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MAGNETIC FIELD STRUCTURE OF SLOW CP-ROTATORS: HD 9996 AND HD 188041

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This is the final paper on a study of the magnetic field structure of CP stars with long rotation periods. It is first demonstrated that the orientation and strength of the magnetic field have no effect on their rotation velocity. The orientation of the dipole structures in slow magnetic rotators is shown to be random, as it is in fast rotators. The hypothesis that magnetic stars are slowed down under the influence of the magnetic field is called into question. The origin of CP stars is probably related to their initial slow rotation.

Keywords: *stars: magnetic fields -- individual: HD 9996, HD 188041*

1. Introduction

With this paper we conclude a cycle of studies of the magnetic field configurations in CP stars with long rotation periods ($P > 25^d$). The previous papers [1-4] dealt with 7 of these stars. The main problem is to compare the basic properties of the magnetic field in fast and slow rotators, in order to clarify the possible effect of the magnetic field configurations on the assumed degree of braking in CP stars.

Our modelling technique is based on the assumed existence of magnetic field sources consisting of magnetic monopoles. Unlike some other methods of modelling the magnetic field in CP stars, our technique has a physical significance, in that the magnetic field, like other fields, must have a source. It differs from some others, such as those which describe the phase dependences of the magnetic field using sinusoids, cosinusoids, etc., which only characterize their shape. Our technique and its physical basis have been described in detail elsewhere [5]. On specifying the coordinates of the monopoles (longitude λ, latitude δ), the magnetic moment M and angle i of inclination to the line of sight, we calculate the phase dependences of the average effective field Be-Φ and average surface field Bs-Φ, which we then compare with the observed dependences. The best agreement is achieved by a method of successive approximations. The angle i is obtained automatically if both phase dependences are known. If only the Be-Φ dependence is known, then i is obtained from $\upsilon \sin i$. The equatorial velocity v is estimated using the standard formula $\upsilon = 50.6\, P/R$, where

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P is the rotation period in days and R is the star's radius in solar units. Compared to the first case, this method generally yields an approximate estimate for the parameters because of the insufficient accuracy in $\upsilon \sin i$ and the inaccuracy of the formulas used.

Because of the slow rotation of the stars studied in this paper, we do not have measurements of $\upsilon \sin i$ that are accurate enough to estimate the angle i, but measurements of the average surface magnetic fields Bs are available. The ratio Bs/Be. of the average fields is very sensitive to the angle i, so this angle is determined quite accurately, with an error on the order of $\pm 1^{\circ}$.

2. The star HD 9996

Quite a few measurements of the effective magnetic field Be of HD 9996 have been made, but there is significant scatter in these data. In order to plot the phase dependence Be-Φ we have used Refs. 6-10. Unfortunately, there are only a few measurements of the average surface magnetic field Bs [9,11], so it is impossible to construct the phase dependence,

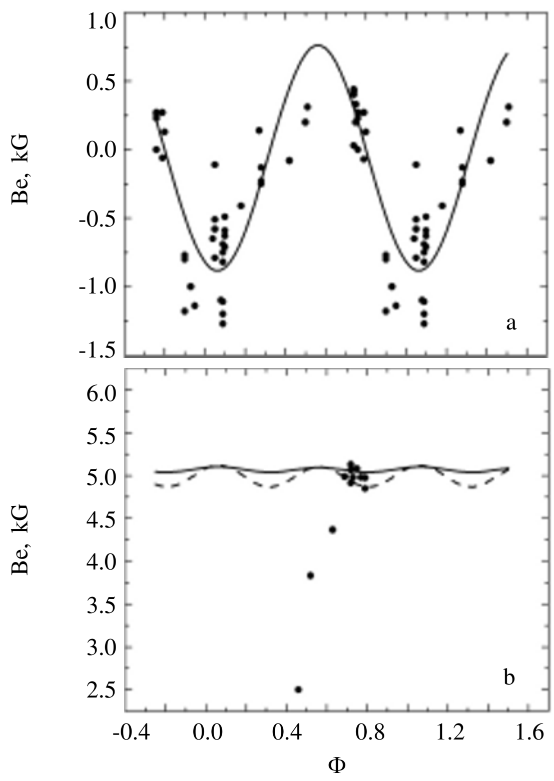

Fig. 1. Phase dependences of the magnetic field for the star HD 9996. (a) The points are observational data, the smooth curve is the model dependences, which are the same for both variants, with large and small angles β. (b) The points are observational data, the smooth curve is for a small angle β and the dashed curve, for large β.

