CORONAL MAGNETOGRAPHY FROM QUASI - TRANSVERSE PROPAGATION

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Abstract. The technique of coronal magnetography based on the analyses of quasi-transverse (QT-) propagation of microwaves in the low solar corona and some coronal magnetograms are briefly reviewed. The technique itself is quite powerful, yet it requires some efforts to improve the determination of the distance between the microwave source and the coronal region of QT-propagation of the microwaves. Some recommendations for the FASR design are specified for the radio measurements of the fields of 1 - 300 Gauss to be completed.

1. Introduction

The ability to measure the strength of the magnetic field in the solar corona is widely regarded as an important task in order to solve some major problems of solar physics. The field measured in the plane of view is of great value for the analysis of the structural peculiarities in an active region magnetosphere.

There are 3 techniques used in coronal magnetography for the microwave wavelength range:
- quantitative analysis of the circularly polarized free-free emission (Gelfreikh, 1999);
- model reconstruction of the magnetic field and plasma characteristics from the radio maps of a microwave source at a set of wavelengths (Brosius et al., 1997);
- field measurements from the polarization inversion which is due to the quasi-transverse (QT) propagation of microwaves (Ryabov et al., 1999).

The technique based on the inversion phenomenon stands out for its clear and direct measurements. Some active regions (ARs) do not show any polarization inversion at all and others do it occasionally. This is the main drawback of the polarization inversion technique. In this report we discuss the inversion technique only. For the comprehensive review of the coronal field radio measurements see (Kundu, 1995; Gelfreikh, 1999; Alissandrakis, 1999).

Let a sunspot-associated microwave source emit radiation with circular polarization ρ^V_0. If the radiation crosses a QT-region (Fig. 1), the sign and the degree ρ^V of the resulted circular polarization mainly depend on the strength B of the magnetic field crossed at the right angle in the QTR. This is the way to measure the coronal magnetic fields, provided the electron density N and the scale of the magnetic field divergence L_d are known in the QTR (Zheleznyakov and Zlotnik, 1964):

(1) $$\rho^V = \rho^V_0 \cdot [2 \cdot \exp(-2\delta_0) - 1],$$

where the coupling parameter $G_\perp$

(2) $$G_\perp \cdot \pi/8 = 2\delta_0 \approx 1.15 \cdot 10^{-25} \cdot B^3 \cdot N \cdot L_d \cdot \lambda^4$$

where λ is an operational wavelength of radio observations. Let us rewrite (1), (2) with $N \cdot L_d = 10^{18}$ cm^{-2} :

$$(3) \qquad B \approx -2.05 \cdot 10^{2} \cdot \lambda^{-4/3} \ln^{1/3} (0.5 \cdot \rho^{V} / \rho^{V}_{0} + 0.5)$$

When the source is near the solar disk center, the QTR is crossed higher up in the corona, where the magnetic field B is weak and the resulted polarization ρ is the same as in front of the QTR, that is ρ_0. As the source moves towards the W solar limb the QTR is crossed lower in the corona and the sign of the resulted circular polarization is reversed. The technique is most sensitive to the strength B corresponding to $\rho^V \approx 0$ (more precisely, corresponding to $\rho^V = \rho^V_0 \cdot [-1 + 2 \cdot \exp(-2/3)] \approx 2.68 \cdot 10^{-3} \rho^V_0$, as can be deduced from $\partial^2 \rho^V / \partial B^2 = 0$).

