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Spectral Polarization Study of the Magnetospheres of the Solar Active Regions using RATAN-600

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Abstract. The reflector type radio telescope RATAN-600 is a unique instrument for diagnostics of the atmospheres of the solar active regions due to combination of the high spatial resolution, detailed analysis of the spectra and polarization in the centimeter wavelength range. The most important results of such study (lasting since 1975) include the several methods of diagnostics of the coronal magnetic fields, detection and localization of the release of nonthermal energy. The study of large number of the local sources connected with the active regions resulted in a conception of the magnetosphere of a solar active region - the plasma structure in the solar atmosphere organized both by magnetic fields due to the local currents and by the influence of the plasma streams and the emissions of the surrounding plasma. Recently the most effective results on the RATAN-600 have been obtained when using it in cooperative observational programs with other large instruments, such as VLA, WSRT, Nobeyama radio heliograph, and also comparing radio data with X-ray imaging of the sun (Yohkoh space telescopes) and ground-based optical observations.

1. Introduction

Many illustrations and discussions of efficiency of radio observations for diagnostics of the solar and stellar plasma have been presented on this conference. In my talk I am going to illustrate this point as it follows from twenty years of the solar study using the 600-meter reflector type radio telescope of the Russian Academy of Science RATAN-600. Special emphasis, however, is made on the recent development of spectral facilities of the instrument with the results gained and proposed future development of the RATAN, directed mostly to improve spatial resolution and achieve two-dimentional mapping of the sun. I would like also to underline importance of cooperative observational programs both to compensate for some limits of each of the radio telescopes available and to make astrophysical interpretation of any object based on observations in different wavelength ranges (optical and X-rays including).

2. The RATAN-600 as a Radio Telescope

The RATAN-600 is a reflector-type radio telescope with variable profile of the mirror. The main reflector is a circular ring 600 meters in diameter consisting of

900 independent mirrors controlled by computers. The instrument also have a large periscope flat mirror which is used with the south sector of the main mirror and allows to follow the celestial object during four hours. It is generally used as a transit instrument presenting one-dimentional scans of the radio sources with moderately high spatial resolution (about 15 arcsec at $\lambda \approx 2$ cm. The instrument have five secondary mirrors with feed systems which can be moved along the rail tracks to controll the direction and the form of the beam. The radio telescope is used in a number of different modes of observations. It can be used simultaneously as up to three radio telescopes with independent observational programs. That helps to include solar observation as a regular routine type of observations.

At present most of the solar observations are made using Panoramic Analyzer of the Spectra (PAS) which covers a wavelength range from 1.7 cm to 32 cm with spectral resolution of about 5%. All 35 frequency channels include circular polarization measurements. This PAS is used in the mode "South sector of the main reflector with the periscope" as a transit telescope.

The RATAN-600 is a powerful tool to study the spectra and polarization of the radio sources. At the same time there was a need to compensate for its lack of two-dimentional mapping in cooperation with the other most powerful radio telescopes of the world such as the VLA, WSRT, Nobeyama radio heliograph and SSRT.

3. Magnetospheres of the Solar Active Regions

The conception of a magnetosphere as a special plasma structure first was developed for the Earth and the planets but now is widely used for very different astrophysical objects. The essential components of such structures are: (i) the presence of strong local currents which define localized magnetic fields and (ii) affect on the structure surrounding plasma flows and emissions (both — electromagnetic and MHD nature). The latter significantly affect the plasma structure of the magnetosphere and are often the main energy source of physical processes inside it.

In the case of a solar active region the local magnetic fields are well known controlling factors of sunspots, plages, coronal arches, prominences and other plasma structures connected with the particular active regions. The affect of surrouding plasma is also well known, e.g. as resulting in streamers or release of flare energy. At the same time the main scene of magnetosphere structuring takes place in the corona, where classical optical observations are very limited and measurements of the magnetic fields are not possible even for X-rays observations from cosmos.