TABLE 1. Calculated Results from the Central Dipole Model for HD 9996

A. Small angle β

Sign of monopole	Longitude λ	Latitude δ	Angle β	Angle of inclination *i*	Field Bp at poles
-	18°	78°	12°	89°.5	-8100 G
+	198	-78			+8100

B. Large angle β

Sign of monopole	Longitude λ	Latitude δ	Angle β	Angle of inclination *i*	Field Bp at poles
-	18°	0°.5	89°.5	24°:	-8710 G
+	198	-0 .5			+8710

but it is possible to make an approximate estimate of the star's angle of inclination *i*. The phase dependence Be-Φ is indicated by the circles in Fig. 1a. The phases were calculated from the ephemeris of Ref. 12. The measurements of Mathys yield an average surface field Bs = 5kG. Preston [8] estimates Bs = 2.2kG and Scholz [10], Bs = 2.5kG. All of these measurements fall within the range of phases 0.48-0.79 and such large changes cannot be explained by any model. We prefer the measurements of Mathys because his method has been tested in a large number of measurements of many stars. Experience shows that a large spread in the measured values of Be and Bs is usually caused by an orientation of the star relative to the observer that is unfavorable for the measurements. In fact, in the following we shall see that the star is turned toward the observer predominantly on the side of the magnetic equator.

As a first approximation for determining the major parameters of the magnetic field we used a central dipole model. This model has two solutions: with a small angle β between the axis of the dipole and the axis of rotation, and with a large angle. Both variants are usually satisfied, and the most probable one is selected. Figures 1a and 1b show the calculated phase dependences for both cases, small and large angles β indicated by the smooth and dashed curves, respectively. In both cases the average $Bs \approx 5$ kG. The model parameters are listed in Table 1. We consider the variant with a lower amplitude of Bs to be more probable based on experience with earlier model cases. The modelled phase dependences Bs-Φ have very small amplitudes in both cases. Thus, the large spread in the data points from different papers can be only be explained by errors owing to an orientation of the star that is unfavorable for the field measurements. In fact, the star is predominantly seen from the side of the magnetic equator, while the magnetic poles lie at the edge of the disk. Thus, fields of different sign act on the spectral source and the distribution of the polarization within the line turns out to be very complicated. The measurements are burdened with large errors. The model of HD 9996 cannot be improved without additional measurements, especially of Bs. Because of these observational difficulties, we keep the central dipole as a first approximation. We indicate the angle *i* with an accuracy of up to 0°.1, because for this orientation of the star the average position of the phase dependence Bs-P has a very strong dependence on *i*.

