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ANALYSIS OF THE MULTIPLE INVERSION OF CIRCULAR POLARIZATION IN SOLAR MICROWAVE LOCAL SOURCES

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Abstract. The multiple inversion of the sign of circular polarization in the microwave local source of an active region is interpreted as a result of the quasi-transverse propagation of microwaves. For further analysis of the inversion, mathematical restrictions on the degree of circular polarization are drawn using the wave mode coupling theory. The polarization depression at wavelengths, adjacent to the wavelength of zero circular polarization, is estimated for three active regions. Also, the dependence of multiple inversion on wavelength as a result of multiple crossing of the coronal QT-regions is verified. We suggest a hierarchy of coronal arches of active regions as a structure responsible for the multiple inversion of circular polarization of microwaves.

Key words: Sun: radio emission, corona, magnetic fields

1. INTRODUCTION

Double inversion of the circular polarization was detected for the first time by Bogod et al. (1993a) in the spectral polarization observations with a new Panoramic Spectrum Analyzer (PAS, see Bogod et al. 1993b) of the RATAN-600 radiotelescope on January 9–10, 1992. It was attributed to the electromagnetic mode coupling in the regions of the quasi-transverse propagation in the solar corona (hereafter, QT-regions) (Zheleznyakov 1970).

The sign of circular polarization of sunspot-associated microwave local sources (LS) correlates with the polarity of the photospheric magnetic field. The sign originates from the excess of the extraordinary mode in the thermal microwave emission. The observations of Peterova & Akhmedov (1974) show that 20% of the bipolar solar active regions (ARs) are subject to inversion of the sign of circular polarization during the passage through the solar disk due to axial rotation.

The regularities of the single inversion of circular polarization have been well established by Peterova & Akhmedov (1974). In contrast to the single inversion, where circular polarization varies gradually from one wavelength to another, abrupt changes at adjacent wavelengths are observed in the case of the multiple inversion (Figs. 1 and 2).

The detection by Bogod et al. (1993a) of the double inversion in the centimeter wavelength range raises at least two questions: how one can verify the reality of the phenomenon and what is the multiplicity of the detectable inversions? Trying to verify if the multiple inversion is due to the wave mode coupling in QT-regions, in the present paper we compare the observed radio spectrum $\rho^V(\lambda)$ of an AR with the theoretical spectrum (Section 3). This comparison can confirm the QT-propagation as the main cause of the multiple inversion. Also, this is important in determining the true number of sign reversals within centimeter wavelengths.

The multiple inversion detected with the PAS of RATAN-600 in the complex of active regions 145+152 SD, 1992 (AR 7154 + AR 7162) is discussed in the following sections. 145 SD and 152 SD are bipolar active regions in the southern and northern hemispheres, respectively (Fig. 1). The inversion is not as pronounced as in the case of double inversion in AR 6996, 1992, discussed by Bogod et al. (1993b), and seems to be dependent on the reduction procedure of radio observations. Hence, some complementary criteria should be elaborated for recognition of the reality and the multiplicity of the multiple inversion. For this purpose, mathematical restrictions on the degree of circular polarization are deduced from the wave mode coupling theory (Zheleznyakov 1970).

What concerns the model simulations of the double inversion, they are performed as in Willson et al. (1996). They do not provide a crucial test for the reality of multiple inversion. The POLAR2 model (see Gelfreikh et al. 1987 for details) is used and it only roughly simulates the flocculi magnetic fields by magnetic dipoles. It does

