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Enhanced temperature regions in the polar zones of the Sun

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Abstract. Some aspects of regions with enhanced temperature in the polar zones of the Sun are studied in this paper, using data from Metsähovi Radio Research station in Finland. In addition to low latitude sources, measurements at 36.8 GHz have also revealed the existence of apparently separate class of sources with enhanced temperatures at latitudes above 40 degrees. The motions of these regions have been used to determine the solar differential rotation rate at high latitudes. We also study both the spatial and the temporal distributions of the enhanced regions. The activity of the low latitude component follows the sunspot activity over a solar cycle. The high latitude component is of unknown origin, but our data indicates a possible connection between these regions and polar faculae.

Key words: Sun: radio radiation – rotation

1. Introduction

Regions with enhanced temperature (ETR in the following) in the polar zones of the Sun have been discussed by several authors: e.g.Kundu & McCullough (1972); Babin et al.(1976); Efanov et al. (1980); Kosugi et al. (1986); Urpo et al. (1989);, Makarov et al. (1991) and Riehokainen et al. (1996). The present work uses data accumulated at Metsähovi Radio Research station in Finland during the period 1982-1995, obtained with the Metsähovi 14-m radio telescope at the frequency 36.8 GHz. In this paper we present a new determination of the differential solar rotation rate at high latitudes derived from microwave observations. We also discuss the distribution and the time variations of the high latitude microwave sources as well as their possible relationship with other solar phenomena.

2. Observations and data analysis

The data discussed in this paper comes from the solar observing programme of the Metsähovi Radio Research station. In the programme maps of the whole or part of the Sun are obtained, the evolution of active regions is followed, and solar oscillations are monitored. The telescope beam size at 37 GHz is 2.4 arcmin, and the estimated quiet Sun level is 7800 K. The sensitivity of the receiver is sufficient for 0.1 sfu resolution. In the temperature scale this corresponds to better than 100 K, and it is limited by short term changes in the atmospheric attenuation. Solar maps are measured by scanning the solar disk in right ascension and by changing the declination in small steps between the subsequent scans. Typical solar maps with an ETR in the North are shown in Fig. 1.

Localised areas of enhanced temperature of microwave radiation are detected frequently, typically lasting from some tens of minutes up to several days in rare cases. In addition to low latitude (< 40 degrees) sources an apparently separate component of high latitude (> 40 degrees) sources is also observed.

According to our observations, the temperature of a typical ETR at 8 mm wavelengh is 100-400 K above the quiet Sun level (7800 K). The regions are extended: in the North-South direction they can reach from a latitude of 40 degrees to the pole, and in the East-West direction they can even surround the entire pole, forming a ring-like region. Embedded in these extended regions are maxima of microwave radiation. Their rotation can be followed in maps taken during the same day, and in some cases over several days, and the solar differential rotation rate at high latitudes can be estimated from such data.

The projected coordinates of the ETR maxima relative to the Sun's apparent center were measured from the solar maps and transformed to heliographic coordinates using current values for the solar parameters. The active areas at 8 mm wavelengh are located only a few thousand kilometers above the photosphere, so no corrections due to the height effect are necessary. Although ETR's were seen closer to the poles, in practice only regions up to the latitude of 70 degrees could be measured. The total number of nothern and southern active areas was counted from the 37 GHz data. Unfortunately, the coverage from year to year is not regular for a a variety of reasons, and the number of days during which maps were made varies greatly. We have therefore scaled the observed numbers of active regions by the number of observing days for each year to obtain the daily average of active regions at each latitude interval $0^\circ \pm 10^\circ; \pm 10^\circ \pm 20^\circ$ etc.:

$$P_{\mathrm{i}} = N_{\mathrm{i}}/n \qquad (1)$$

where N_{i} is the total number of active regions in a given latitude interval during a year, and n is the number of observing days

