SEMI-EMPIRICAL MODELING OF SUNSPOTS MAGNETIC FIELDS ON THE BASIS OF RADIO ASTRONOMICAL AND MAGNETOGRAPHIC OBSERVATIONS

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ABSTRACT

A semi-empirical method to model spatial configurations of sunspot magnetic fields is presented and discussed. To calculate the strength and diversity of the magnetic fields in the chromosphere-corona transition region (CCTR), radio astronomy and magnetographic observations are used.
Multifrequency radio observations with RATAN-600 allow to measure magnetic fields above sunspots using a method described in [1]. Our model calculations confirm that the measured value is the maximum magnetic field of the sunspot at the height of the CCTR.
Two-dimensional maps of the longitudinal component of sunspot magnetic fields at the photospheric level produced with Ondřejov magnetograph (Czech Republic) along with the magnetic field strength measured in the corona with RATAN-600 are used for calculations of the strength and diversity of the magnetic field and for the estimate of the height of the CCTR above sunspots.

1. MODEL TREATMENT OF THE MAGNETIC FIELD MEASUREMENTS IN THE SOLAR CORONA ABOVE SUNSPOTS

Gyroresonance emission of thermal electrons in the corona is generally accepted to be responsible for the sunspot-associated radio emission. Its brightness temperature is determined by the kinetic temperature of the gyroresonance layers. The layer which effectively emits the extraordinary mode (s = 3) is generally higher than that of s = 2 responsible for the emission of the ordinary mode. A method was developed to measure the magnetic fields at the CCTR level using spectral and polarization observations of RATAN-600 [1]. Such measurements of the magnetic field at the third harmonic of the gyrofrequency for each radio source are treated regularly with RATAN-600 [2].
This method was analyzed and modeled to gain high quality and accuracy and refine its physical meaning. Emission spectra of sunspot-associated radio sources are modeled in terms of the thermal gyroresonance emission at the first four harmonics of the gyrofrequency.

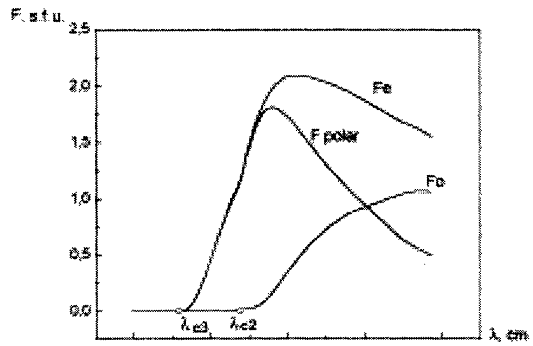

Fig. 1. Model sunspot emission of the e-mode, o-mode and the ($F_e - F_o$) polarized flux

Simple models for the CCTR, two-step model and the model with thin transition region, as well as a dipole approximation of the magnetic field were used. The model calculations were carried out for various locations of a sunspot on the solar disk and for various magnetic field strengths. Modeled sunspot emission of the e-mode F_e and o-mode F_o as well as the outcome of the ($F_e - F_o$) polarized flux spectra are presented in Fig.1. The positions of the critical wavelength λ_{c3} and λ_{c2} are shown. If we make the same plot for the observed flux, then the extrapolation of the emission flux density F_e (or F_o) to zero gives us a critical wavelength λ_{c3} (or λ_{c2}), and we can find the magnetic field strength from observations as it was made in [1], according to Eq. 1 or Eq. 2:

$$H[Gs] \approx \frac{3570}{\lambda_{c3}[cm]} \qquad (1)$$

$$H[Gs] \approx \frac{5355}{\lambda_{c2}[cm]} \qquad (2)$$

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The model calculations confirm that the measured value is the maximum magnetic field of the sunspot at the height of the CCTR. According to the modeling, the magnetic field strength measured in observations with RATAN-600 at the 3-th harmonic is about 7% less then the real value with an accuracy of about 3%, and for the measurements of the magnetic field with the ordinary wave at the 2-nd harmonic, the accuracy is better than 3%.