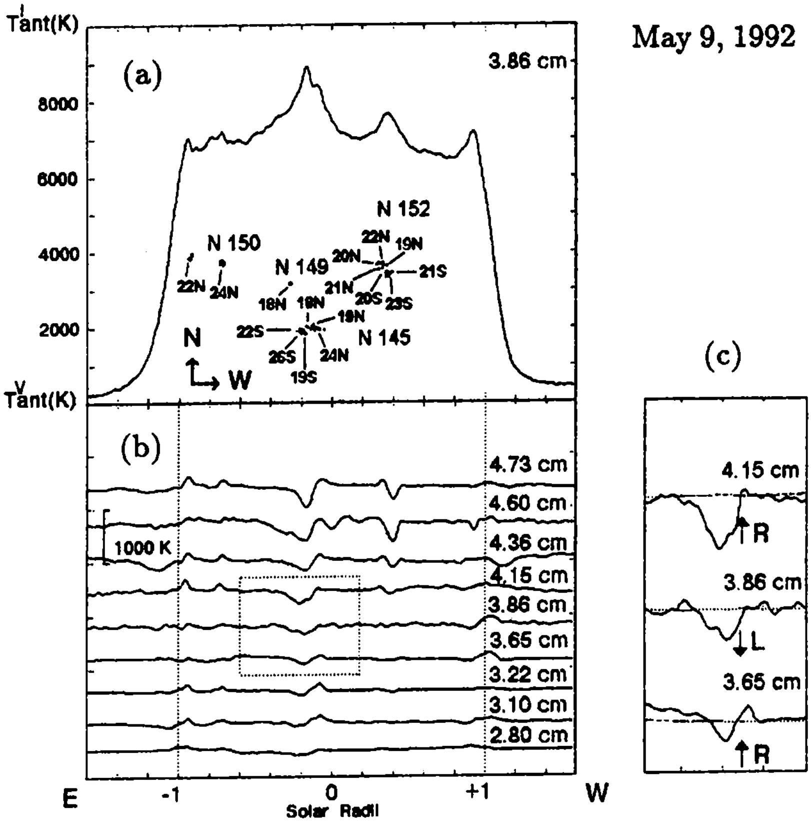

Fig. 1. One-dimensional fan beam scans of total intensity I (a) and Stokes parameter V (b) made with the PAS of RATAN-600 on May 9, 1992. The sunspots and peak magnetic field strengths H (in a units of 10^2 G) are depicted from the bulletin *Solnechnye Dannye 1992*. In (c), the double inversion of circular polarization in the leading sunspot-associated source AR 152 SD is shown on a larger scale.

not take into account the coronal currents in the AR magnetosphere (Section 2).

2. MODEL ANALYSIS

The double inversion of the sign of circular polarization through centimeter wavelengths in the microwave source, associated with the

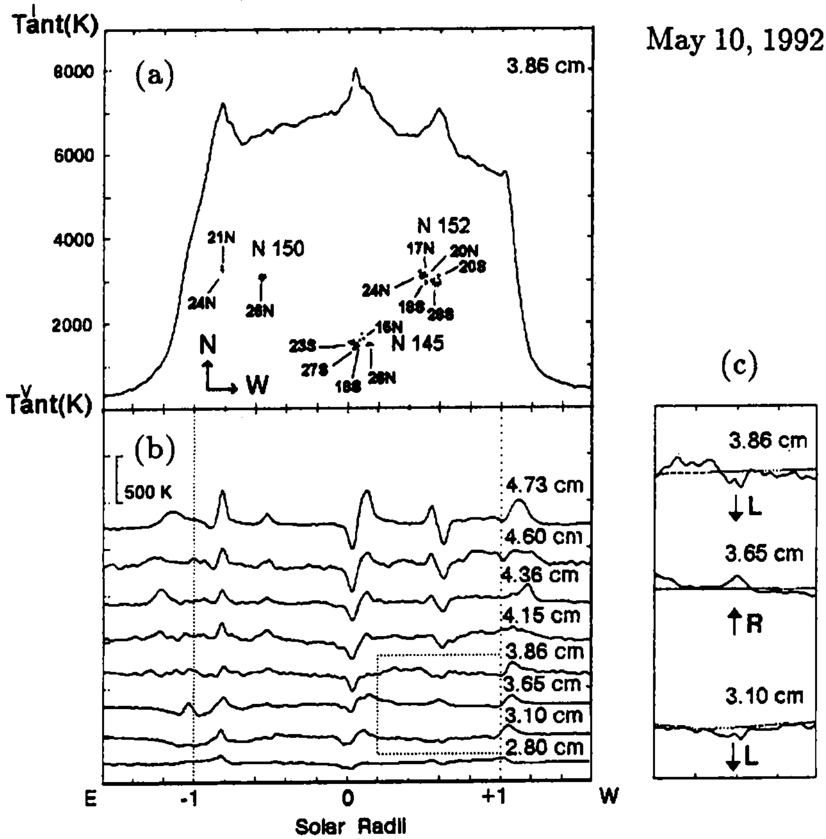

Fig. 2. The same as Fig. 1 but for ARs 145+152 SD on May 10, 1992. In (c), the double inversion of circular polarization in the leading sunspot-associated source AR 145 SD is shown on a larger scale.

