Solar Physics with Radio Observations, Proceedings of Nobeyama Symposium 1998, NRO Report 479

Physics of the Solar Active Regions from Radio Observations

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Abstract

Localized increase of the magnetic field observed by routine methods on the photosphere result in the growth of a number of active processes in the solar atmosphere and the heliosphere. These localized regions of increased magnetic field are called active regions (AR). The main processes of transfer, accumulation and release of energy in an AR is, however, out of scope of photospheric observations being essentially a 3D-process and happening either under photosphere or up in the corona. So, to investigate these plasma structures and processes we are bound to use either extrapolation of optical observational methods or observations in EUV, X-rays and radio. In this review, we stress and illustrate the input to the problem gained from radio astronomical methods and discuss possible future development of their applicatications.

Historically speaking each new step in developing radio technique of observations resulted in detecting some new physics of ARs. The most significant progress in the last few years in radio diagnostics of the plasma structures of magnetospheres of the solar ARs is connected with the developing of the 2D full disk analysis on regular basis made at Nobeyama and detailed multichannel spectral-polarization (but one-dimensional and one per day) solar observations at the RATAN-600. In this report the bulk of attention is paid to the new approach to the study of solar activity gained with the Nobeyama radioheliograph and analyzing the ways for future progress.

The most important new features of the multicomponent radio sources of the ARs studied using Nobeyama radioheliograph are as follow:

1. The analysis of magnetic field structures in solar corona above sunspot with 2000 G. Their temporal evolution and fluctuations with the periods around 3 and 5 minutes, due to MHD-waves in sunspot magnetic tubes and surrounding plasma. These investigations are certainly based on an analysis of thermal cyclotron emission of lower corona and CCTR above sunspot umbra.

2. Magnetography of the solar active regions presenting the weak magnetic fields (with the sensitivity of several G) reflecting longitude component of the magnetic field in chromosphere and corona and solar faculae structure. The method is based on an analysis of the weak polarization (of the order of 1% or less).

3. An analysis of the structure, temperature, and density of arches seen above neutral magnetic field lines (seen in most ARs with spots and without ones).

4. Study of temporal and spatial behavior of inversion of the sign of the circular polarization with the result of magnetography of the solar corona.

5. An analysis of the solar activity at high heliographic latitudes, observed mostly as polar faculae (increased brightness structures having counterparts in optical white light observations). In modern study of the solar activity analysis of the activity of polar zones are of principal importance. Nobeyama probably presents the most reliable way to study this.

The above points present not exactly completed results but rather the directions for future studies. These should use full time coverage of observations at different phases of the solar activity and combination of observations with other radio, optical, EUV and X-ray observations whenever possible.

Key words: Sun: active regions: radio magnetography; plasma diagnostics; radio observations

1. Introduction

Most manifestations of the solar activity originate in the localized islands of increased magnetic fields in the solar atmosphere called traditionally solar active regions. These are essentially three-dimensional plasma structures in the solar atmosphere and we may call them magnetospheres of the solar ARs (MAR). This term implies a structure clearly isolated from surrounding plasma, physical process inside a MAR being controlled both by local magnetic fields (isolated currents) and by emission and matter fluxes from surrounding media. It was just radio observations which made it possible to propose the term MAR because radio diagnostics of plasma parameters of the solar corona and upper chromosphere (such as magnetic field strength, acceleration of particles) became regularly possible using radio observations.

In an analysis of the structure and physical processes in MAR there are three main directions presenting most significant results. They are

- diagnostics of the magnetic fields;
- diagnostics of thermal structures (distribution of temperature and density);
- diagnostics of long-lasting non-flaring acceleration of nonthermal particles.

Modern solar physics consider the solar activity as essentially global process covering all heliographic latitudes. In radio we also have exclusive means to analyze not only classical active regions at low and middle latitudes but also in polar regions known in optical physics as polar faculae. Observations of dark filaments on the disk and prominences over the limb open a method to follow development of global magnetic field structure.

2. Global solar activity

In the previous session we discussed some of the problems of global changes of the magnetic field structure and its presentation in radio observations. However, today we need to study manifestation of the solar activity on the surface of the whole solar sphere. The latest results in helioseismology gained from SOHO have shown that we have solid body rotation of the sun at latitudes about 50° while gradient of angular rotation of the sun with depth $d\omega/dr$ has different sign at high and low solar latitudes. That implies a search for some new ideas in the theory of the solar cycle. One can see from magnetograms that it looks as if there are sub-photosheric circles of magnetic field lines at lower latitudes and circles of current at higher ones. So, we can expect different structures of active regions in these zones of solar activity.

The most obvious structures of polar activity of the sun are polar faculae. Now we know that fine elements of these may include magnetic fields exceeding 1500 G (Makarov et al., 1997) — value comparable with the magnetic fields of classical ARs.

It is worth mentioning some other important features of polar faculae as manifestation of polar activity of the sun. These are

- Strong magnetic fields amounting 1500 G in fine structural elements.
- Maximum number of the polar faculae near the minimum of the low-latitude solar activity.
- Repetition of the fluctuations of the level of the polar activity in classical ARs with a delay of about six years.
- Fast variability of the fine structure of the polar faculae on the time scale of one minute observed with very high spatial resolution of 0.2 arcsec (Makarov, private communication).