However, this method does not allow estimating the height of the CCTR. We can suppose this height to be not constant and to vary in different active regions. It is difficult to estimate the height of the CCTR with observational methods because it is very small (~ 2000 km). Hence the development of a model method is required. Such a semi-empirical method inferred from radio and optic observations is presented in the next section.

2. THE METHOD OF THE EVALUATION OF THE HEIGHT OF THE CCTR ABOVE SUNSPOTS

The model method we propose to estimate the height of the CCTR above sunspots is based on the magnetographic and microwave observations. It is possible to measure the distribution of the sunspot magnetic field along photosphere with the magnetographic observations (spatial resolution of about 3–5"). In several early papers, e.g. [3], the magnetic field distribution observed for some sunspots was shown to be in accordance with the dipole approximation. At the same time, the dipole approximation (Eq. 3-6) is widely used for modeling of the sunspot-associated radio emission.

$$H_x = H_{phot} \frac{1}{2} z_{dip}^3 \frac{3zx}{(\sqrt{x^2+y^2+z^2})^5} \qquad (3)$$

$$H_y = H_{phot} \frac{1}{2} z_{dip}^3 \frac{3zy}{(\sqrt{x^2+y^2+z^2})^5} \qquad (4)$$

$$H_z = H_{phot} \frac{1}{2} z_{dip}^3 \frac{2z^2 - x^2 - y^2}{(\sqrt{x^2+y^2+z^2})^5} \qquad (5)$$

$$H(x,y,z) = \sqrt{H_x^2 + H_y^2 + H_z^2} \qquad (6)$$

Here H_x, H_y, H_z are components of the dipole magnetic field vector $\boldsymbol{H}$ in a point (x,y,z), H_{phot} is the magnetic field strength in the center of a sunspot at the photospheric level, z_{dip} - is the depth of the magnetic dipole under the photospheric level. The *z*-axis passing through the center of the sunspot is perpendicular to the solar surface and points above it. The origin of the coordinate system is in the center of the magnetic dipole.

The dipole representation of the magnetic field allows us to summarize within the framework of the same model the measured photospheric and coronal magnetic field strengths, and to derive the height of the CCTR above a sunspot. The dipole model is described by two parameters, which can be found from magnetographic measurements, the magnetic field strength at the photosphere level H_{phot}, and the depth z_{dip}. The parameter H_{phot} is defined as the maximum value of the sunspot magnetic field in magnetographic measurements taking into account the projection effect. The dipole depth z_{dip} is calculated under the assumption that H_z is equal to zero at some distance R from the sunspot center. The distance R can be found from the figure of the sunspot obtained in the spectral continuum as the radius of the sunspot penumbra R_{spot}, or, following [4], as $1.3R_{spot}$. Then, the dipole depth z_{dip} and the height of the CCTR z_{cor} are obtained from Eq. 7 and Eq. 8:

$$z_{dip} = \frac{R}{\sqrt{2}} \qquad (7)$$

$$z_{cor} = z_{dip} \sqrt[3]{\frac{H_{phot}}{H_{cor}}} - 1 \qquad (8)$$

where H_{cor} is the coronal magnetic field strength at the CCTR height z_{cor} above the sunspot. The value H_{cor} can be measured in microwave observations as described in section 1.

From these considerations, a method is proposed of estimation of the CCTR height based on the microwave observations with RATAN-600 (Russia) and Ondřejov magnetograph (Czech republic). According to this method, it is necessary to have a figure of the sunspot obtained in spectral continuum and the value H_{cor}. To improve the calculation accuracy, single symmetric sunspots are assumed.

