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The models of magnetic field of CP stars having long rotation periods

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Models of the magnetic field of the stars HD2453, HD12288, HD200311 having a great rotational periods, are constructed by the method of “magnetic charge distribution”. Two variants of models are considered: angles β between the rotation and dipole axes are small or large (as a result of duality of the solution). It turned out that the magnetic field structure of the first two stars is best described by the central dipole model, while in HD200311 by the model of the decentred dipole shifted by Δr = 0.08R. For all the stars angles β prove to be large. Models with close axes (small β) are less consistent with observational data. Maps of magnetic intensity distribution over the surface are constructed.

Key words: stars: chemically peculiar – stars: magnetic fields – stars: rotation – methods: numerical

1. Introduction

This paper is devoted to a detailed investigation of slowly rotating CP stars, having a period of P> 25^d. It is the continuation of the investigation of HD2453 (Glagolevskij 2004), with the following main objectives:

1. Comparison of properties of magnetic fields of fast and slow rotators.
2. Proof of Stepien’s hypothesis (Stepien 2000) that stars with long rotation periods have lost the rotation moment with the magnetic field involved. This loss is more effective when angle β between magnetic and rotation axes is small.
3. Comparison of magnetic field modeling results obtained by our “magnetic charge distribution” method (see below) and by other methods, bearing in mind that each of them has its advantages and disadvantages, which gives a fuller appreciation of star properties.

2. “Magnetic charge distribution” model

Let us first briefly discuss the modeling method. The position of the dipole with the moment $M = Ql$ (Q – charge, l – distance between charges) is assigned inside the star in accordance with the coordinates of each monopole, longitude λ and latitude δ (latitude is measured from the equator).

Assigning the charge Q, star inclination to the line of sight angle i and longitude δ, then computing the mean effective value, and the mean surface field Bs at different phases P of the rotation period, we obtain model phase dependences. By the convergence method we can achieve the best agreement of calculated relation with the observed one. The “magnetic charge distribution” method is described in detail in the paper by Gerth et al. (1997), theoretical bases are presented in the papers by Gerth, Glagolevskij (2000), Glagolevskij, Gerth (2003), Khalack et. al. (2001), and specific examples of using the method are adduced in the papers by Glagolevskij (2001; 2002; 2003a).

3. Main parameters of the star HD2453

Following the assumption (Stepien 2000) on the necessity of small angles β between the rotation and dipole axes of slow rotators, we built a magnetic field model of the star HD2453 under the condition that angle β is small (Glagolevskij 2004a). However, for the calculated phase dependence to coincide with observation data, we had to assume that dipole of HD2453 is shifted along its axis towards negative magnetic charge by the value $\Delta r = 0.09$ of the star radius. From the magnetic field parameters

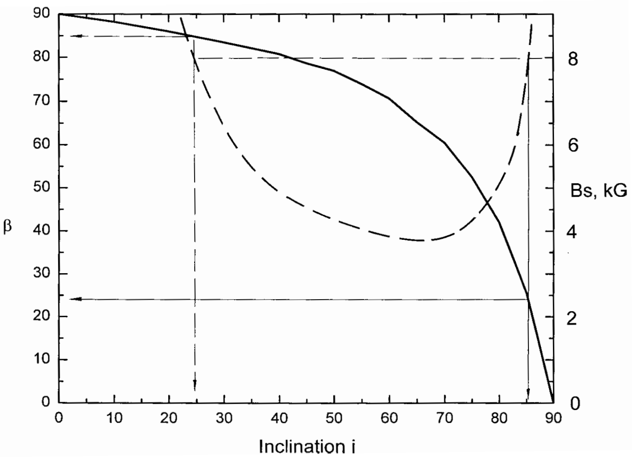

Figure 1: *Typical change of mean surface magnetic field Bs (dashed line) and β angle (solid line) between rotation axis and dipole axis with the change of star inclination angle relative to observer i.*

obtained in such a way it follows that the star is visible almost from the rotation equator and magnetic field equator. As a rule some chemical elements are concentrated on the magnetic poles, while others are concentrated on the magnetic equator, therefore we may expect a photometric variability of small amplitude. HD2453 has the value $\Delta V = 0\overset{m}{.}02$ (Catalano, Renson 1998). The amplitude value is typical of CP stars. Our method gives the magnetic field parameters of HD2453 close to those obtained by means of the model having collinear dipole, quadrupole, octopole (Landstreet, Mathys 2000), however, we believe that the model presented below is more realistic.

