NOISE STORMS AND THE STRUCTURE OF MICROWAVE EMISSION OF SOLAR ACTIVE REGIONS *

V. M. BOGOD, V. GARIMOV and G. B. GELFREIKH
Special Astrophysical Observatory RAS, St. Petersburg 196140, Russia

and

K. R. LANG, R. F. WILLSON and J. N. KILE
Department of Physics and Astronomy, Tufts University, Medford, MA 02155, U.S.A.

(Received 16 September, 1994)

Abstract. Solar radio and microwave sources were observed with the Very Large Array (VLA) and the RATAN-600, providing high spatial resolution at 91 cm (VLA) and detailed spectral and polarization data at microwave wavelengths (1.7 to 20 cm – RATAN). The radio observations have been compared with images from the Soft X-ray Telescope (SXT) aboard the *Yohkoh* satellite and with full-disk phoptospheric magnetic field data from the Kislovodsk Station of the Pulkovo Observatory. The VLA observations at 91 cm show fluctuating nonthermal noise storm sources in the middle corona. The active regions that were responsible for the noise storms generally had weaker microwave emission, fainter thermal soft X-ray emission, as well as less intense coronal magnetic fields than those associated with other active regions on the solar disk. The noise storms did, however, originate in active regions whose magnetic fields and radiation properties were evolving on timescales of days or less. We interpret these noise storms in terms of accelerated particles trapped in radiation belts above or near active regions, forming a decimetric coronal halo. The particles trapped in the radiation belts may be the source of other forms of nonthermal radio emission, while also providing a reservoir from which energetic particles may drain down into lower-lying magnetic structures.

1. Introduction

The high spatial resolution provided by the Very Large Array has permitted unique investigations of the hot, quiescent, or nonflaring, plasma that is constrained within magnetized coronal loops (Brosius *et al.*, 1992; White, Kundu, and Gopalswamy, 1991). When the high-resolution VLA data is combined with detailed spectral-polarization data obtained with the RATAN 600, important information is obtained about the quiescent coronal structures surrounding solar active regions (Bogod *et al.*, 1992). Because the basic structures and physical processes are controlled by the magnetic fields/electric currents, these structures have been called the *magnetospheres* of solar active regions (Lang *et al.*, 1993).

One of the more interesting results of the combined VLA–RATAN 600 data has been the discovery of long-lasting (hours to days) nonthermal microwave sources in the coronal magnetospheres at centimeter wavelengths (Akhmedov *et al.*, 1986; Lang *et al.*, 1993). These so-called peculiar sources have relatively small (about 104 km across) sizes with high brightness temperatures (up to 10^8 K) and steep

* Presented at the CESRA-Workshop on 'Coronal Magnetic Energy Release' at Caputh near Potsdam in May 1994.

Solar Physics **160:** 133–149, 1995.

radiation spectra; they can occur above the magnetic neutral line in the underlying photosphere and are often associated with complicated, multipolar configurations of the underlying photospheric sunspots suggesting localized neutral curent sheets in the corona (Alissandrakis *et al.*, 1993).

Noise storms are another type of nonthermal radiation associated with active regions. Indeed, they are the most common type of activity observed on the Sun at metric wavelengths, often lasting for hours or even days. The VLA has been used to resolve noise storms at 91 cm wavelength, showing that they were located near the apex of magnetic loops within an active region or between two nearby active regions (Lang and Willson, 1987). Observations with the Nancay radioheliograph indicate that some noise storms are emitted from large magnetic arches that connect active regions with their surroundings (Mercier *et al.*, 1984), and other VLA observations show that other noise storms are located on large-scale coronal magnetic loops that connect opposite hemispheres of the Sun (Willson *et al.*, 1994).

Here, we discuss VLA observations that have resolved 91 cm noise storm emission on several days in 1992 May, 1993 May, and 1993 August and compare them with microwave (RATAN), soft X-ray (*Yohkoh*) and photospheric magnetic data (Kislovodsk Station). The long-lasting nonthermal radio emission of these noise storms is located near and above relatively weak active regions whose thermal microwave emission, thermal X-ray radiation and sunspot and coronal magnetic field strengths are all less intense than those of other visible active regions. However, the active regions associated with the noise storms exhibited a relatively strong decimetric halo source. We interpret the long-lasting noise storm radiation in terms of accelerated, nonthermal particles trapped in radiation belts above active regions, also creating the decimetric halo. This model is additionally applied to the nonthermal peculiar sources of other active regions as well as their thermal microwave emission.

2. VLA, Soft X-Ray and Magnetic Observations

The VLA was used to observe the Sun at 91 cm (327.4 MHz) for 4–5 hr periods on May 1, 3, 9, 10, and 11, 1992, on May 6, 8, and 9, 1992 and on August 19 and 22, 1993. The full solar disk was observed with a time resolution of 3.3 s and a bandwidth of 3.25 MHz for consecutive 45-min periods followed by a 5-min observation of a nearby calibration source. The data were edited and calibrated using the standard AIPS software available at the NRAO and then used to produce synthesis and well as snapshot maps of total intensity, I, and Stokes parameter, V.

On all days of observation, the 91 cm synthesis maps were dominated by a single source having a brightness temperature of $T_b = 10^7$–5×10^8 K and a circular polarization of $\rho_c = 50$–100%. Plots of the VLA correlated flux on a short baseline as well as individual snapshot maps of 3.3 s duration revealed slowlyvarying (tens of minutes to hours) flux levels and frequent, impulsive ($\Delta t < 3.3$ s) bursts that were up to 100% circularly polarized, suggesting that the 91 cm sources are Type I noise storms (Lang and Willson, 1987; Raulin *et al.*, 1991).

In Figures 1–3 we compare our VLA maps with full-disk soft X-ray images from the *Yohkoh* satellite as well as with maps of sunspot magnetic fields from the Kislovodsk Station of the Pulkovo Observatory. The *Yohkoh* images were obtained from the on-line data base available at the Hiraio Solar Terrestrial Research Center in Japan (courtesy of Y. Ogawara and Y. Uchida). The 91 cm noise storms are located near active regions although the source centroids do not always lie directly above the soft X-ray loops that connect underlying sunspots nor are the noise storms always associated with the brightest X-ray emitting active regions.

Of particular interest are the noise storms detected on May 6–9, 1993 (Figure 2). On May 6, a noise storm was detected about $2'$ above the east limb. Because no other active regions rotated onto the solar disk at these nothern latitudes during the next several days, we believe that this noise storm was most likely associated with one or both of the closely-spaced active regions AR 7496 and AR 7500 in the northeast quadrant of the Sun. The limbward displacement may be interpreted as a projection effect due to the height of the noise storm above the solar surface. For an angular displacement of $\Delta\theta \sim 3.9'$ between the source centroid and a point on the solar surface midway between the two active regions, we infer a height of $h \sim 2 \times 10^{10}$ cm ($0.29\ R_{\odot}$). This height is in good agreement with the heights inferred for other noise storms detected with the VLA (e.g., Willson, Lang, and Liggett, 1990).

Both AR 7496 and AR 7500 have bright, extended soft X-ray loops that stretch between regions of opposite magnetic polarity in the photosphere. Fainter X-ray emission also exists between the two regions and the maximum extent of the extended loops above AR 7500 coincides with the western boundary of the noise storm on May 6.

On May 8 and 9, 1992. a different noise storm was detected above another active region, AR 7499, whose magnetic structure had grown in complexity and whose X-ray emission had increased since May 6. The noise storm associated with AR 7496 and AR 7500 on May 6 was then not detected at any level above a brightness temperature of $T_b = 2 \times 10^6$ K. That is, even though AR 7496 and AR 7500 still had brighter and more extensive X-ray loops, it was the weaker, but more rapidly evolving, region, AR 7499, that had developed noise storm emission.