Radio study of multi-component local sources of the solar active regions made it possible to study the processes and structures of their magnetospheres. As far as radio observations with the RATAN-600 are concerned of special interest here is the progress in two directions: (i) the development of four methods of measurements of magnetic fields in the solar corona and (ii) the detection of long-lasting "nonthermal" radio sources allowing to localize the regions of release and storage of nonthermal energy. As a result of these studies the magnetosphere of an active solar region changed its position from an *a priori* existing object to the goal of observations and quantative analysis (e.g. see Lang et al. 1993).

4. Radio Measurements of the Magnetic Fields

Radio observations with spectral-polarization analysis makes possible measurement of the magnetic field in the solar corona and upper chromosphere where traditional optical methods present very poor information. Using the observations with the RATAN-600 we have developed at least four different methods based on the theory of generation and propagation of the radio waves in the solar plasma. (for a survey see Gelfreikh 1994)

4.1. Thermal Bremsstrahlung

This mechanism of generation of the radio emission (electron-ion collisions or free-free transitions) of the solar active regions during long period of time was considered as the main one responsible for the S-component. Future detailed analysis of the spectra and the structures of the local sources has shown that only a fraction of the centimeter radio flux is generated by free-free transitions of electrons. Yet at shorter wavelength ($\lambda \leq 2$cm) this mechanism plays the central role in the enhanced radio intensities over the plages. This is true both for the active regions and polar zones. The enhanced emission is due both to denser and hotter chromosphere and enhanced electron density in the corona (loops in particular). The emission of the prominences is also mostly generated by bremsstrahlung.

The presence of the magnetic field increases the opacity for extraordinary mode and decreases optical thickness for ordinary mode with resulting partial polarization of the emission. For an optically transparent region (e.g. coronal condensation) the degree of polarization is

$$P = 2\frac{f_B}{f}\cos\alpha \tag{1}$$

or

$$B_l = 107\frac{P\%}{\lambda} \tag{2}$$

In the case of opticaly thick and isothermal plasma brightness temperature for both modes are equal to electron temperature and no polarization is observed. If, however, there is gradient of temperature or/and the structure is semitransparent the expected polarization is not zero and is connected with the gyrofrequency by

$$P = n\frac{f_B}{f}\cos\alpha \tag{3}$$

where spectral index $n = -\frac{\log T_B}{log f}$. So, the magnetic field can be found from spectral-polarization measurements:

$$B_l = 54\frac{P\%}{\lambda n} \tag{4}$$

This method can be effectively used to study magnetic fields of flocculae, of prominences and coronal arches. In the case of the active regions there are some problems in separating the emission generating by other mechanisms, gyroresonance especially. To overcome this problem one should use observations at shorter wavelengths where $\omega \ll \omega_B$. However, in this case the degree of polarization is very low and instrumental effects become significant (small fraction of a percent — necessary polarization sensitivity).

4.2. Thermal Cyclotron Emission

The cyclotron emission of thermal electrons of the corona and possibly corona-chromosphere transition region was found to be an essential mechanism in generation of the bright sources above solar sunspots and some coronal loops. For the typical parameters of the solar atmosphere the dominant emission is connected with the third and second harmonics of the gyro-frequency. So, for a particular wavelength λ one deals with the regions in the source of the magnetic field strengh:

$$B = \frac{3570}{\lambda}\,(s = 3) \tag{5}$$

$$B = \frac{5400}{\lambda}\,(s = 2) \tag{6}$$

On the RATAN-600 we have spectral observations. So, for each sunspot we were able to determine the shortest wavelength where this type of emission is observed. Using the Formula 5 we find the strongest magnetic field strengh penetrating the basis of the corona. With the new Panoramic Analyzer of the Spectra used for solar observations on the RATAN-600 the accuracy of measurements of magnetic fields of sunspots attains about 3%.

Of great interest for the physics of solar sunspots is the comparison of these fields with other data on the magnetic fields for the same sunspots. An important point is the good correlation of the maximum photospheric magnetic fields of sunspots with radio values. So, the magnetic fields in large sunspots often exceeds 2000 G in the lower corona. In one of the latest results when a comparison of magnetic field for a number sunspots measured in different optical lines was made with the radio observations, the latter again were found in good agreement with optical measurements. However the height distribution of the magnetic field proved to be rather complicated — with minimum in the lower chromosphere and maximum at higher level (Abramov-Maximov et al. 1995 and Gelfreikh et al.).

