DIAGNOSTICS OF THE SOLAR PLASMA USING RADIO OBSERVATIONS WITH THE RATAN-600

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ABSTRACT. This paper summarises the methods and main results of studying physical parameters and processes in different structures of the solar atmosphere from the chromosphere to the outer corona as based on the observations with a 600-meter radio telescope the RATAN-600 (1975-1989). Diagnostics of the solar plasma have been made using the spectral-polarization measurements in the wavelength range 0.8-32 cm with high spatial resolution. The most important results concern the structure and strength of the magnetic fields at different levels of the solar atmosphere and detection of localized regions of long-lasting (several days) energy release in the lower corona.

1. INTRODUCTION

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 valuable information about the magnetic fields and particle acceleration in the solar corona. Such diagnostics depend on detailed spectral analysis and accurate polarization measurements with high spatial and temporal resolution.

2. SCIENTIFIC PROBLEMS

An understanding of structuring in the solar atmosphere in connection with magnetic fields and their evolution as well as MHD-oscillations, constitutes the main objective of studying the Sun with the RATAN-600. We hope to understand the nature of the plasma structures as well as their important role in the storing, transfer and release of energy in the solar atmosphere. The RATAN can uniquely measure magnetic fields in a range of heights in the solar atmosphere from the higher chromosphere to the low corona. Regions of nonthermal release of energy are also localized in different regions of the corona. Structures in the plasma (and their generation) are also of special interest for recent

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developments non-linear physics and mathematics; the Sun is capable of giving many important examples of such structures.

3. MEASUREMENTS OF SOLAR MAGNETIC FIELDS

We hope developed three methods of measuring magnetic fields in the upper chromosphere and lower corona of active regions.

3.1. Thermal Bremstrahlung Mechanism

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

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

where the spectral index

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

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 longitudinal component of the magnetic field H.

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

where λ [cm]- wavelength. In the case of an optically thin plasma we have n = 2, and (3) becomes

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

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 the magnetic field strength of about 20 G at the height of 70 000 km in a coronal condensation.

3.2. Thermal Cyclotron Emission

The most elaborate study using this method was made for the radio cores above the umbra of sunspots. Both the emission at the second and third harmonics are essential. The spectra of these types of sources, obtained with the RATAN-600, have shown the practically linear increase of polarized intensity (Stokes parameter V) with wavelength (Akhmedov et al., 1986). One can find from observations the shortest wavelength

λ, where the emission is observed, thereby estimating the maximum value of the magnetic field strength, H, penetrating the corona as

$$H = 3570 / \lambda \quad (5)$$

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

$$H = 5400 / \lambda \quad (6)$$

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

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

- strong magnetic fields amounting to 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 CIV 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!); in some cases, however, a strethening of the magnetic field in the corona above a sunspot preceeding development of the active region has been observed, so radio data may be an important parameter for forecasting development of an active region.

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

3.3. Inversion of Polarization in QT-region

The RATAN observations also demonstrated the change of the sign of polarization both with wavelength and time (Gelfreikh et al., 1987). This is due to propagation through a 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)

$$H = 1.57\times10^{8} / (\lambda \sqrt[3]{\lambda NL}) \quad \text{or roughly} \quad H = 43/\lambda, \qquad (7)$$

where λ is 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. Using this method it was found that the magnetic fields are in reasonable agreement with potential extrapolation of the photospheric fields. Some important departures, however, may occur, especially at lower heights.

4. PECULIAR SOURCES

Peculiar sources have been detected with the RATAN in the most developed active regions with high flaring activity (Akhmedov et al., 1986). In many respects 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)x1000 km;
(iii) high brightness temperature amounting 10^7K at some wavelength in the range of 2-4 cm;
(iv) steep spectrum with the index amounting n =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 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 H>1000 G in this case);
(ii) thermal cyclotron emission at higher harmonics (one here needs very high temperature $T=10^8$K and high electron density $N=10^{12}$);
(iii) nonthermal cyclotron emission (then a stable and effective mechanism of acceleration of electrons is necessery);
(iv) thermal bremsstrahluhg of a strongly inhomogeneous plasma (electron density should amount $>10^{12}$ cm^{-3}).