3. RATAN-600 Observations

The RATAN-600 was used to observe the Sun in May 1992, May 1993 and August 1993 with the Panoramic Spectrum Analyzer (PSA) at up to 24 wavelengths between 1.7 and 8 cm (for a description of the PSA see Bogod *et al.*, 1993). The east–west (north–south) half-power beamwidths of the RATAN range from

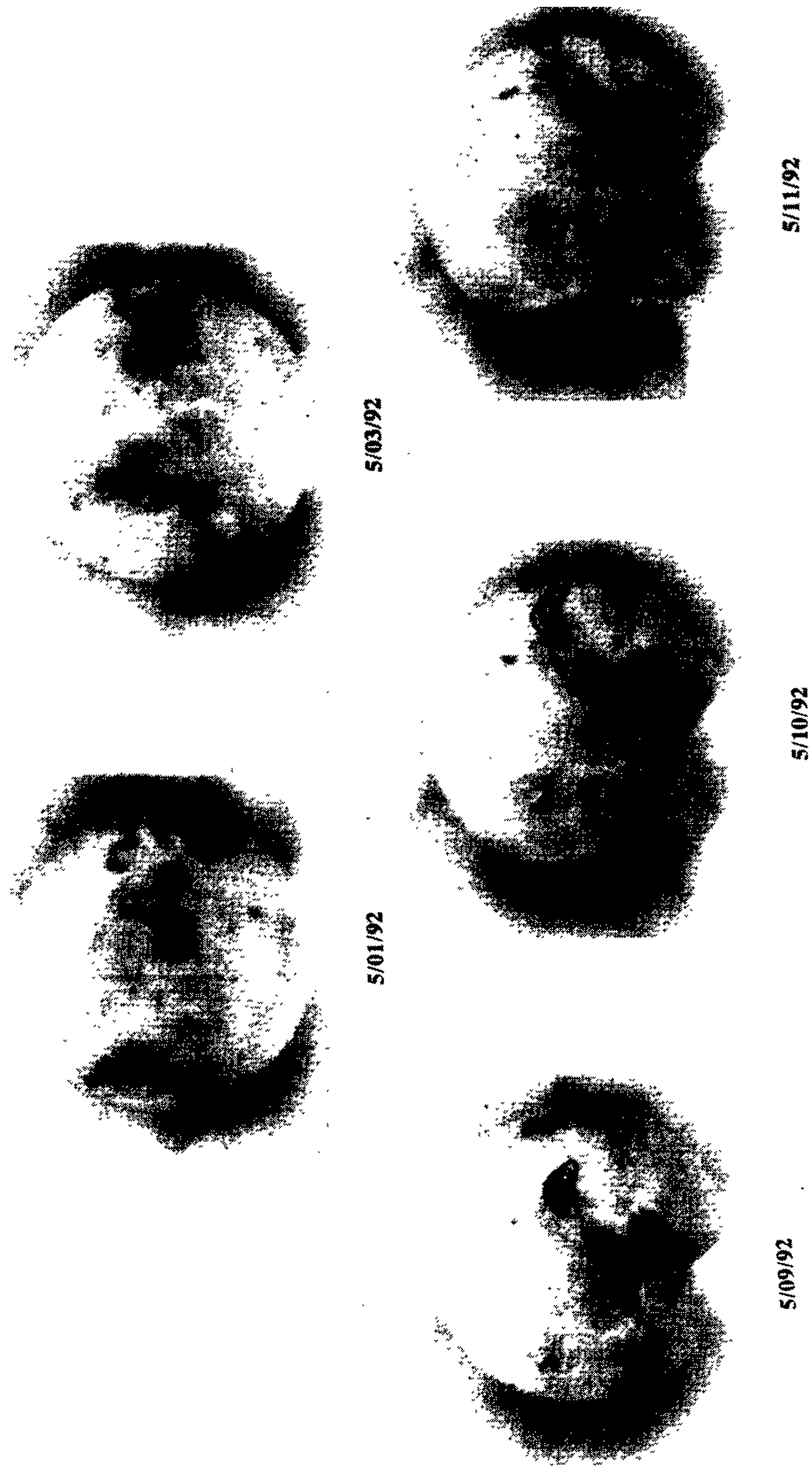


Fig. 1a.

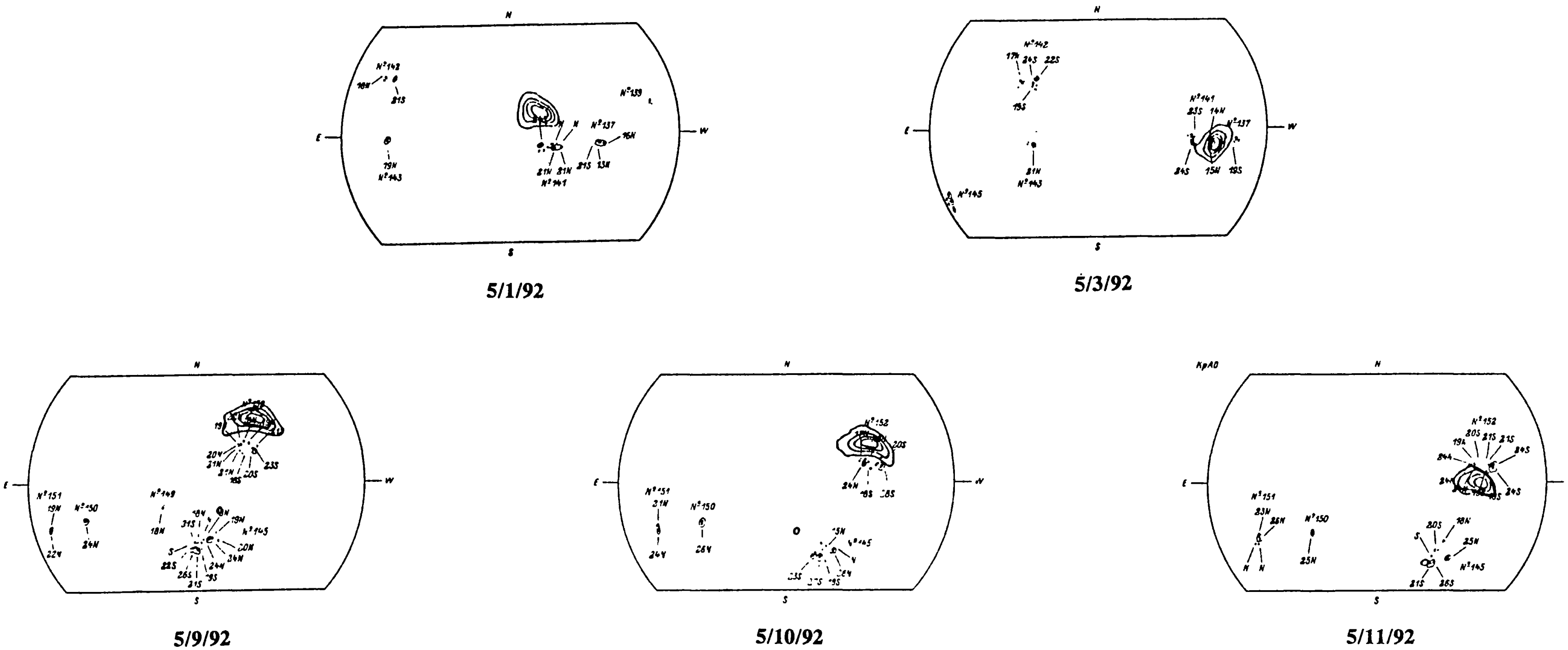


Fig. 1b

Fig. 1a–b. VLA synthesis maps of total intensity at 91.6 cm on May 1, 3, 9, 10, and 11 are compared with soft X-ray images obtained from the *Yohkoh* SXT (a) and with Kislovodsk magnetic field maps from the *Solnechnye Dannye* bulletin (b). The radio contours mark levels of equal brightness temperature, T_b, corresponding to 20, 40, 60, and 100% of the peak ($T_{b\max} = 5.9 \times 10^7$ K, 9.0×10^6 K, 1.2×10^7 K, 1.0×10^6 K, and 9.5×10^6 K on May 1, 3, 9, 10, and 11, 1992, respectively).