leading sunspot ($H_{ph} = 2400$ G) of AR 145 SD (Fig.1), was registered on May 9, 1992, the day of the central solar meridian passage. While at the wavelength range $4.73 \leq \lambda \leq 3.22$ cm the source had the right-hand circular polarization, the sign of polarization seemed to change twice between wavelengths 4.15 - 3.86 cm and 3.86 - 3.65 cm. On May 10 a double inversion was detected in the central part of AR 152 SD at 3.65 cm (Fig. 2b).

To simulate the microwave QT-propagation, a POLAR2 model of Gelfreikh et al. (1987) is used. The model allows to calculate the generation of microwaves in the potential structure of the AR coronal field by the gyroresonance and the bremsstrahlung mechanisms and the quasi-transverse propagation. Computations with POLAR2 are routinely used to determine the coronal position of the QT-regions overlying the sunspot-associated microwave sources. The aim of this simulation is to obtain the sign of circular polarization for any resolved microwave source within the ARs. It is worth noting that each bipolar pair within an AR can be shown as containing a QT-region. Two sunspots or a sunspot-flocculus pair with the opposite magnetic polarities create the QT-region which is more or less inclined to the vertical and elongated within the solar corona (Fig. 3). The multiplicity of the polarization inversions does not exceed the total number of the bipolar pairs.

The results of the routine model simulations for ARs 145+152 SD on May 9–10, 1992 are as follows:

(1) The problem is with simulating the double inversion at the wavelengths around 3.86 cm. The dipole model fails to explain the second crossing of QT-regions at the strength of the coronal magnetic field H of 20 G. It is supposed that two crossings of QT-regions at two close values of H, 25 G and 20 G, could be simulated by extrapolation of magnetographic measurements to the coronal levels. This approach could give a smaller characteristic scale of the coronal field and close values of the strength in both crossings of QT-regions.

Nevertheless, our model simulations have provided evidence that a part of ARs 145+152 SD is "occulted" by QT-regions *twice* (Fig. 3). According to the routine technique and using Eq. (1) (see Gelfreikh et al. 1987), the field strength H from 13 G to 48 G at the corresponding heights h from 16×10^9 to 9×10^9 cm has been evaluated.

(2) With the POLAR2 it was possible to simulate the double inversion itself, but the degree of circular polarization $\rho^V(\lambda)$ could not be estimated quantitatively.

(3) The field line structure computed on the basis of the model dipoles resembles the Yohkoh soft X-ray structure. The absence of apparent coronal currents can be concluded. However, the fine coronal structure of the ARs cannot be presented properly by a superposition of the model dipoles. The rough simulation of the coronal structure cannot predict the complicated effect of the multiple inversion or demonstrate it in details.

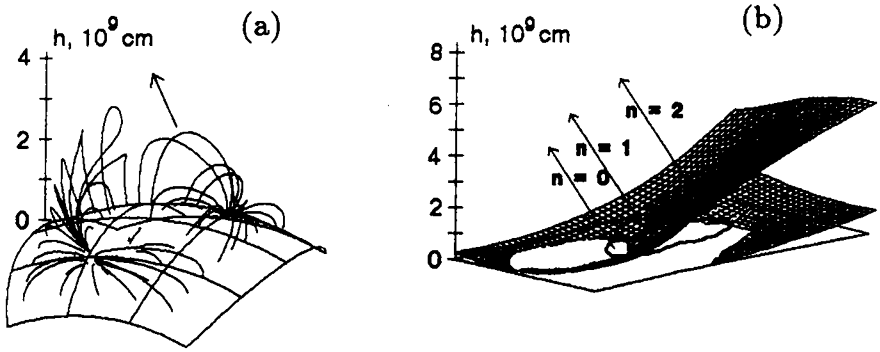

Fig. 3. The results of model simulations for ARs 145+152 SD: (a) the lines of force of the coronal magnetic field and (b) the coronal regions (twofold surface) of the quasi-transverse propagation of microwaves covering a sunspot-associated source.

