RADIO MAGNETOGRAPHY OF SOLAR ACTIVE REGIONS USING RADIO OBSERVATIONS

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ABSTRACT

Measurements of polarization of the thermal bremsstrahlung at microwaves presents essential information on the longitude component of the magnetic field in the solar plasma. The Nobeyama radio heliograph opens a new page in applying the observations of polarized component to make radio magnetograms of the whole solar disk, based on analysis of the thermal bremsstrahlung: (i) the instrument has 10 arcsec 2D resolution, (ii) regular eight hours per day observations during the last seven years, and (iii) using ten minute averaging of the radio maps in V Stokes parameter gains sensitivity of few Gauss. The results mostly refer to chromospheric magnetic fields in the solar active regions and are in good agreement with optical data. However, three ways to measure also coronal component of the magnetic fields are possible: (i) observations of coronal structures behind the limb; (ii) usage additional spectral observations made with the radio telescope RATAN-600 with proper solution of the equations of radiation transfer; (iii) an analysis of the transformation of circularly polarized signal in quasi-transverse region of propagation (inversion or smoothing of circularly polarized component). In the present paper we consider, analyze and illustrate the above problems on some observational results of the solar active regions with special attention to the thermal bremsstrahlung emission.

Key words: Sun: magnetic fields; Sun: plasma structures; thermal bremsstrahlung.

1. INTRODUCTION

The maps of the solar magnetic fields found from the radio observations became of special interest today due to the development of the observational facilities and unique abilities of the radio diagnostics of the coronal and chromospheric magnetic fields. Of special value in solar radio magnetography are the progress in spectral analysis of the microwave radio emission of the solar active regions and coronal holes (see paper by Bogod et al. in this issue) and regular 2D-mapping the sun with the Nobeyama radio heliograph at the wavelength of λ=1.76 cm with the 2D resolution of about 10 arcsec (Nakajima et al. 1994). A general description of the radio diagnostics of the solar magnetic fields is given in the papers (Gelfreikh 1994; Gelfreikh 1996; Gelfreikh 1998; Gelfreikh 1999). The recent development of the methods is also represented in (Grebinskij et al 1998, Grebinskij et al 1998).

In this paper we mostly analyze the method based on observations of the thermal bremsstrahlung - the dominated mechanism of generation of the radio emission at the wavelength λ=1.76 cm — the basic radio domain of the Nobeyama radio heliograph. We should stress here the main advantage of the instrument for the solar study — the bank of observational data covering the seven year period of daily observational (eight hours per day) since 1992.

The main topic of discussion in this paper is based on comparison of the radio magnetograms with the optical ones. The goals of this study were (1) to find out a possible usage of the polarization maps from Nobeyama to analyze magnetic fields of the solar active regions and (2) to investigate connections of the intensity structures with some peculiarities of the solar photospheric magnetic fields.

2. THEORY

2.1. The Basic Equations

The absorption coefficient κ can be found from the equation:

$$\kappa^{r,l} = \frac{\zeta \cdot N_e^2}{T^{3/2} \cdot (f \mp f_B \cdot \cos(\alpha))^2} \qquad (1)$$

Here N_e is electron density, T — temperature, f — frequency of the radio wave, f_B — electron gyrofrequency, angle α — direction of the magnetic field. The sign of the polarization depends on the direction of the magnetic field and the wave mode: in case of an extraordinary — x-mode it is right-handed (r), when the magnetic field is directed to the observer

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(N — polarity) and it is left-handed for the other direction of longitudinal component of the magnetic field. For the ordinary — o-mode we have opposite sign of circularly polarized component. In the formula above '+' refer to the ordinary mode in case of positive (directed to the observer magnetic field.) Naturally absorption is higher for an x-mode.

Optical depth is determined by the expression:

$$\tau^{r,l} = \int \kappa^{r,l} dl \tag{2}$$

The degree of circular polarization is defined as

$$P \equiv \frac{T_b^r - T_b^l}{T_b^r + T_b^l} \tag{3}$$

The brightness temperature T_b^I in the intensity (I-channel) is defined as

$$T_b^I \equiv \frac{T_b^r + T_b^l}{2} \tag{4}$$

and in the circular polarization (V-channel) as

$$T_b^V \equiv \frac{T_b^r - T_b^l}{2} \tag{5}$$

So, the excess of brightness temperature when compared two polarized waves is $\Delta T_b = T_b^r - T_b^l = 2 \cdot T_b^V$.