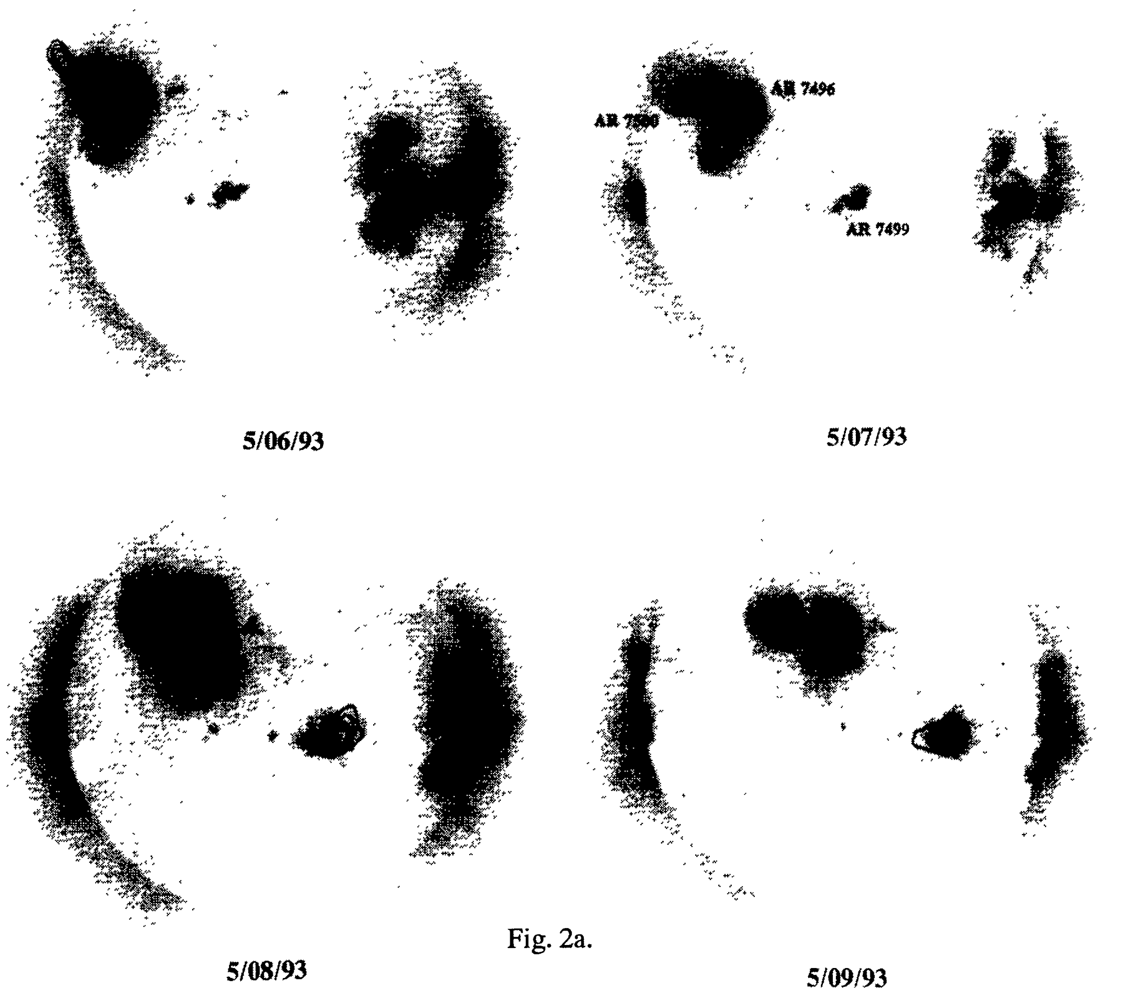


Fig. 2a.

15.3″ (10.6′) at 1.7 cm to 70″ (50′) at 8 cm. One-dimensional fan beam scans of total intensity, I, and circular polarization, or Stokes parameter, V, were obtained daily near 09:00 UT at different azimuths and these data were combined to specify the position of the microwave sources on the Sun.

The transit records of total intensity show enhanced emission from active regions which can be grouped into three main categories:

(1) Compact ($\theta < 20''$) sources which are lie above sunspots having high ($H > 1000$ G) photospheric magnetic fields. Most of these sources are circularly polarized with the sign of polarization deterrnined by the polarity of the magnetic field at the photospheric level (right-handed polarization for north polarity of the photospheric field and left-handed polarization for south polarity in the photosphere).

(2) Extended ($\theta \sim$ several arc minutes) 'halo' sources which have no significant detectable structural details and which exhibit no net circular polarization.

(3) Compact ($\theta < 20''$) sources which lie along the inversion line of photospheric magnetic polarity and which are generally unpolarized.

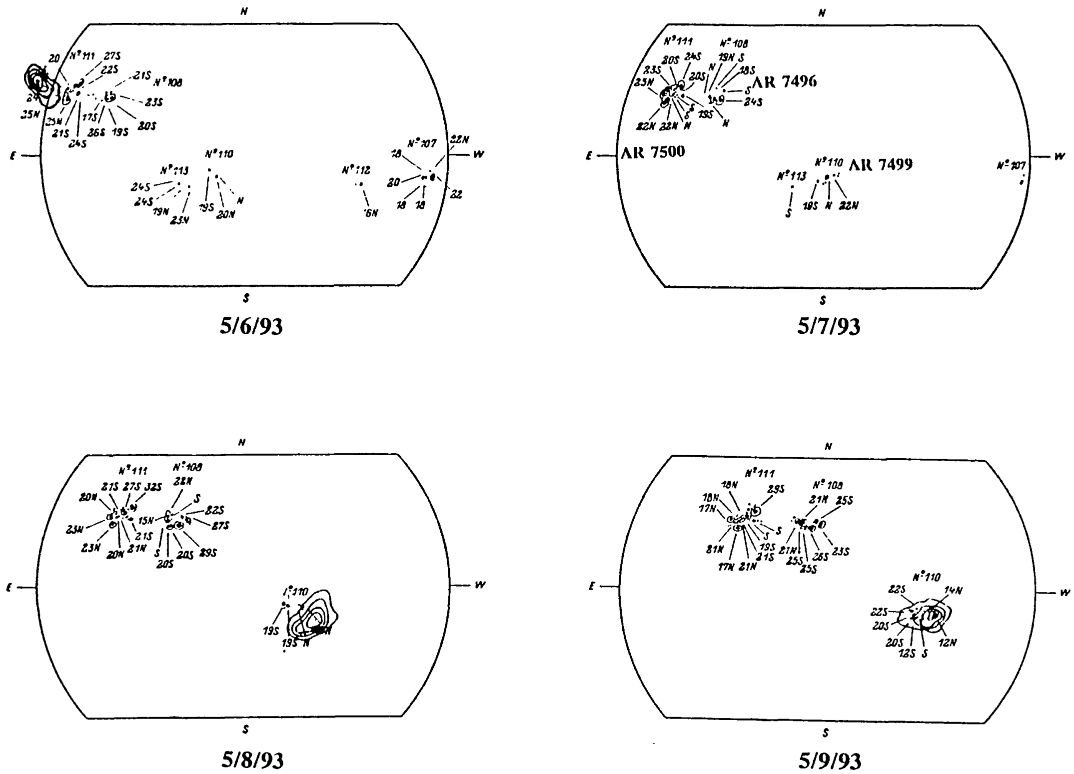


Fig. 2b.