Whatever their possible nature is, the peculiar sources localize the region of long-lasting and stable nonthermal source of energy release in the corona above an active region.

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 or faster, the maximum being achieved near λ=10cm.

The brightness temperatures for λ> 10 cm are near coronal value (10^6K) but they can be as high as 10^7K. High resolution (VLA) observations at 20 cm have show some bright (sometimes loop-like) structures but their impact to the general flux of the active region generally is not significant (a few per cent or less). The above spectrum needs a more complicated interpretation taking into account possibly such nonthermal components as accelerated particles and plasma turbulence.

6. CONCLUSIONS

The above results demonstrate the importance of microwave observations. High resolution observations combined with spectral and polarization measurements yield new information on structure of coronal magnetic fields and locolize sources of the release of nonthermal energy and probably of plasma turbulence as well. Future important conclusions will result from joint radio, optical, EUV and X-ray observations. Having in mind new opportunities provided by the international programs of the 22-nd cycle of solar activity (such as STEP, MAX^91, FLARE 22 etc) we have begun a modernization of the radio telescope RATAN-600 to improve its spectral, spatial and time resolution (Bogod et al., 1988). This work is now under way and may (we hope) result in much more detailed diagnostics of the plasma structure on the Sun.

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DISCUSSION

HOLLWEG: Can one use radio observations to determine how much the coronal magnetic field is tangled or braided as in the models of Parker, Heyvaerts and Priest, van Ballegooijen, and others?

GELFREIKH: We can measure magnetic field strength in the corona in a number of special situations such as: gyroresonance at the second, third and probably higher harmonics; well determined bremsstrahling (both optically transparent or not), where the ray is crossed by a transverse magnetic field. Our program is to combine radio data on magnetic fields with extrapolation of the photospheric magnetic field to check and correct the latter. Some special complicated magnetic field structures with annihilation of magnetic fields and current sheets could be found from high-resolution spectral-polarization radio observations (and most probably are found), since some peculiarities in the radio maps of the Sun are not easy to interpret in generally accepted thermal models of the S-component. Such radio sources are connected with long-lasting acceleration of particles, plasma turbulence and other non-thermal total releases of energy.

KUNDU: Maybe I can answer Joe Hollweg's question from my own point of view. It is not possible to see the braided field lines directly in the radio. However, if there are braided field lines, the angle between the line of sight and magnetic field will be close to 90° since the gyro-resonance absorption coefficient increases by a couple of orders of magnitude as the angle increases from 0° to 90°, we shall see bright clumps in regions of braided fields, because of the increase in optical thickness.

KNEER: You gave us a value of 2000 Gauss measured above sunspots. Could you tell us the height above photospheric levels to which this measurement refers and give us also the magnetic flux density in the photospheric layers of the sunspot?

GELFREIKH: Certainly, yes. We have found statistically for a large number of sunspots that the strength of magnetic fields from radio data (at the base of the corona) is some 20% lower than at the photospheric level for the *same* sunspot. The level of radio emission used for these measurements has been found from the projection effect (the displacement of a polarized radio source relative to the sunspot umbra); it is normally not more than 3,000 km above the photosphere. We assume that the corona above a sunspot may begin at very low heights (but the transition region must be very inhomogeneous to exclude contradictions with the measurements of magnetic fields from CIV EUV from SMM).

SHEVGAONKAR: Using multifrequency observations from the VLA the evolution of active regions as well as flares has been studied in the past. The change in the polarization characteristics during a flare indirectly supports the presence of new magnetic flux probably emerging flux loops or deformation of the magnetic field, as in the model of Heyvaerts, Priest and Rust.

GELFREIKH: The observations made with the RATAN-600 have lower resolution than the data obtained with the VLA and more limited opportunities to study the development of a radio source on the Sun. At the same time, the RATAN has better wavelength coverage (10 wavelengths in the range from 0.8 cm to 31 cm at the moment), better polarization sensitivity and much longer periods of observations of the Sun. That suggests that the data from the two instruments concern different aspects of the structure of magnetic fields and other physical parameters of active regions. Cooperative programs of observations with both instruments would result in a better understanding of the nature of the plasma structures observed in the solar atmosphere.