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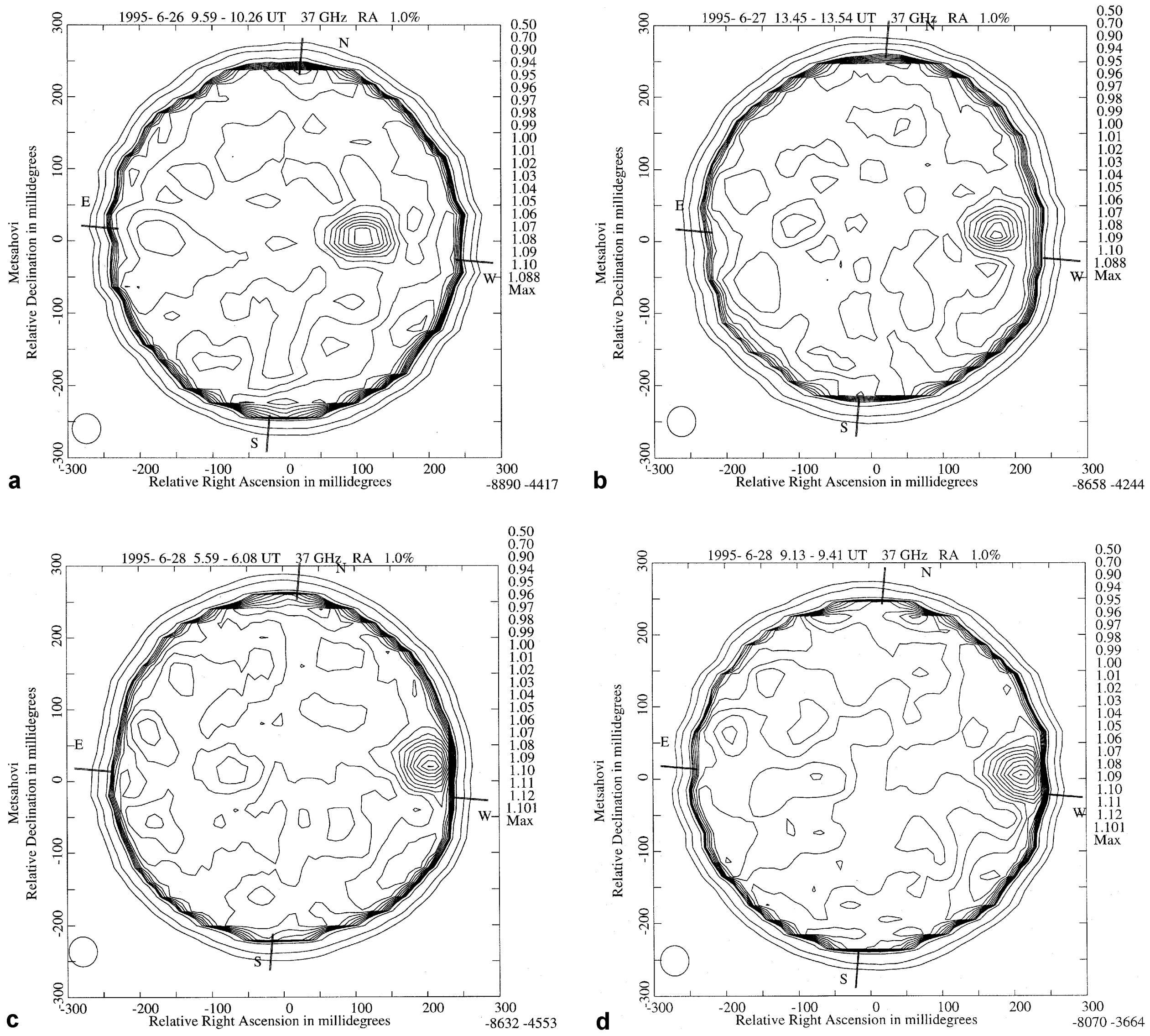

Fig. 1a–d. The 37 GHz solar maps on June 26–28, 1995. Note the motion of the small microwave ETR close to the N pole (only some of the solar maps obtained during the three days are shown).