Fig. 2a–b. VLA synthesis maps of total intensity at 91.6 cm on May 6, 8, and 9, 1993 are compared with soft X-ray images form the *Yohkoh* SXT (a) and with Kislovodsk magnetic field maps from the *Solnechnye Dannye* bulletin (b). The radio contours mark levels of equal brightness temperature, T_b, corresponding to 20, 40, 60, 80, and 100% of the peak ($T_{b\max} = 2.3 \times 10^8$ K, 1.5×10^7 K, and 4.9×10^7 K on May 6, 8, and 9, 1993, respectively.

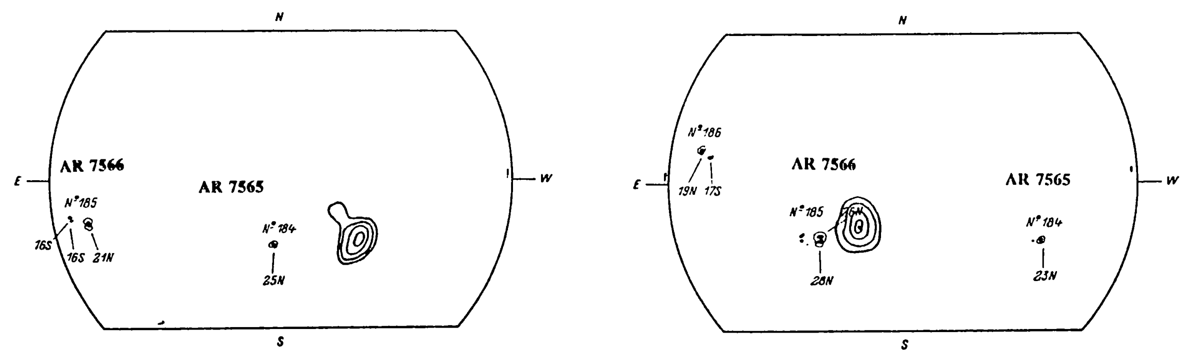
The total flux, size and degree of circular polarization at each each wavelength were determined from the one-dimensional scans using a Gaussian fitting procedure that separates the compact sources from the extended halo.

Of particular interest is the period of May 6–9, 1993 when three active region complexes, AR 7496, AR 7499, and AR 7500 were visible on the solar disk. Figure 4 shows radio scans at $\lambda = 3.07$ cm on 1993 May 8 and 9 in total intensity and circular polarization together with an optical map of the Sun as published in the *Solnechnye Dannye* bulletin. The optical data from the Kislovodsk Station of the Pulkovo Observatory showed that the active regions AR 7496 and AR 7500 in the northeast had a large number of sunspots whose total area evolved throughout the period of observation while the area of the smaller group of sunspots in AR 7496 rapidly increased beginning on May 6 (Figure 5). Though mostly of bipolar magnetic structure, all sunspot groups had high photospheric gradients due to the close proximity of the large spots of opposite magnetic polarity.

As discussed in the last section, the *Yohkoh* soft X-ray maps show intense and extended coronal loops above AR 7496 and AR 7500. This is in accord with the

8/19/93 8/22/93

Fig. 3a.



8/19/93 8/22/93

Fig. 3b.

Fig. 3a–b. VLA synthesis maps of total intensity at 91.6 cm on August 19 and 22, 1993 are compared with soft X-ray images from the *Yohkoh* SXT (a) and with Kislovodsk magnetic field maps from the *Solnechnye Dannye* bulletin (b). The radio contours mark levels of equal brightness temperature, T_b, equal to 20, 40, 60, 80, and 100% of the peak ($T_{b\,\max} = 1.5 \times 10^8$ K, and 5.0×10^7 K on August 19 and 22, 1993, respectively).

higher radio flux of these active regions and their larger sunspot areas. The total sunspot area of AR 7499 was an order of magnitude smaller than the two other regions, although the sunspot area and soft X-ray intensity increased significantly between May 6 and 9 (see Figures 2 and 5). The RATAN observations also showed that the flux of the halo associated with AR 7499 increased by about a factor of 2 during this period (Figure 6), suggesting a physical relationship between the electrons that produce the microwave halo and the thermal plasma that produces the soft X-ray emission.

All of the radio sources show spectra which increase with increasing wavelength and in Figure 7 we show examples of RATAN spectra for both sunspot and halo-associated sources. Following the procedure given by Akhmedov *et al.* (1982) and Lang *et al.* (1993), we can estimate the magnetic field strength in the

RATAN Fan-Beam Scans

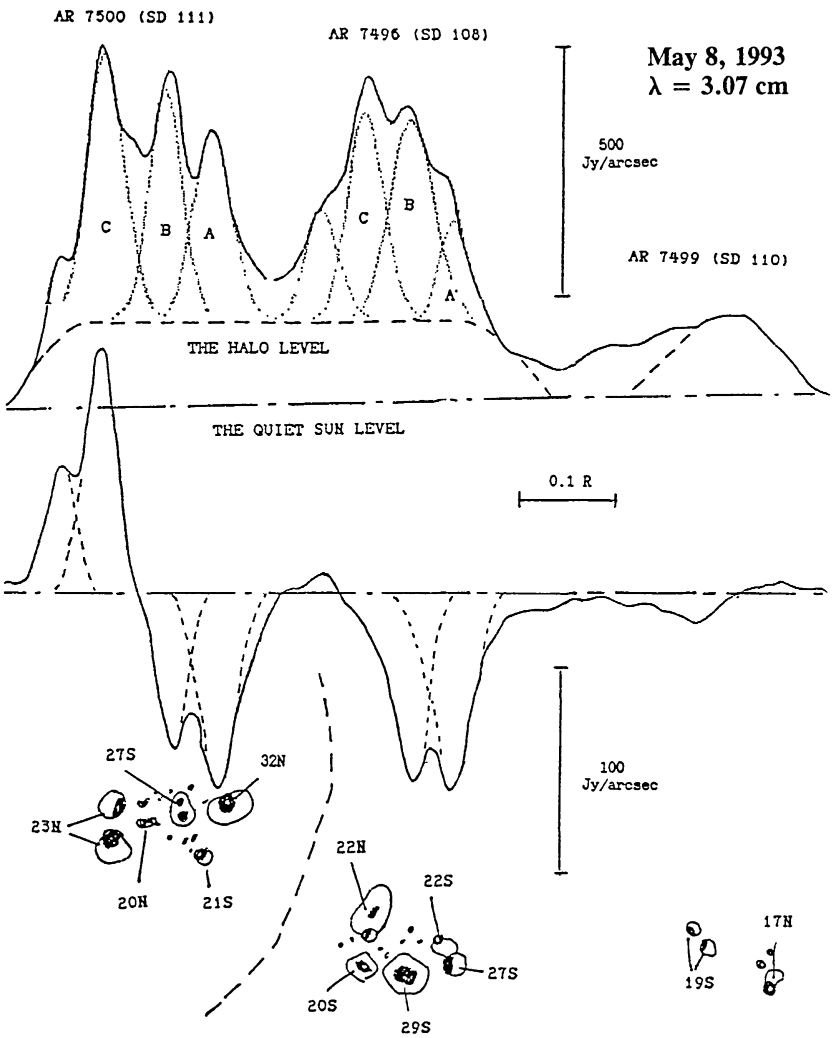


Fig. 4a.