The solution of the equations of transfer of radiation for the weak magnetic field when $f_B \ll f$ (see Gelfreikh. 1972, Bogod and Gelfreikh. 1980)may be written for the percentage of polarization:

$$P = n \cdot \frac{f_B}{f} \cdot \cos(\alpha) = n \cdot Y_l \tag{6}$$

or for longitude component of the magnetic field:

$$B_l = \frac{107}{\lambda \cdot n} \cdot P\% \tag{7}$$

In this formula B_l G, the sign of circular polarization should be included in percentage of polarization $P\%$, the wavelength λ — in cm; $Y_l \equiv \frac{f_B}{f} \cdot \cos\alpha$.

2.2. Application to Nobeyama Heliograph Observations

The observations show that increase in brightness in solar active regions at λ=1.76 cm is usually rather small. So. it looks reasonable to assume n=0.61 (in agreement with observation of the quiet sun data). Then we get simple formula to estimate the magnetic field strength from the Nobeyama radio maps for the percentage of polarization:

$$B_l = 100 \cdot P\% \tag{8}$$

The usage of the spectral index n is often connected with the observed type of the spectra, like $T_b \propto \lambda^n$. So, for optically thin region we have $T_b^I \approx T \cdot \tau \propto \lambda^2$, (n=2) and the Formula (7) becomes

$$B_l = \frac{54}{\lambda} \cdot P\% \tag{9}$$

$$B_l = 30 \cdot P\% \tag{10}$$

The second formula is written for λ=1.76 cm and may be used for Nobeyama radioheliograph observations. In this case we do not need any additional spectral information to measure magnetic fields in coronal loops, for example. Although spectral data are very useful to be sure that we really deal with optically thin bremsstrahlung emission.

We can use the Formula (10) for an analysis of magnetic fields in a coronal structure (e.g. loop) observed behind the limb. In this case

$$T_b = T \cdot \tau \tag{11}$$

where $\tau < 1$.

The main base for the analysis of the solar magnetic fields from polarized component of the bremsstrahlung (free-free) radio emission was the solution of the equations of transfer in the form

$$P = n \cdot Y_l \tag{12}$$

which is valuable for weak magnetic fields: $Y = \frac{f_B}{f} \ll 1$. Here we define the longitude component of magnetic field $Y_l = Y \cdot \cos\alpha$, here α is the angle of direction of magnetic filed in respect to direction of the wave propagation, f_B — electron gyrofrequency, f — frequency of the wave.

As an increase of brightness temperature in plage/faculae-associated component of an active region (Section 4) is usually rather small ($\Delta T_b \leq 50\%$). So usage of the value($T_b^I \approx 10^4$K and $n \approx 0.6$), typical to the quiet sun radio emission may give a reasonable approximation. This leads us to another simple formula for the chromospheric magnetic fields in an active regions:

$$B_l \approx T_b^V \tag{13}$$

In fact, we always deal with the sum of chromospheric, CCTR and coronal radio emission. Their input in the value of T_b^V may be comparable (for some model estimation see Grebinskij 1998). There are, however, two important differences in the structure of the solar atmosphere for chromospheric and coronal layers:

1. The emitting layer for cm wavelength range in the chromosphere geometrically is very thin (few hundreds km). So, the approximation of the homogeneous magnetic field (Formula (7)) is reasonably good, at least at the scale of beam averaging ($\approx 10^4$km) at the radio observations. At the same time it is optically thick ($\tau \gg 1$), both for o- and x- modes. It follows that polarization here is totally defined by the presence of gradient of temperature (for ordinary mode we look deeper, usually in colder plasma).

2. The length scale of an emitting region in the corona may be significant, generally comparable with height scale for hot corona plasma ($\geq 10^4$ km). In this case, however, we have optically thin layer ($\tau \ll 1$) at short cm wavelengths. So, the ordinary and extraordinary waves come exactly from the same volumes, but of different intensity (the x-mode brighter). It follows that even for not homogeneous magnetic fields we can propose a simple interpretation: we get an average value of longitude component of the coronal magnetic field with weight function just equal to N_e^2. In this case spectral index in intensity channel (T_b^I) is n=2 and in polarization channel (T_b^V) n=3 (see Formula (10)).