Observations of the polar faculae in white light, however, have important limitations due to their low contrast (below 10%) and small-scale (arcsec) features. Nobeyama radioheliograph presents a new powerful tool to study this type of solar activity. Figure 1 presents an example of the I-map at wavelength of $\lambda = 1.76$ cm with distinguished picture of polar faculae, both near the North and South poles. The observed time variations of the radio polar faculae are shown in Figure 2, where the structure of the radio sources is presented with time interval of 10 sec.

The maximum brightness excess of separate structural elements were found in the limits of 10 to 40%. That implies the brightness temperature in the limits of 11 to 14 10^3 K. The size of a separate elements is few tens of arcsec. If we are going to use this kind of observations as an index of solar activity it is essential to find out whether we deal with a new index or just find more reliable way to measure level of the same solar activity in polar zones. To this end we tried for a chosen date to compare positions of optically observed polar faculae with these found from Nobeyama radio maps. The coincidence was real but not very high (about 50% of optically observed features could be identified with the radio bright sources). Then we compared not separate optical features but the groups of polar faculae. Using this method we have come to practically total identification of the radio bright features with groups of faculae observed at Kislovodsk mountain station in white light. Earlier a similar comparison was made using the RATAN-600 observations. One-dimensional resolution limited the reliability of identification. Nevertheless the correlation coefficient in brightness distribution was in the range 0.5 - 0.9. These results lead us to the conclusion that both optical and radio methods deal with the same index of the solar activity.

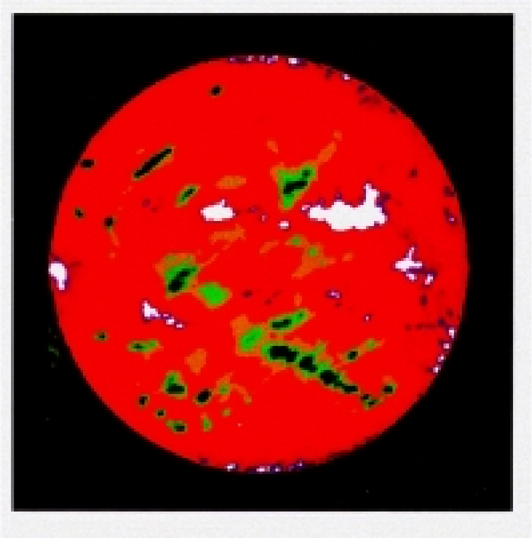

Fig. 1.. Radio map of the sun at the wavelength $\lambda = 1.76$ cm on June 30, 1993 obtained with Nobeyama radioheliograph. Interval of brightness temperatures the $\Delta T_b = (7-12)\cdot 10^3$K.

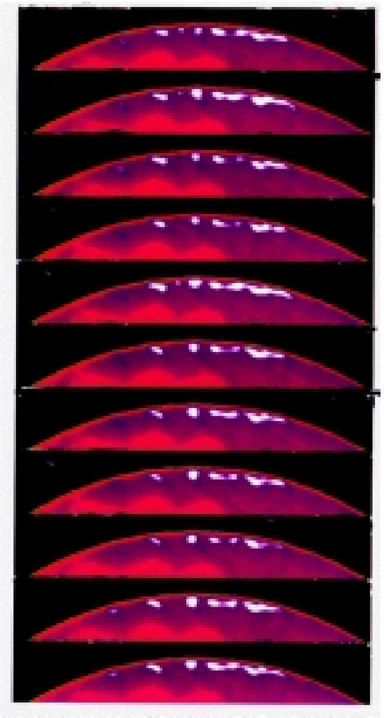

Fig. 2.. Radio maps of the polar region of the sun at the wavelength of $\lambda = 1.76$ cm on June 29, 1993 obtained with the Nobeyama radioheliograph. Time interval between successive pictures is 10 seconds.

3. Basic Components of Radio Emission of an AR

A "classical" active region is observed at microwaves as a local source of the solar radio emission. The observations to-day present a local source as a multi-component plasma structure generated by a number of different mechanisms, both of thermal and non-thermal origin. One should have in mind that classification of these components and their identification is still under consideration and far from being completed due to the absence of multi-frequency, regularly working solar instrument with high two-dimensional resolution. Below we discuss their appearance and physical diagnostics using the Nobeyama radioheliograms.

3.1. Sunspot-associated Sources

Identified in early sixties, this component became one of the most obviously determined in the wavelength range of short cm (2-4 cm). These radio sources are generated by thermal cyclotron emission at the second and third harmonics of the electron gyrofrequency in the magnetic field,

$$B(s=2) = \frac{5400}{\lambda}; \quad B(s=3) = \frac{3570}{\lambda} \tag{1}$$

This implies that at Nobeyama we can see sunspots as bright strongly polarized regions with B=2000 G magnetic field in the lower corona or CCTR. An example of such a case was studied by Shibasaki et al. (1994). We illustrate some other examples later.