Fig. 4a–b. (a) One-dimensional fan beam scans of total intensity, I, and Stokes parameter, V, made with the RATAN Panoramic Spectrum Analyzer (PSA) at $\lambda = 3.07$ cm on 1993 May 8. An optical map of sunspots and their magnetic fields, obtained from the *Solnechnye Dannye* bulletin, is also presented. The peak umbral fields of the sunspots are expressed in units of gauss, and N and S denote positive and negative photospheric polarity, respectively. The dashed and dotted lines below the radio profile of total intensity represent sunspot-associated and halo components of the microwave emission from AR 7500 (sunspot-associated sources A, B, and C), AR 7496 (sunspot-associated sources A, B, and C and neutral-line source D) and AR 7499 (only structureless halo and small sunspot-associated source). On the bottom, the dashed lines below the radio profile of Stokes parameter, V, represent sunspot-associated components of the microwave emission. (b) One-dimensional fan beam scans of total intensity, I, and Stokes parameter, V, made with the RATAN PSA at $\lambda = 3.07$ cm on 1993, May 9. On the top are shown scans in the range 2.3–12 cm in the form of a three-dimensional picture. At the bottom is shown an optical map of sunspots and their magnetic fields. The dashed and dotted lines below the radio profile represent sunspot-associated and halo components of the microwave emission above the quiet-Sun level from AR 7500 (sunspot-associated sources A, B, and C in total intensity and circular polarization), AR 7496 (sunspot-associated sources A, B and C), and AR 7499 (a weak sunspot-associated source associated with the leading spot).

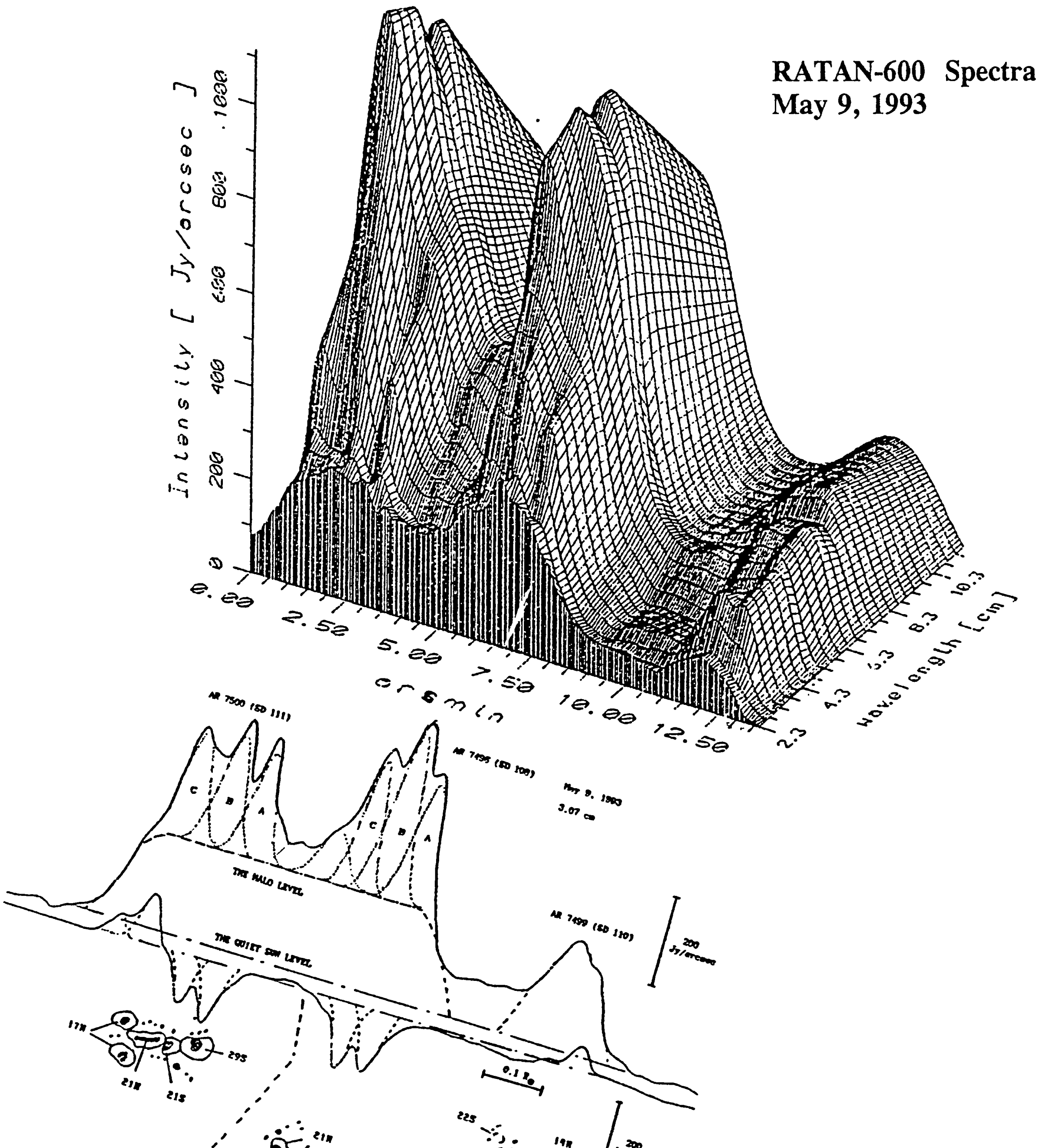

RATAN-600 Spectra
May 9, 1993
Intensity [Jy/arcsec]
0
200
400
600
800
1000
0.00
2.50
5.00
7.50
10.00
12.50
arcmin
Wavelength [cm]
THE HALO LEVEL
THE QUIET SUN LEVEL
3.07 cm

Fig. 4b.

