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Three-dimensional Structure of the Magnetospheres of Solar Active Regions from Radio Observations

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Abstract. The physics of the sun is entering a new era, based on observations in many electromagnetic wavelength ranges which make possible to study in detail the structure and physical processes in the outer regions of the solar atmosphere, the corona especially. In spite of powerful methods based on the observations in EUV and X-rays made from space, radio observations provide a lot of independent information on the strength of the coronal magnetic fields, the acceleration of the particles, plasma turbulence, emission measure etc. These data play important role in reconstructing and modelling different types of plasma structures accessible to observations in the solar atmosphere, including the three-dimensional structure and physical processes in the magnetospheres of solar active regions. On the other hand, the potential resources of the radio diagnostics of the solar plasma are far from being exhausted and further progress in the development and application of the observational techniques in the microwave range is a promising goal in the physics of the sun.

1. Introduction

The three-dimensional structure of various plasma configurations observed in the solar atmosphere is the central topic of interest of this conference. In many respects it is really a new approach to the problems of solar physics, solar activity especially. The reason is due to the fact that traditional optical observations, and even those made from space, provide us with information which, although very rich, refers only to very thin layers of the solar atmosphere (the photosphere and chromosphere), not usually exceeding 1% of the solar radius in extent. Coronograph observations yield the coronal structure only beyond the limb. Thus the optical wavelength range is not a satisfactory tool for studying the development of an active region (AR) and cannot provide any reliable restoration of its three-dimensional structure in the corona.

At present we have come to an era of space observations of the solar activity which resulted in quite a new approach to the problem of the three-dimensional structure of solar active regions at the coronal level. Observations of the sun made from the cosmos in EUV and X-rays give us today regular information on the coronal structures, both on the disk and off the limb. Spectral analysis provides rather detailed information on the temperature and differential emission measure of coronal structures. Fast development and strong acceleration processes are also accessible through these observations.

In previous years, when only sporadic solar observations from the cosmos were done, radio methods provided information on coronal structures and processes much more regularly. It is important to note that the radio methods supply a lot of informational not accessible from the X-ray or EUV wavelength ranges.

In this presentation I would like to show the unique possibilities provided by radio astronomy in studying the structure and physics of solar active regions in the upper chromosphere and the corona. At the same time, some instrumental limitations do not permit us to exhaust the information that one could expect from these methods.

2. Why Radio Observations?

The magnetosphere of an active region is a plasma structure in the solar atmosphere which is organised by two sources:

1. The local currents in the photosphere and subphotospheric levels. These currents, with the resulting structure of strong magnetic fields, are what we traditionally assume to be an active region.

2. The effect of the surrounding plasma of "quiet" regions. The latter include the flows of plasma, MHD-waves, and electromagnetic emission.

Though the existence of such structures is obvious from the point of view of the general physical considerations, in fact, for the first time they were made accessible for observation by the methods of radio astronomy. A typical active region associated radio source and its multi-component structure is illustrated by an example presented in Figure 1. Investigations of such *local sources* have shown many features which could not be expected from our previous level of knowledge. These include, among others, strong magnetic fields in the corona ($B > 2000\,\mathrm{G}$) and the existence of "radiation belts" with continuously accelerated particles, even in weak active regions.

At present, when such an impressive variety of data on coronal structures is available from observations made with the Yohkoh and SOHO spacecrafts, it might appear that the radio data do not add any important information on the physical processes in the atmosphere of solar active regions. In fact, however, we can get a lot of information on additional physical parameters and detect physical processes from the radio diagnostics of the solar plasma, compared with the observations made in EUV and X-ray wavelength ranges. These are:

- The measurement of the strength of the magnetic field. Although pictures of the corona often show loops which are usually considered as a reflection of the magnetic field lines, the strength of the magnetic field does not follow from their study. At the same time, at least four radio methods of diagnostics of magnetic fields applicable to the solar corona have been successfully developed and have given important information on the physics of the magnetospheres of solar active regions. Some details will be given below.

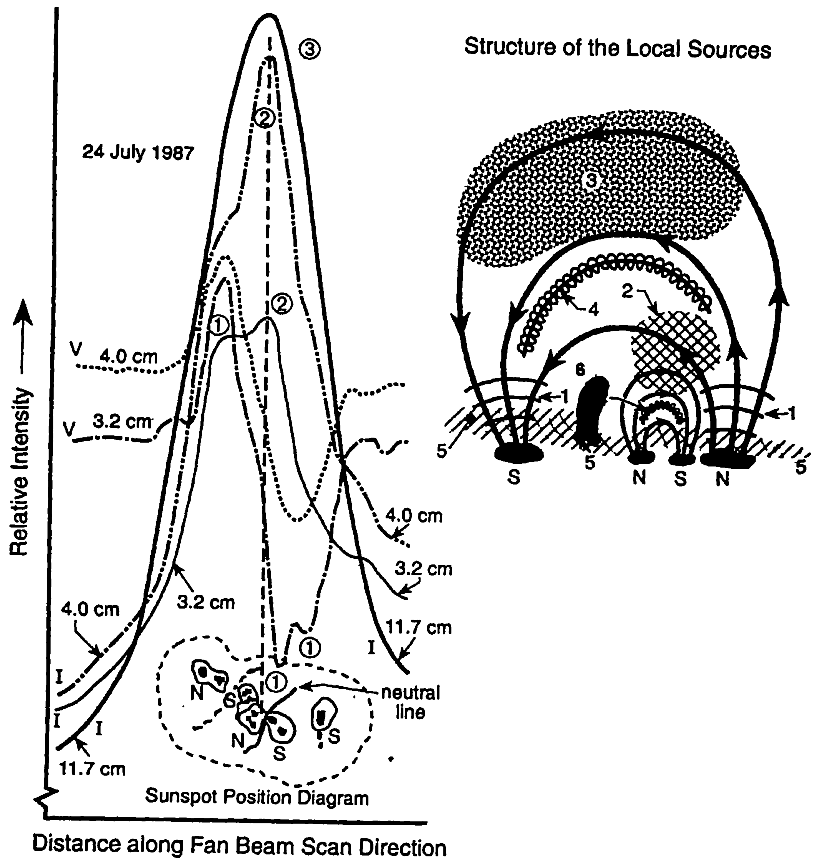

Figure 1. One-dimensional scans of an active region at three wavelengths in polarized emission and total intensity obtained with the radio telescope RATAN-600. The structure and position of the components of the radio source are shown on the right: 1: sunspot-associated sources; 2: peculiar sources; 3: decimetric halo; 4: coronal loops; 5: facular component; 6: neutral line (NL) - associated component (courtesy of A. N. Korzhavin)

- Accelerated particles can be observed by their X-ray emission (mostly bremsstrahlung). However, at present this method is usually applicable only in flare events, while radio observations of magnetic bremsstrahlung (cyclotron or synchrotron emission) are much more sensitive for diagnostics of fast particles and do not require any dense plasma to be emitted. As a result we can detect radiation belts in quiet active regions, not visible by any other method.