Table 1. The number of observing days n and the active regions $N \pm \sqrt{N}$ in different latitude intervals between 1982-1995. Data from northern and southern latitude intervals are grouped together in the table.

year	n days	N $0° \pm 10°$	N $\pm10° \pm 20°$	N $\pm20° \pm 30°$	N $\pm30° \pm 40°$	N $\pm40° \pm 50°$	N $\pm50° \pm 60°$	N $\pm60° \pm 70°$
1982	10	46 ± 6.8	54 ± 7.3	38 ± 6.2	24 ± 4.9	14 ± 3.7	12 ± 3.5	0 ± 0
1983	18	71 ± 8.4	70 ± 8.4	48 ± 6.9	25 ± 5	5 ± 2.2	17 ± 4.1	5 ± 2.2
1984	15	28 ± 5.3	18 ± 4.2	24 ± 4.9	8 ± 2.8	1 ± 1	7 ± 2.6	2 ± 1.4
1986	4	6 ± 2.5	2 ± 1.4	2 ± 1.4	2 ± 1.4	0 ± 0	7 ± 2.6	2 ± 1.4
1987	30	66 ± 8.1	75 ± 8.7	101 ± 10	50 ± 7.1	21 ± 4.6	15 ± 3.9	26 ± 5.1
1988	23	21 ± 4.6	62 ± 7.9	122 ± 11	36 ± 6	9 ± 3	11 ± 3.3	10 ± 3.2
1989	25	39 ± 6.2	104 ± 10.2	114 ± 10.7	34 ± 5.8	16 ± 4	8 ± 2.8	3 ± 1.7
1990	88	52 ± 7.2	150 ± 12.2	115 ± 10.7	52 ± 7.2	55 ± 7.4	43 ± 6.6	5 ± 2.2
1991	184	414 ± 20.3	654 ± 25.6	454 ± 21.3	216 ± 14.7	307 ± 17.5	229 ± 15.1	56 ± 7.5
1992	81	185 ± 13.6	265 ± 16.3	128 ± 11.3	41 ± 6.4	66 ± 8.1	95 ± 9.7	27 ± 5.2
1993	61	151 ± 12.3	185 ± 13.6	75 ± 8.7	30 ± 5.5	40 ± 6.3	42 ± 6.5	40 ± 6.3
1995	12	48 ± 6.9	50 ± 7.1	25 ± 5	19 ± 4.4	20 ± 4.5	26 ± 5.1	9 ± 3

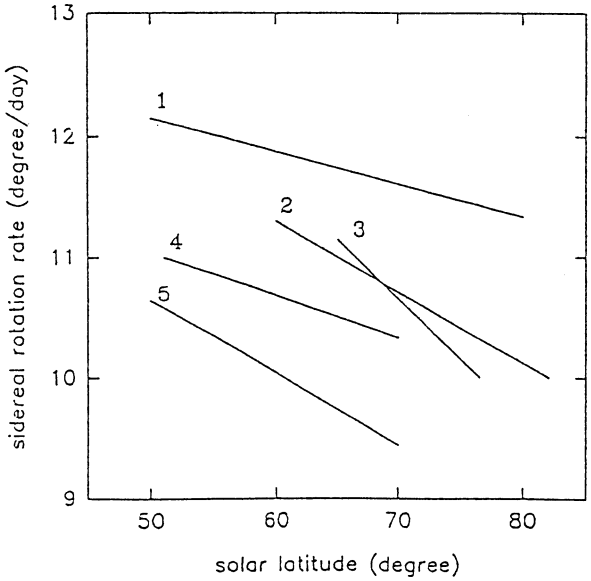

Fig. 2. Sideral rotation rates at high solar latitudes from microwave observations of high temperature regions compared with previous results: 1: Polar faculae (Makarova and Solonsky 1987) 2: Spectroscopic observations of the photophere (Howard & Harvey 1970) 3: Polar faculae (Waldmeier 1955 and Muller 1954, as presented in Hansen et al. 1969) 4: Enhanced temperature microwave regions (Urpo et al. 1989) 5: The present work.

during the same year. Table 1 lists the total numbers of active regions counted on the solar maps, and Table 2 the corresponding daily averages.

3. Results

The Metsähovi data enable us an estimate of the differential rotation.For high latitude (50°-70°) ETR's the sideral rotation rate was obtained by using linear regression, giving the result

$$\Omega(\phi) = 13.64(\pm 4.79) - 0.06(\pm 0.08)\phi, \qquad (2)$$

where Ω is the sideral rotation rate and ϕ is the solar latitude. As Fig. 2 shows, these values are, within observational errors, in agreement with the sideral rotation rate for the polar faculae obtained by Waldmeir (1955) and Muller (1954), as presented in Hansen et al.(1969), and with the photosphere spectroscopic observations obtained by Howard & Harvey (1970). It also agrees with the previous work of Urpo et al (1989) using much more limited radio data.