The lower part of the CCTR may be considered as belonging to the chromosphere (it is physically thin) and the upper part does not affect the polarized flux essentially. So, for two-component model (chromosphere + corona) we get the equation of transfer in the form

$$T_b = T_b(chr) \cdot (1-\tau) + T_e(cor) \cdot \tau(cor) \quad (14)$$

$$T_b^1 = \lambda^n + T_{cor} * \tau_{cor}^1 * \lambda^2 \quad (15)$$

So we can get the following equations representing the radio brightness T_b^I and polarized emission T_b^V with reasonably good approximation:

$$T_b^I = T_b^1 \cdot \lambda^n + T_{cor} \cdot \tau_{cor}^1 \cdot \lambda^2 \quad (16)$$

$$T_b^V = n \cdot Y_l^{chrom} \cdot T_b^I(chr) + 2Y_l^{cor} \cdot \tau(cor) \quad (17)$$

$$= C_1(B_l^{chr})\lambda^{n+1} + C_2(B_l^{cor}) \cdot \lambda^3 \quad (18)$$

It follows that spectral observations at several frequencies are capable of measuring both chromospheric and coronal magnetic fields from one set of data.

3. OBSERVATIONS

To make the analysis of similarity and differences in magnetograms of the solar active regions made on the basis of the optical and radio observations several sources of information have been used.

3.1. Radio Observations

As a basis for radio magnetography we have used radio maps of the sun obtained with the Nobeyama radio heliograph (Nakajima et al. 1994). Three types of the radio maps were used:

1. The radio maps in total intensity (I-maps).
2. The radio maps in circularly polarized component (V-maps).
3. The radio maps of the percentage of circularly polarized emission $P = \frac{V}{I}$ (P-maps).

The angular resolution of the maps was in the limit of 10 to 15 arcsec in both directions. The noise level (one sigma) was about 70 K for typical time averaging of 10 sec. In some cases we have used averaging over ten minute interval to increase the sensitivity to the level of about 10 K (implying the sensitivity of about 10 G on magnetograms according to the Formula (13).

The most reliable and accurate measurements of magnetic field above sunspots in the lower corona are based on an analysis of spectral-polarization observation of sunspot-associated sources (see Akhmedov et al. 1982). Nowadays such measurements are made regularly using Panoramic Analyzer of the spectra on the radio telescope RATAN-600 and are available through Internet.

3.2. Optical Observations

The optical magnetograms for longitudinal and transverse magnetic fields in the photosphere (Fe I line 5324.2 Å) were obtained with the Solar Magnetic Field Telescope (SMFT) at the Huairou Solar Observing Station (HSOS) (Ai and Hu 1986). This vector magnetograph has a tunable birefringent filter, which can tune its passband working either at the photospheric line FeI λ5324.19 Å, or at the chromospheric line H_β. For the photospheric observations, the passband is tuned to -0.075 Å off-band to measure longitudinal components of solar magnetic fields, while at the line center to measure transverse components of the fields for achieving the maximum sensitivity. In the measurement of magnetic fields in solar active regions, the integration of 255 frames and a 4 × 3 pixels smooth average are usually made so as to increase the signal-to-noise ratio. The magnetograms processed by smooth average have the spatial resolution about 2″. The calibration for magnetic fields has been developed by Ai (1982).

While analyzing the radio data on magnetic fields in sunspots we have used observations made at Crimean Astrophysical Observatory and presented at the web page through Internet.

4. COMPARISON OF OPTICAL AND RADIO DATA

4.1. Faculae Magnetic Fields

The radio maps in the channel of the circular polarization can be considered as radio magnetograms of the solar active regions for the longitude component of the chromospheric magnetic field (for the regions in the central part of the disk). To study relation between optical and radio magnetography we have used the optical observations of the Huairou station which were preliminary averaged with the beam size of the Nobeyama radio heliograph. An example of such comparison is shown in Figure (1).

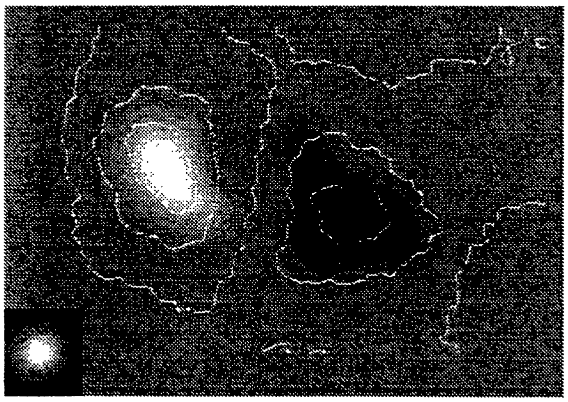

Figure 1. Comparison of optical magnetogram of the solar active region averaged over the beam size of the Nobeyama radio heliograph with the map of percentage of polarization at λ=1.76 cm shown by contour lines. The observations were made on June 09, 1996.
The size of the beam of the radio heliograph is shown in the lower left corner.