- The diagnostics of the emission measure (eventually the electron density) of coronal structures using radio thermal bremsstrahlung is weakly dependent on the plasma temperature and, as a result, provides more reliable estimates.

- The measurement of the electron temperature needs observations at wavelengths where the optical thickness of the object, $\tau \gg 1$. In the case of sunspot-associated sources the observations allow us to associate the temperature with the distribution of the magnetic field in the solar corona.

- The fine spectral structure of polarization inversion in some active regions may give information on the presence, position and development of special magnetic structures, such as current sheets.

The above list (which is far from being exhaustive) illustrates the independent diagnostics of the solar plasma which can be performed using radio observations, compared with other wavelength ranges.

Before coming to the next section, I would like to remind you that local sources present in radio images of solar active regions are multi-component features. They are generated by different mechanisms and differ essentially in the physical parameters of the plasma in the regions of radio emission. Figure 2 illustrates the different types of the spectra typical to the above components.

3. How to Obtain the 3D-structure from 1D or 2D Radio Observations?

This problem is certainly general enough and typical for observations in all wavelength ranges. However, the degree of applicability of different solutions depends on many factors peculiar to a particular type of observation. We therefore focus our attention to the radio astronomical methods.

3.1. The solution of the Transfer Equation

The observed brightness distribution of an active region under consideration can be described using the equation of transfer of the electromagnetic radiation, representing the sum of the accessible emission taking into account its absorption in the overlaying plasma. For the brightness temperature, T_b, the solution of the transfer equation looks like this

$$T_b(\lambda) = \int_0^\infty T(\tau) e^{-\tau} d\tau. \qquad (1)$$

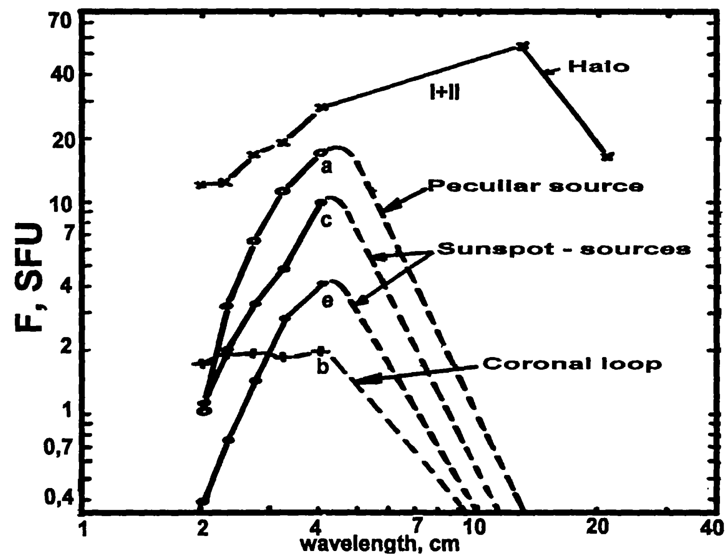

Figure 2. Spectra of the total flux of different components of the radio emission of an active region observed on July 15, 1982. The data were obtained from observations with the RATAN-600 radio telescope (see also Akhmedov et al. 1986)

In some cases it is more convenient to consider the intensity, I, (in fact, equal to brightness) instead of the brightness temperature:

$$I(\lambda) = \int_0^\infty \epsilon(l)\, e^{-\tau(l)} dl. \tag{2}$$

The optical depth, $\tau(l)$, is

$$\tau(l) = \int_0^l \kappa(l) dl \tag{3}$$

Here ϵ and κ are the emission and absorption coefficients of the thermal plasma. They are connected by Kirghoff relation:

$$\frac{\epsilon}{\kappa} = \frac{2kT}{\lambda^2} \tag{4}$$

The bulk of the radio emission of an active region at short centimeter wavelengths is generated by thermal electrons, that is the electrons with Maxwellian distribution in the velocity space. So, here we limit ourselves to considering thermal radio sources. However, the two mechanisms of radio wave generation should be taken into account: thermal bremsstrahlung (free-free transitions) and thermal cyclotron radiation (gyroresonance emission).

We expect that a 2D-distribution is recorded from observations using high spatial resolution antenna systems. To find the distribution of the physical parameters along the ray path we need to find a solution of the above equation (this approach to the problem is called sometimes *tomography*, see e.g. Aschwanden 1993, Bogod & Grebinskij 1997). From the observations we have one function of one parameter (i.e. $T_b(\lambda)$, $T_b(f)$, $I(\lambda)$ or $I(f)$); we thus expect from the solution of the equation 1 or 3.1. to find one function of the distance, l. In fact, the emissivity ϵ and absorption coefficient κ depend on distance through such physical parameters as temperature T, density N_e, and magnetic field strength B. All of them, generally speaking, are unknown functions of the distance l. In other words, even if we successfully find the solution of the transfer equation we still need some model data or a physical (also model) equation to find the spatial distribution of the physical parameters.

The choice of parameters and other problems for the two thermal mechanisms mentioned above is quite different. In the case of the thermal cyclotron mechanism the emission is generated in very thin resonance layer of spatial thickness

$$\Delta l = L_B \frac{v_T}{c} \tag{5}$$

Here L_B is the scale length of the magnetic field and v_T is the thermal velocity of electrons. From this formula we find that typically the observed emission at a particular wavelength is generated inside a very thin layer of a few hundred km in thickness. Some estimations show that it is normally optically thick. So, the brightness temperature presents the electron temperature:

$$T(l) = T_b(\lambda) \tag{6}$$

This formula connects the electron temperature $T(l)$ with the magnetic field strength according to relation:

$$B(l) = 3570/\lambda \tag{7}$$

for emission at the third harmonic of the gyrofrequency (extraordinary mode). We have a similar formula for the magnetic field corresponding to the second harmonic (the main source of the ordinary mode):

$$B(l) = 5400/\lambda \tag{8}$$

This type of emission happens in most obvious case in some narrow layers above the umbra of sunspots (see Figure 3).

3.2. Stereoscopy

The other way to get the 3D-structure of the magnetosphere of a solar active region is to look at it from the different directions — the stereoscopic method. Practically the only way to do this is to observe the same active region for a number of days (having in mind the effect of the solar rotation).

