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ON THE RELATION BETWEEN SUNSPOT AND INTERSPOT COMPONENTS OF MICROWAVE RADIATION OF SOLAR ACTIVE REGIONS

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ABSTRACT. *The results of investigations of the structure of 4 local solar radio emission sources are given. They are based on observations with the RATAN- 600 in the wavelength range 1.7-21.7 cm. Three of the sources are shown to include a considerable interspot component (halo), exceeding 50% of the total flux of the emission. The spectrum and polarization of the interspot radiation are analysed. The presence of very steep spectra (n~6) is confirmed for some cases. The flux density grows with wavelength. In one case a high degree of polarization (P~45%) of the interspot radiation is found. The deduced parameters of the interspot component can not be interpreted in terms of a simple model of thermal bremsstrahlung generation of radio radiation.*

The microwave emission from local sources (LS) located in the solar atmosphere above the active regions (AR) is considered to have thermal origin and be due to the joint effect of bremsstrahlung and cyclotron mechanisms (Zlotnik, 1968). Such a notion of the LS is based, in particular, on observational results (with a resolution of 1-3 arcmin) of the structure of LS, which suggest it can be divided into two main components: interspot radio emission (halo) and sunspot associated components. The former has the characteristic size of the whole AR and is supposed to be genetically related to plasma that is kept in the magnetosphere of the AR. It generates radiation of a bremsstrahlung character in weak (hundreds of Gs) magnetic fields. The spot component is close to the penumbra of the spots in size and is associated with the cyclotron radiation of thermal electrons in strong (thousands of Gs) magnetic fields of the solar spots.

Now, with the observations of much higher resolution (<1 arcmin) we can distinguish these components more reliably, estimate the relative contribution of both components to the total radiation and separately determine their characteristics. Special attention should be paid to the interspot radiation, the information on the spectra and polarization of which has been accidental up to now. There is some evidence that the characteristics of "halo" radiation are in contradiction with the concept of bremsstrahlung mechanisms (Akhmedov et al., 1987; Korzhavin and Peterova, 1992).

Investigation of the structure of LS is now under way using the new data of the RATAN-600 observations. In this paper the observations of four AR are analysed, and the results are given as a series of possible relative variations of the spot and interspot components in LS.

I. THE OBSERVATIONS

We used the RATAN-600 observations of the Sun made during the years 1980-1991 in the wavelength range (1.7-21.7) cm. The Stokes parameters I and V were registered. The one-dimensional resolution in this wavelength range was $\Theta_{0.5}$(E-W) = (15-196) arcsec. The data was analysed according to the procedure proposed by Akhmedov et al. (1987). In addition the LPR (Large Pulkovo Radiotelescope) observations, and the strip-scans of the Sun, published in "Solar-Geophysical Data" (SGD) and "Solnechnye Dannye" (SD), were used. The structure of LS was compared with the photoheliograms made at the Kislovodsk Mountain Astronomical Station.

The division of the structure of LS into separate components is not a simple task. Here the interspot component is determined as the lower smoothed curve of the one-dimensional distribution of radio brightness over an entire region. The interspot component is the background to the brighter and more compact sunspot associated source. However such an approach is only possible if some conditions are taken into account: the sizes of bright details must be larger than the width of the diagram pattern $\Theta_{0.5}$(E-W), and the degree of polarization must not exceed 100%. Due to these conditions we have chosen for consideration only large AR with sizes Θ>2 arcmin and an area Sp>600 m.s.h. Besides, periods of rapid development of AR when the structure of LS may vary quickly were excluded.

After all, four AR were chosen and investigated, it was found that the ratio of the sunspot and interspot components of microwave radiation can vary over a very wide range, from 0 to 100%.

II. THE RESULTS OF ANALYSIS

II.1. "Degenerate" halo. The AR SD No.281/1991

This case derived such a name because the LS's structure had a lack of halo and the interspot component looked like a compact "degenerate" detail.

The AR SD No. 281/1991 had an almost symmetrical bipolar structure consisting of two spots of opposite magnetic polarity, with approximately equal area and pores situated between the main spots. The distance between these spots was about 3 arcmin (see Fig. 1).