Typical $\beta(i)$ and $Bs(i)$ relationships for an oblique rotator are demonstrated in Fig. 1. They show that for one and the same Bs value there exist two models of the star magnetic field, having large and small angle β.

There are no formal ways of separating these models in the context of our method, therefore, we have to make choice between them based on some assumptions. So, firstly, for the star HD2453 a model with small β angle was chosen, because such a model better corresponds to the magnetic braking hypothesis, but at the same time, we had to allow a significant shift of the dipole along the axis. However, it turned out that the central dipole model describes perfectly both phase dependences without any need for dipole shift along axis. But in this case angle β turns out to be large. Thus, the central dipole model seems to be preferable.

In Fig. 2A, B the solid line represents the calculated dependences and the dependences being observed for the central dipole, constructed with the parameters given in Table 1A. Parameter Bp is the field strength on the magnetic poles. For comparison the phase curve is presented by the dashed line (with small angle β).

For the central dipole the rotation axis inclination angle $i = 14°$, and the angle between the rotation and dipole axes $\beta = 80°$. Thus, the dipole axis is close to the equatorial plane. The close fit of the calculated and observed phase dependences, under the assumption of the simplest model with no supplementary hypothesis, serves as an argument in favor of the considered model version.

In Fig.3 there is Mercator map of magnetic field strength distribution over surface for central dipole model.

4. Main parameters of the star HD 12288

Data for the phase dependence of the mean effective magnetic field *Be(P)* shown in Fig. 4A by dots are taken from (Wade et al. 2000). The phase dependence for the mean surface magnetic field $Bs(P)$ presented in Fig. 4B by dots, is taken from the paper by Mathys et al. (1997). While plotting these relationships, we used the ephemeris from the paper by Wade et al. (2000):

$$\mathrm{JD} = 2448499.87 + 34\overset{d}{.}9\mathrm{E}.$$

The average effective magnetic field ≈ 1.5 kG always has the negative sign, consequently the star is visible predominantly from the direction of hemisphere having mainly a field of negative sign, and an average value of the surface field Bs ≈ 8 kG. The inclination angle of the rotation axis relative to the line of sight i was defined on the basis of modeling, since it is impossible to find the i value from *vsini* because of the extremely slow rotation, $P = 34\overset{d}{.}9$.

The first step is calculation of the model with the dipole located in the center of the star. We can see from Fig.4 that the $Be(P)$ and $Bs(P)$ dependences reach their extrema at phases 0.0 and 0.5, so the initial values of λ equal 0° and 180°, respectively.

Let "Variant 1" correspond to the assumption of small angle, and "Variant 2" — of large angle. Using the convergence method, we achieved the best coincidence of the observed phase dependences $Be(P)$ and calculated ones, which were obtained using parameters shown in Table 2.

In "Variant 1" the inclination angle of the rotation axis relative to the line of sight $i = 85°$, the angle between the rotation axis and dipole axis $\beta = 10°$, in "Variant 2" $i = 24°$, $\beta = 66°$.

In Fig.4A the calculated dependences for both

Table 1:

A. HD2453 central dipole model parameters

Sign of charge	λ	δ	Bp, G
$+$	144°	10°	6560
$-$	324	-10	-6560

B. Comparison of HD2453 magnetic field parameters, obtained from different models

i	β	Δr	Bp, kG	References
62°	11°	–	–	Landstreet, Mathys (2000)
79	5	0.09	+4400–7660	Our decentred dipole model (Glagolevskij 2004)
14	80	0.0	±6560	Our central dipole model