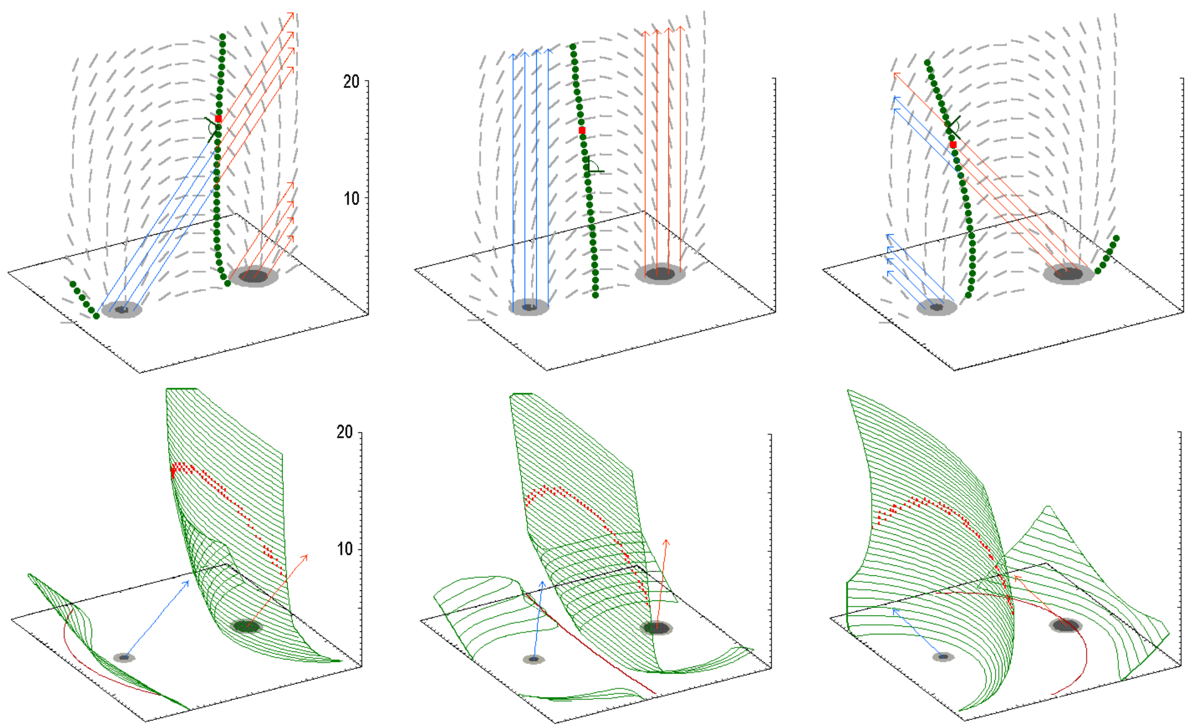

Figure 1. Representative geometry of QT-propagation of microwaves in a bipolar active region simulated with respect to an observer. (a) A number of green dots are the points where circularly polarized microwaves cross the magnetic field vectors (gray segments) at the right angle. (b) The coronal magnetic neutral lines as a set of points where the propagation angle = 90^o form the QT-surfaces. On both sides of the QT-surface there are QT-regions extended to distance of $2\pi^{-1} L_d \ \nu_B/\nu \propto 10^8$ cm at ν = 10 GHz, where ν_B is the electron gyro frequency (Kravtsov and Naida, 1976).

The isogaussian of 20 Gauss on the QT-surface (red dots) is supposed to produce the depolarization of circularly polarized microwaves at λ = 5.2 cm. So, the isogaussian projected to the plane of the microwave source is the depolarization line (red line). The length units are 10^9 cm. Three panels in each row represent the heliographic longitude of -42^o, 0, and +42^o correspondingly.

To make the most of the relation (3), the full range (-1, +1) of the normalized degree of circular polarization $\rho^V/\rho^V_0 = P$ is used by Ryabov et al., 1999. As a result, not only the coronal field responsible for a zero circular polarization, but the entire 2D coronal magnetogram is evaluated. The normalized degree of circular polarization P is sensitive to the QT-propagation alone and quite insensitive to the emission mechanism. A coronal magnetogram in the plane of view implies the fields of the coronal QT region, which “screens” the microwave source.

The aim of this report is to list the merits and the possibilities of the inversion technique of coronal magnetography. The next chapter deals with well-defined observational features.

2. Observational findings

The relations (1), (2) lie at the basis of coronal magnetography. In the beginning the polarization inversion should be tested whether it is due to the QT-propagation. The test depends on whether the inversion is observed at a single wavelength with time or it is followed through cm wavelength range at a time. Spectral polarization observations are preferable.