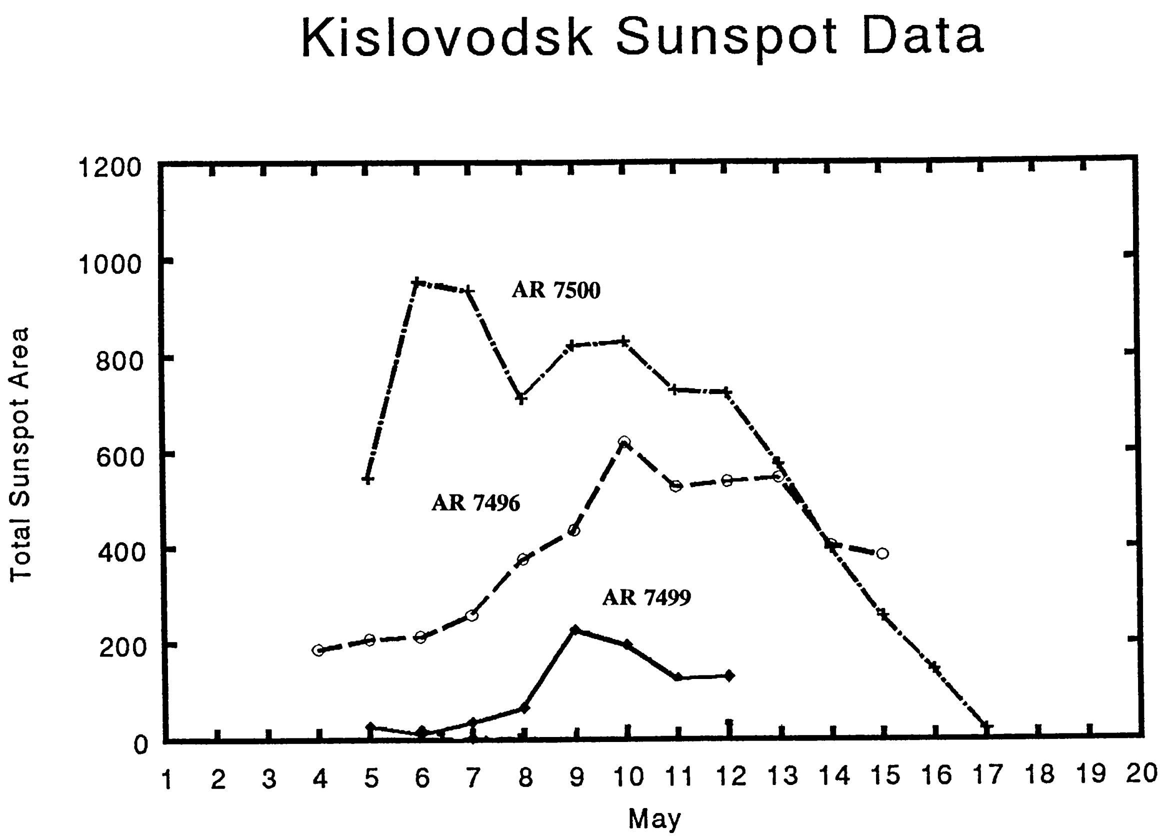


Fig. 5. A plot showing the development of the areas of the sunspot groups AR 7496, AR 7499, and AR 7500 in 1993 May as obtained from the *Solnechnye Dannye* bulletin. The total sunspot area is in units of 10^{-6} of the solar disk.

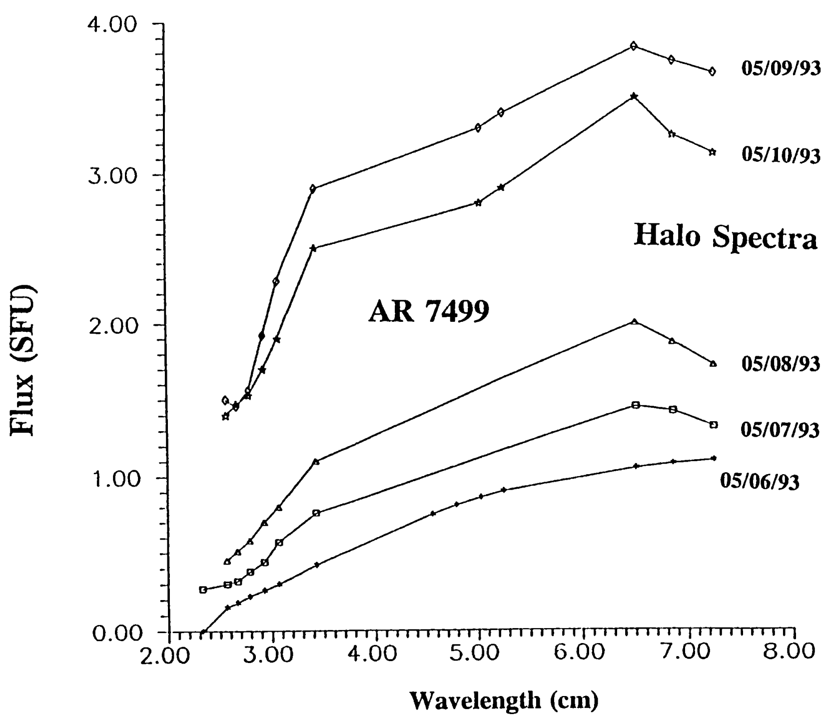


Fig. 6. RATAN microwave spectra of the halo emission associated with the evolving active region AR 7499 on different days between May 6–10, 1993.

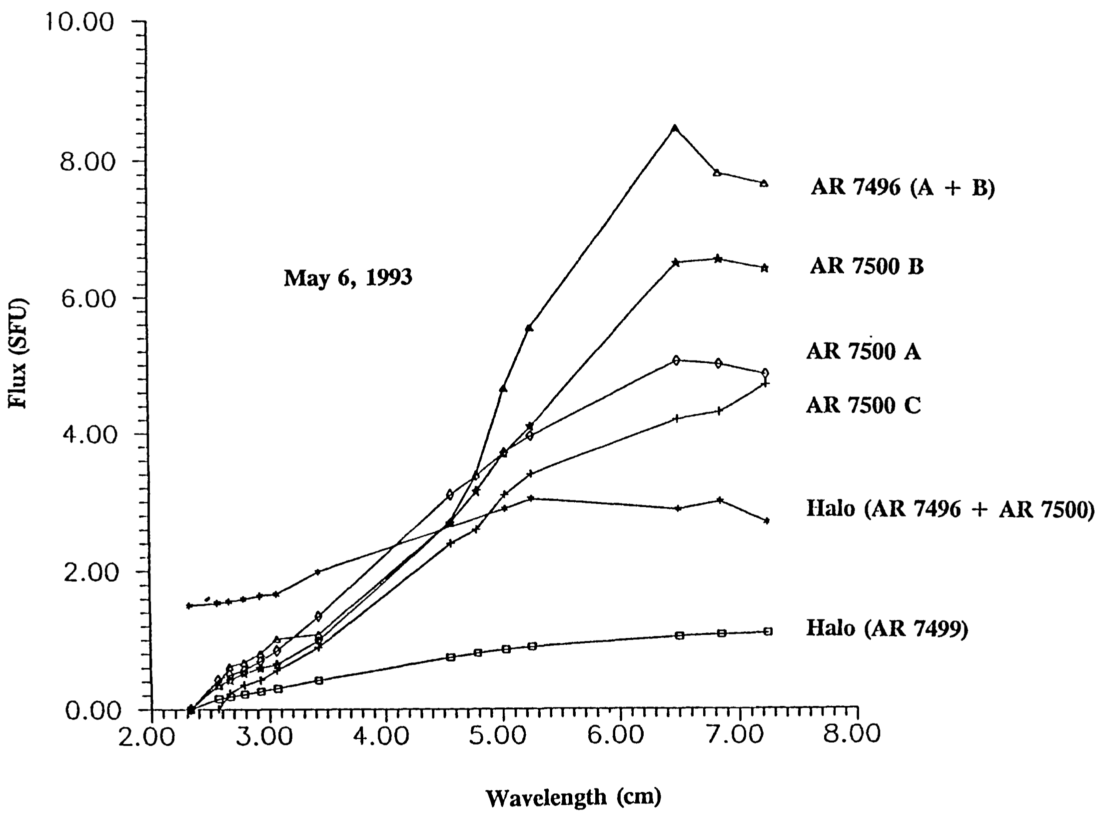


Fig. 7. RATAN flux density spectra for the core and halo sources associated with AR 7496, AR 7499, and AR 7500 on May 6, 1993.

corona above the sunspot-associated microwave sources under the assumption that the radio emission is generated by thermal cyclotron (or gyroresonance) radiation at the third harmonic of the gyrofrequency. Observations at a wavelength λ refer to regions with magnetic field strength H, given by $H = 3570/\lambda$, where λ is the wavelength in cm. Our assumptions are based on observations which show that sunspot-associated sources at microwave wavelengths are usually moderately circularly polarized in the extraordinary mode of wave polarization. Third-harmonic emission is therefore assumed because gyroresonance radiation at the second harmonic is usaually optically optically thick in both the extraordinary and ordinary modes and hence unpolarized while fourth-harmonic radiation may be two orders of magnitude weaker that the third harmonic and therefore undetectable. The RATAN measurements therefore refer to the third harmonic of the gyrofrequency in the 10^6 K plasma above sunspots, and this has been confirmed by detailed models for a number of active regions (e.g., Gelfreikh and Lubyshev, 1979; Krüger and Hildebrandt, 1983; Brosius *et al.*, 1992; Lang *et al.*, 1993). The shortest wavelength, λ_{crit}, generated at the third harmonic by gyroresonance radiation therefore determines the strongest magnetic field in the coronal region above a given sunspot.