4.2. Sunspot-associated Sources

In case of the strong magnetic fields above sunspots emission/absorption of the radio emission may be also affected by gyroresonance (cyclotron) mechanism. In typical condition of the solar atmosphere this may become essential at the level of the third harmonic of the electron gyrofrequency. The latter happens in the region of the magnetic field strength

$$B = \frac{3570}{\lambda} \quad (19)$$

where λ=1.76cm is the wavelength of observations. For λ=1.76 cm the resonance at the third harmonic takes place at the field B = 2000G. If the magnetic field above a sunspot in the corona or transition level amounts 2000 G we see high brightness strongly polarized source both at the I-map and V-map. For weaker magnetic fields no significant increase in brightness on I-map of Nobeyama is registered. However, strong polarization still may present due to combined effect of the both mechanisms (thermal cyclotron and bremsstrahlung). This is illustrated by the Figure (2) where strongly polarized source on the P-map is significantly shifted from the bright region on the I-map.

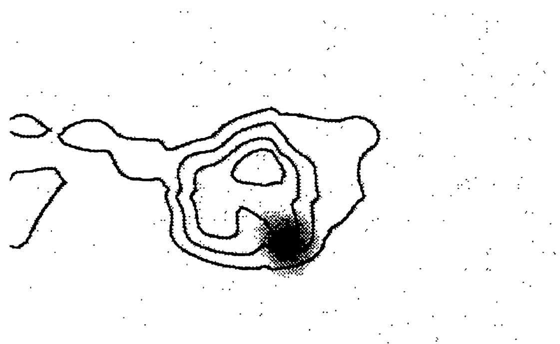

Figure 2. Comparison of I-map (Contours) of the solar active region with the map of percentage of polarization at λ=1.76 cm (dark spot). The maximum value of P=51/is T_b=28 000K. The observations were made on June 28, 1993.

4.3. Magnetic Fields and Structures on I-maps

As we have seen above the V-maps and especially P-maps gain a good presentation of the general (usually bipolar) structure of the magnetic fields of the solar active regions. For faculae component a reasonable estimation of the longitude component of the magnetic fields can also be obtained. The position of the islands of the strong magnetic fields above sunspots is also available though additional spectral information for an estimation of the field strength is usually necessary.

Here we also illustrate a possibility to get some information on the magnetic field structure from observations of distribution of intensity at λ=1.76 cm (Nobeyama I-maps). The Figure (3) shows the typical situation while comparing an I-map with a V-map for the same AR: the maximum intensity is located above the photospheric neutral line of the longitude magnetic field. The comparison with the optical magnetogram also shows that the highest brightness happens near the area of the local complicated structures of the magnetic fields implying position of the highest gradient of the magnetic fields, — not accessible for resolving by radio observations at Nobeyama.

5. DISCUSSION

In this paper we put main attention to development of the methods of radio magnetography based on an analysis of thermal bremsstrahlung. We have found high effectiveness of the method when 2D radio maps of Nobeyama radio heliograms are used, especially in combination with spectral observations with the radio telescope RATAN-600. Most of information, however, refer to the chromosphere and lower corona. To proceed in measurements of magnetic fields in higher levels of the solar corona one ma use the methods based on the inversion of the sign of the circular polarizations due to mode coupling in the region

Figure 3. Comparison of I-map (Contours) of the solar active region with the map of percentage of polarization at λ=1.76 cm. NL of the longitude magnetic field ($P = 0$) is shown by thick line. (The observations were made on July 24, 1999.

of quasi transverse propagation. For more details of this method of the radio magnetography we refer the reader to paper (??). Some more information on the development of the method can be found also in (Bogod et al. 1993; Gelfreikh et al. 1997).

6. CONCLUSION

The main results of this study can be summarized as follows:

1. The radio maps for percentage of polarization ("P-maps") present a reasonably good magnetograms for longitude component of the magnetic field — in general agreement with optical magnetograms (outside the sunspots).

2. The position and structure of large sunspots are clearly seen on P-maps; the strength of the magnetic fields, however, is not generally accessible from Nobeyama radio heliograms without additional spectral observations. The RATAN-600 measurements of the sunspot magnetic fields is a valuable source for this information.

3. The radio maps for total intensity ("I-maps") usually demonstrate an excess of brightness above neutral line of the photospheric magnetic field with well defined increase of brightness above the regions of fine magnetic structures with local increase of gradients of the photospheric fields.

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