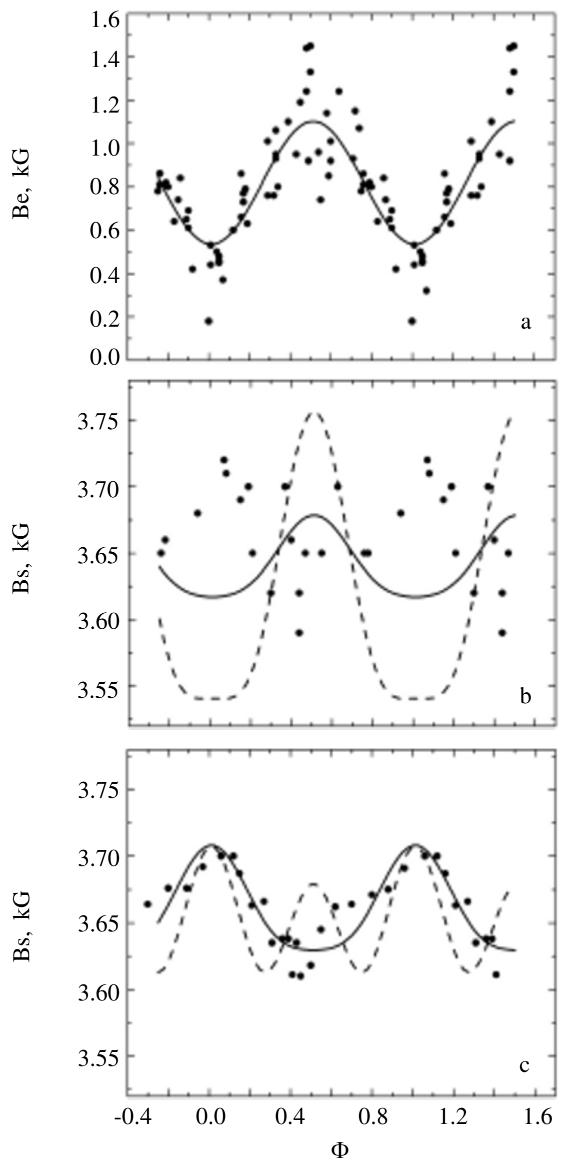

Fig. 2. Phase dependences of the magnetic field for the star HD 188041. (a) The points are observational data, the smooth curve is the model dependences, which are the same for all variants of the calculations. (b) The points are observational data, the smooth curve is for the model of a central dipole and a small angle β, the dashed curve, for a central dipole and large β. (c) The points are observational data, the smooth curve is for the model of a shifted dipole and small angle β, the dashed curve, for a shifted dipole and large β.

3. The star HD 188041

To construct a model for the magnetic field of the star HD 188041 we first examined all the papers [13-18] on measurements of *Be* and *Bs*. It turned out that all of them are characterized by an excessively large scatter in the values of the field. the only series containing a significant amount of data for *Be* with a relatively small spread is that of Babcock [13]; hence we have only used his data. We took the measurements of *Bs* from Refs. 11 and 19. For convenience in the demonstrations of the calculated and observed *Bs* – Φ dependences, we have used a sliding average over 4 points in the plots.

The measured values of Be and Bs are indicated in Figs. 2, a-c, by points and the values of Φ were calculated using the ephemeris of Ref. 13.

The magnetic field minimum $= JD2432323 + 226E$.

As usual, the first approximation is based on assuming a central dipole for two cases, small and large angles β. Here we first obtained agreement for the *Be* - Φ dependence and then for *Bs* - Φ. The result of this procedure is shown in Tables 2, A and B, and Figs. 2, a and b.

The smooth curve in Fig. 2b shows the calculated dependence for small β and the dashed curve, for large β. It is evident that neither variant is similar in form to the observed *Bs* - Φ dependence. This means that the structure of the star's magnetic field is not consistent with the model assumption of a central dipole.

The next step consisted of finding the position of the magnetic charges inside the star which yields the best agreement between the two calculated phase dependences and the observations. As in the preceding case, we first obtain agreement for the *Be* - Φ dependence in Fig. 2a. Choosing all the parameters by the method of successive approximations, we obtained two solutions, with small and large angles β. In Fig. 2c the first variant is indicated by the smooth curve and the second, by the dashed curve. It is quite clear that the large β variant does not correspond to the observed dependence at all, but small β variant fits. The parameters with which these two solutions were obtained are listed in

TABLE 2. Calculated Results from the Central Dipole Model for HD 188041

A. Small angle β

Sign of monopole	Longitude λ	Latitude δ	Angle β	Angle of *i*	Field Bp at poles
-	0°	-84°	6°	80°.5	-5780 G
+	180	84			+5780 G

B. Large angle β

Sign of monopole	Longitude λ	Latitude δ	Angle β	Angle of *i*	Field Bp at poles
-	0°	-13°.2	76°.8	14°	-6310 G
+	180	13.2			+6310 G

TABLE 3. Calculated Results from the Shifted Dipole Model for HD 188041

A. Small angle β

Sign of monopole	Longitude λ	Latitude δ	Angle β	Angle of *i*	Field Bp at poles
-	0°	-83°	7°	83°	-7400 G
+	180	83			+4850 G

The dipole is shifted by $\Delta a = -0.07$ relative to the star's center .