The multiple wavelength polarization scans reveal up to three sunspot-associated sources for each active region and measurements of λ_{crit} were then used to com-

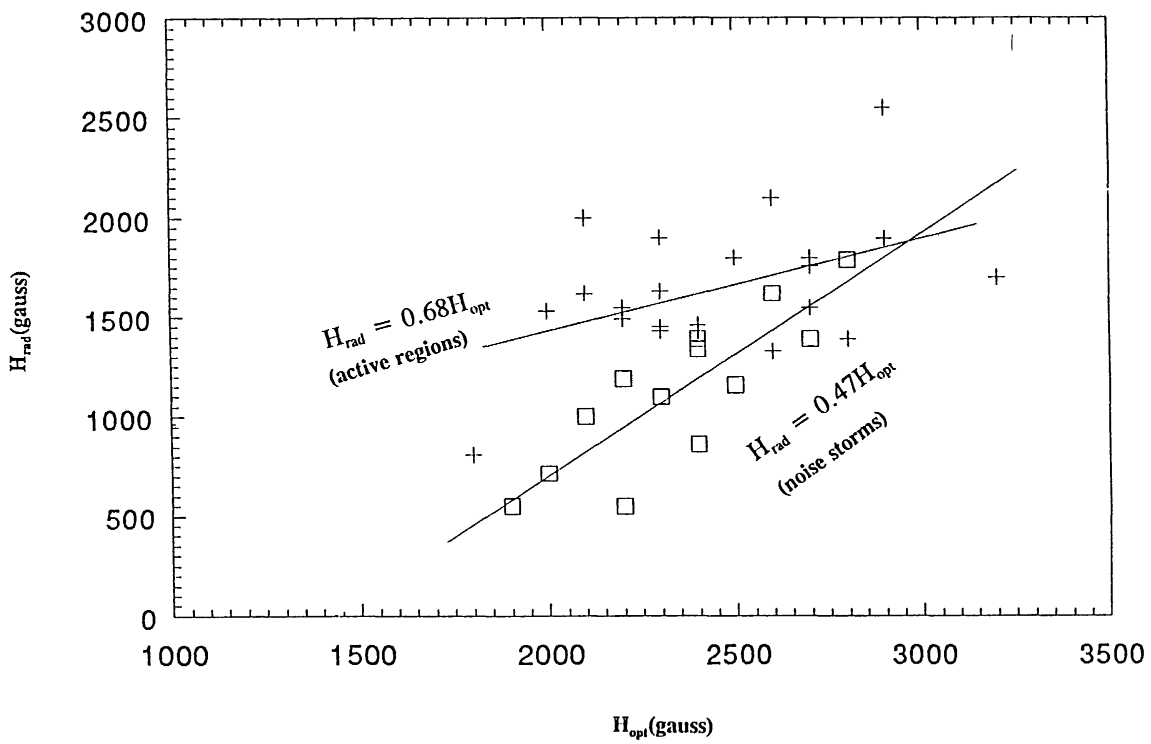


Fig. 8. A plot showing the relationship between the photospheric (H_{opt}) and coronal (H_{rad}) magnetic fields of core radio sources which were detected by the RATAN in May 1992, May 1993 and August 1993 (Tables I and II). The boxes correspond to core sources with active regions that had overlying 91.6 cm noise-storm sources; the crosses correspond to microwave sources that were not associated with noise storms.

pute the maximum magnetic field strength for each sunspot. The results of the measurements of the field by this method, H_{rad}, are given in Table I together with the maximum sunspot umbral fields, H_{opt}, and their ratio, $H_{\mathrm{rad}}/H_{\mathrm{opt}}$. Our results, which are also shown graphically in Figure 8, indicate that for noise storm-producing regions, $H_{\mathrm{rad}}/H_{\mathrm{opt}} \sim 0.47$, while for other regions $H_{\mathrm{rad}}/H_{\mathrm{opt}} \sim 0.68$, in agreement with our previous results (Akhmedov *et al.*, 1982). This means that the magnetic field strengths in the corona above regions with noise storms appear to be relatively weaker or more divergent in comparison to active regions that are not associated with noise storms.

4. Discussion

Despite forty years of investigations of the origin of noise storms, the radiation mechanism and energy source have still not been identified. A general consensus exists nevertheless that the emission is due to nonthermal electrons accelerated to between a few keV and tens of keV energies, and that they are located within large-scale loops that are either located above or near active regions or connect active regions to more distant areas on the Sun (Mercier *et al.*, 1984; Lang and Willson, 1987; Raulin *et al.*, 1991). In fact, the onset of noise storms apparently

TABLE I

Active regions observed with the VLA and RATAN

Date	AR number	Sunspot	Area ($10^{-6}A_0$)	H_{opt} (G)	Noise storm	H_{rad}	H_{rad}/H_{opt}
May 1, 1992	AR 7150	A (west)	158	2000 N	+	880	0.44
	(141SD)	B (east)	≤100	2000 S	+	960	0.48
	AR 7143	A (west)	68	2100		1370	0.65
	AR 7151		70	2000 N		1210	0.61
	AR 7152		114	2200 S		1550	0.7
May 3, 1992	AR 7150	A (west)	146	1500 N		1150	0.76
	AR 7150	B (east)	≤100	2400 S		1210	0.5
	AR 7143		36	1900 S	+	1210	0.64
	AR 7151		60	2100 N		930	0.44
	AR 7152		49	2200 S		1190	0.54
	AR 7154		247	1800 N		1550	0.86
May 9, 1992	AR 7162	A (west)	33	2300 S	+	1100	0.48
	(152SD)	B (east)	≤330	2100 0N	+	1000	0.47
	AR 7154	A (west)	200	2400 N		1390	0.58
	(145SD)	B (east)	≤200	2200 S		1550	0.70
	AR 7160		≤124	2400 N		1430	0.60
	AR 7163		≤40	2200 N		1490	0.68
May 10, 1992	AR 7162	B(east)	≤33	2400 N	+	860	0.36
		A (west)	200	2800 S	+	1790	0.63
	AR 7154	B (east)	≤200	2800 S		1450	0.63
		A (west)	33	2800 S		1390	0.49
	AR 7160		≤124	2600 N		1330	0.51
	AR 7163		≤40	2400 N		1460	0.61
August 19, 1993	AR 7565		134	2599 N	+	1800	0.72
	AR 7566		317	2100 N		1620	0.77
	AR 7563		16	1800 S		810	0.45
August 22, 1993	AR 7563		140	2300 N		1430	0.62
	AR 7566		228	2600 N	+	1620	0.62

follows the formation of extended, dense loops in the middle corona, suggesting that noise storms are related to the large-scale rearrangement of coronal magnetic fields (Stewart *et al.*, 1986).