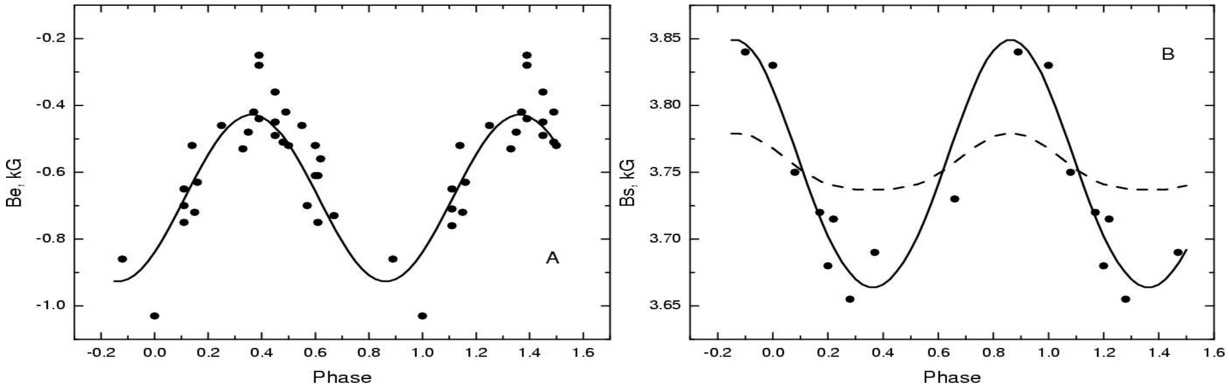

Figure 2: *Measured phase dependences of mean effective $Be(P)$ and mean surface $Bs(P)$ magnetic field of the star HD2453 (dots). A: solid line — calculated phase dependence for central dipole in the case of big and small β angles (they coincide). B: solid line — calculated phase dependence for central dipole and big β angle, dashed line — for central dipole and small β angle.*

Table 2: *Parameters of the model of the central dipole of HD12288*

A. Variant 1 with small angle β

Sign of charge	λ	δ	β	Bp, G
$-$	0°	80°	10°	12600
$+$	180°	$-80°$	10°	-12600

B. Variant 2 with large angle β

Sign of charge	λ	δ	β	Bp, G
$-$	0°	80°	66°	13400
$+$	180°	$-80°$	66°	-13400

variants coincide and are shown by a solid line, and in Fig.4B the first one is presented as a dashed, and the second one — as a solid line.

It is obvious that variant 2 corresponds to observational data better. In this case the observed and calculated phase dependences coincide. Consequently, in variant 2 the model of the central dipole describes the field structure of the star HD12288 more accurately.

In order that the calculated and observed phase dependences coincide in variant 1, the dipole should be shifted along the axis, as in the case of HD2453.

In case of variant 1, when dipole axis practically coincides with the rotation axis, noticeable photometric variability can hardly be expected. However, Wolff and Morrison (1973) adduced the amplitudes of variations $\Delta V = 0^{m}.02$ and $\Delta U = 0^{m}.03$, which are considerable values for CP stars. The noticeable photometric variability is not at variance with assumption of large angle β.

A Mercator map of magnetic field intensity distribution over the surface, which we computed for the central dipole, is shown in Fig. 5.

5. Model of the decentred dipole of HD12288

Let us try to analyze one more possible variant, namely a decentred dipole model. When examining Fig.4B, it can be seen that to correct the dependence $Bs(P)$ we need to shift the dipole towards negative

Table 3:

A. Parameters of the decentred dipole model of HD12288

Sign of charge	λ	δ	β	Bp, G
$-$	0°	78°	12°	+9700
+	180°	−78°	12°	15800

B. Comparison of parameters of the magnetic field of HD12288 obtained from different models by different authors

i	β	Δr	Bp, kG	Reference
62°	22°	–	–	Landstreet, Mathys (2000)
61°	21°	+0.01	11.8	Wade et al. (2000)
78.5°	12°	+0.08	+9.7; −15.8	Our decentred dipole model
24°	66°	0.0	±13.4	Our central dipole model

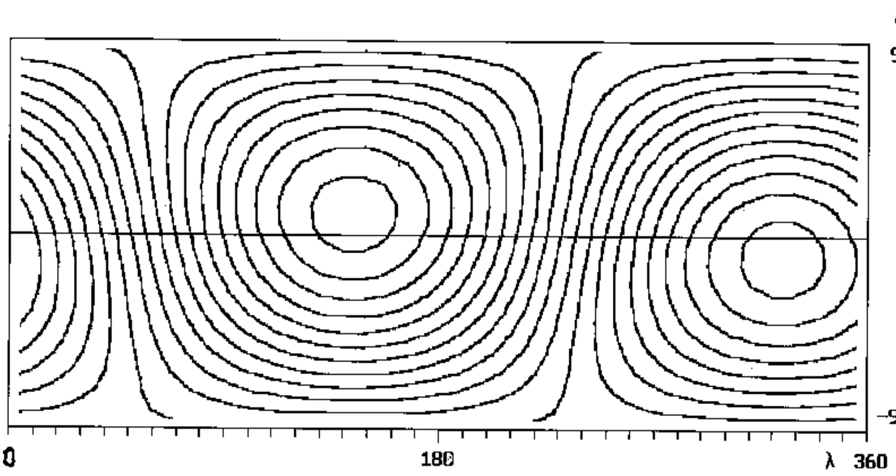

Figure 3: *A Mercator map of distribution of magnetic field strength over the surface of HD2453 for central dipole model and large β angle.*

charge. In this case the Bs value at phase $P = 0$ will increase, while at phase $P = 0.5$ it will decrease.

