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Basic results and a perspective for future observations on RATAN-600

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The modernization of the radio telescope RATAN-600 for solar observations is intended to improve significantly parameters concerning the spatial, temporal and spectral resolution of the instrument. The main scientific objective of radio observations planned on the RATAN is to study the process of structuring the solar atmosphere and to find out the role of the plasma structures in accumulation, transfer and release of energy in the solar atmosphere. In this paper the results of the study of magnetic fields and different structures both for quiet and active regions on the Sun are summarized. The main problems for future RATAN observations of the Sun are discussed.

Es wird eine Modernisierung des Radioteleskops RATAN-600 beabsichtigt, um die Werte der räumlichen, zeitlichen, und spektralen Auflösung wirksam zu verbessern. Das wissenschaftliche Hauptziel der am RATAN-600 geplanten Sonnenbeobachtungen liegt in Untersuchungen von Strukturierungsprozessen der Sonnenatmosphäre und im Herausfinden der Rolle von Plasmastrukturen bei der Speicherung, dem Transport und der Freisetzung von Energie in der Sonnenatmosphäre. In der vorliegenden Arbeit werden Ergebnisse von Untersuchungen des Magnetfeldes und verschiedener Strukturen für ruhige und aktive Gebiete der Sonne zusammengefaßt. Die Hauptprobleme zukünftiger RATAN-Beobachtungen werden diskutiert.

Key words: sun — atmosphere — active regions — magnetic fields

AAA subject classification: 071; 075

1. Introduction

We are now in the beginning of the 22nd cycle of the solar activity, which is expected to have maximum phase in 1991. Having in mind the importance of investigations of solar activity both for general understanding the active astrophysical objects (magnetospheres of the planets, flare stars, X-ray sources, cores of some galaxies e.t.c.) and for practical goals in the solar-terrestrial physics, in many countries major projects of solar observations in 1991 and the following years are under way. Investigations connected with the 22nd cycle of the solar activity in general will last about ten years. That includes the first three years (1989—1991) of modernization of the present instruments as well as constructing some new ones. During the same period most of organizational work should be done concerning international program observations (MAX' 91, FLARES 22, STEP, ISY e.t.c.), forms of exchange of data should be coordinated e.t.c. During the next three to four years the observations will be the main objective, followed by three to four years of treating the gained observational material and astrophysical interpretation.

Among the groundbased observations based on an experience gained from previous cooperative programs of studying solar activity, special attention is paid to analysis of radio emission of the Sun. Solar observations using the world's largest radio telescopes (VLA, WSRT, RATAN-600 et al.) have shown during the Solar Maximum Year program that the radio observations yield the most valuable information about the magnetic fields and particle acceleration in the solar corona. At the same time it proved obviously that efficiency of radio diagnostics of solar plasma essentually depends on combination of detailed spectral analysis, accurate polarization measurements with high spatial and temporal resolution.

To meet the needs of new cycle observations and take an active part in the cooperative programs, we have elaborated a proposal for modernization of the RATAN-600 (see Bogod et al. (1988) and the separate paper by Bogod in this issue). Some of these are now under way. In this paper we summarise some results of the solar investigations carried out using the RATAN observations by the Pulkovo group of solar radioastronomers (Central astronomical observatory and Special astrophysical observatory of the Academy of Sciences of the USSR) during 1975—1988. For each problem we discuss a possible future progress on the basis of modernization of the instrument and using cooperative observational programs.

2. Scientific problems

The problem of structuring the solar atmosphere in connection with magnetic field structure and evolution as well as MHD-oscillation constitutes is the main objective of studying the Sun with the RATAN-600. The goal is to proceed in understanding the nature of structuring the solar plasma and the role of the structures in storing, transfer and release of energy in the solar atmosphere.

