Microwave Measurements of the Solar Magnetic Fields at Chromosphere-Corona

Alexander GREBINSKIJ,[1] Kiyoto SHIBASAKI,[2] and Hongqi ZHANG,[3]

[1] *Special Astrophysical Observatory, SPb Branch, St.Petersburg 196140, Russia*
E-mail(KI): agreb@vag.stud.pu.ru
[2] *Nobeyama Radio Observatory, Minamimaki, Minamisaki, Nagano 384-1305, Japan*
[3] *Beijing Astronomical Observatory, Chinese Academy of Sciences, Beijing 100080, China*

Abstract

We present new techniques for measurements of magnetic fields in solar chromosphere - corona by observations its free-free microwave emission in intensity and polarization. We discuss the results of such measurements with Nobeyama imaging at ν=17 GHz and Beijing vector magnetograph for typical photospheric active region structures (isolated spots, plages, bipolar active regions). We discovered strong differences of photospheric and chromospheric field patterns and discuss possible explanations. These results may be useful for problems of 3D reconstruction of magnetic fields through its photospheric boundary values extrapolations.

Key words: Radiative transfer – Sun: magnetic fields – Sun: radio radiation

1. Introduction

The structure of coronal magnetic fields plays a crucial role in problems of heating and flare energy release, but our knowledge of it is rather limited relative to photospheric fields. Two main sources of information viz., (a) extrapolating techniques for coronal fields by its boundary photospheric values, and (b) microwave emission due to gyroresonance emission at 2-nd or 3-rd harmonics of electronic gyrofrequency $\nu_B = 2.8 \cdot 10^6 B$ often display some inconsistency of results (see White and Kundu, 1997 for review). Here we discuss a third independent source of information, based on an analysis of free-free emission mechanism of solar plasma. This radiation becomes circularly polarized in the presence of magnetic field, and observations of such polarization effects opens a way to measurements of magnetic field B at chromospheric and coronal layers. Up to now, possibilities of such approach were not carefully studied nor practically implemented, because of two limitations: (a) for strong sunspot fields radiation in cm waveband is dominated by gyroresonance emission, masking free-free contribution and (b) for weak fields (plage area(s) around spots) the expected polarization rates $\rho = V/I$ are extremely low (about several percents) for its valid measurements.

This situation had changed after the construction of Nobeyama Radioheliograph. Its high working frequency of 17 GHz validate free-free techniques for study of rather strong fields $B \leq 2000\ G$ (below a third gyrofrequency harmonic), and high sensitivity of polarized imaging (with $\rho_{rms} \preceq 1\%$) has opened ways for measuring weak fields also. To separate contributions from coronal and chromospheric levels for observed polarized emission, we use here new theoretical results for radiation transfer of free-free emission in inhomogeneous medium (see Grebinskij et al., 1999).

Here we discuss the existing state of theory and give some preliminary interpretation of results of observations with Nobeyama Radioheliograph at 17 GHz and photosphere-chromosphere vector magnetograph of Beijing Observatory for several classes of active regions (ARs).

2. Radiation transfer in inhomogeneous atmospheres

Free-free emission of plasma in magnetic fields becomes circularly polarized with different opacities $d\tau^{e,o} = d\tau_o(1 \pm 2\nu_B \cos\alpha/\nu)$ for ordinary/extraordinary normal modes. Previouse attempts of measuring magnetic fields (see Bogod and Gelfreikh, 1980) were based on the use of the scaling law $T_b^{\pm}(\nu) = T_b(\nu \mp \nu_B)$, relating free-free emission brightness $T_b^{\pm}(\nu)$ for normal modes in a magnetic field with its unpolarized brightness (Stoke's parameter I of full intensity) $T_b(\nu) \equiv \frac{1}{2}(T_b^+(\nu)+T_b^-(\nu)) \equiv I$. For relatively weak fields ($\nu_B << \nu$), after introduction Stoke's parameter $V = \frac{1}{2}(T_b^+ - T_b^-)$ one can get an estimate of the magnetic field through observed values of V and I as