We would like to remind you that in early studies of some sunspots the contradiction between magnetic field measurements in EUV line of CIY and radio data was found, the latter exceeding the SMM magnetic field strength by 50% or so. This discrepancy was found possible to overcome by essentialy nonhomogeneous models of the solar atmosphere.

4.3. Inversion of the Circular Polarization in QT-regions

The observations show that during its passage through the solar disk some strongly polarized components of the active regions change the sign of circular polarization. The effect usually begins with longer wavelength and lasts a few days. It has found reasonable explanation in the theory of propagation of a radio wave in quasi-transverse (QT-) region and is due to the reversal of the longitude component of the magnetic field inside such a region. The strong dependence of the effect on the magnetic field and radio frequency can be used to measure magnetic fields in the solar corona (see paper by Gelfreikh, Pilyeva & Ryabov in this volume and Gelfreikh et al. 1987).

4.4. Faraday Rotation of the Plane of Polarization

The rotation of the plane of linear component of polarization in an QL-approximation is called Faraday rotation. The angle of rotation χ is determined by the well-known formula:

$$\chi = 2.6 \cdot 10^{-17} \lambda^2 \int N_e B_L dl \quad (7)$$

So, the observation of the effect can present information on the rotation measure

$$RM = \int N_e B_L dl \quad (8)$$

and consequently on the magnetic field (if we use some independent estimate of electron density N_e). The problem, however, is the absence of linearly polarized sources in the solar atmosphere. This is the result of two effects: the limiting circular polarization of the wave escaping from the solar corona and strong dependence of Faraday rotation on the wavelength and magnetic field.

One solution of the problem was found using galactic/extragalactic sources which are partially linearly polarized. A large program of this type was carried out on the RATAN-600 by N.S. Soboleva who observed the occultation of the Crab Nebula by the outer solar corona.

The first experiment with the proper linearly polarized solar sources was made by C.Alissandrakis and Ch.Drago (Alissandrakis 1995) using observation on the WSRT. Such experiments need very narrow preferably many-channel receivers and high sensitivity to linear polarization. Similar experiment has been carried out on the RATAN by A. Korzhavin (private communication). Both experiments seem to give agreeable results in an estimate of the value of the magnetic fields (RM) and the unexpected presence of linearly polarized (though very weak) signal in some solar local sources.

5. Nonthermal components

In the spectral observations of the solar active regions we often deal with the components which meet serious problems while trying to interprete it in terms of thermal bremsstrahlung or thermal cyclotron emission. The spectra of flux density (or intensity) for such sources show significant growth with the wavelength — in contradiction with the assumption of free-free emission (either transparent or optically thick regions). Though you can always find an adequate model configuration of the magnetic fields and temperature distributions to get the observed spectra the found physical parameters of the magnetosphere seem unreasonable when compared with optical and other data. So, the only way to find a reasonable interpretation for such sources is to assume the presences of nonthermal particles in the region. This meets the cause of the problem of continuously lasting processes of acceleration of particles.

5.1. NL-associated Sources

While at short centimeter wavelengths $\lambda \approx 2 - 4$ cm the brightest component usually belong to sunspot-associated sources (generated dominantly by thermal bremsstrahlung) at longer wavelengths $\lambda \approx 4 - 8$ cm the brightest features of well-developed active regions overlie the neutral line (NL) regions of photospheric magnetic fields. In some cases the spectra of these sources were hardly possible to interprete in terms of thermal mechanisms (Alissandrakis et al. 1993).

5.2. Peculiar Sources

Among all kinds of the components connected with the neutral lines of the photospheric magnetic fields the most impressive are the so-called *peculiar sources.* This type of the radio emission is generally met in sunspot groups with delta-configuration of the magnetic field when we have umbra with different magnetic polarity within the same penumbra. The peculiar sources appear at the stage of development of sunspot groups and last for several days being rather stable. They seemingly have the highest brightness temperatures among the nonflaring components of active regions ($T_b \approx 10^7$). The polarization of emission is comparetively weak ($P \approx 5 - 15\%$).

