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The Magnetic Field Structure of CP Stars

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Abstract. After having applied the modelling method of "magnetic charges" to the published observational data on nearly 50 magnetic stars, the authors draw a résumé. Sufficiently numerous results have allowed to consider some common properties of magnetic stars and to obtain a general idea about them from the statistics. It clearly emerges that the configuration of the magnetic dipole sources in the interior of a star determines the structure of the surface field in a calculable way.

Key words: magnetic stars – modelling – fields – dipoles

1 Introduction

Since Babcock started his works on stellar magnetism in 1947 (Babcock, 1947), it was assumed that the structure of the magnetic field on the surface of chemically peculiar stars goes back to magnetic sources in the interior of stars. However, it was not known what are the sources, and what is the cause for the structures of the surface field, as it was derived from observations.

"Spotty" features of magnetic field, similar to those we observe on the Sun cannot be excluded but do not prove to be the common features in CP stars. The surface is, moreover, regularly and uniformly magnetized over wide areas according to the structure of a dipole field. It is logical to assume that on some depth a magnetic dipole could not exist because of the action of a convective core inside the star, which would distort a large–scale magnetic field of the poloidal type. The structure of the magnetic field inside a star is unknown still, as ever, representing a serious problem for interpretation. The lack of knowledge has to be filled by reasonable hypotheses and theories, which allow to construct models of the source configuration and to draw consequences for the surface field in comparison with the observations. It should be emphasized that such models cannot explain the inherent physical processes of generation of magnetism in the interior of a star, but they give a practical framework for numerical calculations and graphical description of the structure of the magnetic surface field based on the potential theory. Nevertheless, every vector field has its sources. Tracing back the field at the spherical surface of a star to the originating sources of virtual magnetic charges and vortices is physically legitimate in any case.

Our technique of modelling (Gerth & Glagolevskij, 2000, 2004) consists in that we do not set the structure of a field beforehand, but we do set a certain amount of *hypothetical magnetic monopoles* placing them inside a star, so that their total action would result in calculated phase dependencies of the effective magnetic field strength B_e, which are compared and fitted to the observed facts. On the basis of such calculations we judge what type of the source of a magnetic field inside a star could be.

The calculations are carried out by a method of consecutive approximations. For the majority of stars it appears sufficient to assume the presence of two magnetic charges inside a star in the center or near to the center, i.e. a dipole configuration of two oppositely charged *virtual magnetic sources*.

Some stars have somehow more complex structures. By application of our technique we try to reveal large–scale structures of magnetic fields. The program of magnetic star modelling by our method allows to calculate any distribution of the intensity of a magnetic field on the star's surface. The first experience of the application of our method has shown that the combination of magnetic sources "dipole + quadrupole" or "dipole + quadrupole + octupole" results in a dipole field on the surface with a deformed distribution. The investigations have shown that the assumption of a central or a shifted dipole is essential and corresponds to the distribution of chemical anomalies we actually observe.

Resorting to an axiom of the potential theory concerning the linear superposition of fields, we can use any quantity of charges to obtain the best concurrence with the observations, but already combining two monopoles (magnetic charges) the observed and calculated dependencies usually agree well. Therefore, there are no reasons to complicate the structure of the sources additionally introducing, for instance, artificial quadrupoles, octupoles, etc. The main shortcoming of our method is that it makes it possible to examine only the large-scale structures of a field. The parameters of a field strongly depend on the accuracy of the angle of inclination i of the star to the line of sight, which is often determined with a large error. If both phase dependencies $B_e(\varphi)$ and $B_s(\varphi)$ are known, then two possibilities of decision occur, but only one of them is favoured for fitting the preconceived data. It is recommended to choose the phase dependency with the minor scattering — i. e.: the sum of the mean square deviations.

Our computation procedure (Gerth & Glagolevskij, 2000, 2004) is based on the magnetic field sources and calculates the components of the vectorial magnetic field strength at the surface of the star, integrates over the visible hemisphere of the rotating star in direction of the line of sight, and takes into account the influence of limb darkening by the so–called "observation window".

