The integral magnetic field of modelled solar-like starspots

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Abstract. For the investigation of solar-like spots in stars we propose a method of the "Magnetic Charge Distribution" (MCD), which has been applied up to now only to stars with global extension of strong magnetic fields. A model of a solar-like spot can be constructed as an arrangement of magnetic dipoles under the surface of the star/sun. After this model the typical phase curves produced by such a magnetic spot and the line profiles according to all 4 Stokes-parameters I, Q, U, V in polarised integral light are calculated using a special computer program.

Key words: Magnetic stars – sunspots – line profiles

1. Introduction

From all stars - excluding the sun, which shows us a detailed topographic structure - we observe only the integral radiation. All information from the star's surface is averaged by integration over the visible disk and convoluted by rotation. The deconvolution, however, is an ill-posed inversion procedure, which would be evaded by reasonably simplified models and fitting to the observational facts. Modelling methods in order to reproduce magnetic sunspots have been applied in solar physics some decades ago (Ambroz, 1989). The sun itself might be observed as a star with the influence of the sunspots on the integral magnetic field.

2. Modelling of starspots

We use for the modelling of magnetic starspots a distribution of magnetic charge sources in the interior of the star (MCD-method). The location of the sources is not bound to the center of the star. Thus, a "decentered dipole" as proposed by Landstreet (1980) might be considered as real. In the case of sunspots we have even the extreme case of decentration with the magnetic sources anywhere under the surface. Each single source is surrounded by a spherical magnetic field, which offers decisive advantages for the numerical computation. Magnetic sources can combine to dipoles and multipoles (Gerth, E. & Glagolevskij, Yu.V., 1998, 2001). The MCD-method of modelling allows a restriction to a minimal number of parameters. A single source is defined by 4 parameters: 1. the magnetic charge, 2. the distance from the center r, 3. the longitude φ, 4. the latitude δ. For a magnetic dipole the positive and the negative charges are equal, so that the number of parameters is 7. A combination of n dipoles is always determined by 7n parameters.

3. The sunspot as a magnetic dipole

A dipole representing a solar-like starspot would be located shallowly under the surface with the direction of the magnetic moment crosswise to the radial vector, thus simulating the arrangement of the proceeding and following spots of opposite polarity and slight inclination to the equator.

The Mercator-map of the magnetic field distribution over the surface for such a magnetic dipole is shown in Fig. 1. The distance between the proceeding and the following spot is assumed to 20^o, and the angle of the connection line of the negative and the positive spots is 15^o, so as it might be in reality. The lines with iso-magnetic field strength mark characteristic circles on the surface, that we attribute roughly to

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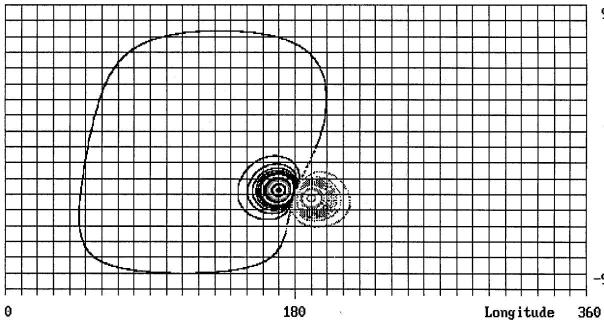

Fig. 1. Mercator-map of the magnetic surface field of a spot.
Sources: $\varphi_1 = 170^o$ $\delta_1 = -27.5^o$ $r_1 = 0.88$ Q_1= +1
$\varphi_2 = 190^o$ $\delta_2 = -32.5^o$ $r_2 = 0.92$ Q_2= −1
Region of positive magnetic field - solid iso-lines
- negative magnetic field - dashed iso-lines
The central parts are filled up by iso-lines to illustrate the structure.

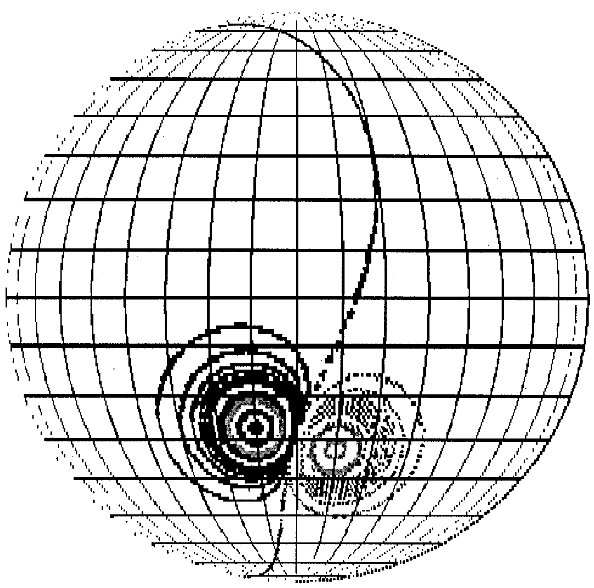

Fig. 2. Spherical projection (globe) to the Mercator-map of a magnetic spot

the magnetic structure of a spot. For the imagination of the star as a sphere the map is transformed into a globe (Fig. 2).

