic field variation curve is known. The B_s value computed by the model varies from 300 to 360 G.

Taking into account the fact that the magnetic field decreases with evolution in proportion with R^{-2} (Glagolevskij, 1992), one can derive the initial magnetic field, $B_p \cong 3$ kG on the ZAMS. Thus, judging by the magnetic field, ε UMa is a medium magnetic star.

Fig. 1a presents the relations $B_e(P)$ and $B_s(P)$ computed with the adopted parameters. Unfortunately, the observational accuracy is insufficient to find out if the quadrupole component is present. It is clear, however, that it contributes less than the measurement errors. Fig. 1b displays a map of the magnetic field strength distribution over the star's surface. The solid line shows the field of positive sign, the negative field is the dashed line, the dash-and-dot line represents the magnetic equator.

Fig. 2 shows a schematic of disposition of oxygen and chromium taken from (Rice et al., 1997). It is well seen that oxygen is located along the magnetic equator. The disposition of chromium has a more complex pattern, however it is seen to be absent at the magnetic equator.

One can see small "spots" of enhanced abundance of Cr on both the negative and positive field hemispheres. Thus, it is apparent that the physical conditions are not uniform at the surface of the star, although it is supposed that all kinds of large-scale motions of matter are absent in the presence of strong magnetic field, and the physical conditions are the same everywhere.

Fig. 3 shows the maps of Cr and Ti distribution taken from the paper of Luftinger et al. (1998) where Cr is seen to be concentrated near the magnetic poles, its abundance being lower along the equator. Ti, on the contrary, is defficient near the poles. From the same paper it follows that Fe is distributed in the same fashion as Cr, while the distribution of Mn is like that of Ti and O.

3. The HD 147010 magnetic model

The star HD 147010, which is unique by its magnetic field strength, has been discovered independently by Brown et al. (1981) and (Glagolevskij et al., 1982). Fig. 4a shows the measurements made by Mathys (1991) from metallic lines (filled circles) and the measures of Thompson et al. (1987) obtained from H_β lines (crosses). The values of the latter paper are systematically larger (by 1230 G) and they are plotted in Fig. 4a corrected for this value. The open circles indicate the measures obtained from metallic lines (Glagolevskij et al., 1985). These estimates are, on average, systematically smaller by 100 G than the measures of Mathys (1991), i.e. our measures are practically in agreement. The rotational period of the star has been estimated by North (1984)

$$JD = 2444808.447 + 3.9210 \pm 0.0001(U\,\max).$$

3.1. Basic parameters

The surface magnetic field B_s has not been measured in HD 147010. This is why it is impossible to accurately estimate the two angles: the inclination angle of the star to the line of sight i, and the inclination angle of the dipole axis to the axis of rotation χ. The

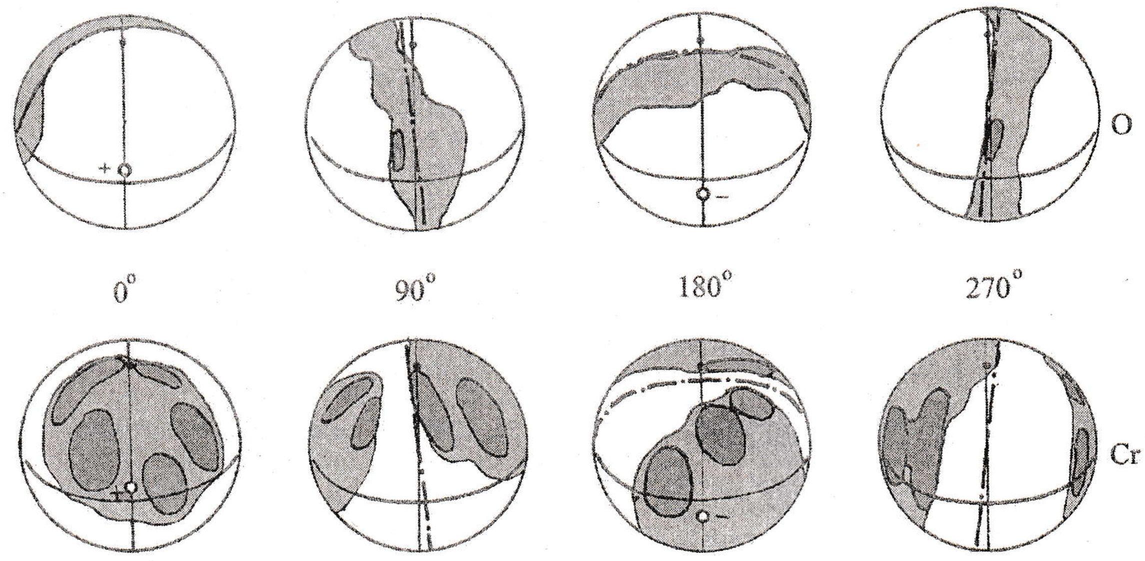

Figure 2: *The diagrams of the chromium (bottom) and oxygen (top) distribution for ε UMa borrowed from Rice et al. (1997); the dash-and-dot line is the magnetic equator. The shaded areas are the element overabundance, the unshaded areas are the element underabundance.*