From Tables 1 and 2 it is obvious that the number of active regions in the different latitude intervals varies significantly from year to year. In Fig. 3 we have plotted the spline-smoothed $P_i(\phi)$-distributions for each year from 1982 to 1995 (no relevant observations were made in 1985 and 1994). Fig. 3 shows that the $P_i(\phi)$-distribution usually has two maxima, one between 0-30 degrees and the other between 40-70 degrees. In 1989 the second maximum is not visible, and in 1982 and 1990 it also is hardly discernible. Furthermore, the year-to-year variations in the intensities of the low and the high latitude active components do not appear to track each other. The low latitude component was strongest during the sunspot maximum time in 1988-1989, while the high latitude component was almost absent during this period. The high latitude component was strongest in 1986 and 1995.

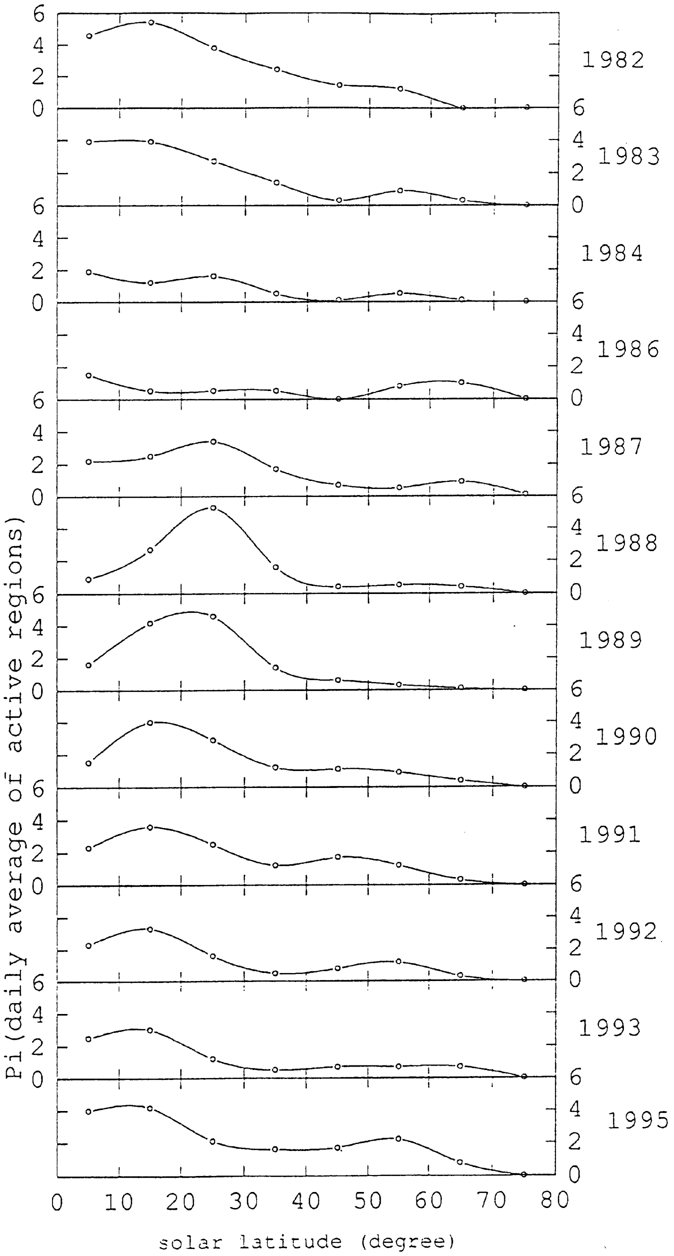

Fig. 3. The spline-smoothed latitude distribution P of the average daily number of ETR's for each year. Data are taken from Table 2. Note that years 1985 and 1994 are missing due to lack of observations.

