RING STRUCTURES IN SOLAR S-COMPONENT RADIO EMISSION: MODEL CALCULATIONS AND OBSERVATIONS

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ABSTRACT. In the present paper numerical calculations of the S-component microwave emission from a region above a sunspot at 4.9 GHz for different values of the magnetic field model parameters are presented. The used electron temperature and density models were derived from recent optical and EUV observations (transition region at h 2000 km with steep temperature and density gradients) and have been extended to coronal heights assuming nonconstant conductive heat flow. As relevant emission processes thermal gyroresonance absorption and bremsstrahlung are taken into account. It is shown that all cases considered here (systematic variation of B_m between 0.12 T and 0.24 T) lead to more or less marked ring structures in both the intensity and polarization maps, vertical incidence provided. Existing differences to real observations are briefly discussed.

КОЛЬЦЕВЫЕ СТРУКТУРЫ СОЛНЕЧНОГО РАДИОИЗЛУЧЕНИЯ S-КОМПОНЕНТЫ - МОДЕЛЬНЫЕ РАСЧЕТЫ И НАБЛЮДЕНИЯ: Определено пространственное распределение микроволнового излучения S-компоненты для разных значений магнитного поля над модельным пятном. Использованные модели электронной температуры и плотности основаны на недавних оптических и ЭУВ-наблюдениях (узкая переходная область при высоте 2000 км) и экстраполированы в область короны предполагая непостоянный тепловой поток. Как определяющие процессы излучения учитываются тепловые тормозное и магнитотормозное излучения. Во всех случаях, рассмотренных в этой работе, показано, что возникают более или менее сильно выраженные кольцевые структуры интенсивности и поляризации. Существующие различия между теоретическими расчетами и наблюдениями кратко обсуждены.

PRSTENCOVÉ ŠTRUKTÚRY S-ZLOŽKY RÁDIOVEJ EMISIE: MODELOVÉ VÝPOČTY A POZOROVANIA.: V práci sú uvedené numerické výpočty S-zložky mikrovlnnej emisie (4,9 GHz) nad škvrnou, pre rôzne hodnoty magnetického poľa (parameter modelu). Po-

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užité modely elektrónovej teploty a hustoty boli odvodené z posledných optických a EUV pozorovaní (plytká prechodná oblasť vo výške h = 2000 km) a boli extrapolované do koróny za predpokladu premenného tepelného toku. Ako možné procesy žiarenia sú uvažované teplotné brzdné a gyrorezonančné emisie. Bolo zistené, že vo všetkých v práci uvažovaných prípadech (indukcia od 0.12 do 0.24 T) vznikajú viac, alebo menej výrazné prstencové štruktúry a to tak na mapách intenzity ako aj polarizácie. Krátko sú posúdené existujúce rozdiely medzi teoreticky vypočítanými a pozorovanými údajmi.

1. INTRODUCTION

The problem of enhanced and highly polarized microwave emission from sunspot regions was principally clarified by interpreting it being due to thermal gyroresonance absorption at low harmonics of the gyrofrequency (Zheleznyakov, 1962; Kakinuma and Swarup, 1962). First simple model calculations made by Zlotnik (1968) and Lantos (1968) showed sufficient agreement with the (not yet highly resolved) observations.

In recent time, forced by new observational techniques with much better angular resolution (VLA, WRST, RATAN-600) the question of the local structure of S-component sources at cm-wavelengths became a matter of interest again.

For the first time, Alissandrakis and Kundu (1982) and Lang and Willson (1982) observed ring or horse-shoe structures associated with active region sunspots, however, in many other cases such features could not be found.

Detailed model calculations were made by Gelfreikh and Lubyshev (1979), Alissandrakis et al. (1980), Hildebrandt et al. (1984), and Krüger et al. (1985), but it seems that this phenomenon is not yet completely solved, especially concerning the behaviour of I and V in the spot centre, as a recent paper by McConnell and Kundu (1984) showed. The aim of the present paper is to consider the problem of ring structures above sunspots from a more systematic point of view.