3.2. Neutral Line-associated sources

Generally speaking this component becomes most prominent at longer wavelengths in the middle of cm-wavelength range (4-6 cm). A number of studies of this component made with the large instruments have shown a significant increase of radio brightness above optically determined neutral lines (NL) of the photospheric magnetic field (zero

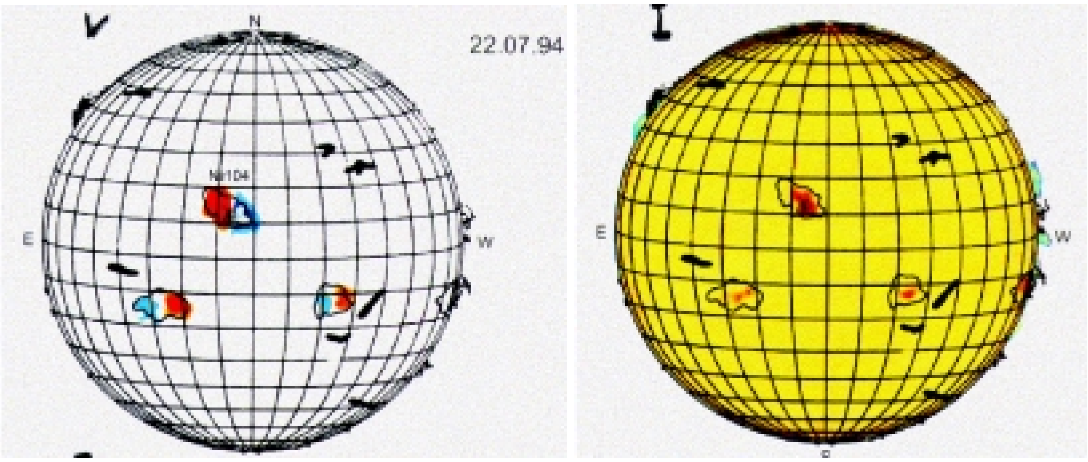

Fig. 3.. Radio maps of the sun at the wavelength of $\lambda = 1.76$ cm on July 22, 1994 obtained with the Nobeyama radioheliograph. The V-map (left) represents the structure of magnetic fields (longitude component). The polarized regions well coincide with Ca^+ plages. The I-map (right) shows that the brightest radio features are connected with the neutral lines of magnetic fields. The optical map of solar activity for both radio maps is shown accordance bulletin "Solnechnye Dannye" of the Pulkovo Observatory.

values of the longitudinal component) (Kundu, Alissandrakis, 1994). This increase in radio brightness is a manifestation of the local larger growth of the release of energy in the regions with increased gradients of the magnetic fields. The nature of the generated radio flux include three components: thermal bremsstrahlung due to increased density in some magnetic tubes overlying NL, gyroresonance thermal emission in structures of compressed magnetic fields and gyrosynchrotron radiation of nonthermal electrons.

It is worth mentioning that the regions surrounding NL of the photospheric magnetic field is a typical spot to develop flaring activity. Important result following from radio observations is declaring the fact of long-lasting, practically continuous acceleration of particles leading to some components of local radio sources. This follows both from the spectra of NL-associated sources (using the RATAN-600 observations) and from comparison of extrapolated magnetic fields into the solar corona and the brightness distribution of the sources at 6 cm (VLA, WSRT and SSRT data).

Of special interest are probably the so called "peculiar sources", typically connected with delta-configurations of sunspot magnetic fields, where gradients of the field is especially strong. In such sources very high brightness temperatures of 10^7 K are met in a stable state of the sources lasting for several days (RATAN-600 observations).

As far as Nobeyama observations are concerned the first thing to be noticed is that radio magnetograms of the active regions (see the next section) give a very accurate presentation of the NL of the longitudinal component of the AR magnetic fields (see Figure 3). This refers both to highly developed active regions including large sunspots and to weaker ones, with no spots at all. A comparison of the magnetograms (V-maps) of the sun with structure of the same ARs observed on the I-maps has shown that the brightest detail in intensity is usually referred to some region above the NL, obviously representing a loop, striding the NL structure. Important information for plasma diagnostics in this case is a reliable estimate of the emission measure $EM = \int N_e^2 dl$ of the loop due to the fact of the weak dependence of the radio flux on electron temperature T:

$$I \propto \frac{EM}{\sqrt{T}} \tag{2}$$

A more detailed analysis of a NL-associated source using the Nobeyama data is presented in a separate paper at this conference (Uralov et al.).

3.3. Halo Sources

Besides sources with characteristic scale of some ten thousands km discussed above we do observe in microwaves some diffuse components of the spatial scale of the whole AR, some 10^5 km. This component is especially typical for wavelength range of 8-12 cm and longer. Diffuse character of the component may be due to processes of plasma scattering (Bastian et al. 1997). At longer wave (say 20 to 30 cm) the bulk of the emission is probably generated by thermal bremsstrahlung of the “coronal condensation” (with $\tau > 1$). However, at its maximum near $\lambda \approx 8\ cm$ the increase of its flux can not be explained in terms of thermal bremsstrahlung because the flux in this wavelength range exceeds flux at short cm waves by several times. Very low brightness of the halo on I-maps of Nobeyama still significantly increase this discrepancy. On the other hand, an attempt to interpret this emission in terms of thermal gyroresonance emission also meets serious obstacles because this component is observed even in very weak ARs with weak magnetic field; there is no ground to cover the whole AR with magnetic field of strength amounting to several hundred gauss (condition follows from equation (1)).