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The RATAN presented the unique possibility to measure the magnetic fields in a range of heights in the solar atmosphere from the higher chromosphere to the corona at different levels. The observations also allowed to localize the regions of non-thermal release of energy at different regions of the corona. Combination of this kind of data with improved observational facilities together with other data may (we hope) result in a significant progress in solving the above problem. One should also have in mind that structures in plasma (and their evolution) are of special interest for recent development in non-linear physics and mathematics, while the Sun is capable to give many important examples of such structures.

3. Measurements of Solar Magnetic Fields

One of the most prominent results in the study of the solar atmosphere using the RATAN-600 was the development of three methods to measure the magnetic fields in the upper chromosphere and lower corona of active regions.

3.1. Thermal bremstrahlung mechanism

In the presence of magnetic fields we have an increase of capacity for extraordinary mode and decrease for ordinary one. This results in a difference of the effective level of generation of the two modes in optically thick plasma (Bogod and Gelfreikh, 1980). In the presence of a temperature gradient the radiation becomes circularly polarized with the degree of polarization

$$P = (nf/f_H)\cos(\alpha)\,, \tag{1}$$

where the spectral index

$$n = -\mathrm{d}(\ln T_B)/\mathrm{d}(\ln f)\,, \tag{2}$$

T_B — brightness temperature, f — frequency of observation, f_H — gyrofrequency, α — angle of the magnetic field. From (1) we get a formula for measuring the longitude component of the magnetic field:

$$H = 107P\%/(n\lambda)\,, \tag{3}$$

where λ — wavelength [cm].

In the case of optically thin plasma we have $n = 2$ and (3) becomes

$$H = 54P\%/\lambda\,. \tag{4}$$

The method has been successfully used for measurements of flocula magnetic fields, for prominences (at the limb), and coronal condensations. Flocula magnetic fields (of the order of 20 G) proved to be in reasonable agreement with the photospheric magnetograms of the same region. We have also found a magnetic field of about 20 G at the height of 70,000 km in a coronal condensation.

3.2. Thermal cyclotron emission

The most elaborated study using this method was made for sunspot associated components — the radio cores above the umbra of sunspots. The simple estimates are known to show that the emission at the second and third harmonics are essential. The spectra of this type of sources obtained with the RATAN-600 have shown the quasi-linear growth of intensity of the polarized emission (Stokes parameter V) with the wavelength (Akhmedov et al. 1986). So one can find from observations the shortest wavelength λ, where the emission is observed. So we have found the maximum strength of the magnetic field penetrating to corona as

$$H = 3570/\lambda \tag{5}$$

which corresponds to the emission on the third harmonic of gyrofrequency. For the second harmonic we have

$$H = 5400/\lambda\,. \tag{6}$$

The limit wavelength λ for emission of the second harmonic can also be evaluated from a spectrum though with somewhat lower accuracy.

A number of interesting results have been obtained using this method:

- strong magnetic fields amounting 2000 G or more may penetrate the corona above a large sunspot;
- the corona above a large sunspot is very low above the photosphere (often not more than 1—3 thousand km);
- the solar atmosphere above a sunspot is strongly inhomogeneous, so the emission in hydrogen lines and C IV lines originate in the comparatively cold plasma amounting to the level of 1000—1500 G, which is probably higher than the level of generation of radio emission;
- the ratio of the radio and optical photospheric magnetic fields is normally about 0.7—0.8 (a good correlation exists!);

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in some cases, however, a strengthening of the magnetic field in the corona above a sunspot, preceeding the development of the active region, has been observed, so radio data may be an important parameter for forecasting of the development of an active region.

More detailed analysis of the magnetic field by this method especially with the coverage of shorter wavelengths ($\lambda < 2$ cm) are extremely needed for the construction of a more comprehensive model of magnetic fields of the structure of the chromosphere-corona above different sunspots. Investigation of temporal variation may give important information on 3D-structure of the magnetic field of sunspots when they emerge or dissipate. Of special interest are observations of quasi-periodic variations of these sources reflecting the flux of MHD waves in a fluxtube of a sunspot. At last ring and horseshoe structures of sources, which are associated with the sunspot, are of great interest for a study of spatial distribution of thermal energy above a sunspot in the corona. The same method to measure magnetic fields is applicable to some other sources (e.g. magnetic loops).