The map of the star with its conspicuous magnetic poles can be revealed only by the stellar rotation. Longitude and phase as corresponding magnitudes are put together in one and the same diagram, coordinating the extrema of the curves of the integral magnetic field to the magnetic poles on the surface of the star. The integration of the surface magnetic field over the visible disk of the star is carried out by a computer program developed by Gerth et al. (1998). The computer performs the integration by averaging the line profiles of the radiation from all surface elements and weighting by the projection and limb darkening conditions. Varying the angle i of the line of sight as the parameter, one gets a group of phase curves, which allows the determination of i by fitting to the observational measurements (Fig. 3).

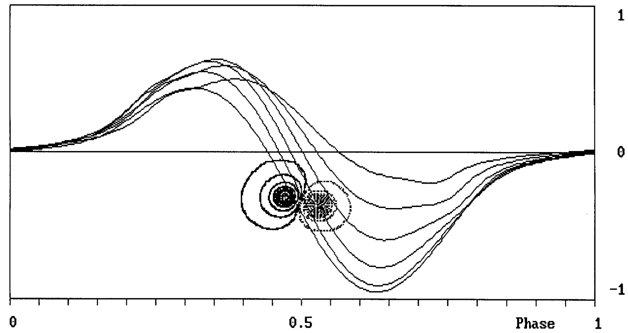

Fig. 3. Spot feature and corresponding phase curves of the integral magnetic field (longitudinal - Stokes V) for the inclination angles $i = 80^o$ to 150^o by step 10^o (from top to bottom).

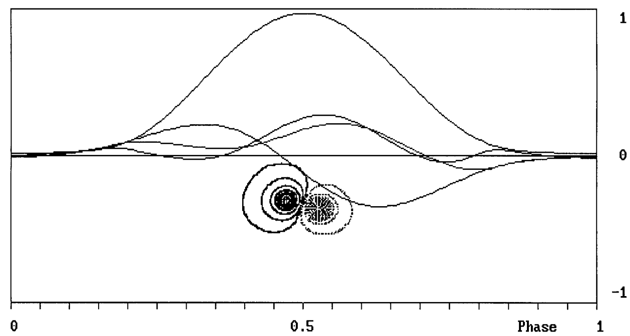

Fig. 4. Phase curves of the integral magnetic field strength measured by the Zeeman-effect in polarized light.
From top to bottom at phase 0.5:
1. - Stokes I - absolute surface field
2. - Stokes U - cross-linearly polarized
3. - Stokes Q - long-linearly polarized
4. - Stokes V - circularly polarized light
All polarization types are vignetted by limb darkening separately.

Movements like translation of the whole star, the rotation or the convection have no influence on the integral magnetic field strength, because the measurement relates to the difference of the profile centers, the $Zeeman - displacement$.

4. The polarised integral magnetic field

Since the measurement of the magnetic field is practicable only as the result of the Zeeman-splitting of the absorption lines, we have to regard the polarization conditions of the atmosphere on each surface element of the star in direction to the observer. Traditionally we measure the longitudinal field by the σ-components of the circularly polarized light with the Zeeman-displacement of the line profile to the left and to the right in the spectrum, which is not disturbed by the linearly polarized π-components. This is the Stokes-parameter V, which gives by integration over the visible disk the effective magnetic field B_e.

The 4 Stokes-parameters I, Q, U, V are functionally connected by the formula

$$I^2 = Q^2 + U^2 + V^2 ,$$

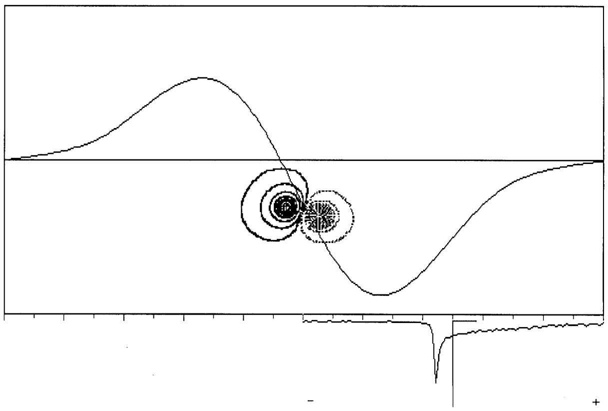

Fig. 5. Phase curve of the integral magnetic field (Stokes V) corresponding to the Mercator-map with spot feature.
The line profile at the phase 0.4 is extremely asymmetric with the peek at the negative side and the gravity center at the positive one. The peek and the gravity center oscillate in antiphase.

which is valid for a homogeneous radiation flux and, likewise, for the flux coming from an infinitesimal surface element.