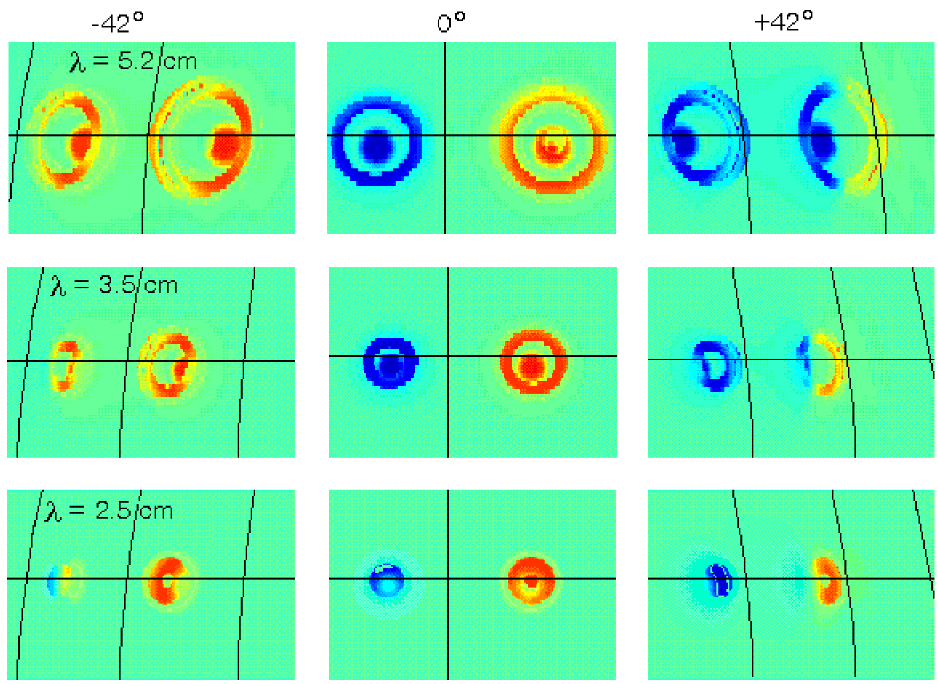

Figure 2. Transformations of a circularly polarized microwave source simulated with due regard to the QT-propagation of microwaves. Three panels in each row correspond to 3 longitudinal displacements θ of the bipolar microwave source from the central solar meridian [-42°, 0, +42°]. Each row of the panels represents the source at the wavelength of (a) 5.2 cm, (b) 3.5 cm, and (c) 2.5 cm. Note the depolarization strip, which is clearly seen within the western sunspot-associated source at θ = +42°.

2.1. Regularities of the inversion phenomena

The inversion of the sign of circular polarization of a microwave source might be caused by a variety of factors. Before dealing with coronal magnetography one needs the unambiguous evidence of the manifestation of the QT-propagation of microwaves in the solar corona (Peterova and Akhmedov, 1974; Kundu et al., 1977). The following regularities summarize some radio observations (Peterova and Akhmedov, 1974) and model simulations (Ryabov, 1981; Fig. 2) of the polarization inversion due to the QT-propagation.

This regularities hold true for the equatorially elongated, bipolar ARs in the course of solar axis rotation (Fig. 2):

{1} the nearest to the solar limb sunspot-associated microwave source is the first which inverts the sign of circular polarization in an AR.

The regularities for the western solar hemisphere are as follows:

{2} the closer an AR to the W solar limb is, the shorter is an operational wavelength required to detect the polarization inversion;

{3} the depolarization line $\rho^V = 0$ moves toward the W solar limb while the polarization inversion is observed at a fixed operational wavelength.

{4} the post-inversion value of the degree of circular polarization , as a rule, does not exceed the preinversion one.

The regularities for the eastern solar hemisphere are as follows:

{5} the farther an AR from the E solar limb is, the longer is an operational wavelength required to detect the polarization inversion;

{6} the movement of the depolarization line $\rho^V = 0$ is directed from the E solar limb while the polarization inversion is observed at a fixed operational wavelength;

{7} if the microwave source of circularly polarized emission is a loop-associated source, as is often the case at long wavelengths, the regularities of polarization inversion seem to be similar to those of a sunspot-associated source. The initial sign of circular polarization corresponds to the sign of the longitudinal component of the magnetic field B_l. The analyses of the polarization inversion at a given wavelength with time must take into account both the QT-propagation and the displacement of the neutral line $B_l = 0$ within the loop (Alissandrakis C.E. and Preka – Papadema, 1984).

The FASR is equiped well enough to provide the test of QT-propagation by the spectral polarization observation inspection. However, implementing coronal magnetography with the FASR it is necessary that the above observational findings be taken into consideration at almost all stages.

The above regularities immediately follow from the relations (1), (2) and from the geometry of QT-surface in a bipolar AR with the magnetic meridian approximately in the east-west direction (Fig. 2).

The ARs different in orientation and the magnetic structure give rise to various polarization inversions. For example, the inverted sign of the circular polarization may remain for many days within a bipolar AR oriented in the north-south direction (especially at non-zero heliographic latitude).

The detail treatment of QT-propagations is promising. Let us examine some possibilities of the coronal magnetography application.

2.2. Multiple inversion

In 1992 the double inversion of the circular polarization sign within a cm wavelength range was detected in a sunspot-associated source (Bogod et al., 1993). How to test the applicability of QT-propagation and what is the number of the inversions of this type?

An appropriate examination provided some model simulations of QT-surfaces and numerical restrictions on ρ^V to be derived from the relations (1), (2). Using the FASR with wavelength spacing $\lambda_{i+1} = \lambda_i + \varepsilon \cdot \lambda_i$, $\varepsilon \le 0.03$, we can observe that the normalized degree of circular polarization at the wavelength λ_{i+1} adjacent to the wavelength λ_i of zero polarization, $\rho^V(\lambda_i) = 0$, is suppressed (Ryabov, 1997):

$$(4) \qquad \rho^V(\lambda_{i+1}) / \rho^V_0(\lambda_{i+1}) = 2^{\,1-(1+\varepsilon)^{\wedge}4} - 1,$$

We get $\rho^V(\lambda_{i+1}) / \rho^V_0(\lambda_{i+1}) \approx -0.0833$ assuming $\varepsilon = 0.03$. Hence, $|\rho^V(\lambda_{i+1}) / \rho^V_0(\lambda_{i+1})| \le 0.09$. It is advisable to have the FASR accuracy high enough to resolve the above value 9% of the normalized circular polarization, which is difficult to attain having a slowly polarized source $|\rho^V_0(\lambda_{i+1})| << 1$.