3.3. Inversion of polarization in the QT region

The RATAN observations demonstrated in more details than ever before the change of the sign of polarization both with wavelength and time (GELFREIKH et al. 1987). This phenomenon is known to be connected with, crossing by a ray path, the region of quasi-transverse magnetic field and may be used succesfully for measurements of magnetic fields in the corona at the heights up to 120,000 km. We may estimate the magnetic field strength using the formula (in QT-region)

$$B = 1.57 \times 10^8/(\lambda \sqrt[3]{\lambda \cdot N \cdot L}) \quad \text{or} \quad B \cong 43/\lambda\,, \tag{7}$$

where λ is the wavelength of inversion ($P = 0$), N — electron density and L — the scale of the magnetic field. On the basis of modelling computations we can try to restore the full picture of the magnetic field in the corona of an active region. It generally proved that the magnetic fields are in reasonable agreement with potential extrapolation of the photospheric fields. Some important departure, however, may occur, especially at lower heights.

Using two-dimensional maps of polarization in combination with more detailed (one-dimensional) spectral observations which are expected to be available after the RATAN's modernization are very promising for developing the method above.

4. Peculiar sources

Peculiar sources have been detected with the RATAN in the most developed active regions with high flare activity (AKHMEDOV et al. 1986). In many respect their observational properties are similar to those of the sunspot associated cores but yet could be definetly distinguished using the following characteristics:

(i) The position above a neutral magnetic line on the photospheric level (often in connection with magnetic delta-configuration of the sunspot group);
(ii) the size (and height) of about (10—20) × 1000 km;
(iii) high brightness temperature amounting $\sim 10^7$ K at some wavelength in the range of 2—4 cm;
(iv) steep spectrum with the index amounting $n \cong 10$;
(v) moderate degree of circular polarization ($P < 30\%$);
(vi) life-time of 2 to 5 days and rather good stability of emission;
(vii) strong photospheric currents were detected near the position of one of the peculiar sources (in July 1982).

The mechanism of generation of peculiar sources is still uncertain. We may consider the following possibilities:

(i) thermal gyroresonance emission at 2—4th harmonics of gyrofrequency. (One needs the strong magnetic field $B > 1000$ G in this case);
(ii) thermal cyclotron emission at higher harmonics (one here needs very high temperature $T \cong 10^8$ K and high electron density $N \cong 10^{12}$ cm^{-3});
(iii) non-thermal cyclotron emission (then a stable and effective mechanism of acceleration of electrons is necessary);
(iv) thermal bremsstrahlung of strongly inhomogeneous plasma (electron density should amount $> 10^{12}$ cm^{-3}).

Whatever their possible nature is, the peculiar sources localize the region of a long-lasting and stable non-thermal source of energy released in the corona of an active region. Two-dimensional mapping, detailed spectra data and time variations are expected to be gained from the modernization of the RATAN resulting in solving the problem of the nature of mechanism of generation of peculiar sources and diagnostics of basis physical process of stable release of nonthermal energy.

5. Decimetric halo

An analysis of spectra of local sources taking into account their structure shows the growth of their flux (intensity) approximately proportional to λ. The maximum is achieved near $\lambda = 10$ cm. The brightness temperature for $\lambda > 10$ cm is near the coronal value (10^6 K) or somewhat more, the average intensity (or flux density) decreases in decimeter range as λ^{-2}. High resolution (VLA) observations at 20 cm have shown some bright (sometimes loop-like) structures but their impact to the general flux of the active region is generally not significant (a few per cent or less).