angle i is therefore estimated roughly from $v\sin i$. The rotation velocity, $v\sin i$=20 km/s, has been estimated by Wolf (1981) and Klochkova et al. (1981). In the paper by Mathys (1995) $v\sin i = 22.1 \pm 4$ km/s. The star effective temperature T_e = 13000 K (Glagolevskij, 1994), the multicolour photometry parameter β = 2.753 (Renson et al., 1991). Hence, as usual, derive M_b = 0.60, R/R_{ZAMS} = 1.12, R=2.6. If $v\sin i$ is adopted to be 22.1 ± 4, the star inclination angle to the line of sight is then between 32° and 50°.

3.2. Model magnetic fields

The results of modeling have led to the computed relation $B_e(P)$ plotted by a solid line in Fig. 4a, the inclination angle $i = 67°(113°)$ and $\chi = 23°$. Thompson et al. (1987) give the following parameters:

$$R/R_\odot = 1.7 - 3.5, i < 25°, \chi < 65°,$$

i.e. the parameters do not coincide. The magnetic field strength at the dipole poles turned out to be B_p = 19750 G and -9800 G, the coordinates of the monopoles are tabulated in Table 3. The curve of the magnetic field variation with the rotation phase has a characteristic shape: one sharp and one wide flat maxima.

Here the longitude is measured from the positive pole, while the latitude from the meridian. Accordingly the sharp maximum phase of the $B_e(P)$ curve coincides with the moment of transit of the positive pole across the visible meridian.

Fig. 4b displays the curve of variation of the average surface magnetic field B_s of HD 147010 (curve 1). When interacting with each other, the dipole and quadrupole magnetic fields form two characteristic maxima of minor intensity on the negative hemisphere, Fig. 5a. It is this configuration that produces the wide flat maximum on the curve of $B_e(P)$.

Table 3: *Disposition of magnetic dipoles in HD 147010*

Model	r	Monopole coordinates	
		Longitude	Latitude
Dipole	0.1	0 ± 1	55 ± 1
	0.1	−180 ± 1	−55 ± 1
Quadrupole	0.1	0 ± 1	55 ± 1
	0.1	90 ± 1	0 ± 1
	0.1	180 ± 1	−55 ± 1
	0.1	270 ± 1	0 ± 1

Table 4: *Disposition of magnetic monopoles in HD 147010*

Monopole	r	Latitude	Longitude
Positive	0.55	0	55
Negative	−0.35	180	−55

Let us consider the possibility of application of a displaced dipole model. As it appeared, one can derive a similar curve of $B_e(P)$ as for the case of the dipole-quadrupole configuration but under the assumption of a large, by 0.45, displacement of the dipole towards the positive monopole. The best result is obtained assuming the parameters given in Table 4.