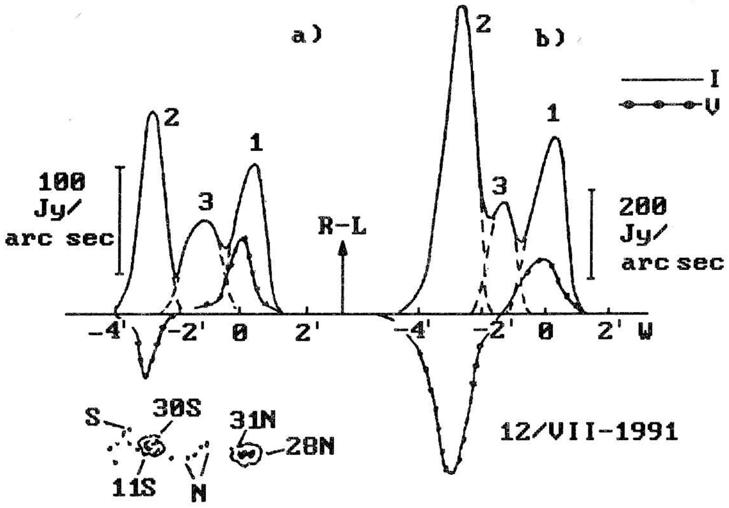

Fig. 1. *One-dimensional brightness distribution of the polarized (V) and non-polarized (I) radiation from the LS of the AR SD No. 281/1991 at the wavelengths 2.3 cm (a) and 6.0 cm (b) from observations at the RATAN-600.*

The one-dimensional brightness distribution for the LS of AR SD No. 281/1991 according to the RATAN-600 observations is given in Fig. 1. Comparison of this distribution with the photoheliogram of AR distinguishes three details. Two of them (No. 1 and No. 2) are connected with the sunspots and have sizes comparable with the penumbra of corresponding spots (i.e. 20-40 arcsec). They present the sunspot associated component. Detail No. 3 is associated with the group of pores. The radiation parameters of all details are listed in Table 1. Analysis of these data shows that the radiation parameters of details No. 1 and No. 2 readily agree with the concept of the thermal cyclotron mechanisms for generating the radio emission. The emission of detail No. 3 at short wavelengths ($\lambda \leqslant 2.3$ cm) can be understood using the assumption of the bremsstrahlung mechanism. However, at longer wavelengths ($\lambda \simeq 6$ cm) the flux increases with λ while the effective size decreases. This implies that a brightness increase of cyclotron nature can be expected. Thus, detail No. 3 may only formally be attributed to the halo. In any case for the LS of AR SD No. 281/1991 the sunspot component gives the main contribution (>50%) to the total radiation (see Fig. 2).

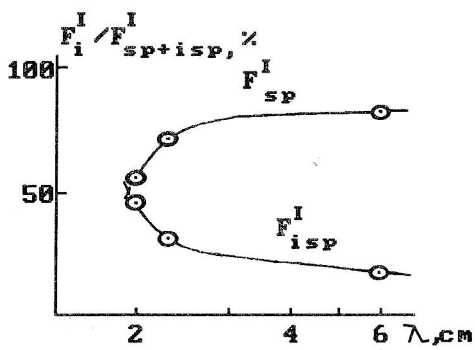

Fig. 2. *Relative contribution of the spot (F^I_{sp}) and interspot (F^I_{isp}) components into summary radiation of the LS of AR SD No. 281/1991.*

Table 1. The radioemission parameters for separate details of the LS of the AR SD No.281/1991

Detail and identification	wavelength	flux	polarization degree	size	brightness *) temperature
	λ cm	F^I s.f.u.	$P=F^V/F^I$ %	B^I_0 arcsec	$\Delta T_B \cdot 10^3$ K
No.1 spot	2.0	0.8	50	44	20
	2.3	1.6	40	42	60
	6.0	5.4	32	38	1050
No.2 spot	2.0	0.4	75	22	50
	2.3	1.6	35	31	120
	6.0	3.1	54	38	1820
No.3 group of pores	2.0	1.0	0	83	10
	2.3	1.4	0	73	20
	6.0	2.0	0	38	640

*) ΔT_B, here and in Tables 2 and 3, is exceeding brightness over the background temperature of the "quiet" Sun.