The restriction (3) is necessary but it is not a sufficient condition for the polarization inversion to be determined by QT-propagation. The multiple inversion as a result of QT-propagation seems to be promising for coronal magnetography at a set of coronal heights simultaneously.

The of tracing of full Stokes vector transformations in numerous QTRs and due to Faraday rotation is validated by the contemporary theory (Segre, Zanza, 2001). To accomplish this both high angular ($\propto$ 1”) and high frequency resolutions ($\propto 4\ 10^2 \cdot [\nu/\mathrm{GHz}]^2$ Hz; see (Alissandrakis, Chiuderi-Drago, 1994)) are required. Not only the value of the strength B, but also the measured factor $N \cdot L_d$ become available.

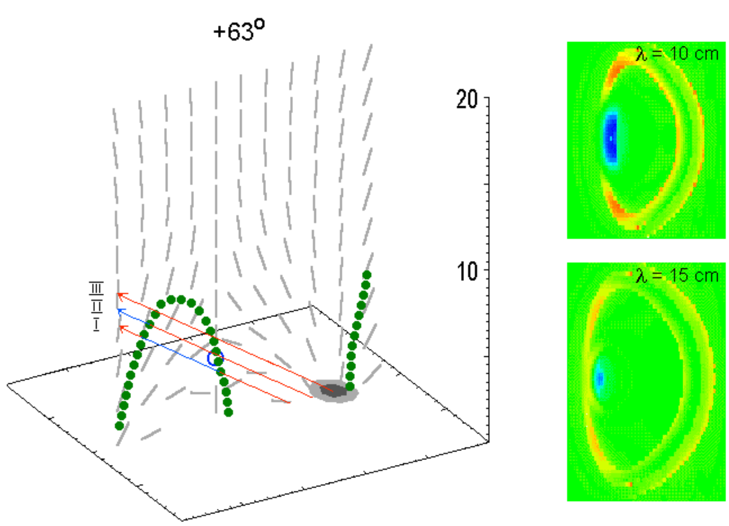

Figure 3. Representative geometry of QT-propagation of microwaves throughout the vicinity of the neutral point of the coronal magnetic fields (NP; blue circle). A number of points (green dots), where circularly polarized microwaves cross the magnetic vectors (gray segments) at the right angle, form a vertical section of the QT-surface. Note the total number N of the polarization sign inversions along the ray paths: I, N=2; II, N=1; III, N=0. Transformations of a circularly polarized microwave source are simulated with due regard to the QT-propagation of microwaves throughout the NP. The sunspot-associated source simulated at the wavelength (b) 10 cm and (c) 15 cm. Warm and cold colors represent the opposite signs of circular polarization. Note the elliptic blue patch as a result of the twofold QT-surface at long cm wavelengths. Double sign inversion is expected in the patch over a cm wavelength range.

A possible decrease of kinetic temperature with height in the region of gyro resonance emission is an alternative explanation of the double inversion (Zlotnik, 1999). If the negative temperature gradient is local, it sets up the prevalence of the ordinary mode emission within some portion of a cm wavelength range. The linearly polarized emission detected in the vicinity of depolarization line $\rho^V = 0$ gives us the possibility to make a choice in favor of one of the explanations. Gyro resonance radiation from the region with a negative temperature gradient is unpolarized at the wavelength of zero polarization (Zlotnik, 1999). The radiation which has crossed the QTR radiation is linearly polarized one (Zheleznyakov and Zlotnik, 1964).

The topological properties of the QTR are intriguing. Indeed, a so called photospheric neutral line, $B_l = 0$, is the lower border of the QTR; all coronal neutral points, B = 0, and neutral current sheets are to be found at the QTR for any direction to the observer. The magnetic structure in the vicinity of a NP is supposed to produce a double polarization inversion (Fig.3). It is expected that a NP will occur as 10”- 30” oppositely polarized insertion to the microwave source situated behind and the FASR is the unique tool to observe a NP. If no new magnetic fluxes appear in an active region the shape of the QTR is modified only due to solar axis rotation.

2.3. Linear polarization in the outer corona

We can assume that circular polarization is transformed to linear polarization in a high coronal QT-region (Zheleznyakov and Zlotnik, 1964) and the linear polarization is not smeared to zero by Faraday rotation within a narrow bandwidth.

