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Averaged magnetic phase curves. A catalog

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Abstract. We collected published measurements of the effective magnetic field of stars on the main sequence and above it and compiled a catalog of periodic B_e variations. We present magnetic phase curves for 139 stars and tables of their parameters. Most of the cataloged objects are chemically peculiar A- and B-type stars (134 stars).

1 Introduction

Variability of the effective magnetic fields B_e in Ap stars was discovered over 50 years ago (Babcock & Bard 1952), and a large number of observational data have been collected ever since.

We have extensively searched literature and selected all the available measurements of the effective (longitudinal) magnetic field B_e for main sequence stars and a few other stars. Averaged magnetic phase curves $B_e(\phi)$ have been constructed for those stars for which we know the magnetic (i.e. rotational) periods, or can determine them.

The picture of a star with a large-scale magnetic field can be described by the oblique rotator model in which the axis of the magnetic dipole is inclined to the rotation axis. The dipole field itself is not time variable. The periodic variability of the effective magnetic field B_e is caused by changes in aspect during rotation of the star. Therefore the period of magnetic B_e variations, P_{mag}, can be identified with the rotational period P_{rot}.

The above model was proposed to explain the behavior of magnetic CP stars which exhibit periodic variations of B_e (Stibbs 1950; Preston 1967). In this model the dipole magnetic field is frozen into the stellar atmosphere and intrisically constant at each point.

Our catalog presents averaged magnetic phase curves in a homogeneous form. We have also determined other parameters of magnetic variability of all stars in the catalog. The list of these parameters is briefly described below.

2 Parameters of magnetic variability

In this Section we present a list of all parameters of the magnetic phase curves, and also the parameter r, which was defined by Stibbs (1950). These are: B_0, B_1, B_2, T_0, P, and r.

3 Sine wave

For all stars with an adequate number of B_e determinations, and for which the period of magnetic variability P_{mag} was known, we have determined, by the least squares method, the best fit for the relation of B_e vs. phase ϕ

$$B_{ei}(\phi) = B_0 + B_1 \cos\phi\,, \tag{1}$$

where

$$\phi = 2\pi \left(\frac{T_i - T_0}{P} \right) . \tag{2}$$

. Here B_0 is the average field, B_1 stands for the half-amplitude, T_i is the time of measurement, P is the period, and T_0 is the zero epoch, i.e. the time corresponding to the zero phase ϕ. We have chosen the zero epoch T_0 in such a way that the phase $\phi = 0$ corresponds to the minimum of the best fit magnetic curve for all listed stars.

4 Parameter r

The parameter r relates both the angle β between the magnetic dipole axis and the rotation axis, and the angle i between the rotation axis and the line of sight

$$r = \frac{\cos\beta\cos i - \sin\beta\sin i}{\cos\beta\cos i + \sin\beta\sin i}\,. \tag{3}$$

Alternatively, one can write

$$r = \frac{B_e(\min)}{B_e(\max)}\,. \tag{4}$$

5 Double wave

In the case where the shape of the magnetic phase curve is more complex than a simple cosine, we include the second harmonic wave

$$B_{ei}(\phi) = B_0 + B_1\cos(\phi + z_1) + B_2\cos(2\phi + z_2)\,. \tag{5}$$

6 Error analysis

For each star in the sample we performed a χ^2 test to evaluate goodness of the assumed fit given either by Eq. 1 or Eq. 4 and estimated the scatter of the available B_e measurements.

The statistical test χ^2 can indicate a large discrepancy between the observed points and the assumed fitting curve if either the fitting curve is intrinsically inconsistent with observations, or errors of observations (i.e. values of B_e) are overestimated.

Error estimates of all parameters, T_0, B_0, B_1, B_2, and r, were performed in the following way. For each B_{ei} measurement with known standard error σ_i we generated a series of secondary B_{ei}^{sec} values with a random number generator. The values of B_{ei}^{sec} had a normal distribution around the observed B_{ei} with the width σ_i. (In the case where the authors did not provide the σ_i estimate, we used the error typical of the given method of observation.) This method generated a set of artificial values of B_e for which the secondary parameters T_0, B_0, B_1, B_2, and r were determined.

The above computations were repeated many times (usually 1000 times or even more). In such a way we obtained numerous sets of fitting parameters and were able to estimate errors of T_0, B_0, B_1, B_2, and r separately.

7 Tabular data

The full catalog of investigated stars and the corresponding parameters of the best fit sine magnetic curves (Eq. 1) is presented in Table 1, which will be available on the Internet. The columns of Table 1 list: HD number, B_0, σ_{B_0}, B_1, σ_{B_1}, period P, T_0, σ_{T_0}, N – the number of individual points, σ – the average scatter of B_{ei} observation around the fitting curve, r, σ_r, value of χ^2 (for one degree of freedom), the reference number, and (in some cases) the running number of brief comments.

