Coronal Magnetograms of Solar Active Regions

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Abstract

The state of the art in the coronal magnetography through quasi- transverse (QT-) propagation of microwaves is discussed. The measurements are based on the fact that the circular polarization modification depends on the intensity of the magnetic field in the QT-region, where microwaves pass through the magnetic field lines at the right angle. The obtained coronal megnetograms are a series of 2D partial magnetograms, covering on each day a part of the active region. The Nobeyama Radioheliograph provides the coronal magnetograms of 110 - 50 G and the Siberian Solar Radio Telescope those of 30 - 10 G. The first results are encouraging in the sense that the features of the measured coronal magnetograms are consistent with the geometry of the QT-region. Two problems of the coronal magnetography are outlined: (1) the correct identification of QT effects and (2) the determination of the only unknown coordinate, i.e., the QTR height.
Key words: Sun: radio emission - low corona - magnetic fields

1. Introduction

This paper discusses some recent results concerning the coronal magnetography through the quasi-transverse (QT-) propagation of microwaves. The other types of coronal magnetography in microwaves make use of (1) the polarization of gyro-resonance emission (e.g. Alissandrakis et al., 1980) and (2) the polarization of free-free emission proposed by Gelfreikh (1999) (see also White 2004; Gelfreikh 2004; Ryabov 2004 for comprehensive reviews of all the types of coronal magnetography).

The observable effect of QT-propagation is the change of the circular polarization in the microwave source "screened" by the region of QT-propagation (QTR). The effect is coronal magnetic field and wavelength- dependent and is most pronounced as the inverted sense of circular polarization.

There is some transformation of circular polarization in the site where the coronal magnetic field is perpendicular to the line of sight. The theory of the QT-propagation (Cohen 1960; Zheleznyakov 1970; Bandiera 1982) predicts that the circular polarization sign reverses if the

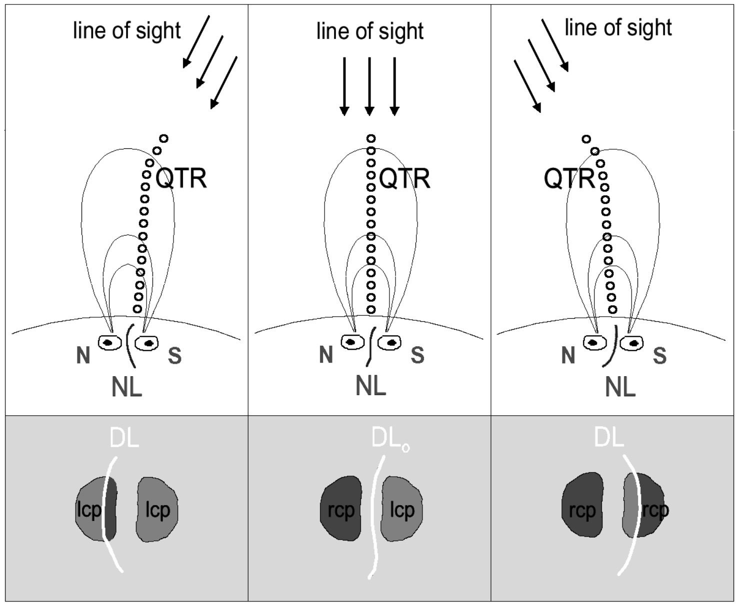

Fig. 1. Sketch of polarization changes in two microwave sources with time (lower row) associated with a bipolar active region (upper row) during its transit on the solar disc. The coronal QT-region (circles) is the site of polarization changes observed in either limbward microwave source.

ray path of microwaves crosses, almost perpendicularly, strong enough magnetic fields (Figure 1). The polarization is only slightly modified in case of weak coronal fields. A moderate field in the coronal QT-region appears as a zero circular polarization line (depolarization line, DL). The sense of the original circular polarization corresponds to the sign of longitudinal component of magnetic fields in a source of microwave emission. The polarization of a sunspot-associated source can be related with the sign of sunspot magnetic fields. Right hand circular polarization (r.c.p.) corresponds to N (positive) magnetic fields; left hand circular polarization (l.c.p.) corresponds to S (negative) magnetic fields, provided the extraordinary mode prevails in the emission of a microwave source.