Proceeding from our modelling experience, we come to a very natural conclusion that the elementary sources of a magnetic field, namely, circular electric currents, create the total magnetic field of a star. The circular electric currents produce a magnetic field described by a *virtual magnetic dipole* with a magnetic moment $M = Ql$ being in the infinitesimal case completely identical with a dipole consisting of two pointlike sources, where Q is the absolute magnetic charge of both sources with the magnetic charges $+Q$ and $-Q$, and l is the distance between the sources. The total magnetic moment is a vector corresponding to one imagined dipole, which is located in the center of a star or at some distance from the center (the shifted dipole).

The magnitude l has the dimension of atoms, however, by means of calculations it is possible to set it at about 0.1 radius R_* of a star. With this spatial size of l and the absolute magnitude of magnetic charges Q, the magnetic moment M numerically has a value comprehensible with the calculations. With regards to the accuracy of measurements, the change up to $0.2R_*$ practically does not influence the form of the phase dependence of a magnetic field.

Sometimes one can find publications on the periodical variation of the stellar magnetic field, in which the phase dependencies of a magnetic field are described by a sinusoid with its parameters. Such an approach violates the physics and virtually has no sense.

2 The Configuration of Magnetic Dipole Sources

1. We confirmed the earlier data on the arbitrary orientation of virtual magnetic dipoles consisting of two sources with opposite magnetic charges.

2. A large number of stars possess magnetic field structures, different from the structure of a central dipole. Figures 1 – 5 demonstrate the diagrams of the basic magnetic structures in the