Figure 3 illustrates a case of observations of the same active region made near the center of the solar disk and at the limb at the wavelength of $\lambda = 1.76\,\text{cm}$, both in intensity and in circular polarization. The top frame shows a magnetic map, which we refer to the chromospheric level, in good agreement with optical photospheric magnetograms and calcium plages. This illustration shows the possibility to find all main parameters of a thermal loop covering the photospheric neutral line of the magnetic field.

There are serious limitations on this method, however:

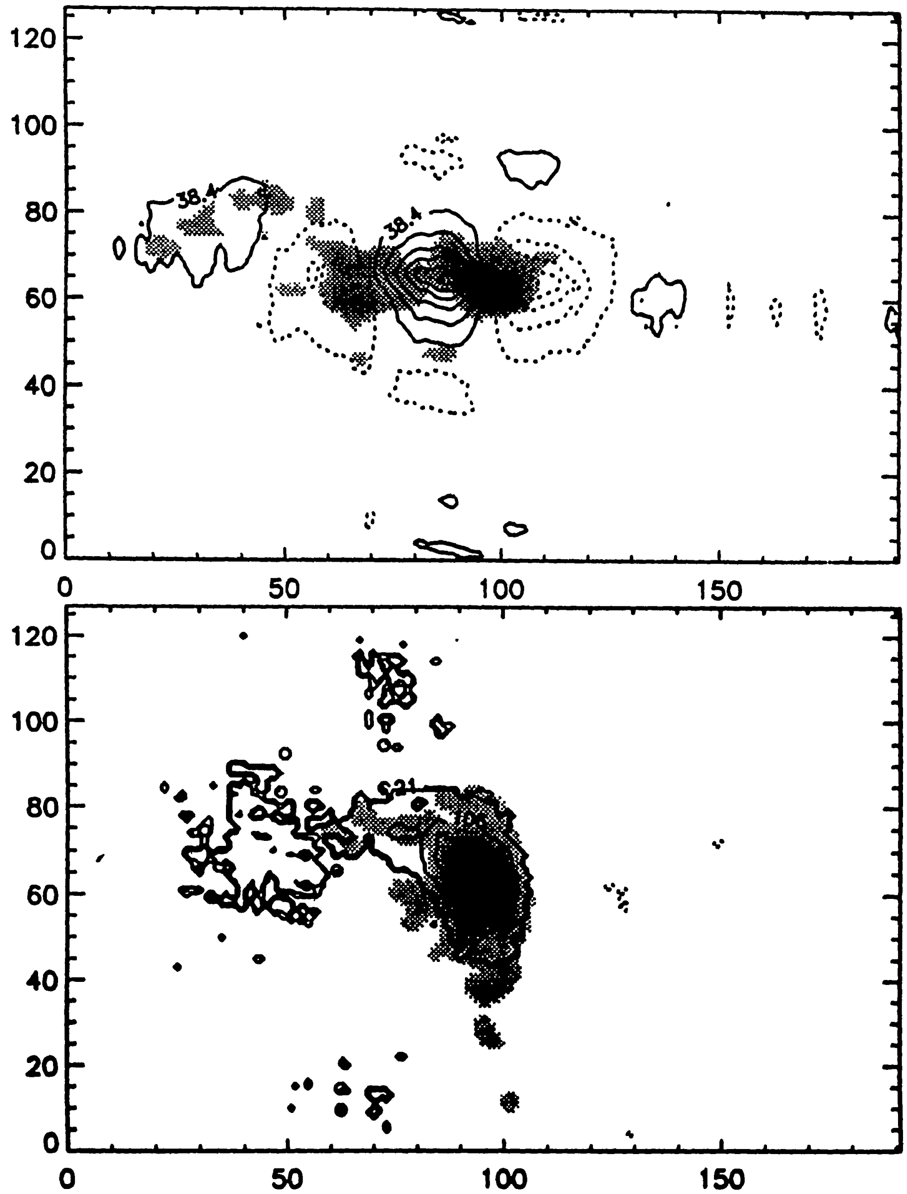

Figure 3. A radio magnetogram of the active region AR7877 near the center of the disk (June 9, 1995 - top). This refers to the chromospheric level. Solid lines represent isogauss contours for the north polarity of the longitudinal component of the magnetic field, broken lines for the south. The intensity map for the same wavelength, 1.76 cm, overlies the magnetogram. At the bottom, a similar picture is shown for the same AR beyond the limb on June 14. In this case the magnetogram refers to the corona. Both pictures were obtained with the Nobeyama radioheliograph.

- We expect that the structure of the region be *stable* for at least a few days, which is generally not typical to solar structures.

- The problem of *opacity* of the region. We may get reasonably good solution for optically thin or optically thick region. The first is a good approximation for some components, namely the emission of a coronal condensation at shorter cm wavelengths. Optically thick structures are often observed for gyroresonance emission, e.g. sunspot-associated components. For the case of semi-transparent regions and nonthermal components additional modelling assumptions may be required.

- In the case of magnetic bremsstrahlung (both thermal and nonthermal) the effect of the *directivity* of the emissivity of plasma becomes essential. To take this into account we need at least to have some knowledge of the direction of the magnetic field in the observed emitting volume. So, it is impossible to solve the problem without using models of the active region.

The limitations above lead us to look for some compromises in the usage of the stereoscopy method. A possible solution of the problem may include some modelling approximations concerning the structure of the magnetosphere under consideration and the physical nature of its radio emission. In this way we may avoid to rely on the absolute stability of its structure.

3.3. Modelling

The construction of a 3D physical model of the investigated object is often the ultimate goal of any astrophysical study. Here, however, we refer to the more limited objective of reconstructing some physical parameters, namely the magnetic field structure, in the atmosphere of an active region.

It is well known that 2D magnetograms at the photospheric level, based on measurements of the Zeeman effect in optical spectral lines, can be used for the extrapolation of the magnetic field into the solar corona. In fact, the results depend significantly on some additional assumptions, e.g. the potential or force-free approximations. This is due to the fact that we hardly know the electric currents present in the solar corona.

Radio observations are used to check the results of such extrapolations (e.g. Alissandrakis, Kundu and Lantos, 1980). The inversion of the sign of the circularly polarized component, usually generated by thermal cyclotron emission at the lower harmonics of the electron gyrofrequency, also gives a good method to check the coronal magnetic fields at heights up to about 10^5 km or more above the photosphere (Kundu and Alissandrakis, 1984; Ryabov et al. 1998). Moreover, we can use such a comparison of the interpolated fields with models of expected radio emission parameters to correct the parameters of the model. In this way we can get much more reliable picture of magnetic fields in the magnetosphere of a solar active region.