Polarization changes and inversions have been detected in some microwave sources both as continuing phenomena at a fixed observational wavelength (Piddington and Minnett 1960; Peterova and Akhmedov 1974) and through the cm wavelength range (Peterova and Akhmedov 1974; Gelfreikh et al. 1987). No corresponding changes of magnetic polarity in the photosphere have been observed. It appears that the polarization is strongly affected by propagation conditions on the way through the solar corona to the observer.

The first problem a solar physicist encounters is the correct identification of the observed polarization inversion. Some other effects, distinct from QT-propagation, can give rise to polarization inversion in microwaves. A persistent problem here is the determination of the accurate distance between the microwave source and the QTR. The distance or the height of the QTR above the photosphere is the only unknown coordinate of the measured magnetic field.

The features of the previously measured coronal magnetograms and some possible ways for solving problems mentioned above are discussed in this paper.

2. On the Technique of Coronal Magnetography

If the original degree of circular polarization ρ_0 is undergoes the QT effect, the coronal magnetic field $B(G)$ to be measured in the QTR reads:

$$B \approx 2.05 \times 10^2 \lambda^{-4/3} \left[-ln \left(\frac{\rho + \rho_0}{2\rho_0} \right) \right]^{1/3}, \tag{1}$$

where ρ is the observed polarization degree affected by QT- propagation and λ(cm) is the observational wavelength. Equation (1) is inferred from Equations (2), and (3), given by Zheleznyakov and Zlotnik (1964), under the assumption $NL_d = 10^{18} cm^{-2}$, where N is the electron density and L_d is the scale of the ambient magnetic filed divergence.

$$\rho = \rho_0 \left[2 \exp(-2\delta_0) - 1 \right], \tag{2}$$

where

$$2\delta_0 \approx 1.15 \times 10^{-25} B^3 N L_d \lambda^4. \tag{3}$$

According to a simple active region model, N decreases with height whereas L_d increases with height. Therefore, the product of these two quantities tends to be constant. Segre and Zanza (2001) found NL_d in the range of $(1.04-2.08) \times 10^{18} cm^{-2}$ on the base of the WSRT observations analyzed by Alissandrakis and Chiuderi Drago (1994). We suppose that the constant value of $NL_d = 10^{18} cm^{-2}$ is a good approximation.

The procedure starts with the selection of an unaffected by QTR radio map with the circular polarization degree $\rho_0(x,y) = V_0(x,y)/I_0(x,y)$. A microwave source associated with a bipolar active region can be considered unaffected if it looks like a bipolar microwave source, with the sense of circular polarization corresponding to that of the extraordinary mode (Figure 2e). This map ρ_0 is used for the normalization of a set of active region polarization maps $\rho(x,y) = V(x,y)/I(x,y)$.

The next step is to shift all normalized ρ/ρ_0 maps to the position of the normalizing map ρ_0. And finally, the normalized maps ρ/ρ_0 are converted into coronal magnetograms using Equation (1). The borders of the coronal magnetograms are derived from the reasonable limitation of $|\rho/\rho_0| < 1 - \sigma$, where σ represents the relative accuracy of these ρ maps.

3. Inspection of Results

3.1. Coronal Magnetography Using Different Microwave Sources: Time and Space Coverage

A bright sunspot-associated source is the most appropriate microwave source to reveal the QT-propagation effect. In this case the emission with strong polarization originates from the