It is interesting to note that the emission capacity of this LS, defined as F^I/S_p, at all wavelengths including centimetre and decimetre, was very low. According to the LPR observations at the 20 cm wavelength this LS has practically no contrast when compared with the background radiation of the quiet Sun, although the area of spot group was rather large (Sp = 645 m.s.h. - 12/VII)). It allows us to assume that in general the interspot component's contribution to the total radiation of LS is rather considerable. It is possible that in the case of the LS of AR SD No.281/1991 the interspot component is manifested in the metre wavelength range. According to Yurovsky et al.(1992) this exact AR was the source of the noise storm. It should be noted that the radiation brightness of detail No.2 is almost twice as large as that of detail No.1. Though the area of the corresponding sunspots was almost equal, they had different morphology - the spot No. 2 consisted of widely distributed umbra, had a bright bridge and probably δ-configuration. These peculiarities determined the conditions for additional heating of the emission region.

2. "Quasi-thermal" halo. The AR SD No.247/1980

Unlike the previous case, the interspot component predominated strongly over the spot component in the emission of this source. This case was named "quasi-thermal" halo, because the flux density of the halo in the wavelengths range (2.0-4.0 cm) was about 7 s.f.u. and almost independent of frequency.

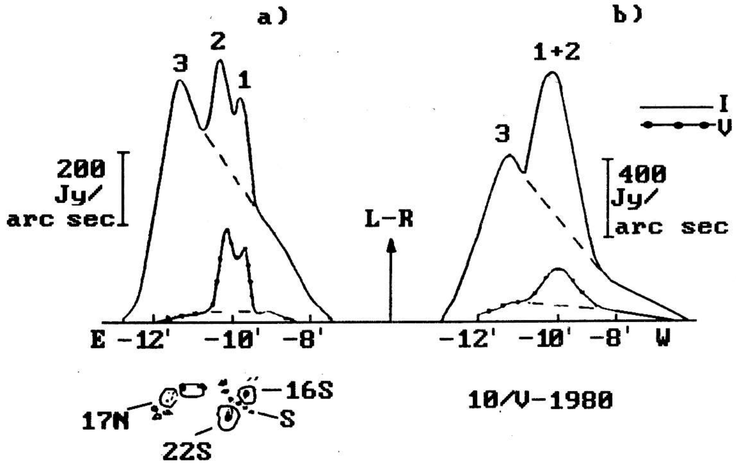

Fig.3. *One-dimensional brightness distribution of the polarized (V) and non-polarized (I) radiation over the LS of the AR SD No.247/1980 at the wavelength 2.3 cm (a) and 4.0 cm (b) from observations at the RATAN-600.*

The brightness distribution (Fig.3) consisted of two components: extended halo of about 2 arcmin in size (detail No.3) and sunspot associated component (details No.1 and No.2). The brightness temperature of the halo emission was rather small at the wavelength 4 cm $T_B^{halo} = 150 \cdot 10^3$ K. A weak polarization of the halo emission was observed, and the degree of polarization for the whole wavelength range did not exceed 7%. At the moment of observations on 10/V the LS was situated near E-limb and the left sign of polarization dominated in the emission of the halo. It corresponds to the predominance of extraordinary mode for the south polarity of the magnetic field, which is assumed the field of the leading part of the group.

When the LS was crossing the solar disk the location of the sunspot associated component changed relative to the halo. The difference between them shows that the halo emission is generated higher in the solar atmosphere than the spot component.

As a whole, the LS of the AR SD No.247/1980 most probably corresponded to the coronal condensation because the main contribution (~75%) to the total radiation of the LS comes from the interspot (halo) component (see Fig. 4).

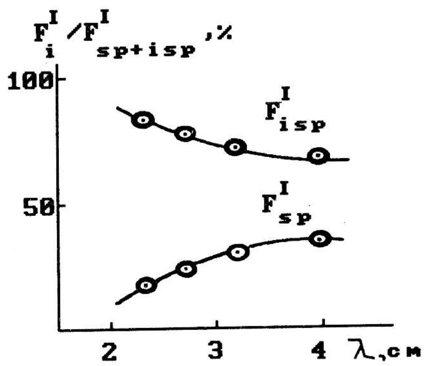

Fig.4. *Relative contribution of the spot (F^I_{sp}) and the interspot (F^I_{isp}) component to the total (F^I_{sp+isp}) flux from the LS SD 247/1980.*

3. Intermediate case. AR SD No.30/1991

The structure of this AR is believed to be a "typical" one, when both components, sunspot associated and interspot, are strongly represented.