So, we must conclude that the halo is due to emission of nonthermal electrons, continuously generated in most ARs, both weak and strong. They are supposed to reflect an existence of “radiation belts” in magnetospheres of the solar ARs. The problem to be solved here is the relative stability of such sources. The reason may be connected with the fine structures of the source and averaging over them by the observations. The other problem still waiting its final solution is comparatively low upper limit of brightness temperature of the dm halo, usually not exceeding several millions K. The essential role of scattering of the emission in thermal plasma may help to understand the physical nature of this limit.

4. Radio Magnetography

Radio observations present a number of methods to measure magnetic fields in the chromosphere and the corona. Probably only the radio has an opportunity to measure more or less directly the magnetic field strength in the solar corona instead of interpolations used while interpreting optical observations or studying the field line structure in EUV or X-rays from Space missions.

4.1. Thermal Bremsstrahlung

Historically thermal bremsstrahlung was the first component identified as the mechanism responsible for the increased emission of the so called slowly-varying component of the solar radio emission. As we have seen above, its role has become rather limited while interpreting the radio emission of the solar active regions. However, as we come nearer to short cm and especially mm wavelengths its role is increasing; it has become dominant already at λ =1.76 cm of Nobeyama. This makes the analysis of this mechanism the most important tool in studying magnetic fields and electron densities (emission measure), especially.

As components of a local source observed at $\lambda = 1.76$ cm at the Nobeyama radioheliograph we can see the following components:

- Wide halo, covering the whole AR is due mostly to increase of magnetic field and temperature-density structure in the chromosphere (Figure 3&4). This component is well identified on the V-maps.

-Narrower structures surrounding the NL of the magnetic fields and representing the coronal loops. These structures we expect to have good coincidence with features observed in soft X-rays. This has been confirmed by Shibasaki (1994) for an AR of August 1992. However, it is not always the case and an AR seen on June 09, 1995 looks much more compact in radio I-map than that on X-ray map. Of special interest is the observation of such coronal loops over the limb where one can see their height distribution of the density and the magnetic field (Figure 4).

4.2. Gyroresonance Emission

The most reliable manifestation of this mechanism are sunspot-associated sources with fast-growing spectra in the wavelength range of about 2 to 3 cm and strong (nearly 100%) circular polarization at shorter wavelength where the source is observed. The presence of this radiation is the evidence of the magnetic field at the third harmonic of the gyrofrequency according to the Formula (1). The high brightness of the source ($T_b > 10^5$) shows that this strength of the field achieved the corona. Due to thin layer of the CCTR the size of the source illustrates the size of the magnetic region of the particular strength at level of the CCTR. So, if we have a number of the radio maps at different frequencies we come to possibility to make a magnetogram at this level of the solar atmosphere (observations with OVRO, Bastian et al. 1997). The shortest wavelength of this emission (observations made with the RATAN-600) gives the highest strength of the magnetic field penetrating the corona (see an example at Figure 5).

Another possible type of thermal cyclotron emission may be due to current sheet and similar structures. A manifestation of “cyclotron line observations” is presented at this session by Zlotnik.

An analysis of combined optical (in several lines) and radio methods of measuring magnetic field strength in a sunspot result in a distribution of magnetic field with height (Abramov-Maximov et al. 1996). An example of such study with the usage of Nobeyama data is shown in Figure 6.

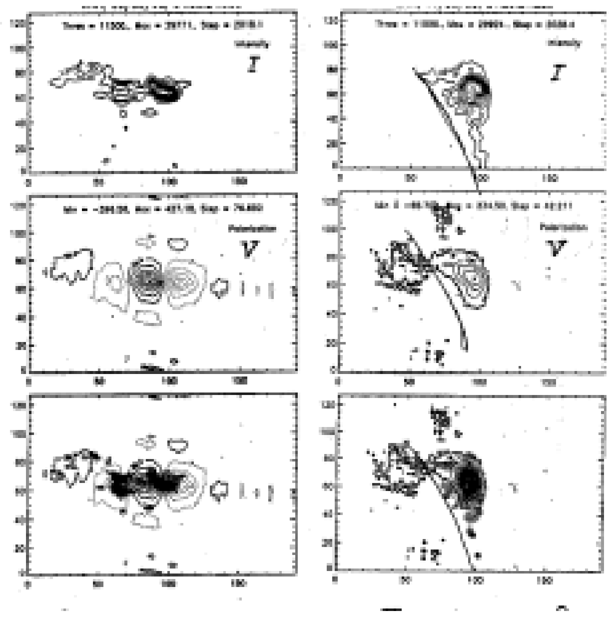

Fig. 4.. Radio maps of an active region on the sun at the wavelength of $\lambda = 1.76$ cm on June 09 (left) and June 14 (right), 1995 obtained with Nobeyama radioheliograph. On the right picture shows the active region (coronal loop) over the limb. I-maps are shown at the top, V-maps — in the middle. Below they are overlaid.