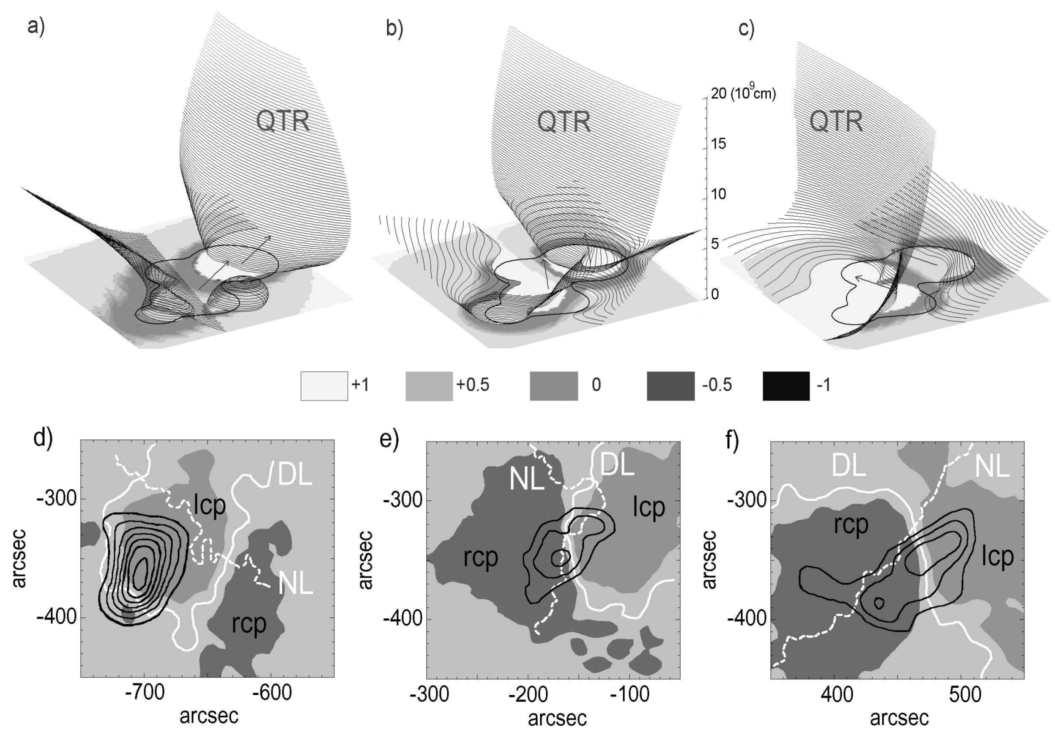

Fig. 2. Simulated QT-surfaces are presented in the top panels as the loci where microwaves cross the coronal magnetic vectors at the right angle. Grayscale images show the modification of circular polarization in the QTR according Eq.(2). The NoRH I (black contours) and V radio maps (greyscale) of the active region 9068 at 1.76 cm are coaligned with neutral line from the KPNO magnetograms on (d) July 3, (e) July 6 (near the central solar meridian), and (f) Jyly 9, 2000.

low-lying gyroresonance layers. The weaker magnetic fields higher up in the coronal QT-region make themselves evident in the changed sense of circular polarization. Since the QTR can lie on the way from the source to the observer, its effect is detectable. A coronal magnetogram as narrow as 30” - 40” was calculated from the Nobeyama Radio Heliograph radio maps of the active region NOAA 7260 with a bright sunspot-associated source at 1.76 cm (Ryabov et al. 1999).

A few coronal magnetograms 60” x 60” of a wide microwave source were determined using the Nobeyama Radio Heliograph (NoRH) and the Siberian Solar Radio Telescope (SSRT) maps at 1.76 cm and 5.2 cm correspondingly (Ryabov et al. 2004). The authors did not analyze the radiation mechanism of the microwave source with the circular polarization degree of 25%. The coronal magnetogram of 50 - 110 G at 1.76 cm and that of 30 - 10 G at 5.2 cm found to be complementary and spread over the heights of $(1.5 - 9) \times 10^9$ cm. The magnetograms were calculated for the day of the polarization inversion (Figure 3).

Recently, Bezrukov et al. (2004) have attempted to determine a long series of coronal magnetograms of the loop-associated sources undergoing polarization inversions in both solar hemispheres. The polarization inversion characteristics are assumed to be of the same origin,