In 1993 the linear polarization was detected by Alissandrakis and Chiuderi-Drago (1994) above the AR 7530 in the course of circular polarization sign inversion due to QT-propagation. The observations were made with a multichannel spectral line receiver at the Westerbork Synthesis Radio Telescope (WSRT; 63 channels 19.6 kHz wide in a 1.2 MHz bandwidth around ν=4995 MHz). The angular resolution of the WSRT is 3" x 9" at this wavelength of 6 cm. The linear polarization components, Stokes U, Q, measured close to the depolarization line, V=0, show a sinusoidal trend as a function of λ^2 in accordance to the Faraday rotation (Alissandrakis, Chiuderi-Drago, 1994). Using the current-free assumption for AR coronal magnetic fields the height of the QTR is estimated to be 10^{10} cm above the photosphere (Alissandrakis et al., 1996).

It is interesting to note that the analyses of full Stokes vector (I, Q, U, V) by Segre and Zanza (2001). yield both the strength of the coronal field B = 12.8 - 11.2 Gauss and the factor $N \cdot L_d$ = (1.4 - 2.1) 10^{18} cm^{-2} for those observations.

2.4. Oscillations

The depolarization line $\rho^V = 0$ is the most convenient line in the plane of view to trace polarization inversion. It is clearly seen in V radio maps and it is not subjected to alteration by the normalization procedure $\rho^V / \rho^V{}_0$. As discussed above, $\rho^V = 0$ is the isoline most sensitive to the coronal magnetic filed. If the coronal fields oscillate, the depolarization line is bound to oscillate too.

Recently the oscillations of $\rho^V = 0$ points were found in the radio scans taken with the Siberian Solar Radio Telescope (SSRT) at the wavelength 5.2 cm (Gelfreikh et al., 2002). The oscillations with the characteristic time of about 20 min were detected in the course of polarization inversion in a sunspot-associated source of the AR 6412.

According to the relations (1), (2), $\rho^V = 0$ at $\lambda = 5.2$ cm is produced by the coronal field of about 20 Gauss with $N \cdot L_d = 10^{18}$ cm^{-2} in QTR. The depolarization line oscillations provide an accurate account of the oscillations of the coronal magnetic field.

3. The technique of coronal magnetography

This coronal magnetography begins with the proof that the QT-propagation is responsible for the polarization inversion and ends with the analyses of 2D coronal magnetograms. *It is the relation (1) which enables to obtain 2D coronal magnetograms, but it has not widely been used up to now.* This technique of coronal magnetography can be improved. Some stages of modern magnetography can be performed by different meathods. Hopefully, we will be able to choice the most accurate one in the future.

3.1. Normalization procedure

According to the relation (1), ρ^V normalized to the circular polarization degree $\rho^V{}_0$ of initial radiation, not modified in the QTR, results in 2D coronal magnetograms, provided $N \cdot L_d$ is given.