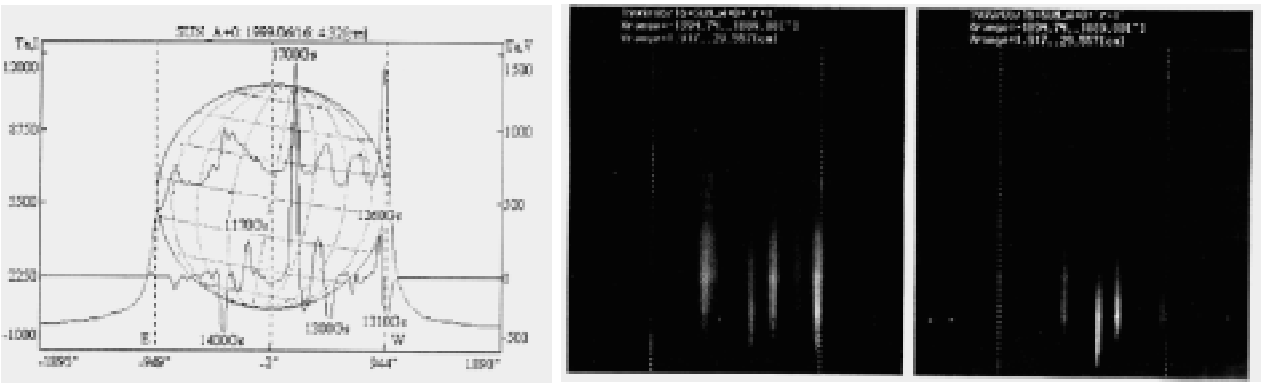

Fig. 5.. Radio scans of the sun (I & V) at the wavelength of $\lambda = 4.32$ cm on June 16, 1999 obtained with radio telescope RATAN-600. Below the spectra of the main sources in total intensity and polarization are shown. The strength of the maximum coronal field for every polarized source is shown above or below its scan.

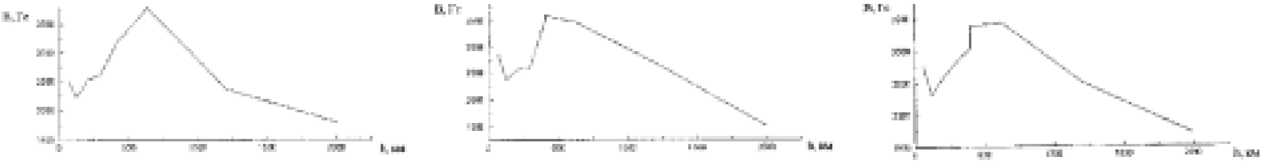

Fig. 6.. The distribution of magnetic field above a sunspot with height for sunspot group No.142 (bulletin "Solnechnye Dannye"). Optical and radio observations were made on June 28, 1993.

