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The magnetosphere of solar active region by radio observations in a wide wavelength range

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The concept of the magnetosphere of the active region (AR), developed with the help of a wide range of radio astronomy tools, allows us to estimate the values of coronal magnetic fields for various objects presented in the AR, the radiation of which is manifested on radio waves from a single position. Due to the expansion of the wave range and the introduction of new radio telescopes and modern modeling capabilities, it becomes possible to analyze the physical properties of plasma structures of the magnetosphere of AR and to give detailed estimates of the coronal magnetic fields at the levels of the transition zone of the chromosphere-corona and the lower corona. New results of observations in comparison with model estimates are presented.

Keywords: Solar active region; magnetosphere; coronal magnetic field

1 Introduction

Observations on large radio telescopes VLA and RATAN-600 revealed a complex multicomponent structure of the atmosphere in AR [Lang et al., 1993], [Bogod, 2011] (called the AR magnetosphere), in which, along with bright polarized sources over spots and sources above the lines of magnetic polarity separation, radio sources in the floccules regions and wide low contrast halo-type formations were present. For these objects, magnetic fields were estimated and the basic mechanisms of radiation were determined [Bogod et al., 2017], among which there were thermal and long-term non-thermal sources of generation. The magnetosphere and its processes cover a wide range of heights in the AR: from the level of the photosphere to the coronal heights. For a detailed study of the magnetosphere structure, combinations of high parameters of antenna systems are needed, including: i) high spatial resolution (for the separation of AR parts); ii) high sensitivity in the radiation flux (for the registration of low contrast details in the intensity and polarization); iii) instantaneous spectrum analysis in a wide multi octave frequency range (to determine the mechanisms of radiation); (iv)

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wide and instantaneous filling of the UV plane of spatial frequencies (for simultaneous separation of parts of different spatial dimensions). Such characteristics can have a large antenna system of RATAN-600, EVLA (configuration D [Lang et al., 1993], ALMA (AKA [Loukicheva et al., 2017]).

The magnetic field plays a dominant role in all magnetosphere processes and its analysis and measurement at different heights of the chromosphere and corona is a complex task and is available to sensitive radio astronomical methods in combination with model reconstructions.

2 The structure of the magnetosphere of a typical AR

Magnetographic observations of the ARs of the Sun clearly show islands of strong magnetic fields (spots), which determine individual, more or less isolated AR, and, consequently, long lived (often many days) local currents in the photosphere or directly under the photosphere. The magnetosphere of AR at the level of the photosphere consists of a structure of strong magnetic spots, surrounded by weaker fields floccules on the background of a network of small-scale structure chromospheres manifested on radio waves as "radio granulation" [Bogod et al., 2017]. Weak and strong magnetic fields with different spatial dimensions extend upwards to the levels of the lower corona, where they can be measured using accurate radio astronomy methods based on spectral-polarization observations on large radio telescopes.

3 Radio sources over strong magnetic fields of spots

The high-altitude structure of the AR is fraught with many uncertainties and is a difficult observational task by optical astronomy methods, due to the high plasma temperature above the spot. In this regard, in recent years, the use of various model methods of reconstruction of the photospheric magnetic field to the coronal heights has become widespread. On the other hand, in radio astronomy observations are already used in a wide wavelength range. Beginning with submillimeter range, in which radiation outside of flares is thermal, to meter wavelengths, and meter wavelength range, where radio emission is completely nonthermal in nature. In the range of centimeter and decimeter waves, the radiation of various parts of the AR can be explained by cyclotron emission on the lower (2–3) harmonics of the gyro-frequency (above spots), free-free radiation of thermal plasma (over floccules, filaments, coronal holes), and non-thermal radiation [Bogod et al., 2017] (inter spot radiation and microbursts at the top of arch structures). The possible methods of high-altitude measurements of the magnetic field are based on astrophysical interpretations associated with all of the above radiation mechanisms.