$$[B]_G = 10700 \frac{1}{n\lambda_{cm}} \frac{V_{obs}}{I_{obs}}, n \equiv \frac{d\log I}{d\log\lambda} \tag{1}$$

where n is the spectral index of the observed brightness spectrum $I(\lambda)$. Such estimates do not give answer to several questions: (a) what are its limitations, (b) to what level of atmosphere a measured field is relevant for different frequencies of observations, and (c) how to use such estimates with single-frequency observational facilities. These problems were addressed recently by Grebinskij et al.(1999), on the basis of solution of the radiation transfer equations

$$I(\lambda) = \lambda^2 \int_0^\infty T(t) e^{-\lambda^2 t} dt, \quad V(\lambda) = \lambda^2 \int_0^\infty \beta(t) \int_0^\infty T'_t(t+t') e^{-\lambda^2 t'} dt' e^{-\lambda^2 t} dt, \tag{2}$$

for a plane layer atmosphere with inhomogeneous height stratification of magnetic field, electronic temperature and concentration. Here $\beta = 2\frac{\nu_B \cos\alpha}{\nu} \ll 1$, $t \equiv \tau(\lambda = 1cm)$ is normalized radiodepth from the top, and $T'_t(t+t')$ denotes derivative with respect to argument t.

Model simulations with these equations show (see Grebinskij et al., 1999 for details) that esimate (1) is valid only for the case of homogeneous magnetic fields $B(t) = const$ throughout the atmosphere, but gives also a correct value of inhomogeneous field $B = B(t)$ at geometrical depth, where its radiodepth $\tau \equiv \lambda^2 t$ is about unity: $[B] \simeq B(t = \lambda^{-2})$. For transparent corona, it always corresponds to the level of transition region (TR) or upper chromosphere.

A major problem of separation of contributions from the corona and chromosphere may be solved approximately for model atmospheres. As a realistic two-component atmosphere, we consider an optically thin coronal layer ($T_e = T_{cor},\ \tau_{cor} << 1$), and opaque chromospheric layer with a small temperature gradient ($T_{chr}(t) = T_o \left(\frac{t+t_o}{t_o}\right)^{-q}$ with $q << 1$), with brightness I as: $I_{cor} =< \tau T >_{cor}$, $I_{chr} = (\lambda^2 t_o)^q T_{chr}$. The main reason for using power-law chromosphere models is from the observed brightness spectra $T_b(\lambda)$ at mm-waveband (see Urpo et al., 1987; Bogod and Grebinskij, 1998). For such model atmospheres we would have for Stoke's parameter I and V (see Grebinskij et al., 1999)

$$I = I_{cor} + I_{chr}, V = \beta\left(I_{cor} + qI_{chr}\right) \equiv V_{cor} + V_{chr} \tag{3}$$

To find magnetic field parameter β from a set of single-frequency observations of $I = I_{obs}, V = V_{obs}$, we use here as I_{chr} its model value, and treat I_{cor} as observed (total) brightness enhancement: $I_{cor} = I_{obs} - I_{chr}$, with the equations,

$$[B]_G = 5350 \frac{1}{\lambda_{cm}} Q(\lambda) \frac{V_{obs}}{I_{obs}}, Q \equiv \frac{1 + \frac{I_{chr}}{I_{cor}}}{1 + q\frac{I_{chr}}{I_{cor}}}, \frac{I_{chr}}{I_{cor}} \simeq \frac{I_{chr}}{I_{obs} - I_{chr}}, \tag{4}$$

Such a model with parameters: $T_o = 15000K$, $t_o = 10^{-2.5}$, $q = 0.095$, $< tT >_{cor} = 95$ for QS, and $T_o = 15000K$, $t_o = 10^{-1.9}$, $q = 0.095$, $< tT >_{cor} = 800$ for plage areas gives good match with observed brightness spectra $T_b(\lambda)$ for quiet Sun (Zirin et al., 1991) and plage areas (Urpo et al, 1987). Correction factor $Q \succeq 1$ compensates the estimated field strength for the supressed chromospheric contribution to the observed polarization, its value is related with spectral index n in estimate (1) as $n = 1/2Q$.