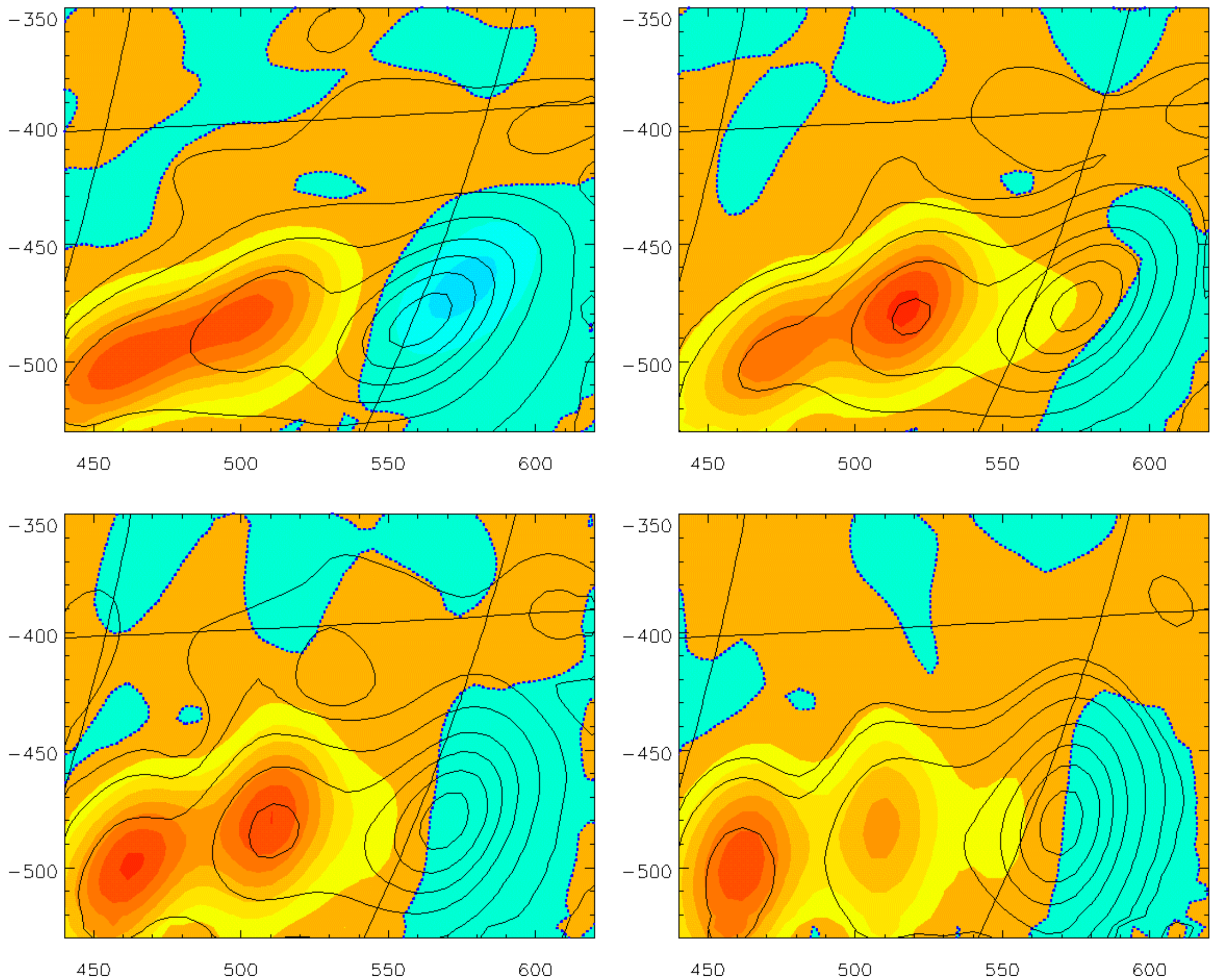

Figure 4. SSRT synthesis radio maps of the AR 8365 in Stokes I (black contours) and V (colors) taken at 5.2 cm on October 22, 1998 at (a) $3^h\ 54^m$ UT, (b) $4^h\ 54^m$ UT, (c) $5^h\ 54^m$ UT, and (d) $6^h\ 54^m$ UT. Note the displacements of the depolarization line $\rho^V = 0$ (blue dotted line) above the western sunspot-associated microwave source. The contour levels of total intensity I are [1, 2, 5, 10, 15, 20, 25]$\cdot 10^3$ K. Warm colors represent the right-handed circular polarization and cold colors represent the left-handed one. V contour levels are [300, 600, 900, 1200, 1500, 1800] K. (From Ryabov et al., 2002).

At the time of polarization inversion the initial circular polarization of the microwave source is modified in the QTR. There are some practical substitutes for $\rho^V{}_0$:

a) circular polarization degree observed at the day of the absence of QT-propagation effects. A limitation of this normalization is quite obvious: the AR evolves and $\rho^V{}_0$ alters with time;
b) circular polarization calculated by the model simulations of the microwave source under study. Not only the sunspot-associated microwave source, but also a coronal condensation should be taken into account at long wavelengths.
c) circular polarization normalized with the help of wavelength dependence of the relation (1). This normalization is just suitable for the spectral polarization observations with the FASR.