The angle $i = 76°$ (104°), the displacement of the

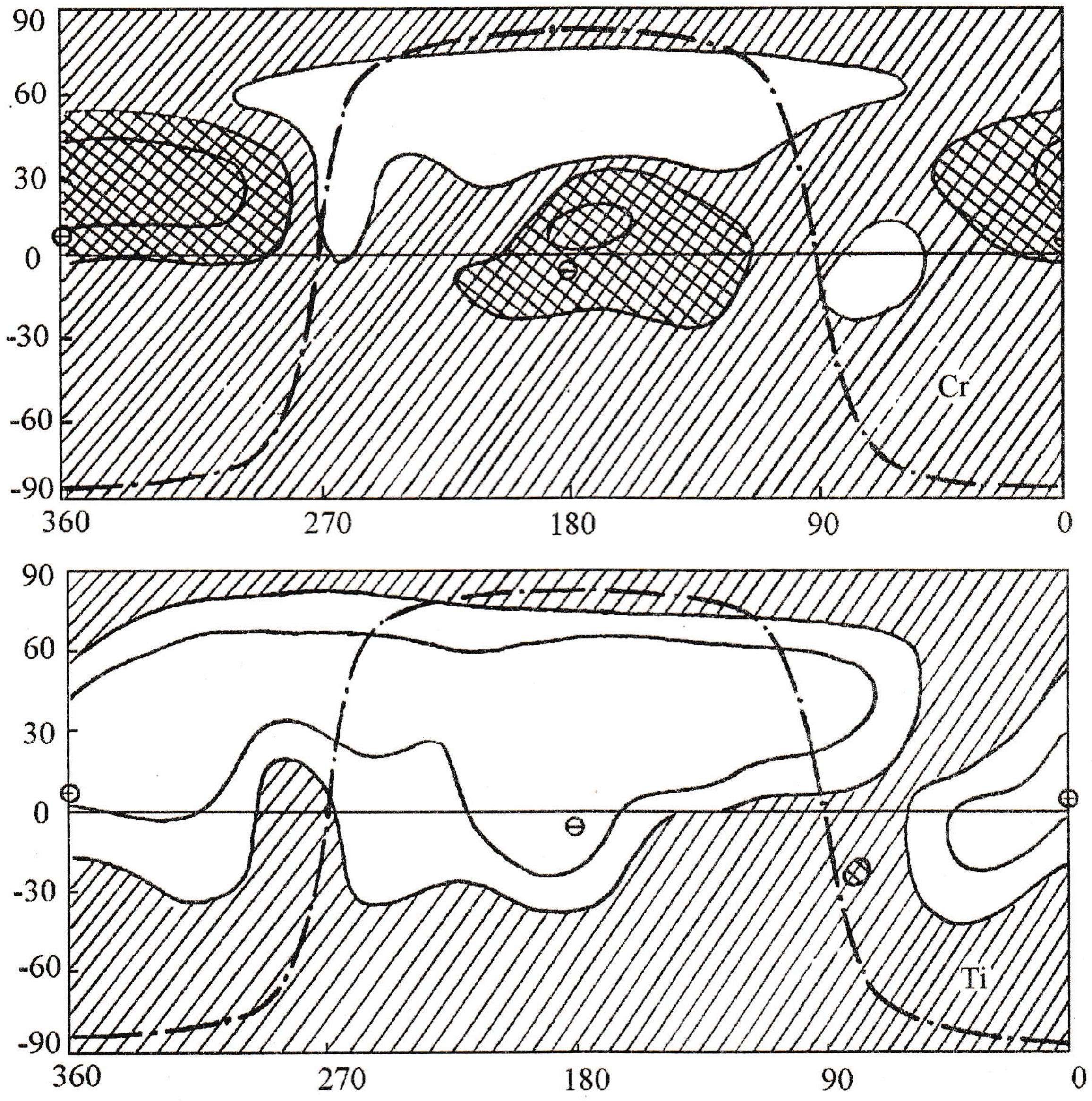

Figure 3: *The diagrams of the chromium and titanium distribution for ε UMa taken from Luftinger et al. (1998). The shaded areas are the element overabundance, the unshaded areas are the element underabundance.*

dipole towards the positive monopole $\Delta a = 0.45$, the distance between the monopoles r = 0.2 R. The angle between the dipole axis and the axis of rotation $\chi = 25°$. The field intensity at the poles turns out equal to B_p = 103 kG and –7 kG. The mean surface magnetic field B_s varies in the manner shown in Fig. 4b (curve 2). Such a great displacement of the dipole and the excessively large field intensity at the positive pole seem unlikely, the dipole-quadrupole model should therefore be considered preferable. With a field strength $B_p \sim 100$ G, completely splitted Zeeman components would be well visible in the spectra. One can decide between the models after the curve of $B_e(P)$ has been refined.

4. Conclusions

We go on with the series of investigations of the magnetic field structure of chemically peculiar stars, using the technique described by Gerth et al. (1997). The ultimate goal is the accumulation of data on the

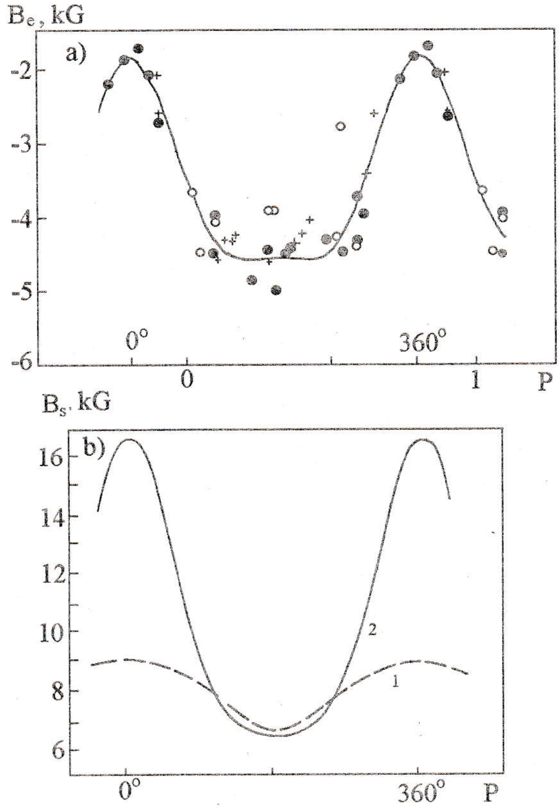

Figure 4: *Magnetic field modeling of HD 147010: a) the filled circles are the measurements of Mathys (1991), the open circles are the measurements of Glagolevskij et al. (1985), the crosses are the measurements of Thompson et al. (1987), the curve is the model computation; b) 1 — the variation of the mean surface magnetic field under the assumption of dipole-quadrupole model; 2 — the same under the assumption of the displaced dipole model.*