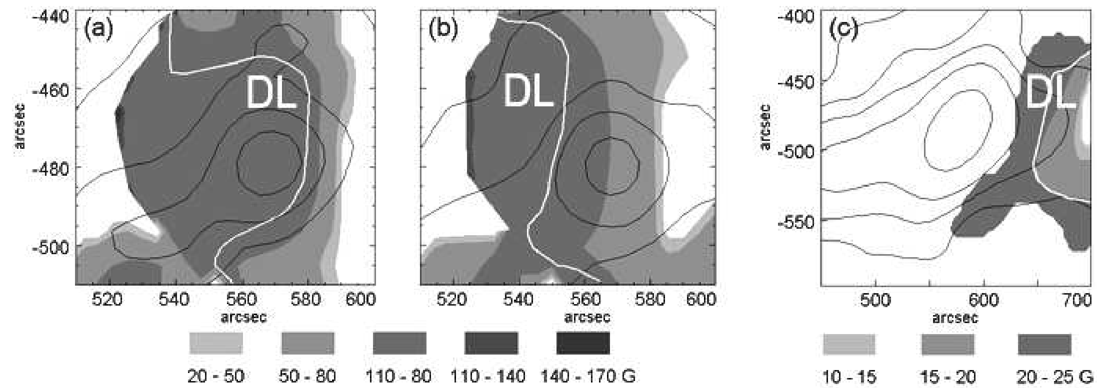

Fig. 3. Coronal magnetograms of solar active region NOAA 8365 on October 23, 1998 (a) and (b) are overlaid on the contours of total intensity I at 1.76 cm (NoRH) in the image plane. A coronal magnetogram (c) is overlaid on the contours of total intensity I at 5.2 cm (SSRT). (From Ryabov et al. 2004).

i.e. the QT-propagation, as those of the sunspot- associated sources (Figure 4).

3.2. Characteristic Lines and Features

An obtainable coronal magnetogram can be defined as the measured strength distribution of the magnetic vectors in the QTR as seen in the plane of view. The QT coronal magnetography is applicable to rather limited portion of the active region, which is effected by the QT-propagation and where the normalized degree of circular polarization ranges from $+1-\sigma$ to $-1+\sigma$. According to Equation (1), the measurable range is 28 -150 G at the wavelength 1.76 cm of the NoRH and 6.7 - 35 G at 5.2 cm of the SSRT, provided the radio map accuracy $\sigma = 0.05$. Stronger fields of each coronal magnetogram correspond to the circular polarization with the inverted sense, while weaker coronal fields correspond to only depressed original polarization. The intermediate strength of the measured coronal field is delineated by the zero circular polarization line (so called depolarization line; Bandiera 1982).

We can conveniently analyze the obtained coronal magnetograms using three characteristic lines:

- The depolarization line DL is the line where V = 0 on the sampled V radio map. At a given wavelength λ (cm) it delineates nearly the most precise magnetic field that can be measured by this technique (Ryabov 2004): $B_0 = 182\lambda^{-4/3}$. When normalizing the sampled maps, the position of DL remains unchanged.
- The depolarization line DL_0 is the line where $V_0 = 0$ on the normalizing map. This line has no direct correspondence in the coronal magnetograms. However, it is responsible for the position and shape of the strongest measurable field: $B_{max} = 318\lambda^{-4/3}$, provided $NL = 10^{18} cm^{-2}$ and $\sigma = 0.05$.
- The magnetic neutral line NL is the line where $B_l = 0$ on the photospheric magnetogram . It