3.4. Helioseismology

The exhaustive reconstruction of the physical structure of the magnetosphere of an active region (AR) needs some knowledge of the physics not only of the atmosphere but also of the subphotospheric layers. This problem in modern solar physics has got a great progress due to methods of Helioseismology based on an analysis of hydrodynamic oscillations coming through the photospheric layers. However, so far this method was limited mostly by the quiet sun, experienced global effects of oscillations (standing waves). The discovery of radio manifestation of the MHD oscillations in magnetic tube of sunspot umbra (see below and Gelfreikh et al. 1997) opens a new way for a more comprehensive analysis of standing waves in sunspots. This may prove to become an essential tool in studying the structure of subphotospheric levels which are believed to be the main source of energy resulting in solar activity observed in the corona.

4. Diagnostics of Physical Parameters of the Components of the AR Radio Emission

4.1. Diagnostics of Thermal Components

When we speak of the thermal components of the radio emission of solar active regions we mean the emission from electrons in the state of thermal equilibrium, which follow a Maxwellian distribution. Two thermal mechanisms of generation of the radio emission in atmospheres of the solar active regions are known.

1. Thermal bremsstrahlung. The main criterion for this emission mechanism is its flux (or intensity) spectra at shorter wavelengths, where the optical thickness $\tau \ll 1$. At longer wavelengths the flux should not increase. This criterion works if the magnetic field and the electron density are not very high ($\omega_B, \omega_0 \ll 1$). From the observations we can get information on the electron temperature and the root mean square density (see above). There are several components in an AR produced by this mechanism:

- *Plage-associated emission* from optically thick regions of the upper chromosphere, mostly seen at shorter wavelengths ($\lambda < 2cm$).
- *Wide halo with flat spectra*, covering the entire AR. Using old-day terminology we would call them *coronal condensations.* In many cases they are not easy to separate from the plage component. They differ by the large height of the emission region (up to 10^5 km) and the flat flux spectrum (normally in the wavelength range of 2-5cm).
- *Compact loop sources*, connecting regions of opposite magnetic polarity (neutral line - associated sources).

2. Thermal cyclotron emission. It is generated at the first few (usually three) harmonics of the gyrofrequency, the second mostly observed in the ordinary mode and the third in the extraordinary one. At the moment we know two types of structures where this mechanism is essential:

- *Sunspot-associated sources*, directly connected in size and position with the umbra and the penumbra of sunspots. They are observed in the lower corona at a height of few thousand km or less above the photosphere.
- *NL-associated sources*, which are manifestations of coronal loops connecting regions of opposite magnetic polarity on the photospheric level. These

loops generate radio emission by different mechanisms, even in different parts of the same loop.

4.2. Diagnostics of Magnetic Fields

As we mentioned above, one of the most important and unique features of the radio diagnostics of the solar plasma is the possibility to measure coronal magnetic fields using Equation 7. As far as the non-flaring state of active regions is concerned, four methods have been developed to measure the magnetic field both in the corona and the upper chromosphere. Some of them are based on the theory of the generation of the radio emission, others on the theory of propagation of radio waves in the solar plasma. Here we have only space to present a very short summary of the basic formulae and to illustrate the most significant and latest results (see also Gelfreikh 1996).

1. Thermal bremsstrahlung in the presence of magnetic field . The magnetic field affects the optical thickness for this mechanism, increasing the absorption coefficient for the extraordinary mode and decreasing it for the ordinary one. The resulting degree of the circular polarization is

$$P = n\frac{f_B}{f}\cos\alpha, \tag{9}$$

where n is the spectral index:

$$n = \frac{\partial \ln T_B}{\partial \ln \lambda}. \tag{10}$$

This solution has been obtained in the approximation of weak magnetic field and low electron density. The longitudinal component of the magnetic field from these equations is

$$B_l = \frac{107}{n \cdot \lambda} \cdot P\% \tag{11}$$

This formula allows us to use radio polarimetry as a method of magnetography of the sun (e.g. Bogod & Gelfreikh 1980). The Nobeyama radioheliograph has made possible to get two-dimensional radiomagnetograms with 10 arcsec resolution. A sample is presented in Figure 3. Good agreement with optical magnetograms and the structure of calcium plages has been found.

2. The thermal cyclotron emission provides a well developed method for *accurate* measurements of magnetic fields in the solar corona. In most cases, for the range of physical parameters of the solar corona, we deal with emission at the third harmonic of the electron gyrofrequency. The associated wavelength is determined by equation 7. From this formula one may conclude that only strong magnetic fields are accessible by this method which, for cm wavelengths, are in the range of 300 - 3000 G. In many cases the ability of the method is limited by the necessity to have spectral-polarization measurements with full wavelength coverage and high spatial resolution. If, however, high resolution observations at several wavelengths are available on the maps of polarized emission, we expect to see a very well defined border of strongly polarized radiation