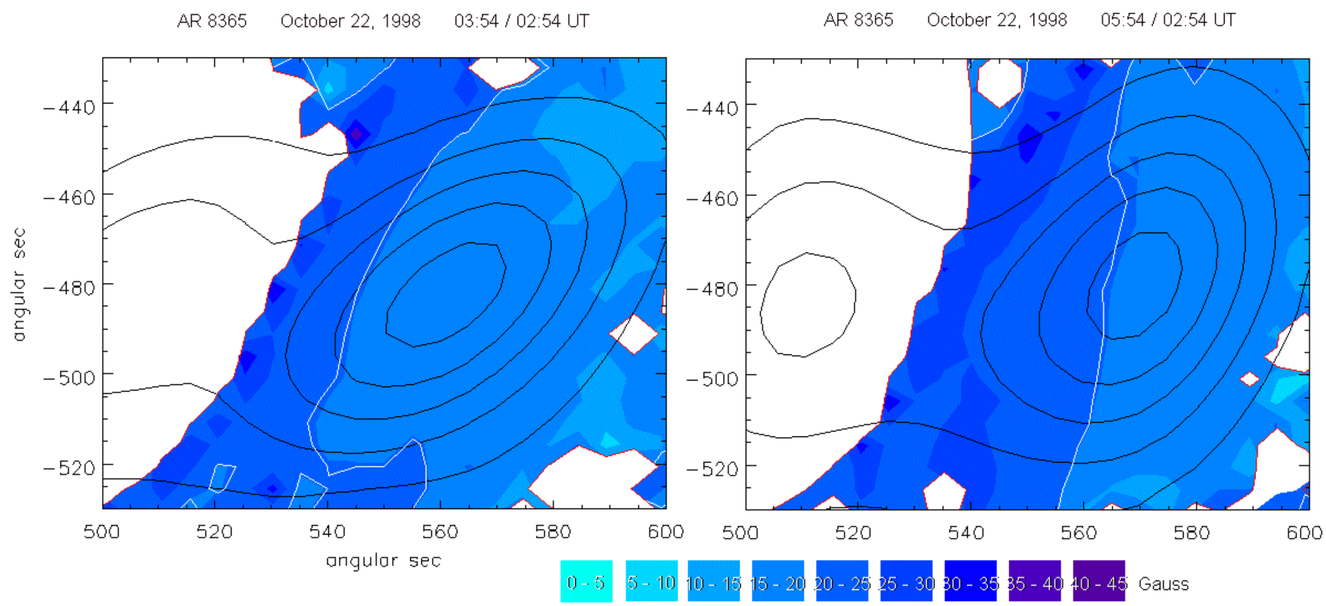

Figure 5. Two coronal magnetograms are overlaid on the contours of radio brightness in the plane of view. Cold colors corresponding to the coronal magnetic fields of 5 - 10, 10 - 15, 15 - 20, and 20 -30 Gauss are clearly seen. The coronal fields are evaluated by means of the relation $B \approx -22.85 \cdot \ln^{1/3} (0.5 \cdot P + 0.5)$, where $P = \rho^V/\rho_0^V$. The normalizing degree of circular polarization $\rho_0^V = V/I$ is calculated with the SSRT radio map taken at $2^h\ 54^m$ UT, while ρ^V refers to the SSRT maps taken in the course of polarization inversion at (a) $3^h\ 54^m$ UT and (b) $5^h\ 54^m$ UT. The above relation holds true, provided $N \cdot L_d = 10^{18}$ cm^{-2}, $\lambda = 5.2$ cm. The depolarization line P = 0 is marked by a white line. The border of the region covered by the QTR (P = ±1) is marked by a purple line. (From Ryabov et al., 2002).

The region accessible for the coronal magnetography in the plane of view is limited by some reasonable values of the normalized degree P : $|P| < 1$.

The authors of (Ryabov et al., 1999) introduce a convenient reference coronal magnetogram. It is a magnetogram calculated by means of the relation (1) with the constant value of $N \cdot L_d$ factor. Taking into account the evaluation of N and L_d in (Segre, Zanza, 2001) and the opposite sense of the variations of N and L_d with height, $N \cdot L_d = 10^{18}$ cm^{-2} is supposed to be a reasonable value.

3.2. The source-QTR distance

The determination of the distance between the microwave source and the coronal QT-region can be improved as well (Gelfreik et al., 1987). Notice that such coronal magnetograms are related to the coronal magnetic fields in the QT-region which are not necessarily located directly above the source of microwaves. There are two methods in use to measure the distance:

a) distance is geometrically determined from the depolarization line displacement in the course of polarization inversion. The height of the magnetic fields "screening" the microwave source is assumed to be constant in the QTR;
b) the distance between the source and the QTR is calculated by means of the magnetic field extrapolation to coronal heights. The extrapolation is supposed to be consistent with the radio observations.

3.3. Coronal magnetograms. 3D topology of an AR magnetosphere

With a number of coronal magnetograms presented in a proper way a solar physicist is able to solve some fundamental problems. The QT-surfaces themselves are significant geometrical features. Both the large-scale outline of an AR magnetosphere and the small-scale structure in the vicinity of a coronal NP (if any) are presented by the QTRs.

The INTAS project titled Solar Coronal Magnetography is supposed to provide a lot of coronal magnetograms evaluated with the help of the Siberian Solar Radio Telescope and the Nobeyama Radio Heliograph. The advantage is taken of bipolar ARs to get a number of coronal magnetograms both for the following part of an AR near the eastern solar limb and for the leading one near the western limb. The topological peculiarities in an AR magnetosphere, a characteristic value of coronal currents, and the oscillations of the coronal fields in an AR are under investigation.

