A&A 382, 935–938 (2002)
DOI: 10.1051/0004-6361:20011629

Astronomy & Astrophysics

Comments on the magnetic field structure of the star CU Virginis

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Received 4 October 2001 / Accepted 8 November 2001

Abstract. The model of the magnetic field structure of the CP2 star CU Vir (HD 124224) constructed by the method of "magnetic charge distribution" (MCD-method) has shown that it is consistent with the model of a displaced dipole. The displacement from the center of the star to the negative monopole is $d = 0.3$ of the radius, the inclination angle of the dipole axis to the rotational axis is $\beta = 87^{\circ}$, and the field strength at the poles amounts to $B_{\rm p}(-) = 7.9$ kG and $B_{\rm p}(+) = 1.2$ kG. The mean surface magnetic field varies within 1.2–3.2 kG. The dipole axis points away from the zero meridian by an angle of +30°. Using the MCD-method we derived the distribution of the field intensity over the surface, which has been compared to the distribution of the chemical elements He and Si, taken from literature. Silicon has turned out to concentrate around the strong negative magnetic pole, whereas helium concentrates in the region of the weak positive pole, where the orientation of magnetic lines of force is mostly vertical. The presence of a double silicon spot suggests a more complex magnetic field structure than the dipolar one, however, the small number of data makes it impossible so far to confirm such an assumption.

Key words. stars: chemically peculiar – magnetic fields – stars: individual: CU Vir

1. Introduction

This paper is one of a series given by the authors, describing the magnetic field structure in magnetic CP stars and its relation to the surface distribution of the chemical elements. The existence of such a relation was suspected and verified in the papers by Michaud (1970), Glagolevskij (1994), Hatzes (1997) and other authors. The longitudinal effective magnetic field $B_{\rm e}$ was measured photoelectrically from the hydrogen lines by Borra & Landstreet (1980). The distribution of He and Si over the surface was studied by Goncharskij et al. (1983), Hiesberger et al. (1995), Hatzes (1997), and Kuschnig et al. (1999). Despite this task had already been performed formerly, we repeated it by applying our new method of "magnetic charge distribution" (Gerth et al. 1997, 1998, 1999, 2000), which offers new possibilities of modelling the magnetic field structure.

2. The magnetic model of CU Vir

We had preliminarily modelled the field of this star (Glagolevskij et al. 1998) under the assumption of a dipolar-quadrupolar configuration. However, it turned out later that such a concept describes rather the shape of the phase relation $B_{\rm e}(P)$ than the actual field structure. Besides of this, the distribution of the surface magnetic field strength in this case proves to be distorted (Gerth & Glagolevskij 2000). More correct results are provided by a technique that we term *"magnetic charge method"* (MCD), which selects the number of *virtual charges*, their coordinates and distances from the star's center and calculates the surface field strength repeatedly, using the procedure of sequential iterative approximations, so that the computed phase curves $B_{\rm e}(P)$ and $B_{\rm s}(P)$ would fit to the observed ones ($B_{\rm e}$ – effective magnetic field, $B_{\rm s}$ – average surface magnetic field). The final version of the relation $B_{\rm e}(P)$ is chosen by the least-squares method.

The *MCD-method* offers excellent advantages for the numerical computation. The potential of a point-like magnetic charge is spherically symmetric. All potentials and gradients are added up linearly. There are no constraints on the number and spatial distribution of sources. However, according to physics, the number of opposite (positive and negative) charges has to be equal and the total of all charges compensates to zero.