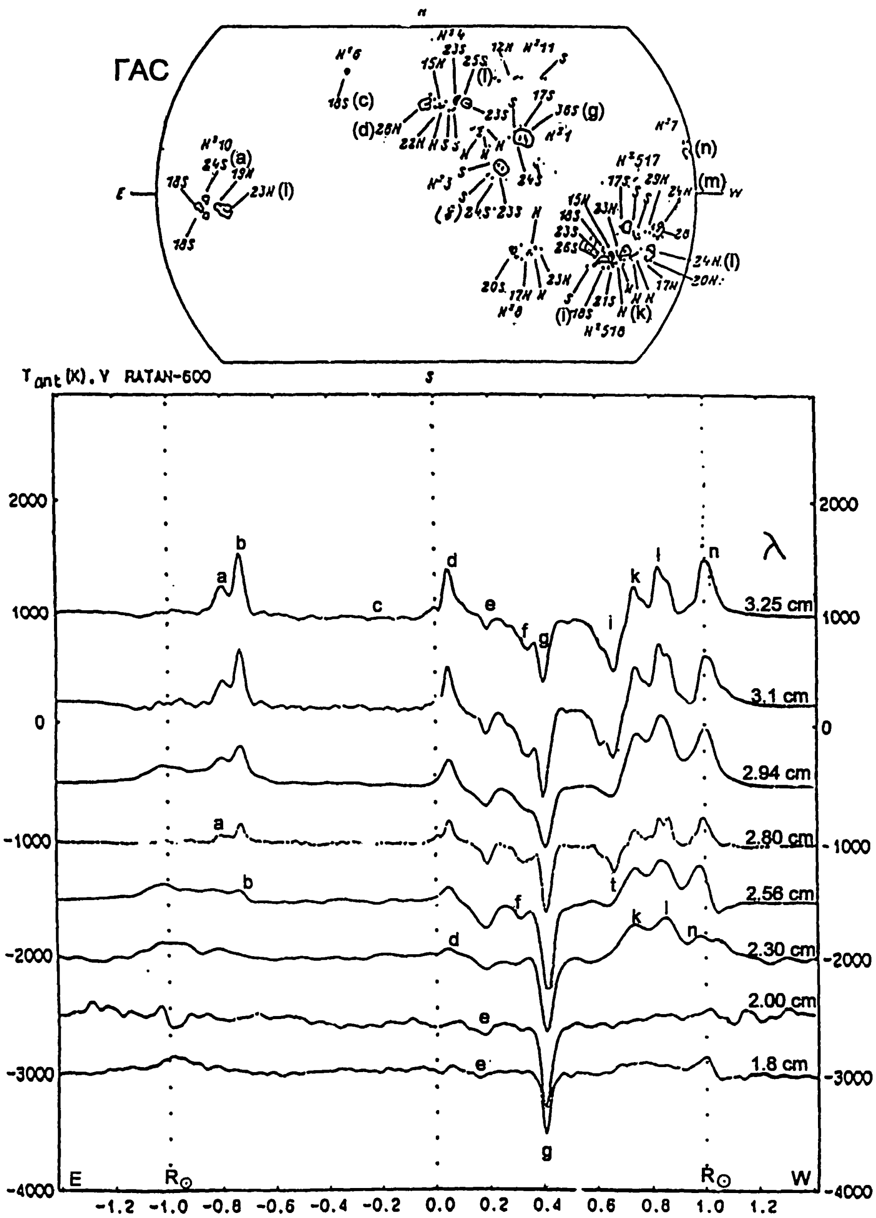

Figure 4. Structure of sunspot-associated sources at a number of wavelengths in the range of 1.8 - 3.25 cm. Radio scans on January 10, 1992, made with the RATAN-600 in circularly polarized emission, are shown. At the top an optical drawing of sunspots and their photospheric magnetic field is given. For each significant spot one can find a corresponding polarized emission in the radio spectrum.

due to high gradient of temperature in the CCTR. This provides a new method of magnetography at the base of the solar corona (Garry & Hurford 1994).

The most interesting results here concern the coronal magnetic fields above sunspots (e.g. Kundu et al. 1977; Akhmedov et al. 1982; Alissandrakis et al. 1993, Shibasaki et al. 1994). Figure 4 illustrates the modern possibility to measure magnetic fields in the corona above sunspots (the maximum magnetic field strength for a particular spot) with an accuracy of about 50 G. The ratio of the "radio" magnetic field to the "optical" one reflects the relative decrease of the field from the photosphere to the corona. This parameter proved to be an important characteristic of the level of activity of an active region.

3. The inversion of the sign of circular polarization in quasi-transverse magnetic regions is due to the change of the direction of the longitude component of the magnetic field and takes place if the approximation of the geometric optics is valid (weak wave coupling). This is often the case only at shorter wavelengths, which results in the inversion of the sign of polarization with the wavelength. The critical wavelength of inversion, λ_c, can be used to find the magnetic field in the corona. This value refers to the point where the radiation from a polarized source crosses a region of transverse magnetic field. To obtain the magnetic field strength a formula of the following type is used:

$$B_t = \frac{182}{\lambda_c^{4/3}(N_e L_\alpha/10^{18})^{1/3}} \quad (12)$$

Here L_α is the scale length of divergence of the magnetic field lines. It is the weak dependence on the electron density N_e and the parameter L_α that makes this method not sensitive to assumed model parameters, such as N_e and L_α (see Gelfreikh et al. 1987).

An example of using this method is illustrated in Figure 5 where the observations as function of time and wavelength are shown. The reconstructed coronal magnetic field as a function of the height above the photosphere is presented in Figure 6 (for a description of the method used see Gelfreikh et al. 1987 and Ryabov et al. 1998).

Observations made with the multi-frequency panoramic spectrum analyzer and the RATAN-600 radio telescope have shown a new effect of multiple inversion of the sign of polarization within the centimeter wavelength range (Bogod et al. 1993, 1997). Two possible interpretations for this phenomenon were discussed:

- More than one region of transverse magnetic field may be crossed by the ray from the polarized source in the corona. These could be due to the magnetic structures of different scales, including magnetic field lines connecting active regions in different hemispheres.
- The effect of very complicated local magnetic structures in the magnetospheres of solar AR, such as a current sheet or a magnetic shear. Similar structures are known in solar physics as probable regions of acceleration of particles and release of nonthermal energy, nevertheless methods of their detection are hardly known. The presence of the narrow band multi-inversion of the sign of the circular polarization was found to be