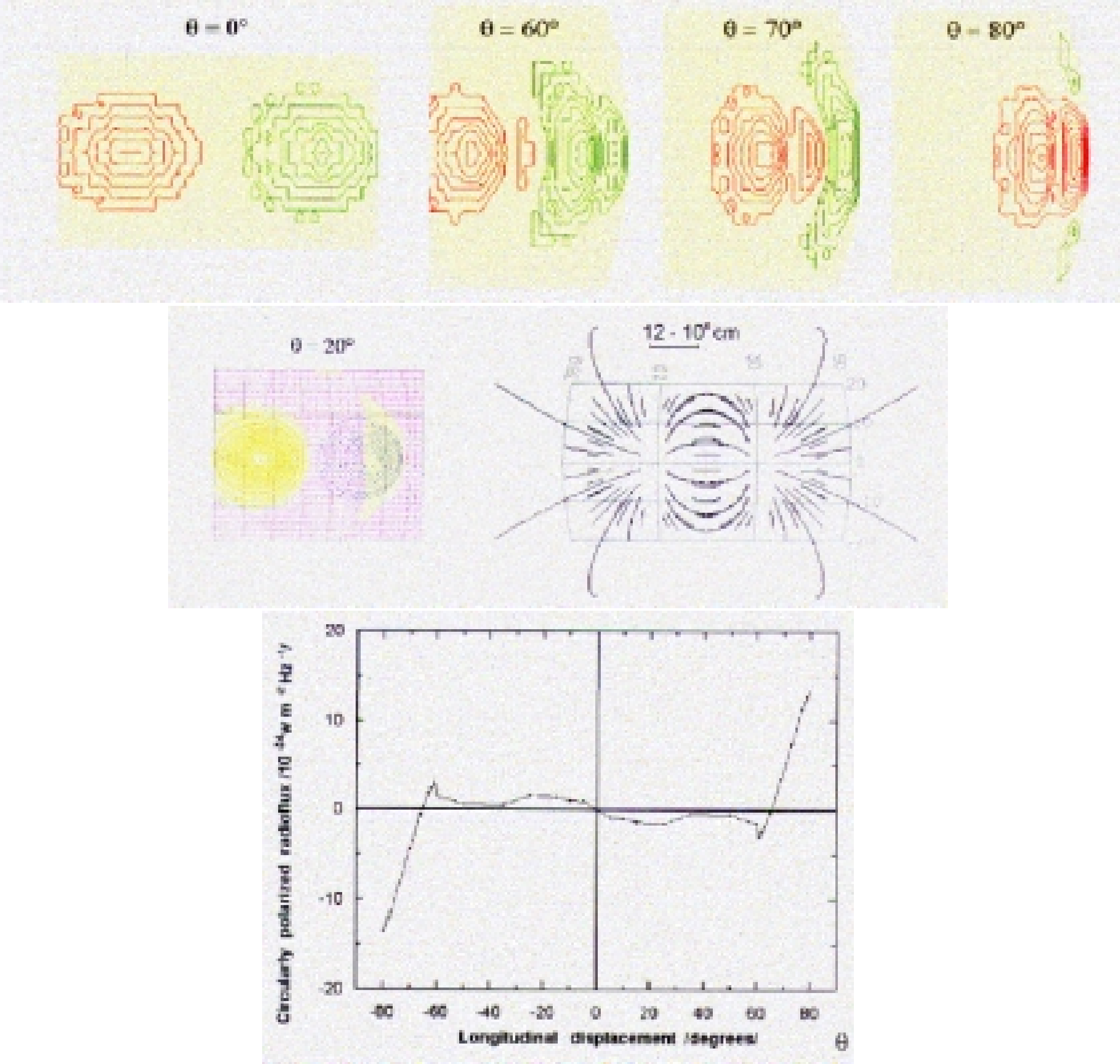

Fig. 7.. Model computations of the inversion of polarization in QT-region for a radio source generated by thermal bremsstrahlung of a symmetrical flocculi for $\lambda = 1.76$ cm. (courtesy by B.I.Ryabov)

4.3. Inversion of Polarization

Circularly polarized component emitted in most stable radio sources in most cases has an excess of extraordinary mode. However, we meet situations when the sign of polarization is reversed. This happens both as a function of time and wavelength. There are several reasons responsible for the effect:

- The effect of propagation across QT-region (the region of quasi-transverse propagation). This effect was observed by many authors at different cm-waves bands, Nobeyama radioheliograph including. It has become an essential tool to magnetography of coronal magnetic field and is presented in more detail (see Alissandrakis, 1999).

- In the case of thermal emission with optical thickness $\tau > 1$, both for bremsstrahlung and cyclotron mechanisms, the inversion of the temperature gradient results in inversion of the sign of polarization.

- In the case of gyrosynchrotron emission of nonthermal electrons trapped in a magnetic loop the inversion of polarization in time (due to solar rotation) may be due to the effects of directivity of the emission. This effect is probably important for longer cm wavelengths.

Coming back to Nobeyama observations we can expect the inversion in QT-region in the solar corona not only of strongly polarized sunspot-associated sources but also weakly polarized emission of halo above flocculi (Figure 3). The expected effect of inversion presented by model computations is shown in Figure 7. If successful, it may present