Let us return to the problem of modelling the CU Vir magnetic field to get a more reliable notion concerning the field structure than we had before. Unfortunately, in the case of CU Vir, we cannot investigate the fine structure of the field because of the small number and the inadequate

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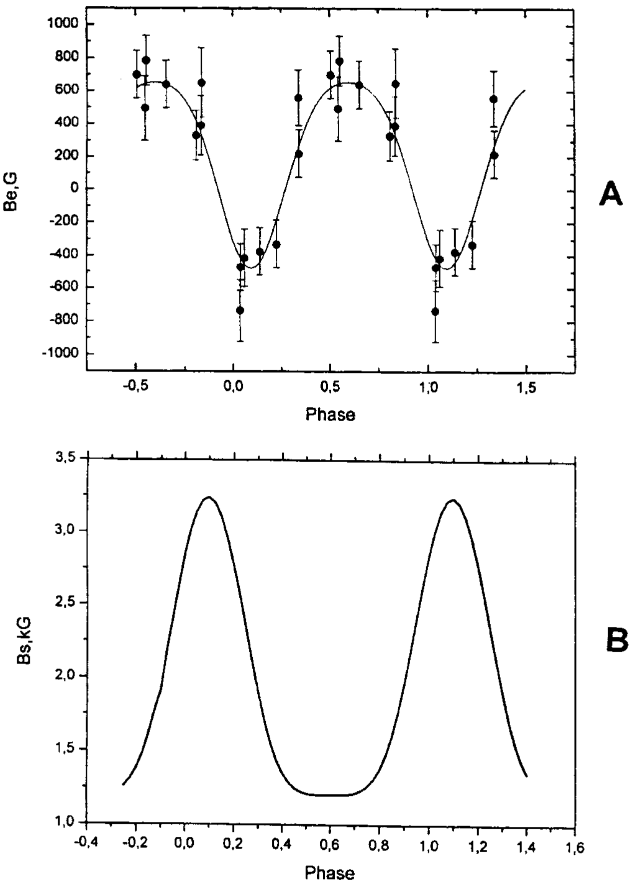

Fig. 1. The result of modelling the magnetic field of CU Vir.
A) dots – measuring data, solid line – model dependence
B) calculated average surface magnetic field variation.

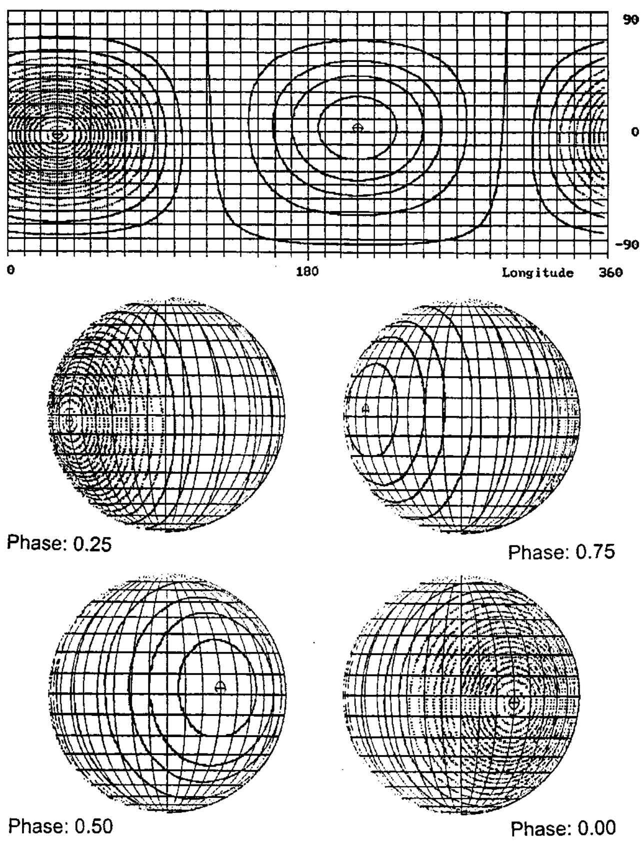

Fig. 2. Surface distribution of the magnetic field strength
Above – pseudo-Mercator map with iso-magnetic lines
Below – spherical projections (globes) of the map.

accuracy of the observational data compiled up to now. But we are able to study the global structure.