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The above spectra need a rather complicated interpretation taking into account possibly such non-thermal components as accelerated particles and plasma turbulence. At the same time one has to explain their high temporal stability and saturation of the spectra for the dm-range.

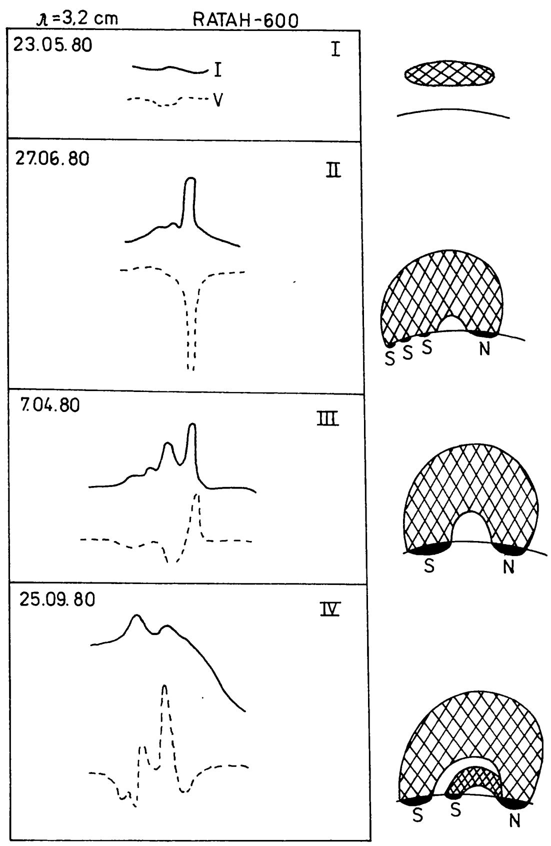
The problem is of special interest if one has in mind that the flux at 10.7 cm is one of the most widely used indexes of solar activity. We hope that future observations with the RATAN due to detailed spectra analysis, investigations of temporal variations and two-dimensional mapping of the sources will give the necessary information for choosing the correct dominant mechanism of generation of radio emission and constructing a realistic model of the active solar atmosphere (magnetosphere of an active region). Of special interest for solving the problem should be the comparison with X-ray observations of high spatial resolution.

6. Classification of the local sources

We have proposed a classification of the local sources — radio images of solar active regions which is based on one-dimensional scans in the wavelength range of 2—4 cm and essentially using measurements of the circular polarization. The features in the structure of strong coronal magnetic fields are the main foundation for choosing the classes. We have used the parameters:

(i) break through of strong magnetic fields ($H > 1000$ G) into the corona;
(ii) unipolar-bipolar-multipolar structure of the strong coronal magnetic fields (above sunspots);
(iii) the presence of peculiar sources (see above) at the neutral magnetic lines.

We illustrate the classification at the Fig. 1. Future investigations should include a larger number of parameters taking into account observations at both shorter and longer wavelengthes, more parameters of the interspot component and the decimetric halo. A good classification may prove an effective tool for many forecasting problems and modelling problems as well.



7. Coronal Holes, Filaments and Cavities

Now we come to structures which have been observed as dark regions on the solar disk at microwaves. Many of them are of interest because of their geophysical effects which are due to fast solar wind coming from these solar regions. Basic results concerning the coronal holes (CH) obtained with the RATAN run as follows (Borovik et al. 1989):

— CH can be seen only at longer centimeters and while the filaments and their cavities are more prominent at shorter wavelengths where we have higher resolution;

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— the radio filaments and their features have much narrower details than CH;
— when a CH is at the limb the radio radius significantly decreases.

The two-dimensional pictures and more detailed spectra of the modernized RATAN will give significant advantage for constructing more developed models of the structures above, resulting probably in better forecasting of their geophysical effects.