Table 2 of our catalog presents for each star: the HD number, the parameter r and its standard error σ_r, $N_V = N - 3$ or $N - 5$ (for sine wave or double wave fits, respectively), χ^2 for one degree of freedom, the method and the reference numbers.

There exist 18 magnetic stars which display more complex phase curves $B_e(\phi)$. For these stars the phase curves were fitted by the expansion in harmonic series with the second cosine term, see Eq. 5 (double wave).

Table 3 presents additional parameters necessary for defining the double wave. These are the coefficients B_2, the phase shifts z_1 and z_2, and their errors σ_{B_2}, σ_{z_1}, σ_{z_2}, N_V, the values of χ^2, the number of references and comments. Here $N_V = N - 5$.

8 Sample phase curve: single wave

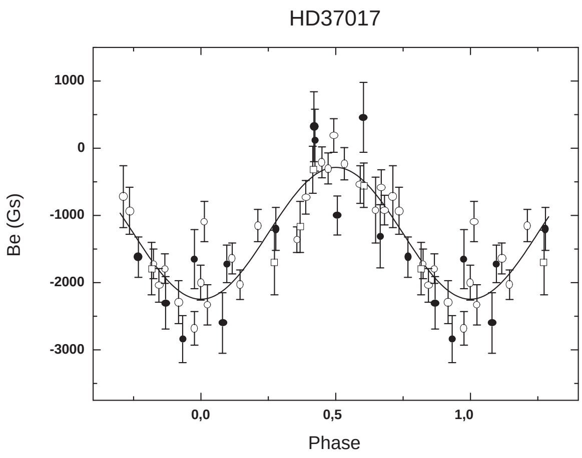

Figure 1: HD 37017. Open circles – Bohlender et al. 1987 (H lines), filled circles – Borra, Landstreet 1979 (H lines), open squares – Bohlender et al. 1987 (He 5867 line).

9 Sample phase curves: double wave

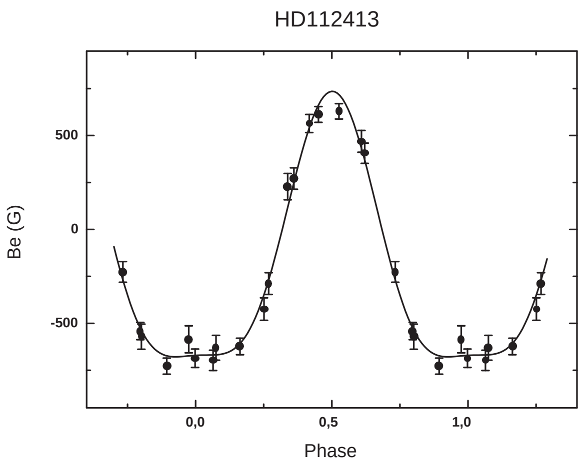

Figure 2: *HD 112413. The figure presents the phase curve $B_e(\phi)$ derived from B_e measurements of Wade et al. 2000 (metal lines, LSD method). Averaged phase curve $B_e(\phi)$ has form of double wave.*

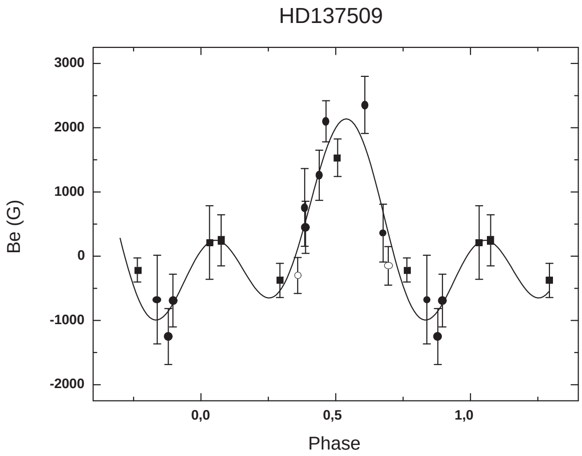

Figure 3: *HD 137509. Magnetic phase curve is described best by a double wave. Filled squares – Mathys, Hubrig 1997, open circles – Bohlender et al. 1993, filled circles – Mathys 1991.*

10 Summary

We have compiled a catalog of magnetic phase curves $B_e(\phi)$ for 139 stars which exhibit periodic variations of the effective magnetic field B_e. Most of the cataloged objects, 134 stars, are chemically peculiar A- and B-type stars. The catalog consists of figures which display individual B_e measurements and error bars, and phase curves approximated either by a sine wave, or by a double wave.

The catalog also presents a list of the following parameters of magnetic phase curves: the coefficients B_0, B_1, and B_2 of the harmonic expansion of $B_e(\phi)$, the period P (in days) and the Julian Date of the zero phase T_0, and the coefficient r defined by Stibbs (1950).

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