It is not suprising that at low latitudes the high temperature microwave regions are associated with sunspots and follow closely their activity cycle. However, sunspots are only rarely detected above 40 degrees, and the high latitude ETR's also appear to be most frequent during periods of low sunspot activity. Other manifestations of solar activity must therefore be considered in trying to understand the connection of the high latitude

Table 2. The average number of active regions P_{i}, in different latitude intervals.

year	P $0^\circ \pm 10^\circ$	P $\pm10^\circ \pm 20^\circ$	P $\pm20^\circ \pm 30^\circ$	P $\pm30^\circ \pm 40^\circ$	P $\pm40^\circ \pm 50^\circ$	P $\pm50^\circ \pm 60^\circ$	P $\pm60^\circ \pm 70^\circ$
1982	4.6 ± 0.7	5.4 ± 0.7	3.8 ± 0.6	2.4 ± 0.5	1.4 ± 0.4	1.2 ± 0.4	0 ± 0
1983	3.9 ± 0.5	3.9 ± 0.5	2.7 ± 0.4	1.4 ± 0.3	0.3 ± 0.1	0.9 ± 0.2	0.3 ± 0.1
1984	1.9 ± 0.4	1.2 ± 0.3	1.6 ± 0.3	0.5 ± 0.2	0.1 ± 0.1	0.5 ± 0.2	0.1 ± 0.1
1986	1.5 ± 0.6	0.5 ± 0.4	0.5 ± 0.4	0.5 ± 0.4	0 ± 0	1.8 ± 0.7	0.5 ± 0.4
1987	2.2 ± 0.3	2.5 ± 0.3	3.4 ± 0.3	1.7 ± 0.2	0.7 ± 0.2	0.5 ± 0.1	0.9 ± 0.2
1988	0.9 ± 0.2	2.7 ± 0.3	5.3 ± 0.5	1.6 ± 0.3	0.4 ± 0.1	0.5 ± 0.1	0.4 ± 0.1
1989	1.6 ± 0.2	4.2 ± 0.4	4.6 ± 0.4	1.4 ± 0.2	0.6 ± 0.2	0.3 ± 0.1	0.1 ± 0.1
1990	0.6 ± 0.1	1.7 ± 0.1	1.3 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.5 ± 0.1	0.1 ± 0.0
1991	2.3 ± 0.1	3.6 ± 0.1	2.5 ± 0.1	1.2 ± 0.1	1.7 ± 0.1	1.2 ± 0.1	0.3 ± 0.0
1992	2.3 ± 0.2	3.3 ± 0.2	1.6 ± 0.1	0.5 ± 0.1	0.8 ± 0.1	1.2 ± 0.1	0.3 ± 0.1
1993	2.5 ± 0.2	3.0 ± 0.2	1.2 ± 0.1	0.5 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1
1995	4.0 ± 0.6	4.2 ± 0.6	2.1 ± 0.4	1.6 ± 0.4	1.7 ± 0.4	2.2 ± 0.4	0.8 ± 0.3