Phase dependences, which coincide well with observational ones, were calculated by method of successive approximations using the parameters presented in Table 3A. It turned out that dipole was shifted towards negative charge by $\Delta r = 0.08$ of a star radius. The angle $i = 78^\circ\!.5$, i.e. the star is visible practically from the rotation equator and magnetic field equator. The angle between the rotation and dipole axes $\beta = 12°$. The calculated phase dependences for the decentred dipole model are displayed in Fig. 4A and 4B by solid lines.

In Table 4B our model parameters are compared with those obtained from the model of the collinearly located dipole, quadrupole, octopole (Landstreet, Mathys 2000), and from the decentred dipole model (Wade et al. 2000). The magnetic and rotation axes are very close to each other. The strength of the dipole, quadrupole, octopole components are equal to −10100, −2800, 4200 gauss, respectively. In (Wade et al. 2000) only one value of the field on the pole, Bp, is presented. Despite certain differences in parameters the general tendency holds: large inclination angle of the rotation axis relative to the line of sight, small angle between the rotation and dipole axes, field values on the poles are of the same order, great difference of the dipole shift values. The number of observational data is so far insufficient for analyzing the causes of the modeling differences. So, in our opinion, the authors of the above papers chose from two possible variants the less grounded one. The necessity for the dipole shift suggests that the given model is less probable.

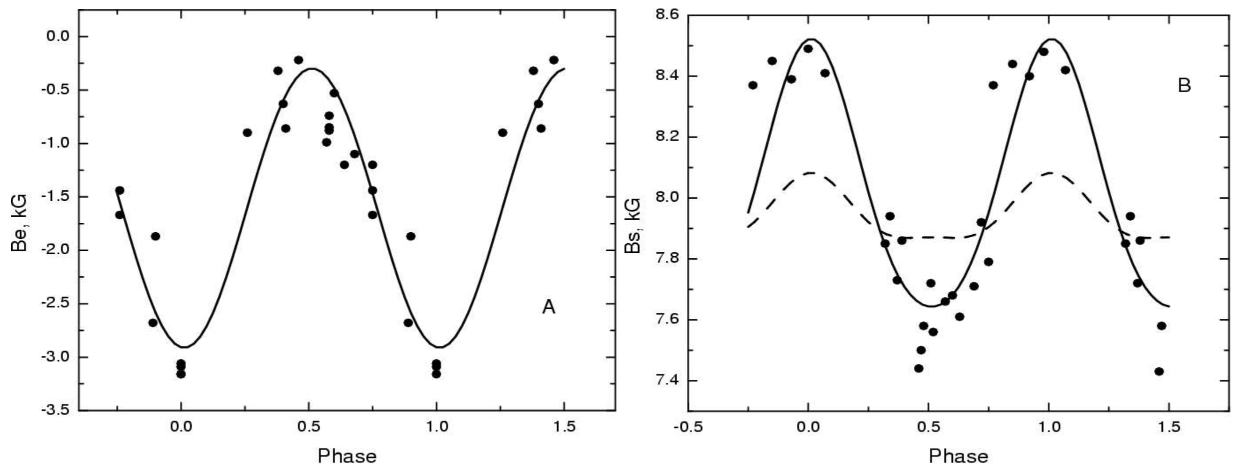

Figure 4: *Measured phase dependences of mean effective $Be(P)$ and mean surface $Bs(P)$ of magnetic field of star HD12288(dots). A: solid line — calculated phase dependence for central dipole in the case of large and small β angles (they coincide). B: solid line — calculated dependence for central dipole and large angle β, dashed line — for central dipole and small angle β.*