8. Quiet sun and radio granulation

The problem of modelling solar atmosphere at the chromosphere-corona level is essentially dependent on the data on brightness distribution over the solar disk. The observational problem is extremely difficult and contradictory results concerning the presence of a bright ring on the limb (prediction of a homogeneous model) are often met in scientific publications.

Long-lasting homogeneous observations made with the RATAN at five wavelengths in the range 2—4 cm (1977—1980) resulted in the following conclusions (BOROVIK 1981):

— homogeneous brightness distribution over the whole disk of the Sun, absence of a narrow bright ring of the optical limb;
— the radio radius is larger, compared with the photosphere, approximately by 3% and increases with the wavelength;
— three is no significant variation in the brightness distribution with the phase of the solar activity.

We should note, however, the existence of the limb brightening at longer wavelength. We expect as a result of the RATAN's modernization to yield the brightness distribution for a much greater wavelength range and get more information on possible variations within the cycle of the solar activity. For modelling problems it is essential to understand the nature of cm-emission in the range from 5 to 20×10^3 km above the photosphere. This layer of the solar atmosphere should be very inhomogeneous taking account of the observed data and is possibly affected by plasma turbulence, the latter being connected with the process of coronal heating.

The RATAN-600 observations first discovered the radio granulation (brightness inhomogeneities) of the quiet Sun in the range 1.3—4 cm (BOGOD et al., 1982). It has been shown that separate radio granules coincide with the structure of the chromospheric network observed in CaII line. Some range granules were found to be circularly polarized. The spectra of radio emission and other parameters were investigated.

Future observations should give more information on lifetime of radio granules, the spectra and polarization in a wider wavelength range, estimates of magnetic fields, more detailed indentification in other wavelength ranges (optical, EUV). We hope to construct the models of the solar atmosphere capable to explain both radio granulation and the limb brightness distribution parameters in one model.

9. Burst and flares

As transit instrument the RATAN-600 was rarely used for investigation of flares. Nevertheless due to long-lasting periods of Solar observations a number of bursts have been studied with high resolution of the instrument. Long-lasting bursts of gradual rise and fall type were the topic of a special program for the RATAN made in the frames of a KAPG program (see a separate paper presented at this conference).

An interesting example of a simple burst was observed on March 29, 1980. This flare was connected with strong gamma ray and X-ray emissions. It was shown that even for a simple event we deal with sources of different nature: one of cyclotron emission above a large sunspot and the other with a flare loop near the region of Hα emission.

It is of great importance that modernization of the RATAN is supposed to result in significantly new accomodations for burst investigation: in the mode B of the radio heliograph we may expect to investigate two-dimensional maps of some flares, while detailed spectral analysis (a few hundred channels) may well be very informative for mechanism of burst emission and diagnostics of flare plasma; at last observations within a millisecond time scale is known to be important for diagnostics of acceleration mechanisms. Developments of the antenna mode "south sector + periscope" yields 4 hours per day observations, increasing significantly the expected number of events attainable for observation.

10. The outer corona

Generally speaking the outer corona is not a dominant goal for centimeter wavelength range of observations. I would mention, however, three approaches where centimetric observations, which prove to yield results hardly available at much longer wavelength:

(i) due to the very low opacity of the hot coronal plasma for microwaves and weak dependence of the emission on plasma temperature observations in this range can give a reliable estimate of electron density (emission measure) in coronal streamers and also can be used for a study of dynamical phenomena like transients. Special measures, however, were needed to exlude the affect of the bright solar disk and active regions registered in side-lobes of the antenna pattern.

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(ii) Observed scintillation of quasars (point sources) due to scattered radio waves on coronal inhomogeneities gives a good opportunity to find the level of acceleration of the solar wind. With high spatial resolution of the RATAN this method becomes effective for much lower altitudes above the photosphere.
(iii) Faraday rotation of linearly polarized emission of galactic radio sources (Crab Nebular particularly) has been used to study very weak magnetic fields in the most outer parts of the corona.