NOAA	Day of observ.	D, arc.sec.	θ	H_{cor} Gs	H_{phot} Gs	z_{cor} km
AR7552	30.07.93	38	16.1	1640	3000	2500
AR8574	07.06.99	46	32.1	1320	1510	600
AR8668	19.08.99	51	12.7	1410	3000	4300
AR8692	13.09.99	51	31.1	1740	2900	2800
AR8699	13.09.99	49	14.1	2030	2300	600
AR8694	09.09.99	28	30.3	900	1500	1500

Table 1. Number of active region, date of the observations, sunspot diameter D, angular distances Θ of the sunspot from the solar disk center, measured magnetic fields H_{cor} and H_{phot}, and calculated height z_{cor}.

The method was tested for six single symmetric sunspots. Magnetographic measurements were carried out in the spectral line Mg I 5172.7 Å. Data of the measurements are summarized in Table 1. As can be seen from Table 1, the calculated CCTR heights vary within a range of 600 to 4300 km above photosphere. The average value is equal to 2000 km that is in a general agreement with expectations.

To verify how the dipole approximation fits a real sunspot magnetic field distribution, we performed the following procedure. The magnetic field strengths measured with magnetograph for a varying distance from the sunspot center were compared with the calculated dipole values. Distributions of the longitudinal component of the magnetic field along the sunspot diameters are presented in Fig. 2. X-line is directed to the solar disk center. The measured photospheric fields strengths are marked by squares, and the calculated dipole values are plotted by lines, with the outer lines to correspond to R = R_{spot}, and the inner lines corresponding to R=1.3R_{spot}.

One could note a common agreement between the calculated and measured values, while the deviations along the sunspot central distance do not exceed 5–7".