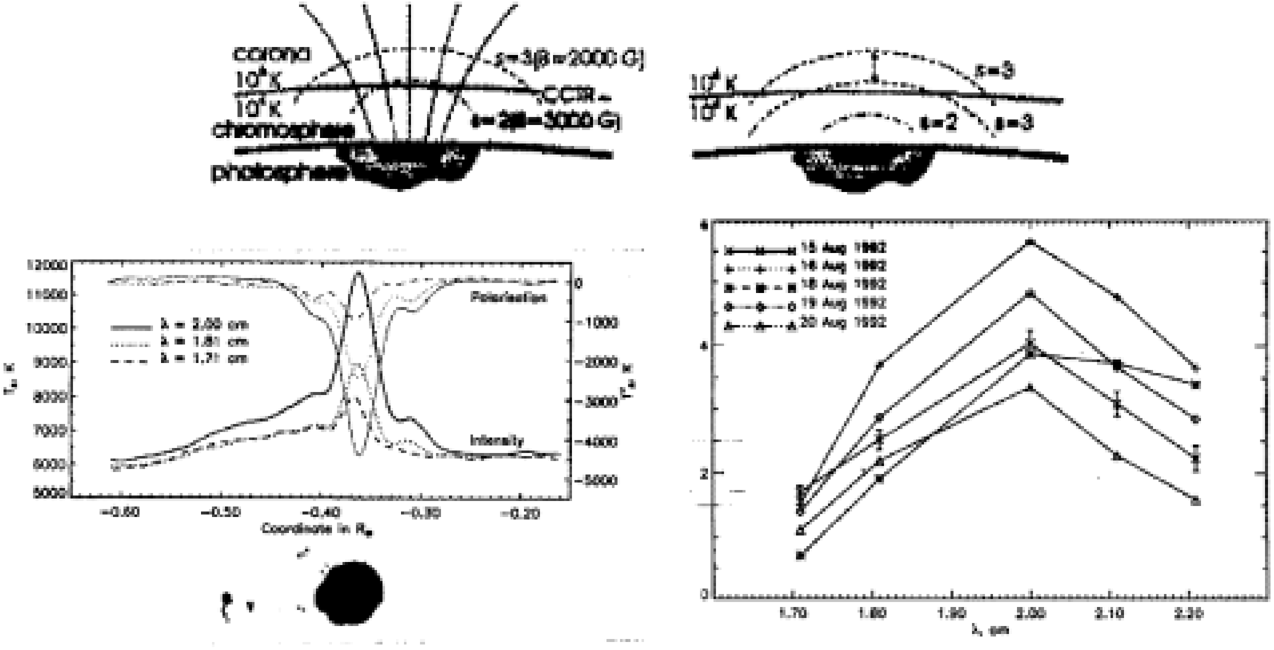

Fig. 8.. The gyroresonance emission layers responsible radio emission of sunspot- associated sources and expected effect of MHD-waves on the emission (top). The structure of the radio source of an active region (August 16, 1992) — the RATAN-600 observations (lower left). The spectra of polarized component of the source for 5 days (lower right).

a new important method for detailed study of the structure of coronal magnetic fields for weak active regions, with no sunspot inside.

4.4. Faraday Rotation

The angle of Faraday rotation is determined by the formula:

$$\theta = const \cdot \lambda^2 \cdot \int B_l \cdot N_e dl \tag{3}$$

The effect is very sensitive to the magnetic field strength and wavelength and needs observations with narrow wavebands. The integral in this equation is called rotation measure. The observations at a number of frequencies may result in its determination. As far as the radio observations of the sun are concerned the main problem is due to the effect of limiting polarization when a radio wave leaves the sun. The presence of linear component is an exception in solar observations. It may be the case of mode coupling in the QT region in the corona above an AR. Such a case was investigated by Alissandrakis using observations with WSRT (Alissandrakis et al. 1994).

The other way is to use observations of linearly polarized sources, like Crab Nebula (Parijskij et al. 1980, Soboleva et al. 1983). Such observations provide some interesting information about magnetic field in the outer corona.

5. Oscillations

The microwave observations are important not only in the study of plasma parameters but also dynamical processes essential for the problems of generation, transfer and release of energy in magnetospheres of the solar ARs. An important agent in transfer of nonthermal energy from below the photosphere is flux of MHD waves. The study of these waves also provides an important tool in diagnostics of sub-photospheric structure of the sun (helioseismology). In plasma-magnetic structures of the solar atmosphere we expect to get resonance cavities of some modes of these waves. We do expect their manifestation in different components of the radio emission of an AR. In fact, many periods, from several minutes to half an hour, were found by a number of researchers.

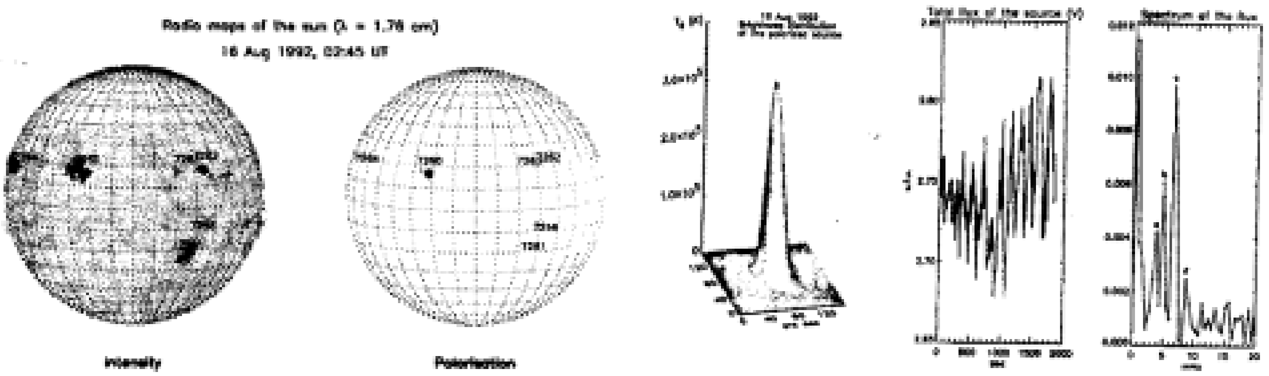

Fig. 9.. Radio maps of the sun at $\lambda = 1.76$ cm (left) and oscillation of the sunspot -associated source (AR7260, right). The structure, time variations and spectrum of these variations are shown.

However, most of these studies were made with instruments of low spatial resolution, and in many cases with strong influence of terrestrial atmospheric effects and other interference. The long continuous stretches of high spatial resolution observations at Nobeyama open a new page in this study (Gelfreikh et al. 1995). We began with an analysis of possible fluctuations of sunspot-associated sources because one can expect here a very sensitive method to study oscillations in magnetic tube of a sunspot (see Figure 9). An analysis of four sunspot groups has been made. An example of such study is shown in Figure 10. In three cases of large stable spots, clearly seen with highly polarized gyroresonance source at the V-maps of Nobeyama we detected periodic oscillations. Spectral analysis of tine variation of the polarized sources has shown presence of several periods in the range of 120-220 sec, in good agreement with the periods of so called umbral oscillations, observed in sunspots by optical methods. In most cases also the five-minute mode was also registered.