By this way we obtained a new CU Vir magnetic field model. Figure 1A presents the data of measuring $B_{\rm e}$ (Borra & Landstreet 1980) versus the phase of the rotation period ($P = 0^{\rm d}\!.52$). The relationship is different from a sinusoid; the positive half-wave is wider than the negative one. The inclination angle of the star to the line of sight is determined accurately enough, provided that the relation $B_{\rm s}(P)$ is available. But there are no data for the average surface field $B_{\rm s}$, which should look like Fig. 1B. Therefore, the star inclination angle i is found from $v \sin i = 147 \pm 2$ km s^{-1} (Hatzes 1997). We derive $i = 60°$ from the absolute bolometric magnitude $M_{\rm b}$ (see below), which is equal to the result of Hatzes (1997) based on the construction of the silicon map.

The best fit of the computed phase curve $B_{\rm e}(P)$ to the measurements we have obtained under the assumption of the following parameters:

No	Q	d	λ	δ
1	+1	0.40	30	−3
2	−1	−0.20	210	3

The table gives the number of the *virtual magnetic charge* Q (relative units), its distance d from the star center as fraction of the radius, the longitude λ and latitude δ. The shape of the relation $B_{\rm e}(P)$ is well described by a dipole model with two equal *"magnetic charges"* of different sign – the sum of the magnetic charges being zero (Gerth & Glagolevskij 2000). The parameter values of d show that we deal with a decentered dipole displaced toward the negative charge by 0.3. The displacement is defined firstly of all by the ratio of the half-widths of the positive and the negative half-wave of the relation $B_{\rm e}(P)$. The value of δ is determined by the ratio of the maxima.

It has turned out that the dipole lies almost in the equatorial plane. The inclination angle of the dipole axis with respect to the rotational axes is $\beta = 87°$. As a result of the lack of data on the average surface field $B_{\rm s}$, the derived angles i and β should be adopted as a first approximation. The modelling done with other inclination angles, differing from 60° by ±10°, has shown that the location of the magnetic poles in latitude changes by about the same value.

The model phase relation is shown in Fig. 1A with a solid line, while the distribution of the field strength over the surface is displayed in Fig. 2.

The field of negative polarity is stronger: the values at the poles are $B_{\rm p}(-) = 7.9$ kG and $B_{\rm p}(+) = 1.2$ kG.

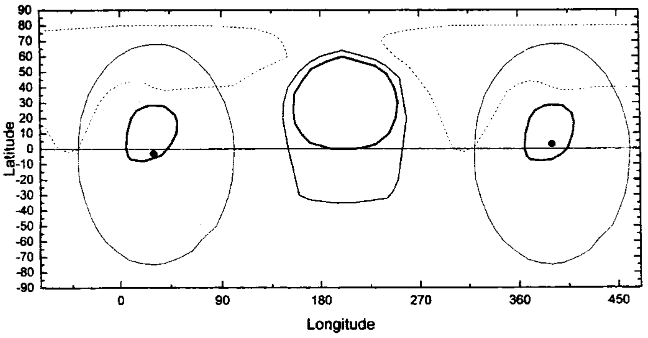

Fig. 3. The schematic view of the helium distribution over the CU Vir surface. The bold line indicates regions with helium overabundance, the dashed line does the ones with helium underabundance. The thin line shows the place where the magnetic field changes its sign.

The average surface field computed from the obtained model varies from 1.2 kG to 3.2 kG (Fig. 1B). The dipole axis points away from the zero meridian by an angle of +30°. The surface region with the negative field is compact, whereas the region with the positive one is rather broad. Obviously, the average surface field with such a low intensity is nearly impossible to estimate from the splitted Zeeman components because of the fast star rotation. If we compare our model relation $B_e(P)$ with the analogous relation in the paper of Hatzes (1997) for the central dipole model, then it can be noticed that our displaced dipole model agrees better with the observations.