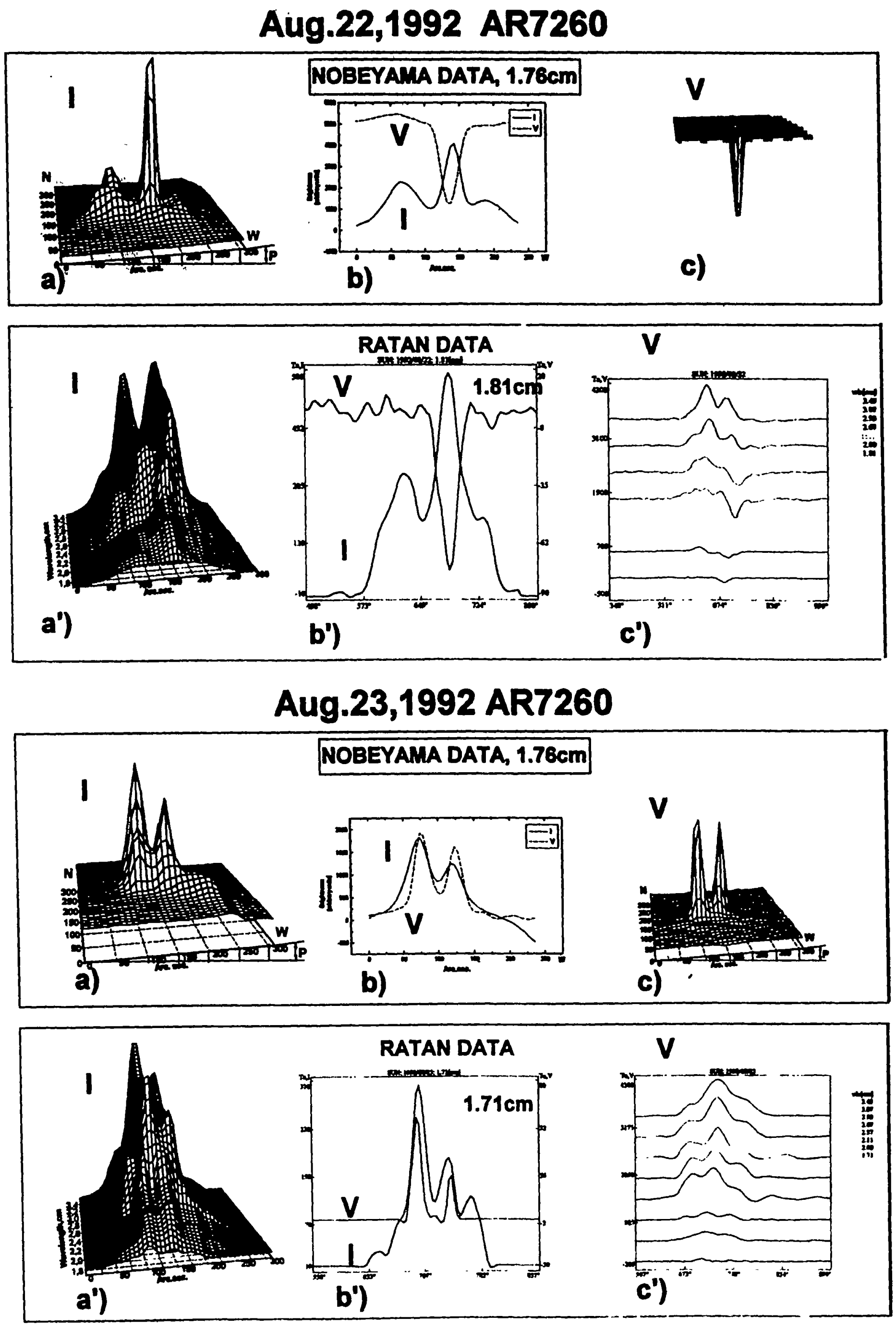

Figure 5. Observations of the inversion of the sign of circular polarization in the components of a local source observed on the solar disk on August 22 and 23, 1992. Radio maps made with the Nobeyama radioheliograph and spectral observations from RATAN-600 are shown. The inversion occurred around 1.8 cm in the following source on August 23, while at longer wavelength it was observed already on the previous day

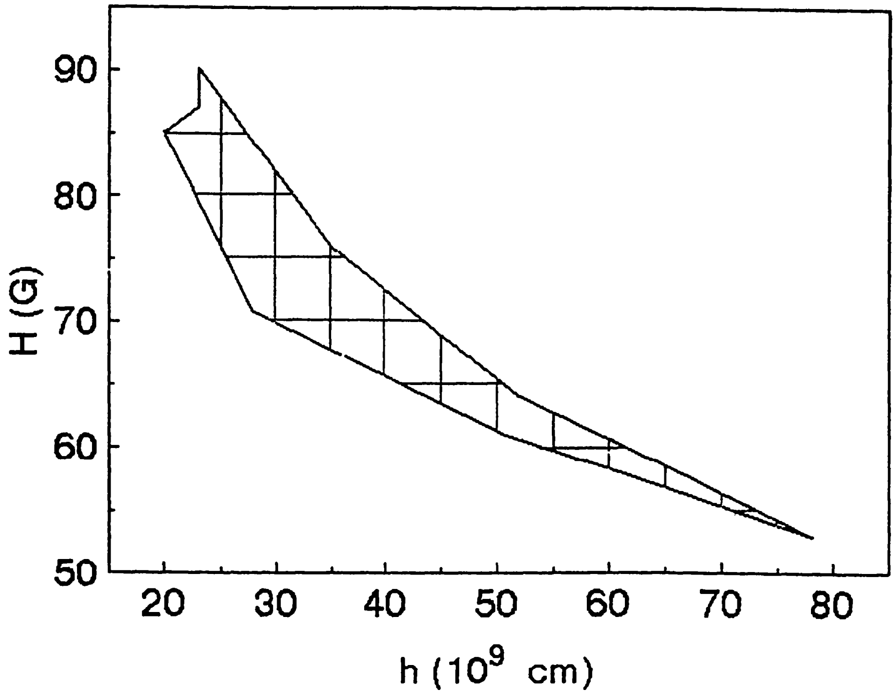

Figure 6. Variation of coronal magnetic field with height obtained from the observations on August 22-23, 1992 of Figure 5

connected with noise storms generated in the same active region. Since the generation of noise-storms needs fast particles, the above effect gives strong evidence in favour of the current sheet interpretation of the multiple inversion. An example illustrating this situation is shown in Figure 7.

4. Faraday rotation of the linearly polarized component. The angle of rotation is

$$\chi = \frac{2.4 \cdot 10^4}{f^2} \int B_l N_e dl \tag{13}$$

The strong dependence on the frequency f makes it possible to find the *rotation measure*

$$RM = \int B_l N_e dl, \tag{14}$$

Spectral observations with a very narrow bandwidth are needed in this case. The other problem is the absence on the sun of linearly polarized sources due to the fact that the limiting polarization is circular. The same Faraday effect suppresses the linear polarization, considering the inhomogenity of a source and its longitudinal extent. The most probable case of generation of linearly polarized emission is the coupling of normal modes in quasi transverse magnetic field regions. Such effect was really observed by Alissandrakis and Chiuderi Drago (1994) and used for the analysis magnetic field in the corona of a solar AR.