We can estimate expected intensity-polarization effects for Nobeyama observations at 17 GHz. For typical plage area parameters with magnetic field $B_{chr} = 100$ G we would have: $\beta = 0.033$, $I_{cor} = 2500K$, $I_{chr} = 11000K$, $V_{cor} = 83K$, $V_{chr} = 34K$, $Q = 3.8$. For umbral atmosphere, a coronal EM is half relative to plage atmosphere (by EUV observations): $< tT >_{cor} \simeq 400$, but its chromospheric structure is poorly known and we use the same values as for plages for simple estimates. For umbral fields $B \preceq 2000$ G (gyrofrequency threshold), we would have: $\beta = 0.66$, $I_{cor} = 1300K$, $I_{chr} = 11000K$, $V_{cor} = 860K$, $V_{chr} = 680K$, and $Q = 5.3$.

Another problem is the separation of contributions from free-free (ff) and gyroresonance (gr) emissions to the intensity and polarization. If umbral coronal fields exceed a threshold value ($B_{cor} \succeq 2000G$), then emission at third ($s = 3$) gyrofrequency harmonic dominates in e-mode, but ff radiation may dominate in o-mode. This conclusion is based on estimates of gr opacities: $\tau_3^e << 1$, $I_{chr} << T_b^e = \tau_3^e T_{cor} << T_{cor}$, and $\tau_3^o << \tau_3^e$, $T_b^o \simeq I_{chr}$ and $\rho \equiv$

$V/I \simeq 1$. Estimates (4) is not valid in that case, but gives a reasonable value of $B = 5350/\lambda = 3000G$ (corresponds to second harmonic of gyrofrequency $\nu = 2\nu_B$). Also, for most large spots, umbral fields with $B_{cor} \succeq 3000G$ are possible, with total domination of $s = 2$ gr emission in both o and e modes ($\tau_2^e >> 1,\ \tau_2^o \simeq 1$). Thus, we have domination of ff emission, if the degree of circular polarization from coronal layers $\rho_{cor} \equiv V_{obs}/(I_{obs} - I_{chr}) \preceq \rho_{\max} = 2\nu_B/\nu = 0.66$ (for $B = 2000G$ and $\nu = 17GHz$), and gr domination in polarization, when $T_b^e >> T_b^o \simeq I_{chr}$, where $T_b^{e,o} \equiv I_{obs} \pm V_{obs}$ with proper signs relative to directions of spot magnetic fields. Other effect is a reduction of ff brightness in o-mode with the growth of umbral fields as

$$T_b^o = I_{chr}(1 - q\frac{2\nu_B}{\nu}) + I_{cor}(1 + \frac{\nu_B}{\nu})^{-2} \qquad (5)$$

due to change of ff opacities in magnetic field. Because ff radiation dominates in o-mode for any strong fields up to $B_{cor} \preceq 3000G$, this effect may be observable with the Nobeyama radioheliograph resolution for big sunspot umbras with $\Delta T^o_{b,\max} \simeq -1000K$.

3. Results of observations

To check our theoretical suppositions, we used Nobeyama observations at 17 GHz and compared results of calculations for expected chromospheric magnetic fields by equation (4) with photospheric vector magnetograph observations (Huiarou Station of BAO) for several classes of active regions. In the following, we summarize the preliminary results for (1) plage areas with and without sunspots, (2) compact sunspot sources, and (3) complex active regions with coronal loops and strong neutral line sources.

3.1. Plage areas

The AR on June 9, 1995 (N20,W10) by Huairou observeations was a bipolar plage area with photosphere magnetic fields up to ±320 G. From Nobeyama images we have two polarized regions (with V = 401 K, I = 14787 K, and V =-407 K, I=13869 K) at bipolar plage locations, and strong emission peak in intensity (with $T_{max} = 32705$ K and near zero polarization) at the middle of coronal arcade above neutral line. By equation (4), we found chromospheric fields as B = 154, -176 G at locations of polarization peaks, about half of its photospheric values. For spotless bipolar plages (for example, on 20 - 22 August, 1992 near disck center) typical observed values ($I = 14100 - 1800K,\ V = 250 - 360K$) gives close estimates of fields near $B_{chr} \simeq 100 \pm 5G$.