Let us make some comments on the philosophy of our method to avoid misunderstandig. Since in the given case we deal with a dipolar field, the surface field distribution depends only on the value of the dipole displacement d, but does not depend of the *separation* l of the magnetic monopole *charges* Q, because the *magnetic moment* $M = Ql$ is a constant of the dipole system.

The strange "separation" of a magnetic dipole into two *magnetic monopoles* of opposite polarity could easily lead to some confusion, because the well-known physics of closed lines of force seems to be violated. However, the lines of force converge generally to separate points in the space, which we regard as the *virtual sources*. The MCD-method proves to be a powerful heuristic approach for the determination of the *virtual sources* of a magnetic field. A definite theorem of the potential theory gives evidence, that any field configuration can be produced by the superposition of the fields of numerous point-like sources.

3. The magnetic field surface structure and the distribution of chemical elements

3.1. Helium

A schematic view of the helium distribution over the star surface is shown in Fig. 3.

The data have been taken from the paper of Kuschnig et al. (1999). Helium is concentrated weaker in the region of the negative compact maximum than in the region of the wide positive maximum. The thin line marks the region where the change of the magnetic field polarity takes place. It is seen from Fig. 4 that a helium spot of small size is located near the negative field maximum. The helium distribution is consistent with the assumption that it is concentrated in the regions with vertical magnetic field lines of force. However, it is not clear why helium has a weaker concentration in the region with the higher field intensity.

The data presented by Vauclair et al. (1979) suggest that the helium anomaly formation is strongly dependent on the helium diffusion flow $\nu_f \rho$ (denotation see Vauclair). If this flow is larger than a certain critical range of the flow value $\triangle_c$, then a normal helium abundance is observed; if the flux is smaller, then the abundance is decreased. The faint helium spot at the negative pole implies that the flow value is either at the upper or at the lower boundary of the range $\triangle_c$. Taking into account that the mass loss at the negative strong pole is more likely to be greater than at the positive pole, it can be assumed that the helium diffusion flow is too strong there.

3.2. Silicon

Figure 4 presents schematically the regions of the Si concentration derived by different authors (**A** – Goncharskij et al. 1983; **B** – Kuschnig et al. 1999; **C** – Hatzes et al. 1997) and the region of maximum field strength (thin line).

At first sight, the Si distribution of different authors differs remarkably, however, one common property is noticeable: silicon is concentrated predominantly around the negative pole. In the region of the weaker positive field, the silicon abundance is lower than normal. Alecian & Vauclair (1981) and also Megessier (1984) discuss the importance of the horizontal field component for the diffusion of chemical elements in CP stars, silicon in particular. The calculation shows that in the case of the displaced dipole model, the horizontal magnetic field component has a maximum in a ring inside the marked circle. For this reason the conclusion of Hatzes (1997), that silicon in CU Vir is concentrated in the region, where the lines of force are mainly horizontal, is correct in first approximation. This inference, however, is contradicting to the absence of any silicon overabundance near the pole, where the lines of force are vertical.

It is seen in the diagrams that the existing techniques are capable of providing the distribution of chemical elements only on the visible area of the surface. From considerations of symmetry the derived map is more likely to describe the invisible hemisphere. When assuming that the chemical elements are, indeed, related to the magnetic field, one can imagine that the regions occupied by silicon (after Hatzes) should be transferred in the diagrams to the lower hemisphere symmetrically to the dipole plane (the plane, in which the CU Vir dipole is located, is practically coincident with the equatorial plane).