The results of analysis are given in Fig. 5 and Table 2. It can be seen from the Table 2 that in the wavelength range (1.7-2.3) cm the flux $F^I_{halo}(\lambda)$=Const which is why the halo emission in this range can be attributed to be the bremsstrahlung mechanism. Beginning with λ=2.7 cm, an additional flux appears and increases with wavelength. It allows us to divide the halo emission rather artificially into a "thermal" component following F^I_t=Const and "non-thermal" component. Taking into account the large size of the halo, it is difficult to believe that this component has cyclotron origin. The halo emission is very likely connected with the weaker, large-scale magnetic fields of the whole AR.

With the growth of wavelength the contrast between sunspot and interspot components decreases. This is illustrated in Fig. 5 where the brightness distribution at different wavelengths, with resolution of 25 arcsec at 2.7 cm and 18 arcsec at 5.2 cm, is given. At the wavelength λ≥6.0 cm it is impossible to separate the sunspot and interspot components, therefore Table 2 presents the average for the whole LS brightness temperature characterizing both the sunspot and interspot components.

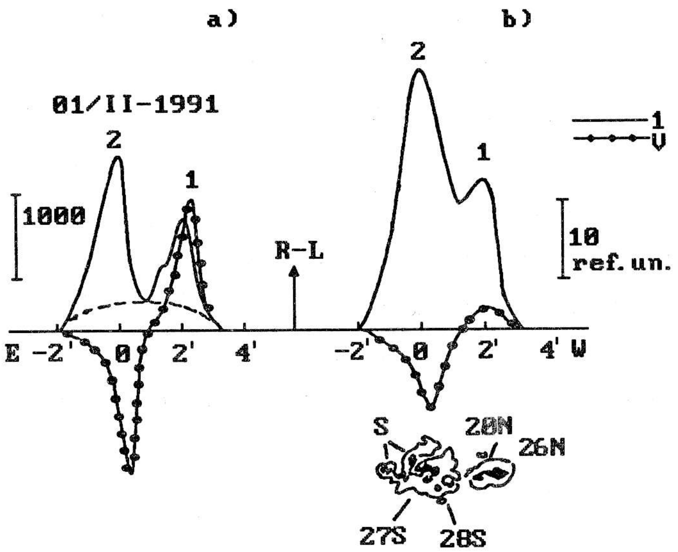

Fig.5. *One-dimensional brightness distribution of the polarized (V) and nonpolarized (I) radiation over the LS SD 30/1991 at the wavelength 2.7 cm (a) from the RATAN-600 observations and at 5.2 cm (b) from the CCRT observations. The dashed line is the demarcation line between the spot and interspot components.*

The halo emission was weakly polarized, and near the moment of CMP the bipolar source corresponded to the halo. However, near the limb the polarized source became a unipolar one (L-sign) and the degree of polarization increased (to 17%). The contribution of sunspot and interspot components to the total radiation was approximately equal (see Fig. 6), although the halo component at short wavelengths (λ~2 cm) and long ones (λ~4 cm) was of different origin ("thermal and "nonthermal", respectively).

4. "Hyperhalo". AR SD No. 249/1988

In one case the emission of the LS was proved to be due totally to the halo compoent. This extreme case we called "hyperhalo".

The brightness distribution for this LS is given in Fig. 7 according to Korzhavin and Peterova (1992). The morphology of this AR was peculiar for the lack of large spots though the total area of the sunspot group was rather significant (Sp≃1800 m.s.h.).

Table 2. Radio emission parameters for separate details of the LS of the AR SD No.30/1991

detail and identification	wave lengh	flux	polarization degree	size	brightness *) temperature
	λ cm	F^I s.f.u.	$P=F^V/F^I$ %	B^I_0 arcsec	$\Delta T_B \cdot 10^3$ K
No. 1 leader spot	1.7	1.5	80	11.6	390
	2.0	2.1	85	15.9	460
	2.3	3.6	70	19.7	660
	2.7	4.6	80	22.4	920
	3.2	5.6	70	28.7	950
	4.0	5.9	70	23.9	2250
No. 2 trailer spot	1.7	2.8	100	15.2	440
	2.0	4.2	60	22.5	450
	2.3	8.7	40	29.2	730
	2.7	9.4	35	35.2	750
	3.2	15.3	50	38.2	1450
	4.0	21.0	30	56.7	1440
thermal halo magnetosphere of AR	1.7	4.4	0	200	4
	2.0	5.5	0	200	7
	2.3	3.5	0	215	5
nonthermal halo magnetosphere of AR	2.7	3.4	0	214	10
	3.2	10.4	0	228	30
	4.0	25.9	0	228	110
the whole LS	6.0	40.0	-	230	400
	11.7	30.0	-	230	1100
	21.7	14.0	-	230	1800