2. MODEL

The model used for the calculations was described in several other papers (e.g. Krüger et al., 1982; Krüger and Hildebrandt, 1985), so that it is not necessary to do it once more.

However, in contrast to former calculations we assume now a nonconstant conductive heat flow for the extrapolation of the temperature distribution to coronal heights. F_c decreases with increasing height and the temperature approaches an asymptotic value T_c, the only free parameter (cf. Staude, 1985). In Fig. 1 the height distributions of the used densitiy and temperature models are shown for two values of the parameter T_c (5×10^6 K and 3×10^6 K).

The magnetic field model was that of a vertical dipole at a distance A below the photosphere (the same as used e.g. by Gelfreikh and Lubyshev, 1979)

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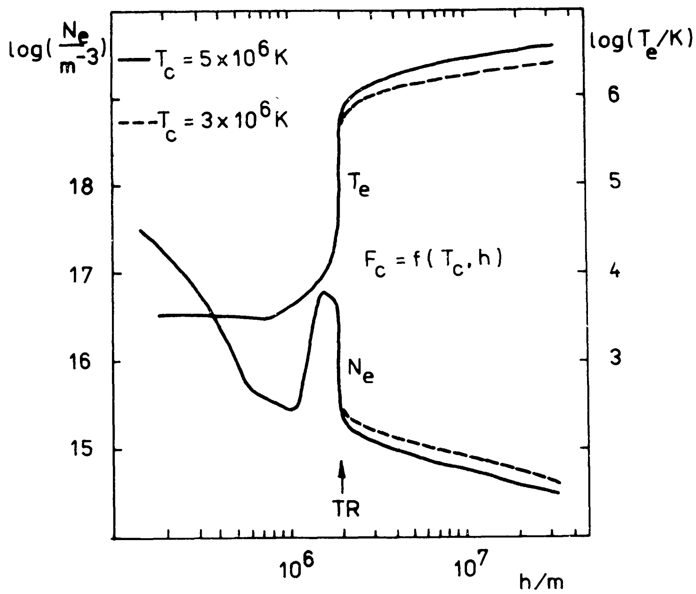

Fig. 1: Height distributions of the used electron temperature and density models above the spot for two values of the parameter T_c (asymptotic coronal temperature).

producing an axial symmetrical field which is in good agreement with typical single spot fields. Because of its symmetry we had to calculate the radiation only along a radius and not for the whole source region.

3. OPTICAL DEPTHS

It is well established that the main two emission processes for solar S-component microwave emission are thermal gyroresonance absorption and Coulomb bremsstrahlung. The second process cannot account for a significant part of the intense sunspot sources, since the corona is optical thin for this kund of radiation. At the levels, where $s\omega_B = \omega$, the absorption coefficient of the gyroresonance process is large enough to produce optical thick radiation with brightness temperatures $T_b > 10^6$ K, providing that strong magnetic fields exist.

Fig. 2 shows the optical depths for each of the first five harmonics in both the ordinary and extraordinary mode under coronal conditions at 4.9 GHz. If the s = 2 level is above the TR, the ordinary mode becomes optically thick for $\theta \gtrsim 22^\circ$ (θ - angle between $\underline{B}$ and the line of sight), whereas the extraordinary mode is optically thick everywhere (excepted at $\theta = 0^\circ$ which can be prac-