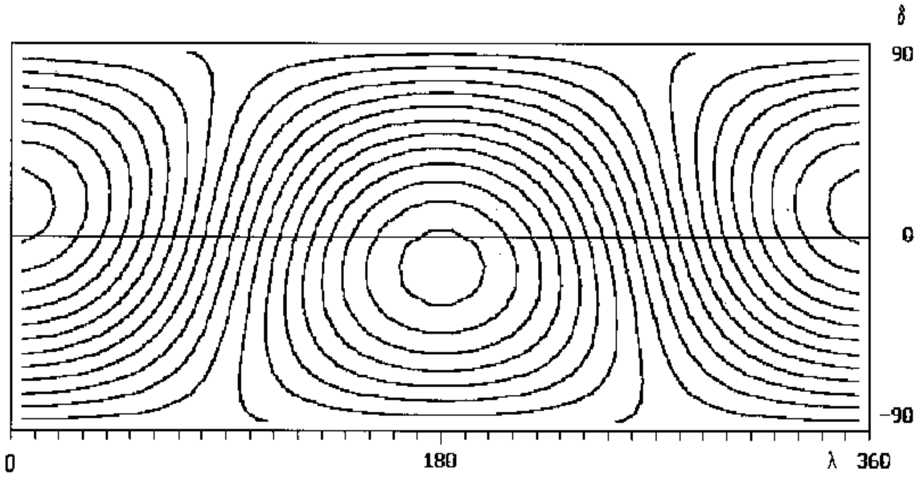

Figure 5: *A Mercator map of distribution of magnetic field strength over the surface of HD12288 for central dipole model and large angle β.*

6. Model of the magnetic field of HD200311

The star HD200311 has a rotation period of 26^d. The phase dependences for the effective magnetic field *Be* are taken from (Wade et al. 1997), and for the mean surface field from (Mathys et al. 1997), they are demonstrated in Fig. 5A,B by dots. As in the previous cases, firstly central dipole models were constructed for the cases of small (variant 1) and large (variant 2) angle β. For the first variant the phase dependence *Be(P)* was calculated by the method of successive approximations, which is a good fit to observed data (Fig.6A, solid line). At the same time it turned out, that the $Bs(P)$ dependence is not consistent with the observed data (Fig.6B, dashed line).

The model parameters are given in Table 4A. The rotation axis inclination angle $i = 89°$, and the angle between the axes $\beta = 13°$. A similar model in (Wade et al. 1997) gives the following parameters: $i = 90°$, $\beta = 28°$, Bp = 12800 G. Let us see what the central dipole model gives under the assumption of large angle β.

In Fig.6A the calculated phase dependence $Be(P)$ coincides with the previous case, while in Fig. 6B the calculated dependence $Bs(P)$ (solid line) does not coincide with observational data, but it is closer to these data than in the case of close axes. Parameters of this model are given in Table 4B. The inclination angle of the rotation axis to the line of sight $i = 30°$, the angle between the axes $\beta = 86°$. In (Wade et al. 1997) $i = 28°$, $\beta = 90°$, Bp = 12800 G, i.e. the values are quite close. Thus, the model with the magnetic axis located near the plane of the rotation equator is more consistent with observational data than the model with coinciding axes. However for complete coincidence with observations there was a need to implement the model of decentred dipole. Consideration of Fig.4B indicates that the shift should be directed towards positive monopole.

7. Model of the decentred dipole of HD200311

Satisfactory coincidence of the calculated and observed phase curves can be achieved when the axes coincide under the assumption of decentred dipole, as in the cases of HD2453 and HD12288. The shift of the dipole towards positive charge by $\Delta r = 0.08$ in the former variant and by $\Delta r = 0.13$ in the latter results in the phase dependences, presented in Fig. 7A, B. Since in the former variant the shift proves to be smaller, we will consider it as a more probable one.

Table 4: *Model of the magnetic field of HD200311*

A. Variant 1 with small angle β

Sign of charge	λ	δ	Bp, G
+	342°	77°	13640
−	162°	−77°	−13640

B. Variant 2 with large angle β

Sign of charge	λ	δ	Bp, G
+	342°	4°	14560
−	162°	−4°	−14560

Parameters of the decentred dipole model are given in Table 5. The star's inclination angle $i = 30°$, the angle between the axes $\beta = 86°$.

The significant photometric variability (Adelman 1997) is more consistent with the model in which magnetic axis is closer to the equator than to the rotation axis. In Fig. 8 a Mercator map of the magnetic field distribution over the surface of HD200311 is exhibited. In Table 5 parameters obtained by different authors are compared. Unlike the first two stars, for HD200311 we had to assume shift of the dipole along the magnetic axis. Generally such a shift points to disagreement between the amplitudes of phase dependences $Be(P)$ and $Bs(P)$. For the first two stars the inconsistency is a result of a wrong model. In the latter case the inconsistency of this kind can be supposed to result from systematic errors in the phase dependences. The causes of the errors may be different, for example, inhomogeneity of the distribution of chemical elements.