In the programs of the 22nd cycle all the methods above are proposed to be used in combination with optical, space and other observations.

11. Modelling the solar structures

A good model is often a destination for an astrophysical study. It is generally accepted that the model is a result of some computation or semi-qualitative consideration presented either in tables or pictorial forms. To discribe the evolution of an object a scenario is often used that is very popular in astrophysical modelling. The same principles are mostly applicable in the physics of the Sun.

However, the Sun presents us with an opportunity to investigate the similar kinds of structure in wide range of their parameters (e.g. sunspots with the area from 10 to 3000 millionths of hemisphere). It seems reasonable to replace the routine idea of a model as a result of some computations by the same algorithm of its, or rather by a program for a computer. We use the term virtual model for this approach to the problem. A virtual model allows an observer to find the best set of parameters for his particular object and, therefore, to investigate in more details its physical nature.

The next step is to add some programming which results in automatic choise by a computer the best set of astrophysical parameters which satisfies the observed properties of the solar structure. Such a model, developed by Gelfreikh and Lubishev (1983), allowed us to find the best fit for the height of CCTR above a sunspot and the temperature of the lower corona in agreement with the spectra of a radio source above a particular sunspot.

Modernizing the system for the treatment of radio observations made with the RATAN we intend to include a number of programs for astrophysical modelling, virtual and automodels including.

12. Cooperative observational programs

The organization of cooperative observations is a good tradition in the solar physics. We may refer to such large international programs as SGY, QSY and others including many programs organized by KAPG. Most of these were very important both for different scientific results in solar physics and as a way to attract the attention of the scientific community to significance of studying the Sun.

Now we are witness of the situation, that the costs for an experiment of solar physics is too high to afford a number of different experiments for a single scientific institution or even a whole country. On the other hand, we need simultaneous observations of the Sun made by different methods. It follows that only cooperative work may result in a satisfactory usage of modern technics while resolving the enigma of the Sun.

A number of major international programs has been prepared allready with the above considerations in mind. We mean such programs as STEP, MAX' 91, FLARES 22, all of them connected with the coming maximum of the 22nd solar cycle and the programs proposed by KAPG.

We hope that RATAN-600 after its modernization which is under way and aimed for better parameters for solar investigation will contribute significantly to this important international activity. Some aspects of proposed scientific programs have been presented above in this report but we hope that many other scientists, which are interested in cooperative or special radio astronomical observations, will participate in the observations of the Sun with the RATAN-600, developing its programs and/or interpreting the results of observations. Only wide participation of solar physicists both from USSR and other countries may insure a success to the effort which are made at present to reach highest possible parameters of the RATAN to study our great Sun.

References

Akhmedov, Sh. B., Gelfreikh, G. B., Bogod, V. M., Korzhavin, A. N.: 1982, Solar Phys. **79**, 41.
Akhmedov, Sh. B. et al.: 1986, Astrophys. J. **301**, 460.
Bogod, V. M., Gelfreikh, G. B.: 1980, Solar Phys. **67**, 29.
Bogod, V. M., Gelfreikh, G. B., Korzhavin, A. N., Pustilnik, L. A.: 1988, SAO AS USSR Preprint No. 22.
Bogod, V. M. et al.: 1982, in: Sun and Planetary System, D. Reidel Publ. Co. Dordrecht, p. 109.
Borovik, V. N.: 1981, Astrofiz. Issled. **13**, 14.
Borovik, V. N., Kurbanov, M. Sh., Shatilov, V. A.: 1988, Soln. Dannye, Leningrad, N. 11, 110.
Gelfreikh, G. B.: 1986, Contr. Astron. Obs. Skalnate Pleso **15**, 33.
Gelfreikh, G. B., Lubishev, V. I.: 1983, SibIZMIR Preprint 21—83.
Gelfreikh, G. B., Peterova, N. G., Ryabov, B. I.: 1987, Solar Phys. **108**, 89.

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