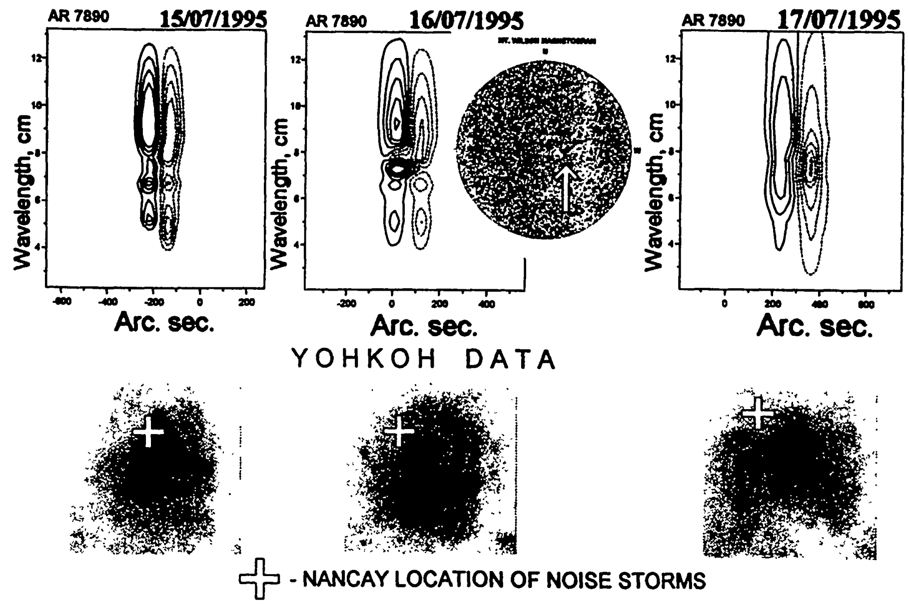

Figure 7. Spectra of polarized radio emission of active region AR7890 according to the RATAN-600 observations from 15 to 17 July, 1995. The double inversion of the sign of polarization was recorded on July 16. Variations of the X-ray source were found on the same date according to Yohkoh observations and a noise storm was found on the radio map obtained at Nançay. (Courtesy of V. M. Bogod)

4.3. Diagnostics of Nonthermal Components

One of the impressive results obtained from the analysis of the radio emission of solar active regions is the detection of a number of components which are very difficult to interpret in terms of thermal mechanisms of generation of the radio emission. Though one cannot conclude that proper models of their generation have been found, we can state that their presence is a sound evidence of continuous acceleration of nonthermal particles which are responsible for this emissions.

We can give three main types of nonthermal components identified in magnetospheres of solar active regions:

- *Peculiar sources* are usually observed in developing active regions with high flaring activity. They have a compact structure (some tens of thousand km) and their position coincides with the neutral magnetic field line inside a sunspot with delta magnetic configuration. The brightness temperature can amount ten million degrees with very steep spectra. In contrast with sunspot-associated sources peculiar sources have only moderate polarization (10-20%). Their typical life time is several days. The highest brightness temperature often occurs at shorter cm wavelength ($\lambda \approx 2cm$). This component represents the most obvious case of rather stable nonthermal processes in an active region.

- *NL-associated sources* are sometimes observed along regular neutral lines of magnetic field present in any active region and have the maximum brightness in the center of cm wavelength range ($\lambda \approx 5 - 6cm$). Usually they are the brightest component of a region, but generally do not exceed by much the normal thermal level (about two million degrees). Whether these sources are really different from peculiar sources or are at the limit of the same family is still under consideration. Some interesting examples of this type of radio sources was observed at Siberian Solar Radio Telescope (Sych et al. 1993).

- *Decimetric halo*, in contrast with the two previous cases, is a very long-living structure and belongs both to well-developed and weak active regions (with no sunspot at all). These are wide-spread sources (several minutes of arc) covering the entire active region with brightness temperature amounting to coronal temperatures. Their flux density (or intensity) increases by three times or more in the range from 4 to 10 cm or so, the maximum being recorded in the low dm range. They may last for weeks and even months.

All the above components are difficult to interpret in terms of thermal mechanisms of radio emission because of the increase of their flux density with the wavelength. At the same time some of the parameters of these sources are difficult to interpret in terms of nonthermal processes, namely their temporal stability and their upper limit of brightness usually not exceeding the typical temperature of the corona in an active region. These properties may be interpreted as emission of thermal plasma structures, however, in the case of extreme plasma parameters (high density, temperature or magnetic field strength). The existence of constantly present nonthermal particles in "radiation belts" of AR magnetospheres would be the most reasonable interpretation. The existence of a stable source of particle acceleration is the central problem here. Possibly the way to solve this problem can be found in constructing a model with many fine structures, so that the statistical parameters of many fine features are responsible for the observed stability of the emission.

4.4. Diagnostics of Oscillatory Processes

Generally speaking, the oscillations of plasma structures in the solar atmosphere may be considered as being the result of trapped MHD waves in a resonant cavity. The so-called three-minute oscillations observed by optical methods in sunspot umbra is a good example of this kind of processes (see e.g. Zhugzda et al. 1983). The variations of physical parameters of a oscillating plasma structure modulate the radio emission generated at its location. Lots of different periods ranging from minutes to hours have been reported by many authors. Their detection in total emission of the sun is a rather difficult problem, because of the comparatively low level of the effect and due to many sources of external origin (e.g. the terrestrial atmosphere). Thus the detection and analysis of oscillations in the radio emission of solar active regions is still an ambiguous problem.

The usage of new facilities provided by the Nobeyama radioheliograph has opened a new and more efficient tool to study some of the oscillatory processes