3.2. Compact sources

¿From Nobeyama images and optical data for 1992 we selected about 30 compact (without visible loop structures) magnetically isolated sources in sunspot range of 50 - 900 millionths of a solar hemisphere (msh) with maximum spot fields 1000 - 3500 G. Statistical study reveals that all microwave sources with $S_p \succeq 300$ msh are strongly polarized ($\rho \simeq 0.7 - 0.9$), have high e-mode brightness ($T_b^e \simeq 50 - 800 \cdot 10^3 K$) and low o-mode brightness ($T_b^o \simeq 10000 - 18000$), which significantly drops (several thousands of K) with umbral field growth. We treat this as domination of e-mode gyroresonance emission (with $s = 3$) with penetration of strong fields ($B_{cor} \succeq 2000G$) into the coronal base. On the contrary, all sources with $S_p \preceq 200$ msh are unpolarized (relative to rms threshold $V_{rms} \simeq 50K$) with same brightness of $I \simeq 18000 \pm 2000K$. We treat it as an artefact of limited angular resolution: polarized signal is proportional to total magnetic flux at antenna beam, which includes a return flux at penumbra areas inside of beam for small spots (linear dimension d of spot is $d = \sqrt{S_p},\ d - 10^3 km,\ S_p - msh$).

3.3. Complex ARs

Nobeyama images of bipolar ARs in intensity usually display much fine structure details, without optical counterparts on photosphere (compact neutral line sources, loops, penumbral enhancements at local contacts with satellite fields), which were known before. Most of these low brightness details display density enhancements of free-free emission in some chromospheric fields, which may be studied by its polarization characteristics. A study of several ARs reveals some common patterns of its magnetic field at chromosphere-corona heights, which are quite different from the case of compact sources.

Our main findings concern with influence of peculiar (neutral line) microwave sources (NLS). In the presence of strong NLS, chromospheric spot fields are reduced. Same effects are observed for ARs with strong coronal loops, legged at bipolar spots. We demonstrate these effects with microwave estimate (equation (4)) for several ARs, discussed in literature as flare productive.

A bipolar AR (S4,W17) on December 13, 1992 have two spots of strong magnetic field about ±2400 G at the photosphere, with strong mixing of opposite fields at the southern part of the neutral line and prominent interconnecting loop, from BAO vector magnetograph observations (see Fig. 3 of Li and Ai, 1993). Its microwave emission pattern includes emission peaks just above both spots (with I = 26000 K, V=10000 K, and I=16000 K, V = -2000 K) and loop enhancement between them, but main intensity peak (I = 42700 K, V = -147 K) is located outside of sunspots in a region of intermixing fields near the neutral line. Microwave estimates of chromospheric fields above sunspots (B = 1600 and -660 G) show gross reduction with respect to typical values for isolated spots. That reduction is most pronounced for a trailing spot, magnetically connected with the NLS region.

The AR (S3.2, W57) on August 27, 1993 was observed with BAO vector magnetograph in the wings of the Hβ line at 8 different wavelengths (chromosphere), where the reversal of longitudinal magnetic field above sunspot umbra (with photospheric field of 1280 G) was registered (Zhang, 1994). Comparison of photospheric magnetogram (see Fig. 7 of mentioned paper) with Nobeyama images reveals a presence of a pecular microwave source just to the east of the spot umbra, at local contact of opposed photosphere fields, with intensity I = 22500 K and near zero (V = 115 K) polarization. We conclude that presence of a NLS is accompanied by reduction of polarized emission and magnetic field above sunspot (I=21300 K, V=224 K, and B$_{cor}$ =30 G).