5.3. Decimetric Halo

Practically all the active regions — both weak and strong possess a diffuse halo source covering the whole active region (a number of minutes in diameter). The highest brightness temperature of this component is achieved at decimiters ($\lambda \approx 10 - 30$ cm) and brightness temperature lies generally within the limits typical to coronal plasmas. Due to the considerations above these sources are also needed for their interpretation of continuously present nonthermal particles which may consist of a kind of the radiation belt of an active region. The generation of noise storm of a very weak active region and its connection with the development of a decimetric halo presents a serious argument to the above interpretation (Lang et al. 1993).

6. Needs for Future Instrument Development

As we have seen in our review modern solar radio astronomy presents powerful methods to study solar corona and chromosphere. At the same time in the solar (and most probably in stellar physics) we deal with the radio emission generated by a large number of different mechanisms in different plasma structures of the solar atmosphere. That implies that the efficiency of methods and their reliability as well depend essentially on parameters of the radio telescopes at disposal. So, the most interesting results are often gained from the usage of a number of instruments performing observations on cooperative basis. We believe that the time has come when progress in technology and gained experience in investigating the sun by radio methods presents us an opportunity to make the next step of combining many essential features in one instrument or a pair of similar radio telescopes.

The project of the Radio heliograph of the RATAN-600 presents an opportunity to make 2D-maps of the sun at a number of chosen frequencies, even at msec scale of time. The latter is important for study of the spikes-bursts, the latter reflecting most closely the acceleration processes in the solar atmosphere. The spatial resolution of the instrument is reasonably high corresponding to the aperture of 600 by 400 meters. An important feature is parallel use of the south part of the main reflector of the RATAN-600 with the flat periscope mirror to get detailed information on the spectra of the radio sources (with one dimensional resolution mode).

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References

Abramov-Maximov, V.E., Vyalshin, G.F., & Gelfreikh, G.B., 1995, submitted to Solar Physic.

Alissandrakis, C.E., & Chiuderi Drago, F. 1994, ApJ428, L73

Alissandrakis, C.E., Gelfreikh, G.B., Borovik, V.N., Korzhavin, A.N., Bogod, V.M., Nindos, A., & Kundu, M.R. 1993, A&A270, 509.

Bogod, V.M., Garaimov, V., Gelfreikh, G.B., Lang, K.R., Willson, R.F., & Kile, J.N. 1995, Noise Storms and the Structure of Microwave Emission of Solar Active Regions. Accepted to the Solar Physics.

Bogod, V.M., Gelfreikh, G.B., Ryabov, B.I., & Hafizov, S.R. 1993, in Transactions of the IAU Coll. 141, ASP Conf. Ser. vol.46, Zirin H., Guaziang A. & Wang H., 302

Gelfreikh, G.B. 1994, in IAU Coll.144 Solar Coronal Structures, Ruisin V., Heinzel P. & Vial J.C. VEDA Publ. Co., 21

Gelfreikh, G.B., Peterova, N.G., & Ryabov, B.I. 1987, Solar Physics, 108, 89

Lang, K.R., Willson, R.F., Kile, J.N., Lemen, J., Stron, K.T., Bogod, V., Gelfreikh, G.B., Ryabov, B.I., Hafizov, S.R., Abramov, V.E., & Svetkov, S.V. 1993, ApJ, 419, 398.

Willson, R.F., Kile, J.N., Lang, K.R., Donaldson, S., Bogod, V.M., Gelfreikh, G.B., Ryabov, B.I., & Hafizov, S.R. 1995, Large Scale Coronal Magnetic Fields: Noise Storms, Soft X-rays and Inversion of Radio Polarization. Adv. Space Res., 17, No. 4/5, 265.

Willson, R.F. et al. 1995, Adv.Space Res. 17, No.4/5, 265.