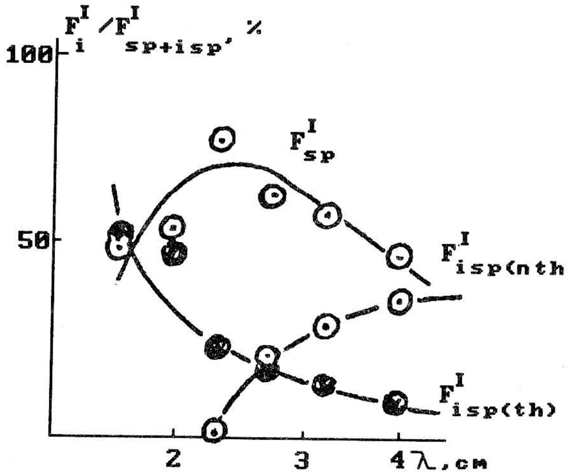

Fig.6. Relative contribution of the spot (F^I_{sp}) and the interspot (F^I_{isp}) component to the total (F^I_{sp+isp}) radiation from the LS of the AR SD No.30/1991. The interspot component is separated artificially into "thermal", $F^I_{isp(th)}$ and "nonthermal", $F^I_{isp(nth)}$ components.

It can be seen from Fig.7 that in the wavelength range (2.0-21.7) cm in the structure of the LS the extent component of ~2.5 arcmin in size dominated. The position of maximum brightness coincided with the neutral line of the large-scale photospheric magnetic field of the AR. In this case the spot component was represented by a rather weak source. We observed the growth of brightness and degree of polarization in the region of greater spots which were situated at the ends of the larger axis of the AR (in Fig. 7 these areas are noted by the letter "d"). As in the previous cases at short wavelengths, $\lambda \lesssim 2.3$ cm, the flux of the halo emission was independent of frequency ($F^I \simeq 5$ s.f.u.) and the halo emission could be interpreted as bremsstrahlung radiation. At longer wavelengths the "nonthermal" halo is again artificially separated as an excess over the "thermal" halo. Its parameters are given in Table 3.