4. Discussion: microwave magnetography

Mentioned results show a possibility of measuring solar magnetic fields at heights between upper chromosphere and corona base (TR region) with observations of ff microwave emission. Such measurements are independent relative to other methods. We now discuss potential merits and faults of such an approach using the example of AR NOAA 7260 on Aug. 18, 1992. This AR was extensively studied before (see Shibasaki et al., 1994; Canfield et al., 1996; Yan and Sakurai, 1997) in optical wavelengths, Xrays and microwaves. From photospheric magnetograph observations (see figure 1b) this AR has a bipolar structure with single large leading spot of S-polarity ($S_p \simeq 900msh$, $B_{ph,\max} \simeq 3000 - 3500G$), and magnetically complicated trailing part with domination of N-polarity and numerous compact intrusions of opposite fields. Such structure of photospheric fields is especially interesting for Nobeyama microwave magnetography, because (a) large linear dimensions of leading spot (about d_{sp} = 90") gives the possibility to resolve radiation from umbral and penumral regions with a Nobeyama resolution of about 15" $\times$ 15"$/\cos h$, and (b) complicated magnetic structure of trailing parts displays numereous examples of pecular microwave sources.

In figures 1a,b we show images of AR in intensity I and polarization V at 17 GHz, coaligned with Mees photospheric magnetogram (figure 1b). Brightest source is located at the umbral area of the leading spot, with the same locations for maximums of brightness in intensity and polarization ($I_{\max} \simeq 115000K$, $V_{\max} \simeq -103000K$). Translation of these values to brightness in o and e modes are $T_b^{o,e} \equiv I \pm V$, where $T_b^o = 12000K and\ T_b^e = 218000K$ for the umbral area. At the trailing part, locations of brightness maximum in intensity and in polarization are different. Brightest source in intensity (with $I \simeq 70000K$) lays at the contact of opposite strong fields ($B_{ph} = \pm 800\ G$) and is a typical peculiar source with low polarization ($V \simeq 600K$). Brightest source in polarization (with $V \simeq 1700K$ and $I \simeq 34000K$) lays south of it in a region of strong N-polarity with $B_{ph} = +800\ G$. Overall structure in polarization V map displays a simple bipolar structure of chromospheric magnetic fields, without any trace of opposite fields intrusions. For the leading spot, a maximum chromospheric field strength $B_S \succeq 2000G$ corresponds to gr emission at third harmonic of gyrofrequency (see Shibasaki et al., 1994). Maximum chromospheric field $B_N \simeq 190G$ at the trailing part is greatly reduced compared to its photospheric value $B_{ph} \simeq 800G$ and corresponds to ff emission mechanism. We may conclude that any satellite fields at the photosphere do not penetrate to the upper chromosphere, but strongly affect (reduce) the large scale fields at the chromosphere, and lead to the appearence of peculiarly bright microwave sources.

We can use expression (4) to construct microwave magnetogram $B(x, y)$ of ARs at the coronal base. As an example, we show (see figure 2) a cross-section of such magnetogram for leading spot through point of polarization and intensity maximum at E-W direction. This magnetogram confirms our theoretical supposition on the contribution of ff and gr mechanisms to the observed emission. We see domination of gr emission at the penumbral area for e-mode with $T_b^e \simeq 218000K$ and low ff brightness at o-mode with possible signs of depression ($T_b^o \simeq 9000 - 11000K$). At the penumbral area we observe unpolarized emission enhancements, up to $I \simeq 28000K$, at the contact penumbra and satellite opposite fields (see optical magnetogram on figure 1b). Such local pecular sources may lead to artefact brightening of compact sunspots (see section 3.2) due to limited resolution.

For most ARs, microwave study gives a similar result on the penetration of magnetic field from the photosphere to corona: large scale (plages) or compact (isolated spots) photospheric fields penetrate to corona without great reduction, and strong cancellations of fluxes with mixed polarity is observed. Validity of such estimates for weak