We propose that the decimetric halo that accompanies active regions provides a long-lived, spatially extended source of nonthermal electrons and that it is responsible for the large-scale source of noise storms and underlying emission. The relative

TABLE II

Active regions observed with the VLA and RATAN

Date	AR number	Sunspot	Area ($10^{-6} A_0$)	H_{opt} (G)	Noise storm	H_{rad}	H_{rad}/H_{opt}
May 6, 1993	AR 7496	A (west)	176	2300 S		1630	0.7
	(108SD)	B (east)	pores	2100 S			
	AR 7500	A (west)	267	2700 S	+	1390	0.51
	(111SD)	B (middle)	≤200	2400 S	+	1340	0.56
	AR 7499	A (west)	5	2000 N		1530	0.76
	(110SD)	B (east)	≤5	1900 S			
May 7, 1993		C (east)	≈200	2500 N	+	1160	0.46
	AR 7499	A (west)	23	2200 N		550	0.24
	(110SD)	B (east)	≤10	1900 S			
	AR 7496	A (west)	134	2400 S		2050	0.85
	(108SD)	B (east)	≤100	1900 S		1320	0.70
	AR 7500	A (west)	258	2400 S		1740	0.72
	(111SD)	B (middle)	≤258	2300 S		1660	0.72
		C (east)	≈300	2200 N		1620	0.74
May 8, 1993	AR 7499	W (main)	24	1900 N	+	550	0.28
	(110SD)	E (tail)	12	1700 S	+		
	AR 7496	W (main)	176	2700 S		1760	0.62
	(108SD)	M (middle)	≥120	2900 S		1900	0.65
		E (tail)	≤120	2000 S, 2200 N			
	AR 7500	W (main)	203	3200S		1700	0.53
	(111SD)	M (middle)	≤200	2700 S		1550	0.57
		E (tail)	≥200	2300 N		1900	0.82
May 9, 1993	AR 7499	W (main)	105	2200 N	+	1190	0.54
	(110SD)	E (tail)	pores	2040 S	+	715	0.35
	AR 7496	W (main)	152	2700 S		1800	0.67
	(108SD)	M (middle)	≤152	2600 S		2100	0.8
		E (tail)	15	2500 S			
		D (source)	–	–			
	AR 7500	W (main)	244	2900 S		2550	0.88
	(111SD)	M (middle)	≤200	2100 S		2000	0.95

strength of this halo may indeed determine whether or not noise storm emission occurs at the longer meter wavelengths. In this interpretation, large-scale coronal loops trap and constrain accelerated particles within relatively large areas above or near active regions, in much the same way that energetic particles are trapped with the terrestrial Van Allen radiation belts. Such a reservoir of nonthermal electrons is observed on the Sun within the decimetric halo, as well as in the long-lasting, peculiar radio sources above magnetically complex active regions (Akhmedov *et al.*, 1986; Lang *et al.*, 1993).

Decimetric halos are apparently associated with most active regions, but their relative strength varies. The spectrum of the halo (Figure 6), which increases with wavelength, is difficult to interpret in terms of thermal bremsstrahlung. Thermal gyroresonance radiation is also probably not responsible for the halo because comparatively strong magnetic fields of about 400 G (third harmonic of the gyrofrequency at 9 cm) over the entire region is necessary for this interpretation.

Our observations suggest, for example, that noise storms are preferentially associated with relatively strong and evolving halos, and that noise storms may not occur near active regions whose decimetric halo component is weak or absent. The active regions that do not emit noise storms may be associated with relatively strong magnetic fields and relatively intense thermal emission at both microwave and X-ray wavelengths. We might therefore speculate that the energetic particles trapped within the halos overlying these active regions have drained down to supply intense gyroemission in the strong magnetic fields located above large sunspots, resulting in less intense decimetric halos and no noise storms.

We propose a model in which nonthermal particles are trapped within large-scale magnetized loops that can exceed an active region in size. These nonthermal particles are responsible fo rthe extended halo component detected at decimetric wavelengths (about 4 to 12 cm). Nonthermal energy that has been accumulated and stored within this reservoir can be released to produce long-lasting noise storms at meter wavelengths. Intense microwave radiation associated with sunspots ('thermal' gyroresonance emission) or with underlying magnetically complex active regions (nonthermal peculiar sources) may be local manifestations of energy released from this much larger, overlying volume.

The noise storms may be triggered when emerging flux perturbs the overlying large-scale magnetic structure, forcing it to become unstable, and in some instances, to expand (Raulin *et al.*, 1991; Willson, Lang, and Liggett, 1990). The noise storms observed during May 1993, were, in fact, associated with evolving photospheric magnetic structures and slowly-enhanced X-ray emission over periods of days. But in our interpretation, the actual source of the nonthermal noise-storm particles is the overlying halo reservoir.

Future investigations of nonthermal noise storms may provide insight to other forms of energetic particle accelerations, such as those occurring during flares. The differences seem to be one of scale, for noise storms are larger in size and last longer (minutes for flares and hours to days for noise storms).

We can finally comment on the unknown source of particle acceleration that accounts for solar noise storms, as well as other long-lasting nonthermal radio emission from solar active regions and nearby active stars. They all require the more-or-less continuous acceleration of nonthermal electrons over periods of hours.

One possibility is persistent low-amplitude flares. Another possibility is particle acceleration within the large-scale magnetic reservoir, perhaps by 'double layers' or some other process that is analogous to the production of long-lived, nonthermal particles within the terrestrial magnetosphere.

Acknowledgements

Collaborative VLA-RATAN observations of the Sun at Tufts University, the Pulkovo Observatory, and the Special Astrophysical Observatory of the Russian Academy of Sciences are supported by the US-FSU Cooperative Research Program of the National Science Foundation under grant ATM-9317795, by the Russian Fundamental Science Foundation under grant 93–02–17220 and by Collaborative Research Grant 921394 of the North Atlantic Treaty Organization (NATO). Radio astronomical studies of the Sun at Tufts University are also supported by NASA grant NAGW-2383. The VLA is operated by Associated Universities, Inc., under contract with the National Science Foundation. The *Yohkoh* SXT operations and analysis are supported under grant NAS8–37334 and by the Lockheed Independent Research Program.

References

Akhmedov, Sh. B. *et al.*: 1982, *Solar Phys.* **79**, 41.
Akhmedov, Sh. B. *et al.*: 1986, *Astrophys. J.* **301**, 460.
Alissandrakis, C. E., Gelfreikh, G. B., Borovik, V. N., Korzhavin, A. N., Bogod, V. M., Nindos, A., and Kundu, M. R.: 1993, *Astron. Astrophys.* **270**, 509.
Bogod, V. M., Gelfreikh, G. B., Willson, R. F., Lang, K. R., Shatilov, V., and Tsvetkov, S. V.: 1992, *Solar. Phys.* **141**, 303.
Bogod, V. M., Vatrushin, S. M., Abramov-Maximov, V. E., Tsvetkov, S. V., and Dikij, V. N.: 1993, in H. Zirin, G. Ai, and H. Wang (eds), *ASP Conference Series* **46**, 306.
Brosius, J. W., Willson, R. F., Holman, G. D., and Schmelz, J. T.: 1992, *Astrophys. J.* **386**, 347.
Gelfreikh, G. B. and Lubyshev, B. I.: 1979, *Astron. Zh.* **56**, 562.
Krüger, A. and Hildebrandt, J.: 1985, *Astron. Nachr.* **306**, 562.
Lang, K. R. and Willson, R. F.: 1987, *Astrophys. J.* **319**, 514.
Lang, K. R., Willson, R. F., Kile, J. N., Lemen, J., Strong, K. T., Bogod, V. M., Gelfreikh, G. B., Ryabov, B. I., Hafizov, S. R., Abramov-Maximov, V. E., and Tsvetkov, S. V.: 1993, *Astrophys. J.* **419**, 398.
Mercier, C., Elgaroy, O., Tlamicha, A., and Zlobec, P.: 1984, *Solar. Phys.* **92**, 375.
Raulin, J. P., Willson, R. F., Kerdraon, A., Klein, K.-L., Lang, K. R., and Trottet, G.: 1991, *Astron. Astrophys.* **251**, 298.
Stewart, R. T., Brueckner, G. E., and Dere, K. P.: 1986, *Solar Phys.* **106**, 107.
White, S. M., Kundu, M. R., and Gopalswamy, N.: 1991, *Astrophys. J.* **366**, L43.
Willson. R. F., Lang, K. R., and Liggett, M.: 1990, *Astrophys. J.* **350**, 856.
Willson, R. F., Kile, J. N., Lang, K. R., Donaldson, S., Bogod, V. M., Gelfreikh, G. B., Ryabov, B. I., and Hafizov, S. R.: 1994, *Proceedings of the 30th Committee on Space Research (COSPAR) Meeting*, to appear.