In Fig. 4 the phase curves for the integral Q, U, V, and I components are shown. In order to represent all 4 curves in one diagram, the curve of the I-component is reduced by the ordinate to 1/3. The computation of the Stokes-components relates to algorithms of analytical expressions derived by Gerth & Glagolevskij (2001).

5. The line profiles of the integral magnetic field

The line profile is an important indicator for the distribution of the magnetic field over the surface or the star.
According to the program the radiation from all surface elements is spread over the classes of a frequency distribution, the curvature of which proves to be the line profile for the momentary aspect of the star in the course of the rotation.

The profile form depends also on the distribution of chemical elements over the surface, which we assume here as being homogeneous. In contrast to the integral magnetic field strength, however, the profile is strongly influenced by movements on the star, which result in line broadening: rotation, meridional and turbulent flows, convection, molecular thermal movement. We consider here only the action of the distribution of the magnetic field on the line profile.

In Fig. 5 the profile is demonstrated in connection with the phase curve and the position of the spot. The profile (Stokes V at phase P=0.4) is extremely asymmetric, the gravity center being at the positive side and the minimum at the negative one. Moreover, the profile is extended with one wing aside, hiding an essential part of the profile.
This is a very intriguing fact in the measuring procedure to determine the Zeeman-shift of the line profile, because the measuring person tends to take the minimum as the spectral location of the profile (Gerth et al., 1977).

The variation of the profile in the course of the phase can be reviewed in a series of profiles put together in one diagram

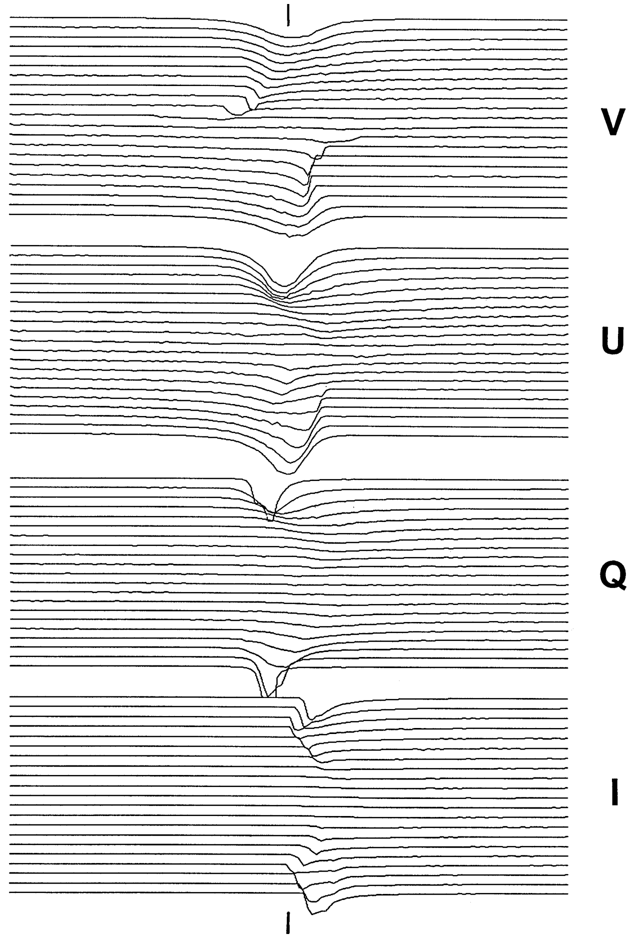

Fig. 6. Course of the line profile over the period by 20 steps.
On the opposite side of the spot a symmetric profile is developed, which becomes asymmetric approaching to the spot in the different modes of polarized light with characteristic behavior.
V - circularly polarized light (phase jump at 0.5)
U - long-linearly polarized light (line broadening at 0.5)
Q - cross-linearly (broadening and rightshift at 0.5, leftshift at 0)
I - natural unpolarized light (rightshift, line broadening at 0.5)

as shown in Fig. 6. We see that the gravity center and the minimum oscillate in antiphase (for Stokes V) with a phase jump at the transition of the (double-)spot. The change of the profile form and the antiphase-oscillation can be demonstrated movingly on the computer screen by the program. The line profiles of the other Stokes-parameters show another but also characteristic phase course.

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