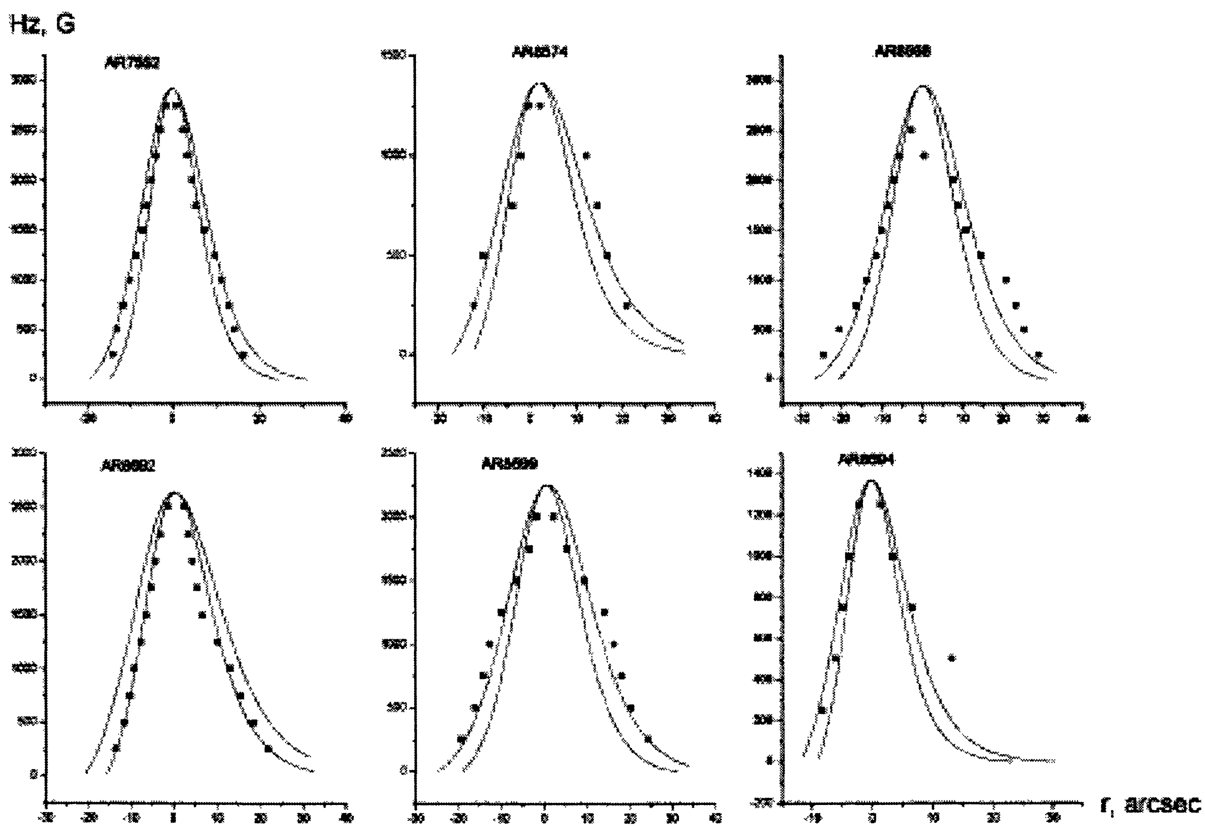

Fig. 2. Distributions of the longitudinal component of the magnetic field along sunspots diameters. X-line is directed to the solar disk center. The measured photospheric fields strengths are marked by squares, the calculated dipole values are shown by lines: the outer lines correspond to R = R_{spot}, and the inner lines correspond to R = 1.3R_{spot}.

The sunspot AR7552, which is the closest approach to the ideal symmetric sunspot, has perfect agreement with the dipole approximation at photospheric level (Fig. 2 and Fig. 3). Thus one can see that the dipole approximation is a possible application for magnetic field modeling of symmetric sunspots.

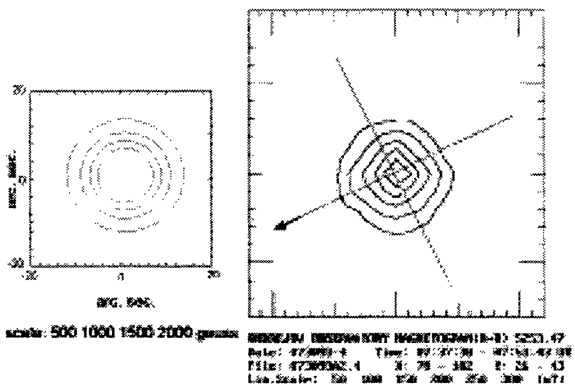

Fig. 3. Contours of the magnetic field distributions for the sunspot at the photospheric level: Ondřejov magnetographic measurements for the AR7552 (right, the arrow points to the solar disk center) and the model dipole approximation (left).

This method can be applied for two (or more) spectral lines. The dipole depth for each line can be calculated from Eq. 7. One should take herewith into account that different spectral lines originate at different heights. Calculating the dipole depth for every line separately, one can compare the calculated values and check the reliability of the estimate. Such investigations were described in more detail in [5] where the dipole approximation is applied to the longitudinal component of the magnetic field measured in the spectral lines Fe I 5253.47 Å and Mg I 5172.7 Å formed at different heights in the solar atmosphere.

4. CONCLUSIONS

The method of the magnetic field measurements at the CCTR level using multifrequency observations with RATAN-600 was analyzed and modeled to gain high quality and accuracy. The model calculations were performed for to refine the physical meaning of the calculations of the magnetic field in corona above sunspots with microwave observations.

The model calculations confirm that the value measured with this method is the maximum magnetic field strength of sunspots at the height of the chromosphere-corona transition region.

To find the height of the chromosphere-corona transition region above a single symmetric sunspot, a method is offered based on optic and radio astronomy measurements. The method connects the magnetic field values measured in the optic and radio domains via the dipole approximation. Then the height of interest can be derived from the obtained relation.

The method was tested for several single symmetric spots. Using these magnetographic observations of sunspot, we confirmed that it is possible to use the dipole approximation for representation of the magnetic fields for symmetric spots.

The calculated CCTR heights above sunspots vary within the range of 600 to 4300 km above the photosphere, which is in a general agreement with expectations.

Acknowledgements

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