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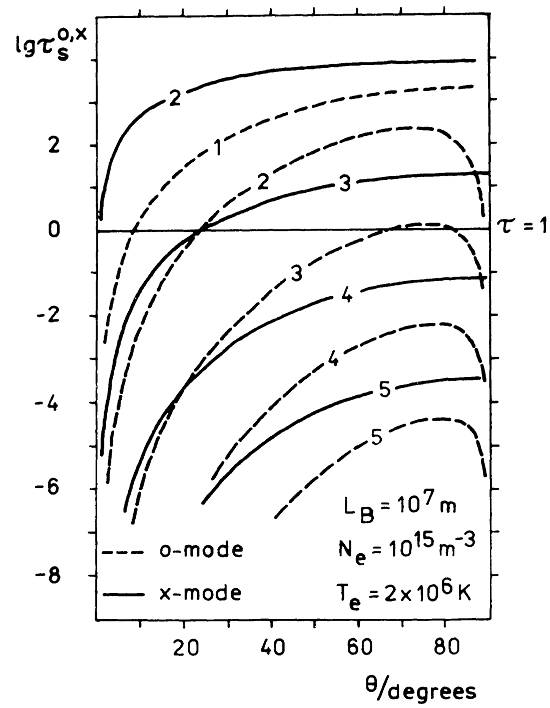

Fig. 2: Optical depths of the first five harmonics of gyroresonance absorption for both the ordinary (dashed lines) and the extraordinary mode (full lines) under coronal conditions at 4.9 GHz.

tically neglected). If only the s = 3 level is situated in the corona, τ^x exceeds unity for $\theta \gtrsim 25^o$, whereas τ^o is greater than unity only for $65^o \lesssim \theta \lesssim 80^o$.

4. RESULTS

In Fig. 3 the position of the resonance layers in form of a cross section along a radius (at the bottom), the corresponding spatial distributions of ordinary and extraordinary mode emission (above them), and the intensity $I = 0.5\ (T_b^x + T_b^o)$ and the polarization $V = 0.5\ (T_b^x - T_b^o)$ in temperature units (at the top) are presented. The maximum field strength B_m decreases from the left to the right. Because of the fact that larger spots show in general larger magnetic scale heights L_b, the parameter A was also decreased.

In the first case (B_m = 0.24 T) a contribution from the first harmonic in the ordinary mode emission occours near the centre, so we have a small additional peak in the intensity. The cases 2, 3 and 4 (B_m = 0.21, 0.18, and 0.15T,

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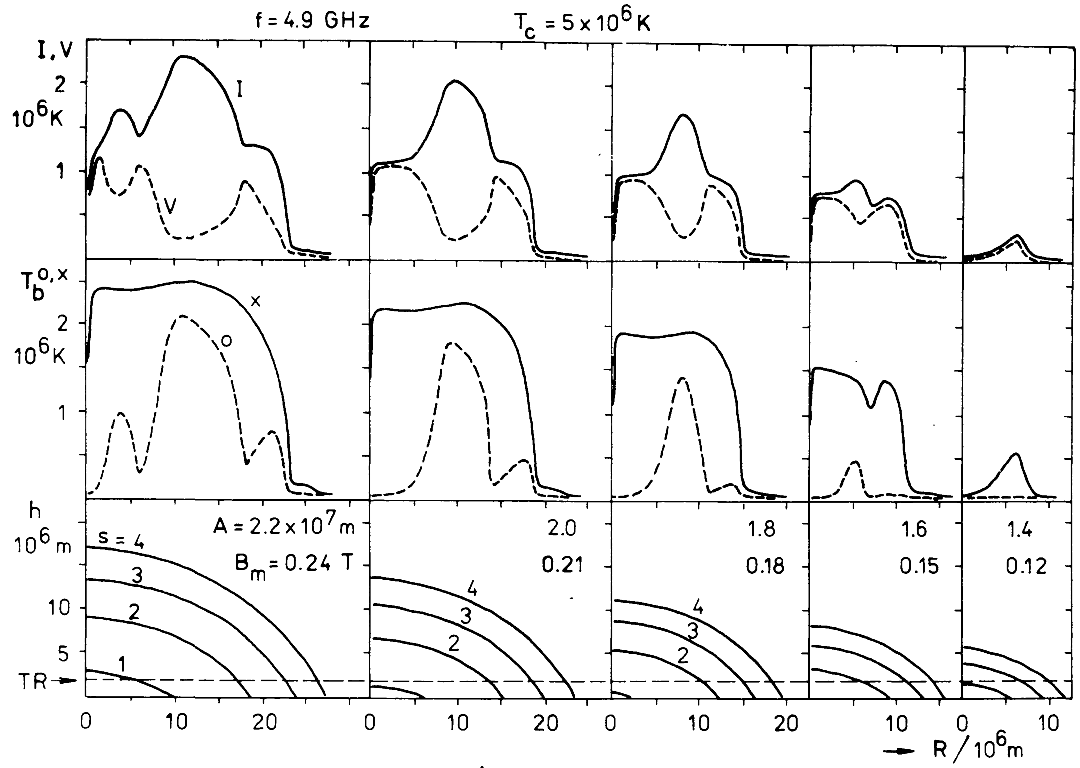