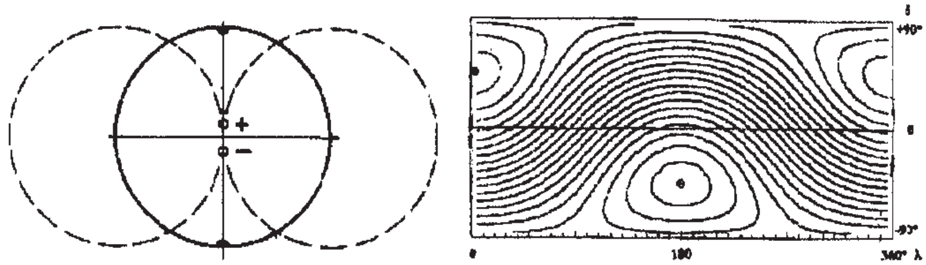

Fig. 1

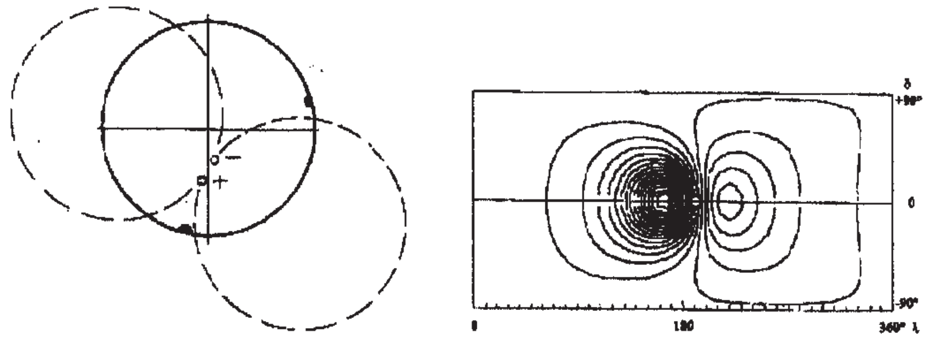

Fig. 2

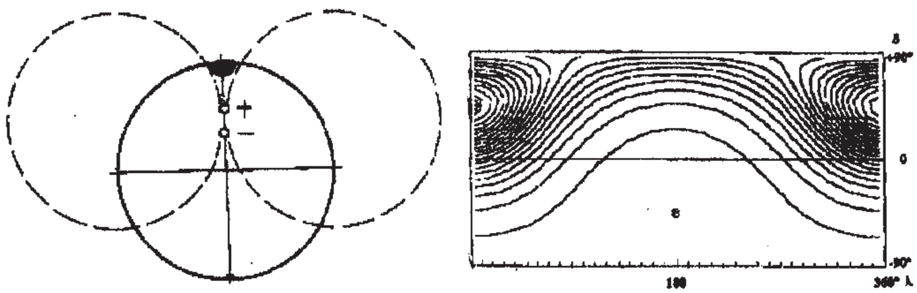

Fig. 3

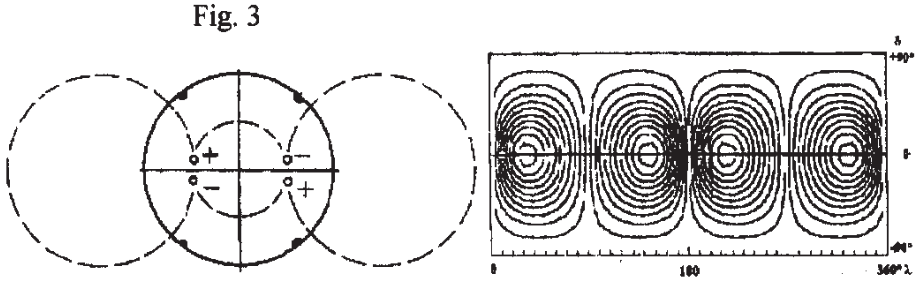

Fig. 4

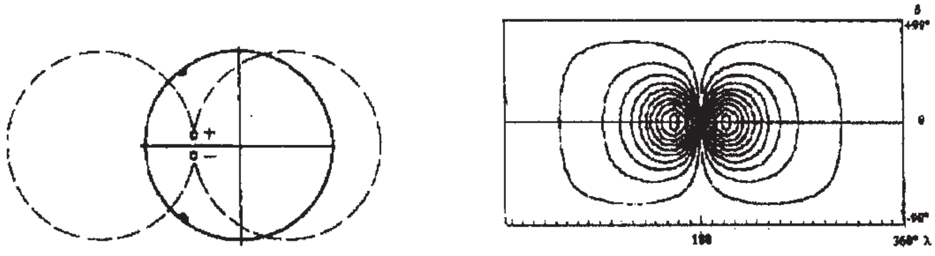

Fig. 5

Figures 1 − 5: Configurations of dipoles in the star and Mercator maps of the surface magnetic field strength represented by iso–magnetic lines.

studied stars. Accordingly, they demonstrate the structure of a central dipole, a dipole shifted along the axis (+)– and (−)–wise, a dipole shifted across the axis, and a structure of two dipoles shifted across the axis. One star has a dipole, shifted along the rotational axis.

3. Based on a yet limited number of examples we can make a preliminary conclusion that the shift of the dipole (i. e. the deformation of the stellar magnetic field) can occur in any direction. The mechanism of deformation is not clear. The dipole placed inside a star describes the observable changeability of the magnetic field well, and the structure of a field on the surface from such dipole configuration corresponds well with the distribution of chemical elements.

4. The modelling results show that the structure of magnetic fields of CP stars most likely corresponds to a bar magnet with a large value of the axis l in the dimension of the star's radius (it can be called a "long dipole") rather than to a point dipole having atomic dimensions, i. e. with a value of l, comparable to the size of eddy currents. Obviously, this can occur due to the violations of poloidal structures inside the star due to yet unknown processes.

5. Such structures can apparently arise, when elementary dipoles are built in parallel between monopoles inside a star. It is possible, that in this case the influence of the convective core is essential. Since the magnetic field cannot keep a dipole intact in a convective medium, the structure is organized only in the top layers of the star, where the lines of force bypass the core. The quantity of stars having such a field structure is $\sim 9\%$. This problem should be further investigated.

6. Some stars have strongly deformed structures, the displacement of monopoles to the surface of the star reaches the value $\triangle a = 0.5R_*$. It is possible that the convective core, which is large in B0 – A5 stars, has such an effect. In fact, poloidal magnetic fields can not exist within convective cores. The observed structures, however, are formed in the surface layers.

7. A considerable quantity of stars possess a structure of the surface field, which can be explained by the configuration of one central or shifted dipole, but a number of stars has a more complicated structure. Such stars as HD 32633, HD 35502, HD 137909, HD 152301 etc. have phase dependencies $B_e(\varphi)$ that are not reproducible precisely by only one dipole. Some of them reveal a relative shift of the extrema of the longitudinal field B_e and the variability of the surface field B_s. The structure of these stars is described by two dipoles located on the opposite sides from the center of the star.