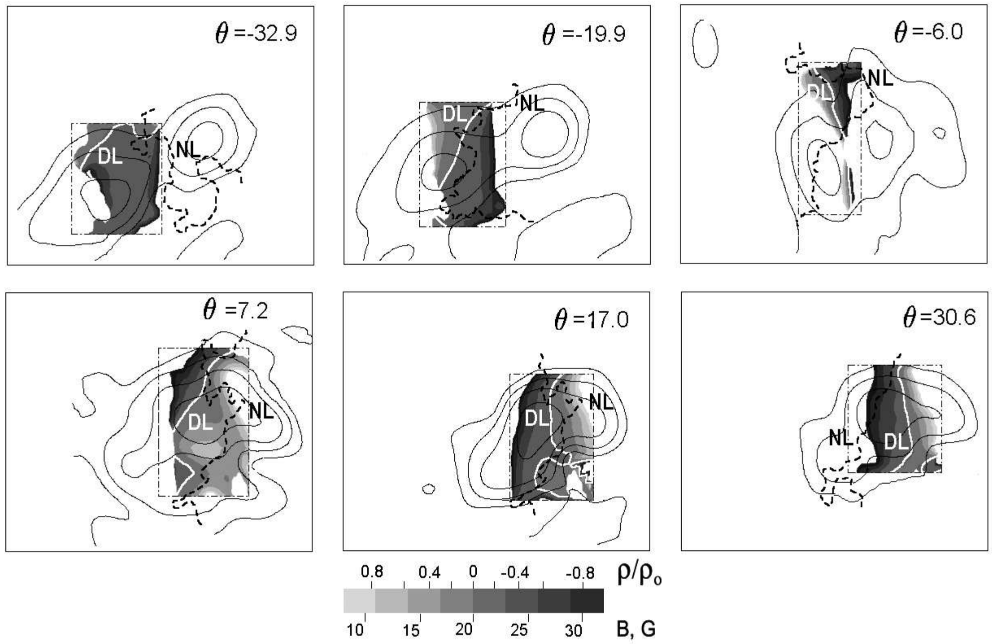

Fig. 4. A series of daily coronal magnetograms (greyscale) of the NOAA 9068 at several longitudinal displacements θ from the central solar meridian are overlaid on the contours of total intensity I at 5.2 cm (SSRT). (Fragment of Figure 4 from Bezrukov et al. 2004).

is also the lower border of the QT-surface, where the propagation angle strictly equals 90^o. The line provides one of the best means o determine the unknown height (Bandiera 1982; Kundu and Alissandrakis 1984), as well as the share and the inclination (Lee et al. 1998) of the QT-surface which "screens" the microwave source.

Bezrukov et al. (2004) have applied the above technique of coronal magnetography to the bipolar active region NOAA 9068 (Figure 4), observed with the SSRT from July 3 to July 10, 2000. During its transit on the solar disk the loop-associated microwave source inverted its polarization sense in each solar hemisphere, thus providing two sequences of coronal magnetograms. Some center-to-limb circular polarization variations in the loop legs have been noticed. Therefore, this technique can be applied as long as those variations do not significantly affect ρ/ρ_0, the quantity assumed to be due to the QT effects only.

Bezrukov et al. (2004) noted the westward movement of the DL due to the projection effect. The gradient of the measured coronal fields is directed east - west in the eastern hemisphere and west - east in the western hemisphere with the characteristic value of $8\times10^{-9}Gcm^{-1}$ in the plane of view. The gradient direction is assumed to be the result of two factors: the opposite inclination of the QT-surface in the eastern and the western hemispheres and the general tendency of the coronal magnetic fields to decrease with height. The relative positions of NL and DL indicate the QT-surface inclination, while smoother shapes of DL as compared with those of NL show the simplification of large-scale coronal magnetic fields with height.

Depolarization lines at two wavelengths together with neutral line outline the QTR with height. Ryabov et al. (2004) have compared the DLs, as they observed at 1.76 cm of the NoRH and at 5.2 cm of the SSRT, with the photospheric magnetic fields and their force-free field extrapolations. The DL is found to be closer to the NL at shorter wavelength in accordance with the Eq.(1) and the general tendency of coronal fields to diminish with height. The spatial location of each point in the QTR was restored and the two-dimensional coronal magnetograms were presented in three-dimensional space. The magnetic field extrapolations and the simulations of the QTR are found to be of great help since it is difficult to ascertain the foldness and correct position in the QTR even for simple active regions (see Lee et al. 1998).

4. Difficulties of Coronal Magnetography

Some radiation and propagation conditions for the polarization changes (polarization inversions) similar to those caused by the QT-propagation have been reported (Zlotnik 1999; Bogod et al. 2003). Bogod et al. (2003) found some rapid non-QT polarization inversions together with the QT polarization inversion in the flare-productive active regions. Recently Uralov and Rudenko (2005) revealed the near loop-top position of a lot of circularly polarized sources at 5.2 cm. This kind of sources may show a polarization inversion, where the radiation and propagation effects are combined (Alissandrakis and Preka-Papadema 1984). Thus, we need to elaborate more stringent requirements on the radio map sampling to avoid confusion with non-QT effects.