B. Large angle β

Sign of monopole	Longitude λ	Latitude δ	Angle β	Angle of *i*	Field Bp at poles
-	0°	-10°	80°	16°	-7540 G
+	180	10			+5580 G

The dipole is shifted by $\Delta a = -0.05$ relative to the star's center .

Tables 3, A and B. We thus find that the star HD 188041 has the magnetic field structure owing to a dipole which is shifted along the axis toward the negative monopole by a distance equal to 0.07 times the star's radius.

Comparing the data for a model with a shifted dipole with the parameters for a central dipole, we find that they are relatively close. Shifting the dipole in the model has little effect on any of the parameters except the value of the magnetic field at the poles. The star HD 188041 is viewed on the equator, while the axis of the dipole is close to the axis of rotation. This orientation of the magnetic field is extremely unfavorable for measurements and this explains the large scatter in the observed points on the phase curves.

We estimate the accuracy of the derived parameters to be ±1° for i, β , and δ, ±10° for λ , and ±30-50 G for Bp.

TABLE 4. List of Slow CP Rotators that Have Been Studied

HD	*Bs*, G	P, days	β	Structure	Source
2453	547	521	80	centered dipole	[1]
9996	8000:	4800	12:	centered dipole?	this paper
12288	35	7900	66	centered dipole	[1]
116458	4600	148	12	shifted dipole	[2]
126515	12300	130	86	shifted dipole	[2]
187474	5000	2345	24	shifted dipole	[3]
188041	3600	224	20	centered dipole	this paper
200311	8600	52	86	shifted dipole	[1]
201601	3800	72 years	50	shifted dipole	[4]

4. Conclusion

We now summarize the basic results obtained by modelling the magnetic fields of slow rotators.

(1) Table 4 lists all our results on the orientation and structure of the magnetic field in slow rotating magnetic stars. The table shows that the orientation of the magnetic dipoles inside the star can be arbitrary, with no preference of any kind. This is the main conclusion of the present study and does not support another paper [20] in which it is reported that slow rotators predominantly have small angles β. Thus, the assumption that the braking of CP stars is caused by magnetic fields with collinear dipole axis and axis of rotation is not confirmed.

(2) Our data [4,21] show that the dependence of Bs on the rotation period for slow CP rotators is apparently the reverse; this also conflicts with the assumption that the rotation is affected by the magnetic field.

(3) In an earlier paper [4] we have modelled the magnetic fields of rapidly rotating magnetic stars; this shows that they, as do the slowly rotating stars, have arbitrarily oriented magnetic dipoles. Hence, the data accumulated thus far do not support the ideal that there are any differences in the structure of the magnetic fields of fast and slow rotators; consequently, the field configuration does not affect the degree of braking in magnetic stars. There are signs that the origin of CP stars is related to their initial slow rotation [21]. In that same paper [21], we also argued in favor of the idea that the magnitude and configuration of the field do not affect the properties of CP stars. The average surface field appears to vary with age beyond the main sequence period only because of evolutionary changes in a star's radius [22].

(4) The magnetic field parameters of the star HD 9996, especially the angle i, are not reliably known because of the small number of measurements of *Bs*.

(5) In principle, the "magnetic charge" technique can be used to reproduce any magnetic field configuration when the phase dependences are measured accurately enough. The data available to us show that, as a first approximation, the structure of slow rotators is consistent with models of a central or shifted dipole.

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