3. RESTRICTIONS ON CIRCULAR POLARIZATION

According to Zheleznyakov (1970), in the frame of the wave mode coupling theory the original degree of the radiation ρ_0^V is transformed to ρ^V in the QT-region as follows:

$$\rho^V = \rho_0^V \cdot \left(-1 + 2\exp(-\left[\lambda/\lambda_t\right]^4)\right) \tag{1}$$

where

$$\lambda_t \approx 1.72 \times 10^6 H^{-3/4} N^{-1/4} L_\alpha^{-1/4} \tag{2}$$

depends on the electron density N, the magnetic field strength H, the observing wavelength λ and the scale length of the magnetic field divergence $L_\alpha = \alpha \left| d\alpha/d\vec{l} \right|^{-1}$ (all units in CGS). The propagation angle (between the line of sight $\vec{l}$ and $\vec{H}$) is $\alpha \approx 90°$ in the QT-region.

Now we will analyze the depression of circular polarization at wavelengths close to the wavelength of the polarization inversion (zero circular polarization). Let us assume that a set of radio observation wavelengths can be written as follows: $\lambda_{i+1} = \lambda_i + \varepsilon \cdot \lambda_i$, $i = 1, 2, 3, ..., m$. In the case of PAS of the radiotelescope RATAN-600, $\varepsilon = 0.05 and m = 27$ (Bogod et al. 1993b). If the wavelength of the inversion is λ_i ($\rho(\lambda_i) = 0$), then according to Eq. (1),

$\lambda_t = \lambda_i \cdot \ln^{-1/4} 2$. Let the normalized degree of the circular polarization be defined as $r(\lambda) = \rho(\lambda)/\rho_0(\lambda)$. Taking into account the mentioned equations, Eq. (1) can be rewritten:

$$r(\lambda_{i+1}) = -1 + 2 \cdot \exp(-[\lambda_{i+1}/\lambda_t]^4) = -1 + 2 \cdot \exp\left([1+\varepsilon]^4 \times \ln 0.5\right)$$

or

$$r(\lambda_{i+1}) = -1 + 2^{1-(1+\varepsilon)^4}. \tag{3}$$

We obtain a restriction on the absolute value of the degree of circular polarization at the wavelength adjacent to the wavelength of the inversion. According to Eq. (3), $r(\lambda_{i+1}) \approx 0.14$ for $\varepsilon = 0.05$, that is

$$\mid \rho \mid \leq 0.14, \tag{4}$$

because $\mid \rho_0 \mid \leq 1$. The restriction $\rho \leq 0.52$ has been found to be valid for the RATAN-600 solar receiver configuration before 1992 ($\varepsilon \approx 0.2, m = 11$), e.g. it is valid for the case described by Gelfreikh et al. (1987) (Fig. 4c). The degree of circular polarization detected on May 9, 1992 does not contradict the above restriction.

If microwaves cross the QT-regions n times, then the degree can be expressed like this:

$$r(\lambda) = \prod_{j=1}^{n} \left(-1 + 2\exp(-[\lambda/\lambda_{tj}]^4)\right), \tag{5}$$

where λ_{tj} is a parameter characterizing the coronal QT-region in j-th crossing. The wavelength dependence of the multiple inversion (5) is clearly seen when λ is expressed in units of λ_{t1} (Fig. 4).

The observed effect of the multiple polarization inversion (in terms of normalized degree $r(\lambda/\lambda_{t1})$) can be compared with the wavelength dependence of $r(\lambda/\lambda_{t1})$ calculated by Eq. (5) for the case of various crossings of the QT-regions.

The calculated curve $r(\lambda/\lambda_{t1})$, where $\lambda_{t1} = 3.73$ cm at $n = 2$, does not fit the normalized polarization of the leading part of AR 145 SD well (Fig. 4a). A possible reason may be the uncertainty of the original (not transformed in the QT-regions) polarization ρ_0 evaluated on May 8 and taken to normalize ρ on May 9, 1992. Another reason may be the additional crossings of QT-regions and additional polarization reversals. A much better agreement of theory and observations is found for the curve at $n = 4$ (Fig. 4a) corresponding to multiple inversion and close to zero polarization at $\lambda = 5.26$ cm.