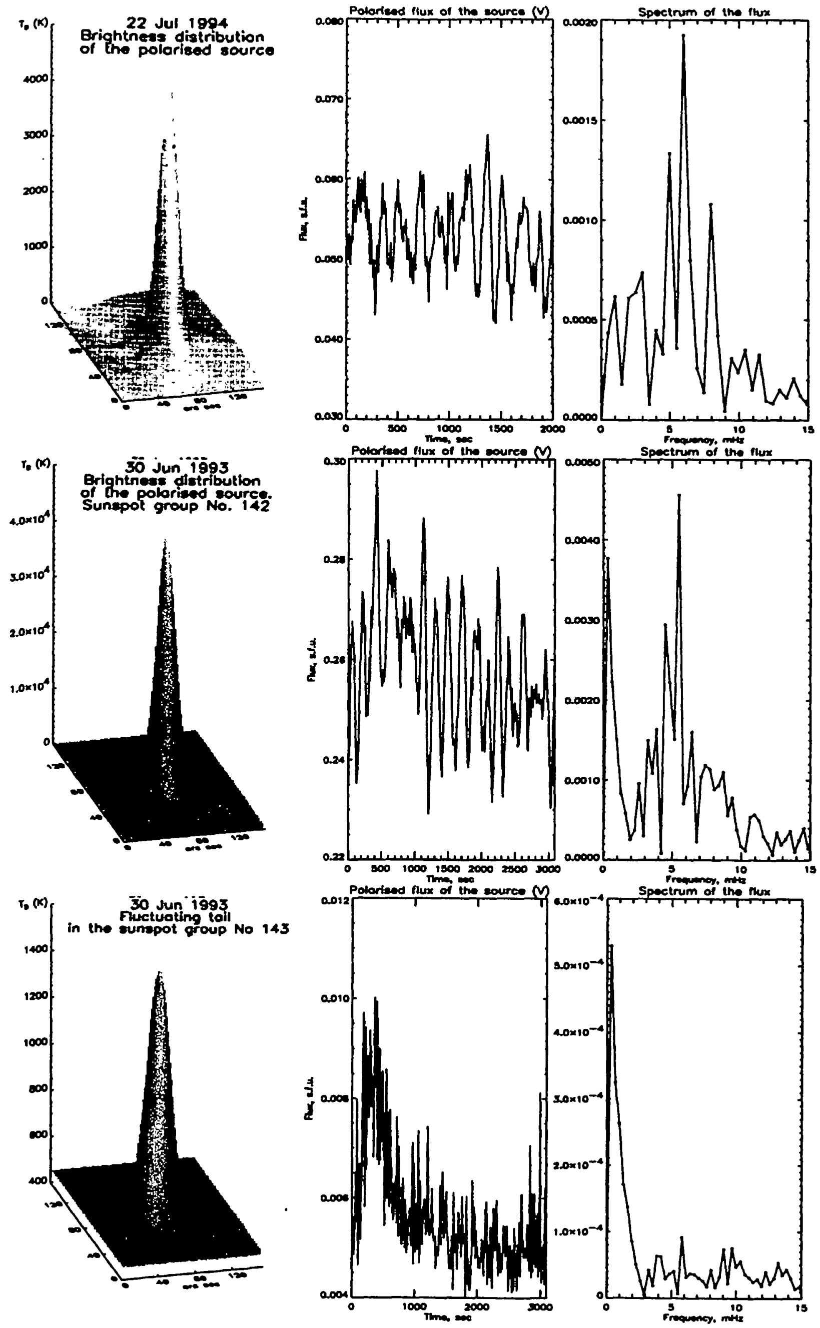

Figure 8. Time variation of sunspot-associated sources on July 22, 1994 (top) and on June 30, 1993 (middle and bottom) at the wavelength of 1.76 cm. On the left the radio images of the sources obtained with the Nobeyama radioheliograph in polarized emission are shown. The central curves represent the time variations. On the right the power spectra are presented. The first source demonstrates well-defined harmonic oscillations at a number of frequencies around a period of three minutes. The lower case shows chaotic oscillations; the latter is connected with a developing sunspot group, SD No 143.

in the atmosphere of solar active regions (Gelfreikh et al. 1997). The idea of the experiment was to use the high sensitivity of the cyclotron emission of sunspot associated sources to the physical parameters of the plasma inside the magnetic tube of sunspots. In the case of the Nobeyama observations, the emission region is situated in the lower corona or in the chromosphere-corona Transition Region, in the presence of a magnetic field of about 2000 G above the umbra of a large sunspot. Usually this emission is strongly circularly polarized (Shibasaki et al. 1994).

In three cases of different but large and stable sunspots we found well defined, nearly harmonic oscillations, with periods in the range of 140 to 200 seconds (see Figure 8). Using spectral observations of the same source (August 16, 1995), we found that the effect could be explained by oscillations of magnetic field with amplitude of about 10 gauss (in the presence of magnetic field of 2000 Gauss!). The diagnostics of the mode of MHD oscillations is still to be done. In the case of a developing active region the oscillations were found to be random in time.

5. What Can We Expect from Radio Observations in the Future?

In this presentation an attempt has been made to show the potential of radio methods in studying the three-dimensional structure and physical processes in the atmosphere of solar active regions. The progress we could expect in this field, however, depends essentially on the level of realization of the observational technics used (see also Bastian et al, 1997). We summarize below the parameters of solar radio telescopes at microwaves needed to make an essential progress in using radio methods to this end.

1. *High spatial resolution in 2 dimensions.* At present we have experience with resolutions of few seconds of arc and have observed minor details, at least at short centimeter wavelengths. These results were obtained, however, with a limited field of view (using VLA). Therefore, for an adequate application to most solar problems, we need an instrument with this level of spatial resolution but covering the entire solar disk.

2. *Wide field of view.* This should be of the order of one degree, to make simultaneous observations of all active regions on the disk and follow processes which continue outside the solar limb. One should stress that simultaneous observations of all active regions are essential for solar physics in principle because there are indications of their interaction (e.g. sympathetic flares). These are realized through coronal structures or even through some subphotospheric processes.

3. *Total wavelength (frequency) coverage.* We have illustrated before that even within the centimeter wavelength range we may find at least four subranges where different components of the radio emission of different nature dominate, corresponding to different structures in the AR magnetosphere. Thus limitations in wavelength coverage will prohibit the efficient analysis of some essential components in the structure of the solar atmosphere above active regions. As an example, we may note that the

most developed solar radio telescope at present, the Nobeyama radioheliograph, can observe sunspot-associated sources (with magnetic field in the corona above sunspots exceeding 2000 G) only in a small number of cases, while the Panoramic Spectrum Analyzer of the RATAN-600 gets this information practically for every sunspot of medium size or larger.

4. *High spectral resolution.* The experience from the analysis of spectra of local sources associated with active regions made with the RATAN-600 has shown that a spectral resolution of about 5% is good enough (and necessary) to measure magnetic fields in the corona. With such a spectral resolution one can also apply methods to detect special magnetic configurations (probably current sheets), from multiple inversion of the sign of polarization. Full coverage of the spectrum is also essential for these purposes. More detailed spectral analysis may be, however, needed for some other problems, such as studying cyclotron maser emission.

5. *High polarization sensitivity.* Analysis of small fraction of a percent of circular polarization is needed to measure polarization of thermal bremsstrahlung and to use the instrument as a radio magnetograph. Linear polarization capability is desirable, to use the method of Faraday rotation for a more detailed analysis of QT-regions. However, it is still under investigation how often linear polarization could be observed.

6. *Full time coverage.* We need an instrument devoted to Solar programs. The sun with its continuous variations of activity in all time scales and hardly predictable events needs 24 hours per day regular observations. It is worth mentioning that, in spite of many interesting results, the VLA has been able to give only limited information on some solar active region structures just because of the very scattered and limited in time periods of observation. Solar physics definitely needs instruments with full-time coverage.

7. *High time resolution.* The sun with its solar activity shows variations in radio emission on all time scales, from milliseconds to decades of years. Constructing an instrument we may include or not include an analysis of msec processes, mostly connected with acceleration of particles in flares. However, processes on a time scale of a few seconds should be accessible, to study the development and fluctuations of active regions.

8. *Wide international access to observational data.* The development of observational techniques in the modern world resulted in some new approaches in studying the sun (and other astronomical objects as well): (i) international cooperation in constructing telescopes and (ii) cooperative usage of overwhelming bulk of observational data. In the case of the sun, we could add that hardly any living being on the Earth may be indifferent to what is happening on our nearest star.

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