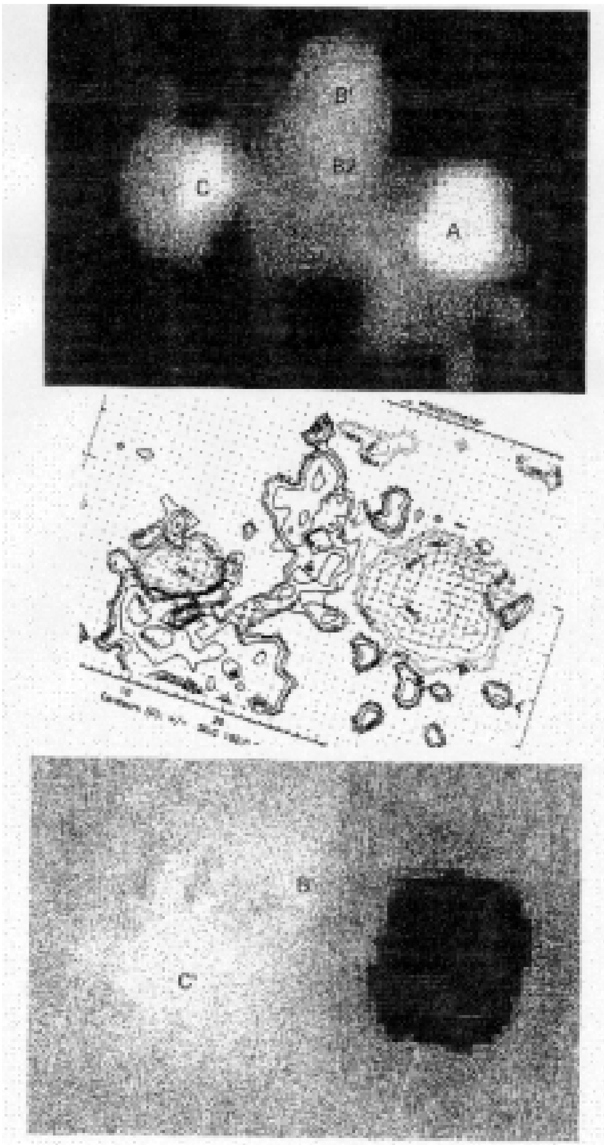

Fig. 1.. (upper),(bottom) Nobeyama 17 GHz, I, V: (middle) Mees photospheric magnetogram

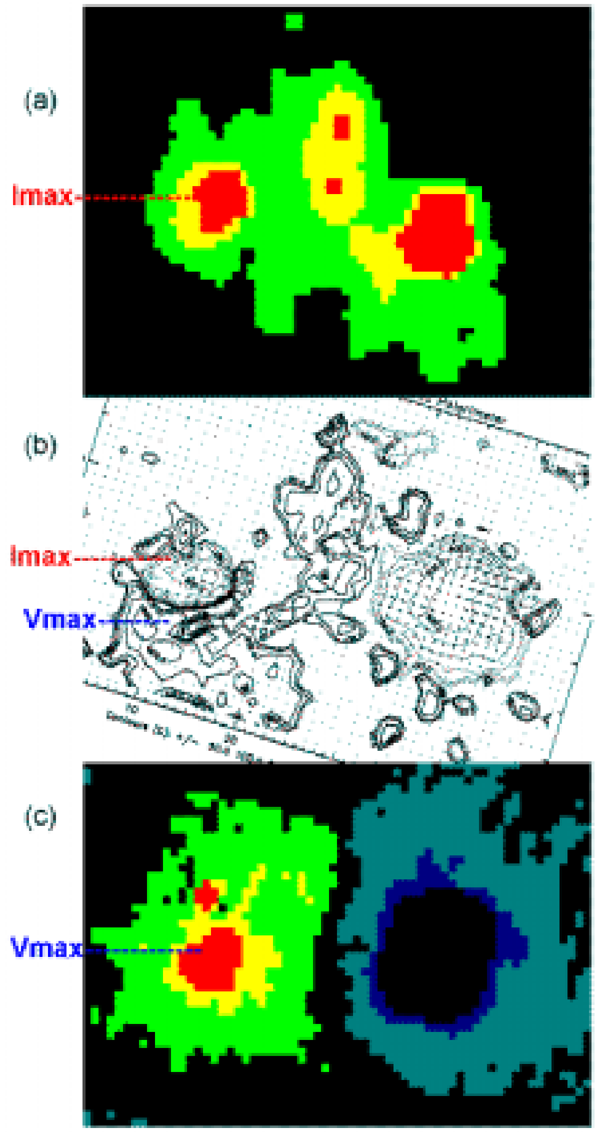

Fig. 2.. Partial images (6' × 6') of the active region. (a) The radio brightness temperature of full intensity (Stoke,s parameter I). (b) Photospheric magnetogram for longitudinal fields. (c) The radio brightness temperature in polarization (Stoke's parameter V)