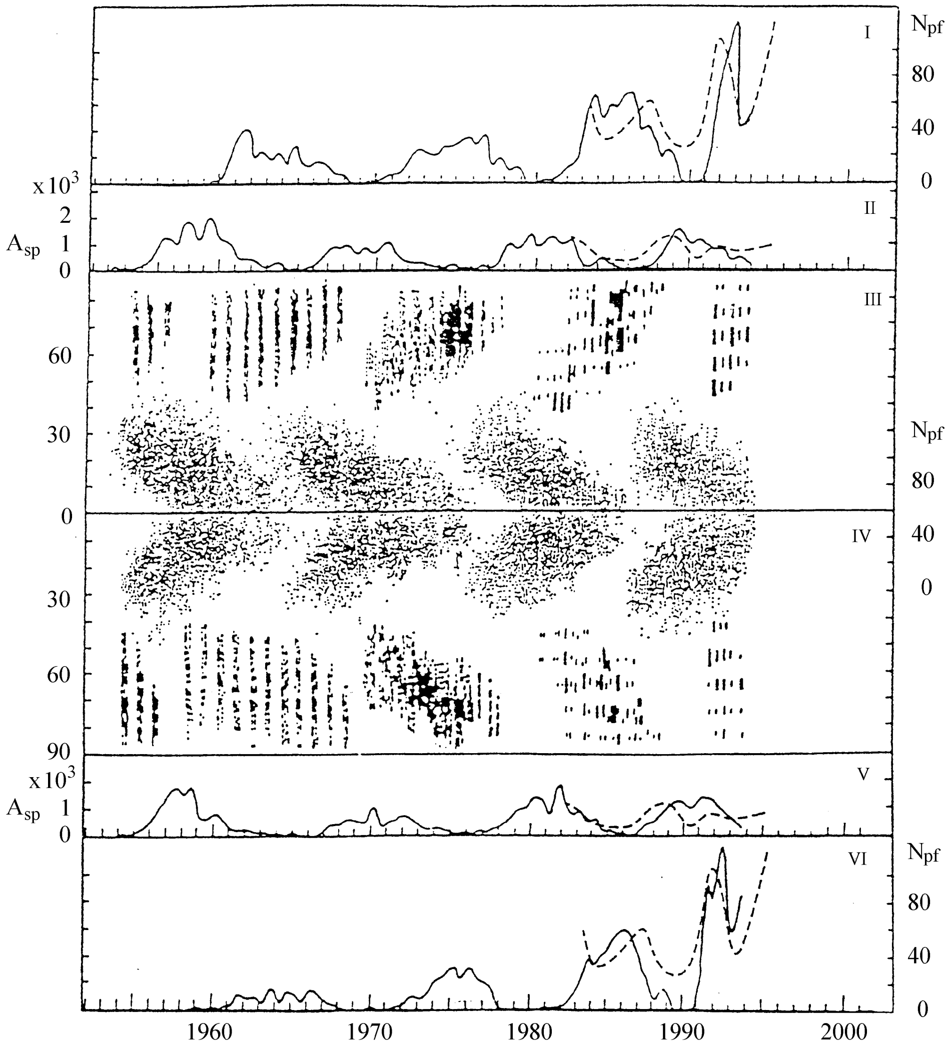

Fig. 4. The yearly variations in the maximum number of low latitude ETR's, P(ll,max), and high latitude ETR's, P(hl,max), compared with the sunspot and polar faculae activity cycles (Makarov & Makarova 1996). I: the number of northern hemisphere polar faculae (solid line) compared with the number of high latitude ETR's (dashed line). II: the northern hemisphere sunspot area (solid line) compared with the number of low latitude ETR's (dashed line). III: the latitude distribution of polar faculae and sunspots (northern hemisphere). IV–VI: corresponding data for the southern hemisphere. (Note that both hemispheres are combined in the ETR data.)

microwave enhancements to other solar phenomena, for example polar faculae or magnetic fields connected with them. We have compared the year-to-year variations in the numbers of ETR's with variations in sunspot and polar faculae activity. We use the largest value of $P_{\mathrm{i}}(\phi)$ (from Table 2) for each year as an estimate of the ETR activity, plotting the changes in this maximum intensity for both the low and the high latitude components separately. This comparision is shown in Fig. 4.

While no final conclusions can be made from radio observations covering only one solar cycle, it is possible to note that the maximum frequency of ETR's at low latitudes seems to follow the sunspot cycle, while the frequency of high solar latitude ETR's correlates with the polar faculae cycle. Thus, the overal distribution and the temporal variation of ETR's could be understood as resulting from the combination of both the sunspot and the polar faculae cycles.

Physically, the high latitude ETR's could be connected to density and temperature enhancements, to polar faculae, to polar magnetic fields or other related polar phenomena observed at the same latitudes as the ETR's and also having comparable lifetimes.

As was shown by V.I. Makarov et al. (1991), radio observations at the wavelengh of 2.3 cm with RATAN 600 could be related to clusters of polar faculae observed in the optical. Babin et al. (1976) and Efanov et al. (1980) showed that enhancements of the radio brightness at 13.5 mm and 8 mm were connected to intensification of the magnetic field strength. Our results, based on the distribution and the time variations in the frequency of enhanced temperature regions at high solar latitudes, support suggestions that these radio phenomena may be connected with clusters of the polar faculae or with local magnetic fields associated with the polar faculae. We are presently studying such possible connections and the nature of the physical mechanisms responsible for the creation of high latitude ETR's with simultaneous optical and radio observations.

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