Both the three-minute (in umbra of sunspots) and five-minute (covering the whole solar surface) modes of MHD-waves are known in solar physics. In case of the three-minute, several alternative interpretations with different boundaries of the resonance cavities and MHD-modes are under consideration. The Nobeyama data gives a new tool to study the manifestation of the oscillations at the basis of the solar corona - the region which most theories consider as a upper level of reflection of the MHD wave in a cavity.

To study this effect we have made a series of pictures of the fluctuating radio source covering time interval of about four periods of oscillations (12.5 minutes). In Figure 10 these pictures are shown with intervals of 10 sec. With the spatial resolution of about 10 arcsec it looks as the whole effect is due to increase in brightness of some small regions, while the whole source looks very stable. This seems to be in general agreement in the observations of effect with high-resolution optical magnetograms (e.g., Horn et al. 1997). For future study in this direction we need parallel optical and radio observations of some oscillating sunspots.

Another progress in the problem uses the spectral observations of a oscillating source with the radio telescope RATAN-600 (Figure 8). The logarithmic spectral index for the sunspot associated source was found to be $n \approx 10$. It follows that oscillations in the magnetic field with amplitude of ± 4G are enough to result in the observed 4% oscillation of the radio flux at $\lambda = 1.76$ cm.

In future we may hope to get some information on the oscillation of these sources in the whole cm wave-length range (observations on the RATAN-600, VLA, WSRT, OVRO). Such observations can give information how deep into the solar corona can penetrate the three-minute mode.

6. Modelling of Magnetospheres of ARs

Modelling of magnetospheres of the solar ARs include two kinds of problems:

- diagnostics of physical parameters representing 3D-structure of the atmosphere of an AR (distribution of intensity and direction of the magnetic field, temperature and plasma density, and also the presence of nonthermal particles);
- study of time-dependent physical processes to find energy sources of heating the corona, producing nonthermal particles (flares), mass ejection etc.

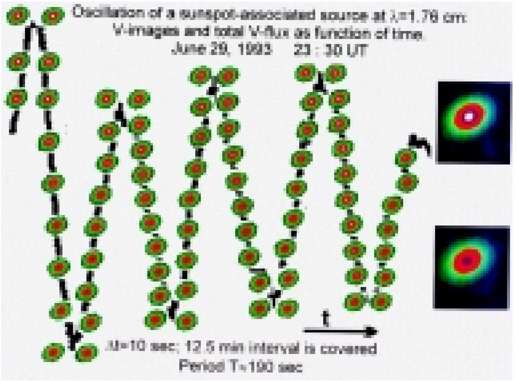

Fig. 10.. Variations of the structure of a polarized source during the three-minute oscillations. (Observations were made with the Nobeyama radio heliograph).

The first problem uses two approaches to get a 3D picture from observed 2D pictures: stereoscopic analysis of a stable AR for several dates (see Aschwanden 1995, and Figure 4).

The second method uses solution of equation of transfer to find longitude distribution, both of the magnetic field and temperature, density of the plasma (Grebinskij, 1999, this proc.).

7. Future Development

Now we summarize some problems to be considered in the near future using the observations of the Nobeyama radioheliograph.

1. I would like to stress the importance of studying activity in polar active regions as part of the global activity of the sun. That implies importance to compare at each step the level and peculiarity of active regions near the poles (polar faculae) and the “classical” low-latitude ARs. We have got already the observations at declining phase of the previous (22-nd) cycle, the growth phase of the present (23-rd) cycle and its maximum is not so far away. We still may have a hope to use the Nobeyama radioheliograph to analyze the behavior of the polar magnetic fields, both using chromospheric structures and possibly still polarization effects (though very weak ones).

2. In analyzing the three-dimensional structures of the magnetospheres of the solar ARs only some first, but very promising steps have been made. Above we discussed some promising methods to restore 3D-structure of magnetic fields in strong and weak ARs, accessible both on the chromospheric and coronal levels of the solar atmosphere. Both stereoscopic and tomography (solution of the equation of radiation transfer) methods are to be used.

3. Studying the physical processes representing the transfer, accumulation and release of nonthermal energy (leading both to hot thermal corona and evidently nonthermal flare and mass-ejecting events). At this stage we should develop the methods of studying 3-minute, 5-minute oscillations detected at Nobeyama above sunspots. However, we have some preliminary results (see e.g. polar faculae at Figure 3) showing that we have tools to investigate plasma oscillations (plasma turbulence) in many structures at $\lambda = 1.76$ cm.

8. Acknowledgements

The author thanks the support to some of the results presented in this paper by RFBR, GRANT 96-02-16268a and Russian program “Astronomy”, grant 1.5.4.6. Especially he feels thankful to the staff of the Nobeyama Radio Observatory for possibility to work with the radioheliograph observations.

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