fields in plage area is limited by random polarized noise ($V_{rms} \simeq 30K$, with $\delta B/B \simeq 0.1$). For strong sunspot fields, systematic errors are more important, due to uncontrolled contribution of some unpolarized (ΔI) unresolved brightness from coronal loops, leading to an underestimation of the fields: $B_{cor} \sim V_{cor}/I_{cor}$, $I_{obs} = I_{cor} + \Delta I > I_{cor}$). We need a detailed comparison of Nobeyama images with multi frequency observations at longer wavelengths to resolve these issues properly.

5. Summary

We revised a current state of radiation transfer theory for free-free emission mechanism and suggested a practical method for measurements of chromospheric magnetic fields with microwave imaging (microwave magnetography). We applied this method to Nobeyama imaging in intensity and polarization at 17 GHz, and discovered several new characteristic patterns of chromospheric fields, closely related to pecularities of its photospheric structure.

Most important finding concerns with the relation of strong sunspot fields and pecular (neutral line) microwave sources outside sunspots. We show that compact spots, or magnetically isolated spots in complex ARs, have strong chromospere-corona fields, $B_{cor} \succeq 2000G$, with domination of medium-brightness gyroresonance emission (with $s = 3$) at e-mode and free-free emission for o-mode, with extremely thin coronal density at spots umbra areas. It may suggest that at longer wavelengths an observed emission with coronal values of brightness corresponds to second, not third gyroresonance harmonic of the gyrofrequency.

Peculiar (neutral line) microwave sources (PMS) are most prominent emission at 17 GHz, at penumbras and outsides of isolated spots, and are practically unpolarized. We are unable to detect such chromospheric sources from photospheric magnetograms (most of the neutral lines regions are not accompanied by PMS). We discovered that every case of the appearence of PMS in intensity images is accompanied by gross reduction of microwave polarization and estimated chromospheric fields of neighboring spots. In such case, the chromospheric and photospheric patterns of magnetic fields are totally different. Such effects may be important for the problem of reconstruction of 3D fields from its photosphere boundary values.

It may be important that the reported locations of concurrent flare events in AR on Dec. 13, 1992 at photospheric magnetograms (see Li and Ai, 1993) coincide with the existence and position of PMS at that region. Further study of such a relation may be performed in the future.

This work has been partially supported by the Russian Foundation for Basic Research (RFBR) Projects 96-02-16598a and 96-02-16268a, INTAS-RFBR 95-316.

References

Bogod V.M. and Gelfreikh G.B., 1980, *Solar Phys.*, **67**, 29.

Bogod V.M. and Grebinskij A.S., 1997, *Solar Phys.*, **176**, 67.

Canfield R.C., Reardon K.P., Leka K.D., Shibata K., Yokoyama T. and Shimojo M., 1996, *Astrophys. J.,* **464,** 1016.

Grebinskij A.S., Bogod V.M., Gelfreikh G.B., Urpo S., Perttula M. and Shibasaki K., 1998, *Astron. and Astrophys.*, subm.

Li Wei and Ai Guoxiang, 1993, *Proc. of Chongqing Workshop on Solar Magnetic and Velocity Fields*, 65.

Shibasaki K., Enome S., Nakajima H. et al., 1994, *PASJ*, **46**, L17.

Urpo S., Hildebrandt J., Kruger A., 1987, *Solar Phys.*, **112**, 119.

Yan Y. and Sakurai T, 1997, *Solar Phys.*, **174**, 65.

Zhang Hongqi, 1994, *Proc. of the Third Workshop on Solar Magnetic and Velocity Fields*, 25.

White S.M., Kundu M.R., 1997, *Solar Phys.*, **174**, 31.

Zirin H., Baumert B.M. and Hurford G.J., 1991, *ApJ*, **370**, 779.