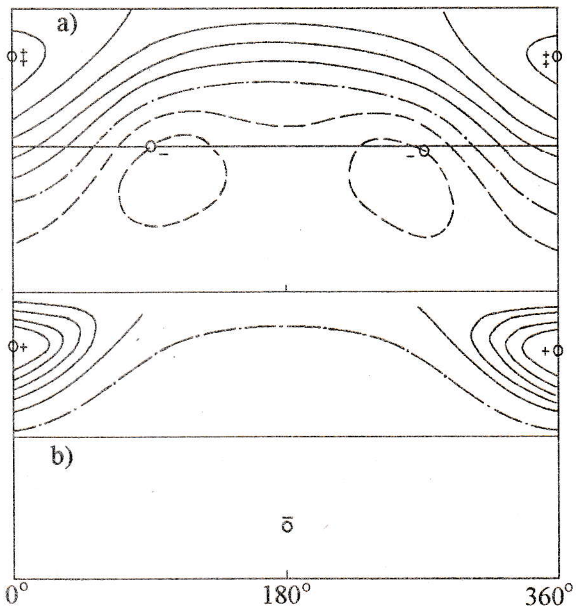

Figure 5: *The magnetic field strength distribution over the surface of HD 147010. a) the dipole-quadrupole model; b) the displaced dipole model. The solid curves show the fields of positive sign, the dashed ones indicate the negative fields, the dash-and-dot line is for the magnetric equator.*

magnetic field structure of CP stars and the study of the structural variations with age, which are expected from considerations of ohmical dissipation. Another objective is in making maps of the magnetic field strength distribution over the surface, which are needed for comparison with the distribution of chemical anomalies.

The results of modeling have shown that the ε UMa magnetic field is dipolar, the dipole being located at the centre of the star. The problem of presence of a quadrupole can be resolved only after obtaining of a more accurate curve of variation of the field B_e with phase of the cycle. However, the presence of the quadrupole is unlikely since the age of the star is very large, lg t=8.8. Configurations more complex than dipolar must disappear during this time because the time of ohmical field dissipation $t \approx l^2$, where t is the decay time and l is the characteristic size of the vortex. The star ε UMa is remarkable for it is leaving the main sequence. However, it does not show any peculiarities with respect to other CP stars having dipolar fields.

Our magnetic field model has confirmed the inferences made by Rice et al. (1997) and Luftinger et al. (1998) that Cr, Fe, Ti, Mn and Mg are concentrated about the magnetic poles, while O and Ca along the magnetic equator where the magnetic force lines are horizontal with respect to the surface of the star. However the location of the magnetic poles at a higher latitude than has been found in our model (7°) would give a better coincidence of the oxygen and calcium belt with the magnetic equator. It would be worthwhile to make additional magnetic field measurements to refine the curve of $B_e(P)$.

The disposition of minor "spots" with a maximum concentration of Cr is in no way related to the global magnetic field configuration. Bearing in mind that the degree of concentration of chemical elements is somewhat dependent on the magnetic field strength (Glagolevskij, 1994), it would be assumed that the basic dipolar configuration has a fine structure. The fine structure does not show up on the relationship $B_e(P)$ because of the insufficient measurement accuracy. If this structure does exist, it must be short-lived because of the fast magnetic field dissipation. Most likely, besides the field ones there are nonuniform distributions of other parameters on the star's surface.

The causes of concentration of chemical elements in the magnetic equator region and outside of it are treated in detail in several papers, in particular (Megessier, 1984; Rice et al., 1997). These are the diffusion under the action of radiation or the ambipolar diffusion.

A younger, as compared with ε UMa, star HD 147010 has a more complex dipole-quadrupole structure as it has been supposed from theoretical considerations. Unfortunately, no maps of the surface distribution of chemical elements have yet been made for it, and we cannot compare the two distributions; this is the task of future concern. For the problem of modeling an extremely important conclusion has been drawn: the dipole-quadrupole model seems to be prefferred to the mixed dipole model. Further investigations of this kind will make it possible to decide between the two models. The magnetic maps can be used to study the processes of diffusion of chemical elements in a magnetic field. As distinct from ε UMa, the star HD 147010 has a magnetic dipole making a large angle with the equator plane.

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