7.1. Conclusions

1. From analysis made one can conclude that for the slowly rotating stars HD2453, 12288 that we considered the central dipole models are best consistent with observational data. For the star HD200311 a shift of the dipole was required. All the models indicate that for the studied stars the angles between the rotation and dipole axes are large rather than small. In this case the models do not correspond to the hypothesis on deceleration of late CP stars with the magnetic field involved (Stepien 2000). In connection with this remark it will be recalled that magnetic fields of young pre–main sequence stars with small $v\sin i$ were not discovered (Glagolevskij, Chountonov 2001), and the participation of the magnetic field in the deceleration process is questionable (Glagolevskij 2003). In this case long rotation periods are most likely to be inherent in less massive CP stars initially ("magnetic" deceleration could occur if at early stages of evolution cold CP stars passed the convective phase of T Tau stars having magnetic field).

The parameters used as the most probable ones are presented in Table 6. The variability amplitudes are taken from the sources mentioned above and have approximately identical magnitudes for all the stars studied.

2. The problem of decentred dipole is of interest. In all the cases the shift takes place along the dipole axis. It means that the phase dependences $Be(P)$ and $Bs(P)$ do not correspond to each other in amplitude. To bring them to conformity, dipole has to be shifted in such a way as to compensate the difference. It seems that the amplitude of Be is insufficient. It is evident that the more probable model variant is the one that requires the least compensation. There are no sufficient data yet to assume if the cause of this discrepancy is methodological or physical. The decrease in amplitude of the Be or Bs variation could be due to many methodological causes: poor spectral resolution, complicated field configuration, line blending, etc., and also inhomogeneous distribution of chemical elements over the surface. In the case of real asymmetry of the field it could be assumed that dipole should be shifted in any direction, but not only along the dipole axis.

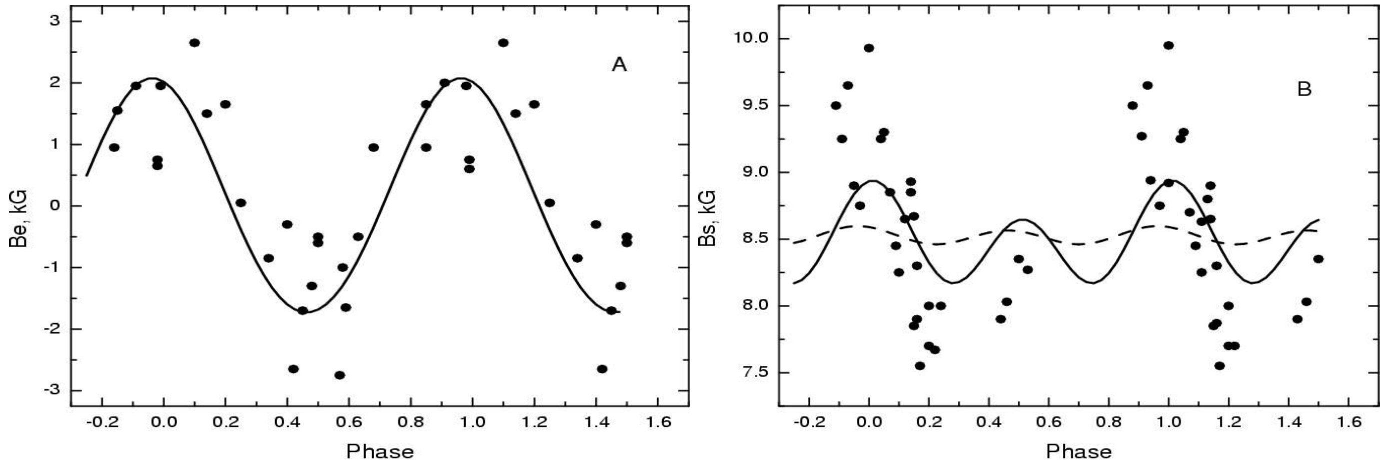

Figure 6: *Phase dependences for HD200311. A: solid line — calculated phase dependence for central dipole in the case of small and large angles β (they coincide). B: solid line — calculated dependence for central dipole and large angle β, dashed line — the same for small angle β.*