8. It is reconfirmed that for many stars, in which the dipole axes are placed in the rotation equatorial plane that the shifts occur in this plane as well, i. e. the field deformation occurs mainly along the equator of rotation. These data must be considered for deriving any theory of the origin and evolution of magnetic stars. Probably the deformation of a relic magnetic field could arise at the early stages of stellar evolution via an as yet unknown mechanism.

9. Figure 6 demonstrates the distribution of the angle β (between the axis of rotation and the axis of a dipole). It is visible here that β prevails in the range of $80° - 90°$, though at a uniform distribution there would be a cosine dependence. The effect of large angles β has been noticed first by Preston and Landstreet. It is remarkable that in completely symmetric stars there emerge asymmetrical structures of magnetic field. This is not comprehensible from the point of view of a relic origin of the magnetic field.

10. Large mass accretion at early stages of evolution is assumed to create the original structure corresponding to a central dipole. Attempts to explain this phenomenon in order to reveal the nature of the observable magnetic configurations have not yielded any essential results. The

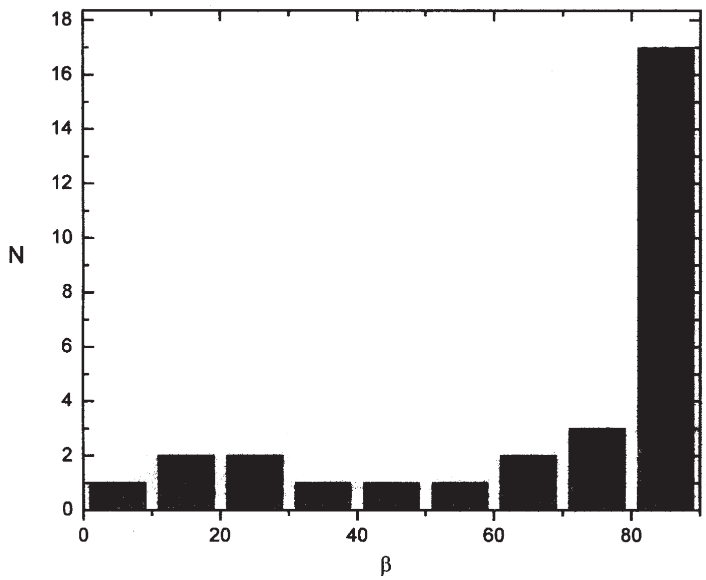

Figure 6: Statistics of magnetic stars showing the dependence of the quantity frequency classes on the angle β between the dipole and the rotational axes

most promising attempt was made in a paper by Braithwaite (2008). Therein the numerical modelling of the formation of a stable magnetic balance in a star with a confusing initial magnetic field was comprehensibly made. In stellar conditions such a field after a certain time "self–organizes" in a poloidal–toroidal structure. In some cases the initial field evolves into a more complex but not axisymmetrical structure consisting of twisted tubes, coiling under the surface of a star. The author considers that this result could help explain the occurrence of CP stars with complex fields. Obviously, the processes inside the magnetic stars are not simple, and hence more complex approaches are required. The main problem of the proposed mechanism is that it results in general in a more complex, confusing system of powerful magnetic tubes, than currently observed. Besides, the observed configurations may be oriented in any direction relative to the axis of rotation (may have any angle β), which can not be explained by the proposed mechanism. Neither can it explain the primary orientation of the axes of dipoles within $\beta = 80° - 90°$. Long–term measurements of magnetic fields of stars do not show any presence of toroidal components, which is predicted by Braithwaite (2008).

11. Anyway, the modelling of stellar magnetic structures by magnetic sources is a proper way to describe the global magnetic structures on the star's surface analytically and rendering the algorithms for computerized calculations.

3 The Quantity of Magnetic Stars with Different Structures

	The structure of magnetic field	Number of stars
1	The central dipole	17
2	The dipole shifted along the axis	26
3	The dipole shifted across the axis	9
4	Complex structure	9
5	Unknown structure	26

4 Questions and Problems

1. Why do we find asymmetrical configurations of magnetic fields in strictly symmetrical star structures?
2. Why do the configurations of a magnetic field shifted along the axis prevail?
3. Why is there a small number of stars with the dipoles shifted across an axis?
4. Why does the number of stars with the dipole axes, located in the equatorial plane prevail?
5. Why do we not find any stars with the dipoles shifted along the rotation axis?
6. The role of a convection core in formation of a magnetic field structure is unknown.

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