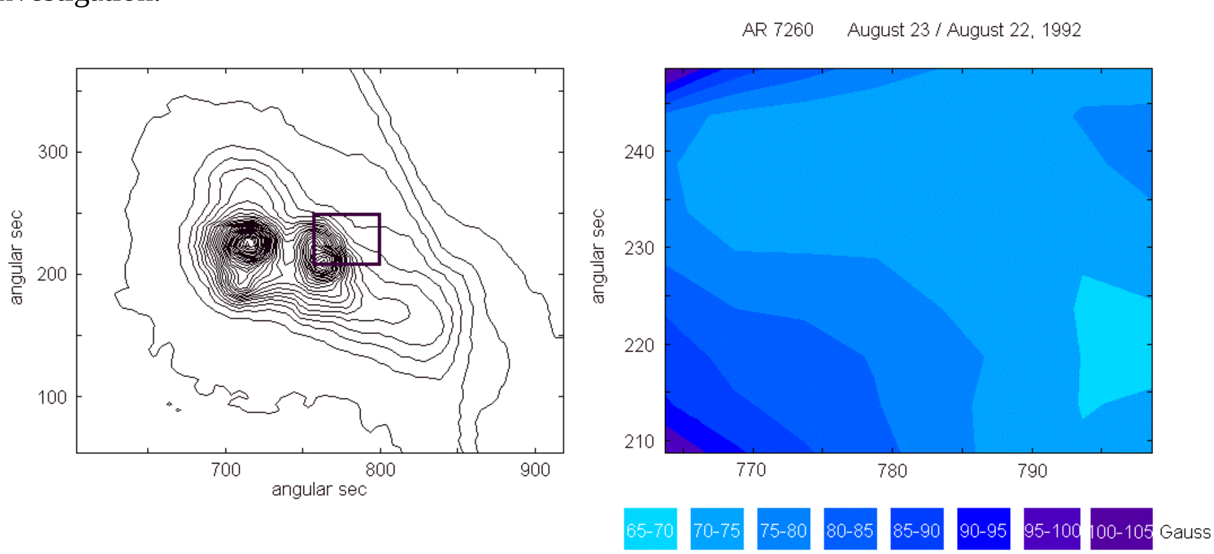

Figure 6 NoRH synthesis radio map of the AR 7260 in Stokes I taken at 1.76 cm on August 23, 1992 (a). The rectangle shows the region 34" x 39" selected for the coronal magnetogram (b). (From Ryabov et al., 1999).

The various shapes of the QT-surfaces constitute the specific character of coronal magnetography of this type. The shape depends on an AR magnetosphere, the position on the solar disk, and on the evolution of an AR.

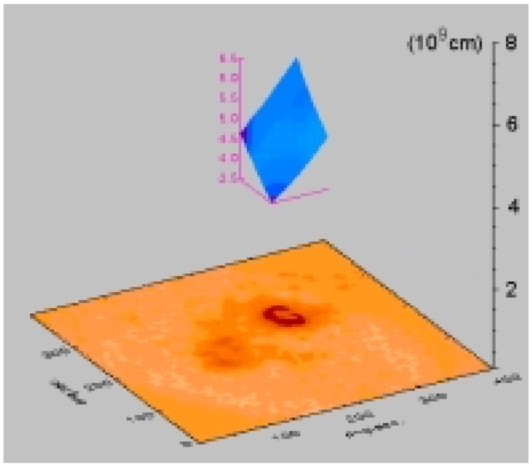

Figure 7. A perspective view of the coronal magnetogram over the photospheric magnetogram of the AR 7260 from the Marshall Space Flight Center.

4. Conclusions and Recommendations

The coronal magnetography is promising for the research of an AR magnetosphere and possesses a powerful potential for further advances. The sporadic radio observations at only a few frequencies do not necessarily enable us to analyze the multiple inversion with some certainty. As for the FASR project, it is best suited for the coronal magnetography. The high angular resolution and wide frequency range of the FASR will facilitate all types of coronal magntography at all stages. The application areas and the technique limitations will be determined by the analyses of the NoRH and SSRT radio observations in the nearest future.

(1) The coronal magnetograms are complete to the extent the angular resolution of the FASR enables to do it (1” at ν = 20 GHz). The coronal magnetic fields of 1 –180 G can accurately be measured by registrating the zero circular polarization within 0.6 – 30 GHz. Using the normalized circular polarization degree within the limits ± 0.9 the magnetic fields accessible for the coronal magnetography lie in the range of $2\ 10^{-3}$ – $3\ 10^{+2}$ G. Attention should be paid to the type of electromagnetic wave mode coupling in the solar corona, especially at short frequencies (Gopalswamy et el., 1994; Lee et al., 1998).

(2) The coronal magnetography accuracy is limited by the accuracy of the circular polarization degree. If the FASR accuracy is $\delta\rho^V/\rho^V \leq 5\ 10^{-3}$ (ρ^V = V/I), the multiple polarization inversion of the radiation from a slightly polarized source, ρ_0^V = 0.05 – 0.1, can be resolved. This possibility enables us to measure magnetic fields at a number of coronal heights simultaneously.

(3) To facilitate the acquisition of a uniform data set from radio observations the linear polarization (Stokes Q, U) is supposed to be measured in an active region close to the line of the zero circular polarization (V = 0) rotation (Alissandrakis, Chiuderi-Drago, 1994). These occasional observations offer a means of determining the product of the electron density and

the scale of magnetic field divergence as well as the magnetic field strength in the coronal QT-region (Segre, Zanza, 2001). A narrow bandwidth of $\Delta\nu \leq (3 - 2)\ 10^3$ Hz is recommended for the FASR measurements of the linear polarization at a wavelength of about 4 – 5 cm, where the polarization inversions are quite common.

Acknowledgments

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