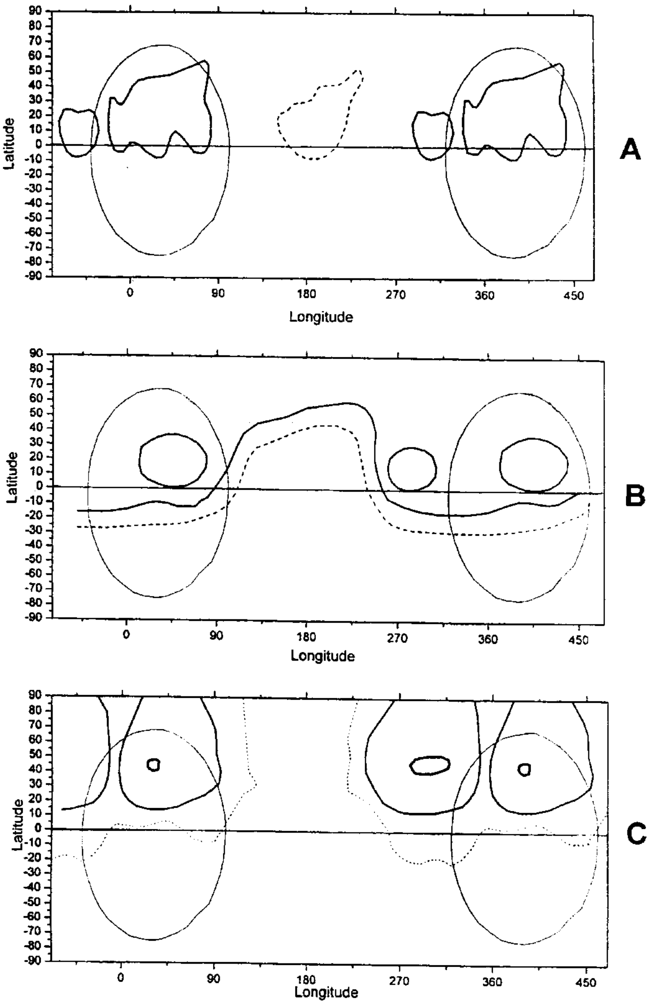

Fig. 4. The schematic view of the silicon distribution over the CU Vir surface (designation the same as in Fig. 3)
A) data from Hatzes (1997),
B) data from Kuschnig et al. (1997),
C) data from Goncharskij et al. (1983).

Thus the silicon regions will occupy all the space inside the area (bound by the thin line in Fig. 1A).

It is very interesting that – after the papers of all other authors – the silicon spot is divided into two ones. The difficulty of the assumptions made is that one of the silicon spots is outside the supposed region with horizontal orientation of the lines of force. If silicon is actually concentrated in the regions with the horizontal lines of force, then the magnetic "spot" can be assumed to have a complex structure. Modelling cannot reveal such a complex structure because of the insufficient number of measurements of B_e.

4. Conclusion

The CU Vir magnetic field modelled by the method of "magnetic charges" verifies the assumption of Hatzes of a displaced dipole mode.

The distribution of chemical elements versus the magnetic field distribution is such that it is impossible to argue unambiguously, that the diffusion theory is justifiable. This uncertainty is connected first of all with the lack of observational data.

The absolute stellar magnitude of the star CU Vir is given by $M_v = 0\overset{\mathrm{m}}{.}3$ (Gomez et al. 1988), the effective temperature is $T_e = 12\,460$ K (Glagolevskij 1994). Hence the absolute bolometric stellar magnitude is $M_b = -0\overset{\mathrm{m}}{.}39$. This implies that the star is located in the Hertzsprung-Russell diagram between the Zero Age Main Sequence and the line of the luminosity class V, that is, the star has only recently been formed as a magnetic CP star after having arrived at the ZAMS (Glagolevskij & Chountonov 1998). It might be proven that the nonsymmetric structure of the surface magnetic field and the complex distribution of chemical elements are the result of recent formation of the magnetic field and chemical anomalies. The field is likely to rise not simultaneously to the surface in individual regions. If it is generated at all, then the generation conditions on the surface are dissimilar. These phenomena are undoubtedly related to the complex distribution of physical conditions in young stars, possibly as a result of fall out of big accretion masses during the previous evolutionary phases.

Additional measurements probably could throw light on the fine structure of the magnetic field in CU Vir.

Acknowledgements. This work has been performed with the support of the Academy of Sciences of Russia by the Grant "Astronomy".

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