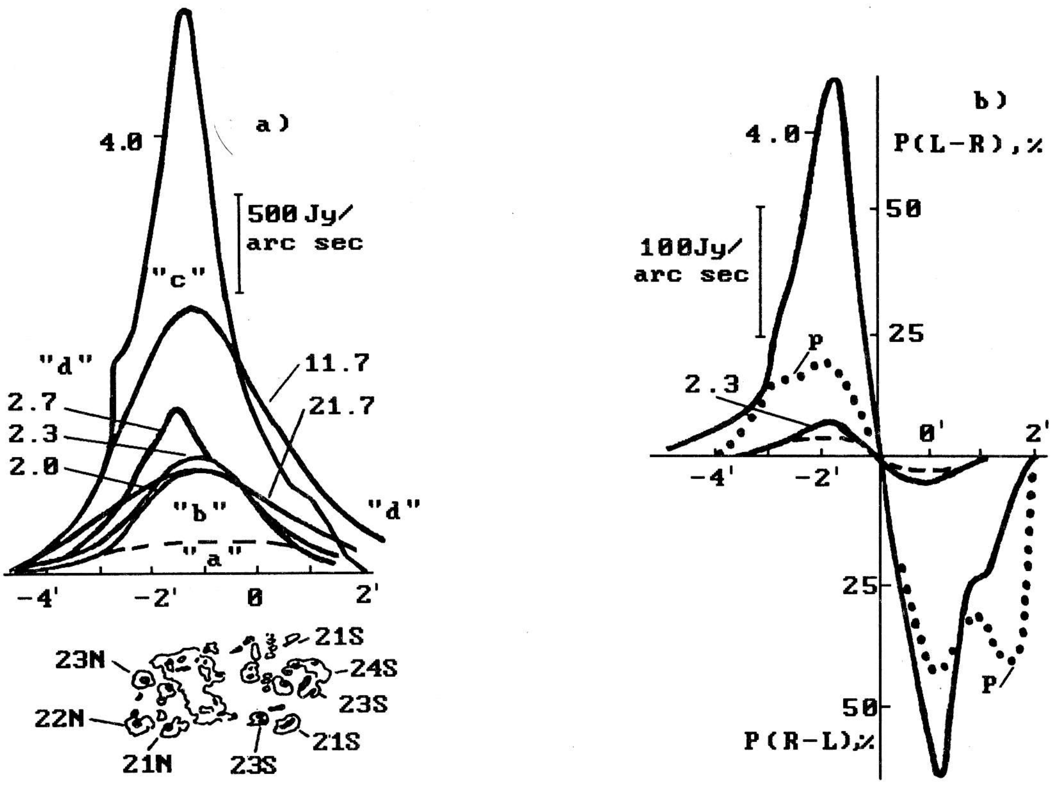

Fig.7. *One-dimensional brightness distribution of the polarized (a) and non-polarized (b) radiation from the LS of the AR SD No.249/1988 at the wavelengths (2.0-21.7) cm, from observations at the RATAN-600. The floccular component is marked with "a", the thermal halo with "b", the non-thermal halo "c", and the spot component "d". P is the degree of radiation polarization at the wavelength 4.0 cm.*

A remarkable peculiarity of the "nonthermal" part of hyperhalo was strong emission polarization at the wavelength λ=4 cm which was comparable with the polarization of the sunspot component (see Fig. 7b). Near the moment of CMP ($\pm 2.5^d$) the polarized emission of "hyperhalo" looks like a bipolar source for which the maximum degree of polarization is 45 % L and 20 % R. None of the distribution maxima of polarized emission coincides with the maximum of intensity. It is natural to connect such a character of polarization with the large-scale magnetic field of the AR, which in the present case has a rather simple symmetric bipolar structure.

Table 3. Parameters of the "nonthermal" halo from the observations of the LS of the AR SD No.249/1988

λ, cm	2.7	4.0	11.7	21.7
F^1, s.f.u.	1.5	18.5	40.0	22.0
B_0^1, arcmin	1.6	1.1	1.7	2.3
$\Delta T_B \cdot 10^3$, K	130	180	2800	4000

III. THE MAIN RESULTS

1. The extent detail (halo) with the sizes of the whole AR is the usual component of the structure of the microwave emission of LS. It is probably identified with the magnetosphere of AR. The "decimetre" halo (or may be noise storm) is assumed to be its continuation at longer wavelengths.

2. The relation between the contribution of the spot and halo components and the total emission of LS depends on the wavelength. For the "typical" structure of LS the spot component dominates (~75%) in only a rather narrow wavelength range near $\lambda \approx 2.5$ cm. At shorter (~2 cm) and longer (~4 cm) wavelengths their relation is about 50% of the total flux.

On the whole, the interspot emission dominates for all types of LS structure.

3. The flux of interspot emission rises with increasing wavelength and the steepness of spectrum grows sharply (n~6), beginning with $\lambda \sim 2.3$ cm. This allows us to artificially separate the interspot emission into a "thermal" bremsstrahlung part for which $F^I_{isp}(\lambda)$=Const, and a "nonthermal" excess.

4. The emission brightness temperature of the "nonthermal" halo component approaches the coronal values only at the decimetre wavelength range, being, as a rule, an order of magnitude lower at the centimetre wavelengths.

5. The emission of "nonthermal" component of the halo is polarized. The extraordinary wave dominates, and the degree of polarization in exceptional cases ("hyperhalo") reaches values which usually characterize the sunspot associated component (~45%).

6. The sources of heating of the solar corona above the AR are supposed to be situated in regions of small spots and pores. This conclusion follows from observations of both sunspot associated and halo components.

Any attempts to use the nonthermal mechanisms of emission generation to interpret the comparatively quiet S-component of solar radio emission have always been subject to serious criticism (e.g. Zlotnik, 1970). However, the high resolution observations reliably show, that in the halo emission of at least large AR, there is an essential additional radiation with nonthermal spectrum character. This emission is probably generated in relatively weak magnetic fields, since the sizes of the halo are much larger than the sizes of separate spots of AR.

It is not clear how the hot particles can be generated or accelerated during long periods of time (~life time of AR). It is necessary to continue the investigation into the structure of LS. It is useful to study such problems as dependence of halo emission intensity on morphology of AR (structure of magnetic trap), the phase of its development, and the bright peculiar details of LS structure. It is obvious that the new observational material presented above demands the development of a more complicated model of LS.

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