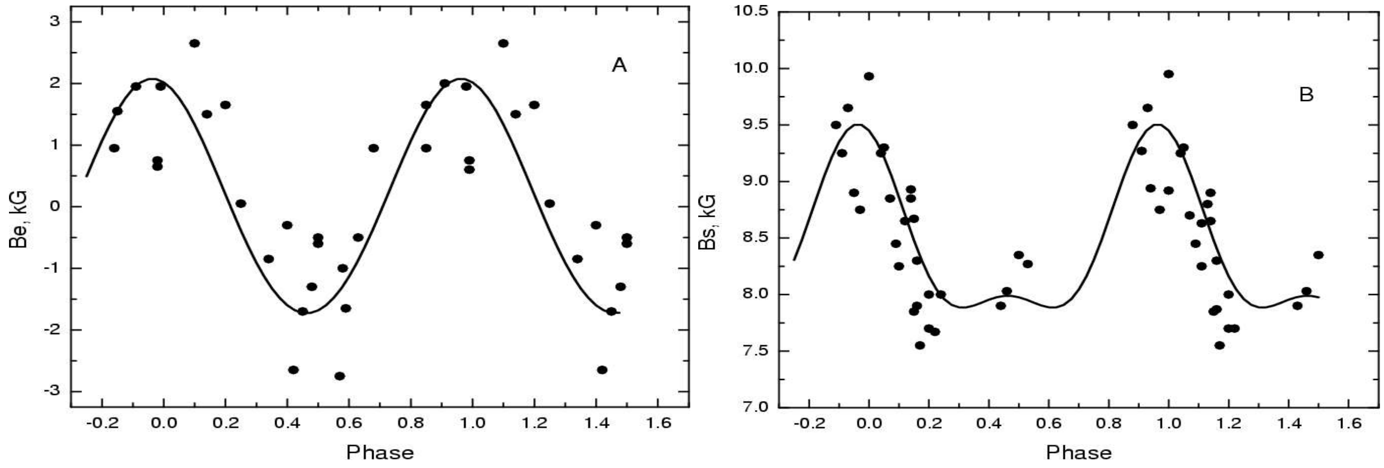

Figure 7: *Same as in Fig. 6, but for decentred dipole.*

Table 5:

A. Decentred dipole model parameters of HD 200311

Sign of charge	λ	δ	Bp, G
+	342°	4°	18520
−	162°	−4°	−11420

B. Comparison of parameters of the magnetic field of HD200311, obtained from different models by different authors

i	β	Δr	Bp, kG	References
88°	24°	−	−	Landstreet, Mathys (2000)
28	90	0.09	±12800	Wade et al. (2000)
30	86	0.08	+18520 − 11420	Our decentred dipole model
30	86	0.0	±14560	Our central dipole model

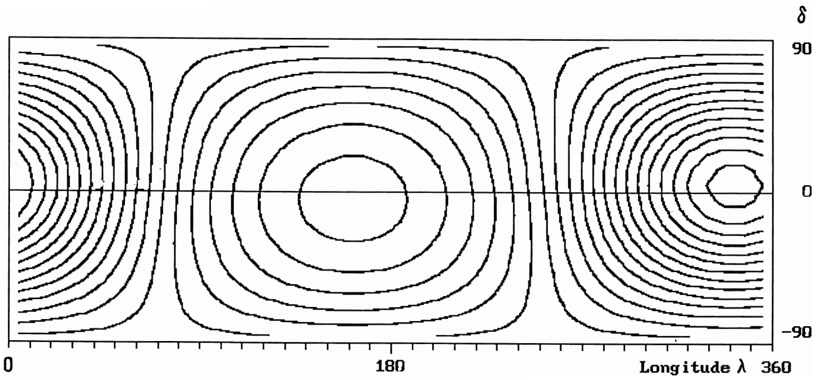

Figure 8: *A Mercator map of distribution of magnetic field strength over surface of HD200311 for decentred dipole model and large angle β.*

Table 6: *Probable parameters of the studied stars*

Star	Type	P	i	β	Bp, G	ΔV
HD2453	SrCrEu	521^d	14°	80°	±6560	$0\overset{m}{.}02$
HD12288	SrCrEu	34.5	24	66	±13400	0.02
HD200311	Si+	52	30	86	+18520 -11420	0.03

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