Fig. 3: Results of model calculations for five different values of the magnetic field parameters (decreasing B_m and A). The influence of the single harmonics upon the brightness temperatures is clearly marked by the positions, where the gyroresonance layers dropped below the TR. Additional explanation appears in the text.

respectively), show qualitatively the same behaviour: the second harmonic layer is above the TR and at the position, where Θ becomes large enough, the main contribution from the oedinary mode leads to maximum intensity ("intensity ring") and minimum polarization. In the outer region, where only the third harmonic level is above the TR, we get higher polarization again ("polarization ring"). Finally, in the last case (B_m = 0.12 T) only a contribution from the third harmonic can be obtained, therefore, we have an unpolarized centre and a small ring of intensity and polarization.

5. DISCUSSION

Summarizing the results of the model calculations we can say that, if the s = 2 level is above the TR, there will be always a polarized centre, a ring

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of maximum intensity, and a more outer ring of polarization.

The comparison with observation shows that in some cases principal agreement exists, in other cases the surely different real conditions (inhomogeneous structure of density and temperature distributions also in horizontal direction and more complicated magnetic fields) may influence the results.

Strong et al. (1984) compared their observations (WRST, May 1980) with model calculations and came to the conclusion that the assumption of cooler material above the umbra (Foukal et al., 1974) is the only reasonable explanation for the very deep intensity minimum observed in the spot centre. In another paper, McConnell and Kundu (1984) tried to interpret VLA observations by general considerations (without model calculations) in a similar way as we did, however, I cannot agree with all conclusions made by them. An unpolarized centre for the s = 2 level and an everywhere transparent third harmonic level seems to me hardly thinkable.

The general conclusion of all attempts to compare observations and calculations is that the angular resolution of the instruments must be further improved, because some (theoretical) features are smapper than 5".

At last, I want to make some remarks about the calculations made by Gelfreikh and Lubyshev (1979). These authors used simple step functions for the density and temperature model and, therefore, their emission maps show sharp changes between maxima and minima in polarization as well in intesity, but are in principal agreement with our calculations, what we have tested. If we assume continuous model distributions, the calculated brightness reflects the electron temperature in that height, where the optical depth becomes greater than unity, as it is seen in Fig. 3.

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DISCUSSION

B. Kálmán
Can you make a computation of the expected radio emission also with real sunspot magnetic field distribution? or is it difficult?

J. Hildebrandt
Yes, it is possible. Our program system was developed for analytical magnetic field models as well as for extrapolated fields from magnetograpfic measurements. The only difference is the much higher computation time in the latter case.

G.B. Gelfreikh
Have you calculated two-dimensional pictures as well and have you seen horse--shoe structure?

J. Hildebrandt
Yes, we have. They have been published e.g. in Astron. Astroph. 134 (1984), 185 and in the Proceedings of Debrecen meeting (1983). Horse-shoe structures can be seen either if you look at a source which is not located near the disk center or if the magnetic field is very complicated.

G.B. Gelfreikh
For the first time probably a ring structure have been obtained from the 1970 solar eclipse observations and presented by Dr. A. Korzhavin and myself at KAPG Consultation in Irkutsk in 1975. The paper have been published in the Proceedings of the meeting.

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