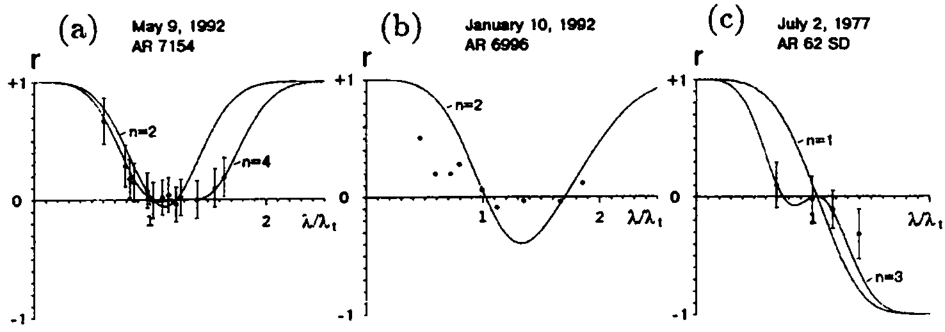

Fig. 4. The theoretical (curves) and the observed (dots) normalized degree of the circular polarization r plotted as a function of the normalized wavelength λ/λ_t for (a) the active region 7154 & 7162 (145+152 SD) on May 9, 1992; (b) the active region 6996 on January 10, 1992 and (c) the active region 62 SD on July 2, 1977.

4. DISCUSSION

Our attempts to fit the observed polarization inversions and the wave mode coupling theory have made it evident that:
- ARs 145+152 SD, 1992 (Figs. 1 and 4a) demonstrate fourfold rather than twofold inversion;
- the inversion in AR 6996, 1992, earlier considered to be twofold (Bogod et al. 1993b), does not obey the restrictions of Section 3 (Fig. 4b) and needs further analysis;
- the inversion in AR 62 SD, 1977, detected with smaller number of radio receivers comparing to PAS (Fig. 4c), should be classified as a threefold, not a single inversion (c.f. Gelfreikh et al. 1987).

In Section 3 the multiplicity of the polarization inversions and their reality are tested by means of mathematical restrictions. The tests have revealed additional reversals of the sign hidden in a sparse polarization spectrum. Abrupt reversals of the sign were rejected because of contradiction with the theory of the wave mode coupling in a QT-region. Consequently, restriction (4), as well as the normalized polarization spectrum $r(\lambda)$ given by Eq. (5), helps to understand the phenomenon of polarization inversion, especially of the multiple inversion.

If the restrictions on $\rho^V(\lambda)$ are satisfied, it is a necessary but not a sufficient condition for polarization inversion to be real and to be determined by the QT-propagation of microwaves.

As is shown in Section 2, the model POLAR2 is unable to simulate the coronal magnetic structure by superposition of magnetic dipoles, taking the real number of QT-regions found by radio observations. A refinement of the model should be made taking into account the fine photospheric structure and the coronal currents.

The multiple inversion seems to be promising way for a coronal magnetography simultaneously at a set of coronal heights, at which microwaves are crossing the QT-regions. For this high resolution two-dimensional spectral polarization observations of microwaves are required.

The topological properties of QT-regions are intriguing. Indeed, all coronal neutral points and neutral current sheets are to be found at a QT-region for any direction to the observer; the magnetic structure in the vicinity of neutral points is inclined to produce double polarization inversion (Ryabov 1985). The coronal structure, responsible for the multiple inversion, could be a hierarchy of coronal arcs of different sizes (e.g. Willson et al. 1996). The vicinity of the coronal neutral points and neutral current sheets is assumed to be responsible for the double inversion.

It should be noted that a hint on additional reversals of the polarization sign determined from the normalized spectrum $r(\lambda)$ is not imperative, if we take into account the accuracy of $\rho^V(\lambda)$ radio measurements. If restriction (4) is not obeyed in the case of sudden reversals, justified corrections of the measured ρ^V may eliminate this problem. On the other hand, the described restrictions seem to be appropriate to test if the multiple inversion is not an artifact due to reduction procedure of V radio scans.

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