Difficulties emerge when one evaluates the only unknown coordinate, that is, the height in the QTR. The QTR height involved in coronal magnetography can be determined either from the displacement of the DL with respect to the NL (Kundu and Alissandrakis 1984; Alissandrakis 1999), or from the averaged rate of polarization inversion (Peterova 1975; Gelfreikh et al. 1987). The height can be calculated using the photosphere magnetic field extrapolation at coronal levels (Alissandrakis et al. 1996; Lee et al. 1998; Ryabov et al. 2004). A lot of uncertainty up to about a factor 2 of various estimates is another problem.

We propose the following improvements of the coronal magnetography technique in an effort to achieve more stable and correct results:

- Although this coronal magnetography is radiation independent, the radiation conditions, especially the position and the directivity $V(\theta)$ of the microwave source, should be analyzed to avoid confusion with non-QT effects.
- To eliminate the polarization changes of fluctuating microwave sources the V maps should be averaged. In case of the NoRH observations at 1.76 cm, we propose averaging over the time interval of 30 - 60 min. Doing so we can improve the estimates of the polarization inversion rate and the QTR height, but miss some possible oscillations of coronal fields. (Gelfreikh et al. (2005) have observed such active regions with an oscillating DL and

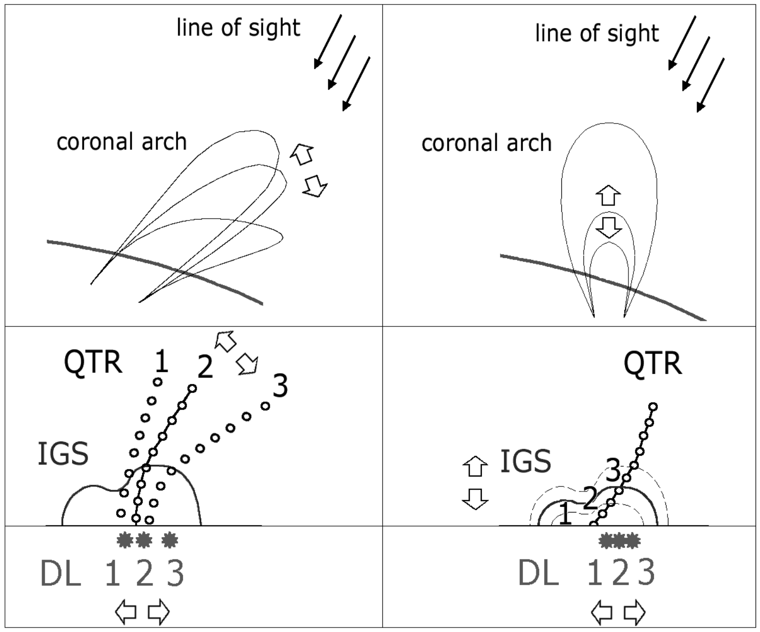

Fig. 5. Sketch of depolarization line (DL) oscillations give evidence of the oscillations of QTR (left column) and/or the oscillations of iso-gauss surface (IGS; right column).

a stable microwave source. The alternative ways to treat the microwave obsevations of oscillating DL are presented in Figure 5.)

5. Concluding Remarks

Radio mapping of the Sun with the NoRH at 1.76 cm and with the SSRT at 5.2 cm has provided data for two-dimensional coronal magnetograms in the range of 50 - 110 G and 10 - 30 G respectively (Ryabov 2004). Each magnetogram covers a QT-propagation affected part of the active region and is consistent with the presumed QTR geometry. For this reason we conclude that the first results of the coronal magnetography through QT-propagation are encouraging. Despite the radiation mechanism independence of this coronal magnetography, we propose an analysis of radiation conditions in microwave sources. This will help to reveal some non-QT polarization changes in a source, including center-to-limb variations during the solar disk transit.

An attempt (Bezrukov et al. 2004) to calculate a series of coronal magnetograms of a few bipolar regions shows that the evolutional changes of microwave sources do not completely distort the expected feature of the coronal magnetograms. For stable and correct coronal magnetograms we propose to sample the normalization map as close to the onset of polarization inversion as possible and average the sampled V maps over the 30 - 60 min intervals.

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