Measurements in the microwave range have shown:

* Coronal magnetic fields as a whole, up to altitudes of about 100 thousand km, satisfactorily follow potential reconstructions of fields on the photosphere. There are some exceptions due to the reconstructions which do not always correspond to observations.

* The magnetic fields in the corona above the spots typically reach values of 70–80% of the photospheric fields.

* Long-term non-thermal radiation sources in the inter spot positions such as: (i) "peculiar" sources associated with delta configurations of magnetic fields of spot groups, (ii) increased radio emission over the neutral lines of magnetic fields, (iii) microburst emission in the decimeter range correlated with the generation of noise storms on meter waves. (iv) non-thermal additive emission, recorded in the spectra of the entire magnetosphere, the value of which varies in different regions. The high-altitude structure of coronal magnetic fields above the spots was observed using the RATAN-600 in the centimeter range using stereoscopic methods for spectral measurements of polarized emission of corresponding radio sources for 2–3 days, registered at different angles due to the rotation of the solar disk [Bogod and Yasnov, 2016].

In the millimeter wave range, the first measurements on the new ALMA instrument show a complex high-altitude structure above spot in the chromosphere of AR 12470 [Loukicheva, et al., 2017]. By use of RATAN-600 on short waves of centimeter range for the same AR (Fig. 1) it was found that, along with the existence of bright radio sources, there is a cold radiation above the spots with a temperature below the ambient plasma temperature. The result of combining the observations using the RATAN-600 and ALMA produced more information about the intensity of the sunspots of the wavelength. At the same time, information on temperatures at the heights of the lower and middle chromosphere is available from ALMA data, and at the heights of the upper transition region and the lower corona from RATAN-600 data. Comparison of the data obtained on the two instruments indicates a significant inhomogeneity of the plasma not only in the picture plane, but also in height, which requires adequate model explanations (see Fig. 1).

Knowledge of the altitude distribution of temperature and density in the spot atmosphere is essential for understanding the process of energy transfer from the solar photosphere up to the corona under strong magnetic conditions. It is assumed that in the atmosphere of the spot there is heating associated with a strong magnetic field, although the mechanism of this heating and its magnitude have not been studied extensively.

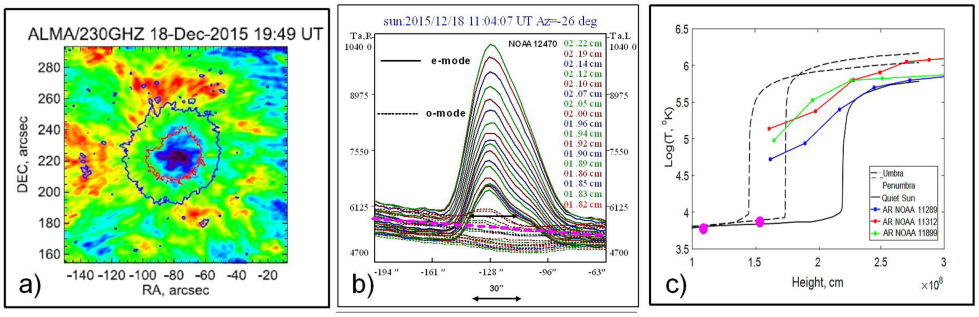


Figure 1 a) Map of AR 12470 obtained on ALMA with resolution 4.9×2.2 arcsec on wave 3 mm [5], b) multi-wave scans RATAN-600 for AR 12470 for e-mode (solid) and o-mode (dotted), c) comparison of the dependence of temperature from elevation, obtained according to ALMA and the RATAN-600 with the accepted models (see [Stupishin et al., 2018], [Fontella et al., 1999]).

4 The chromosphere and the transition region to the corona

The altitude structures in the transitional region above sun spots from spectral polarization observations demonstrated using the RATAN-600 were also investigated [Korzhavin et al., 2010]. It was found that the temperature distribution in the transition region is smooth, and significantly different from the models of the transition region with a sharp increase in temperatures, which are widely used in modeling the characteristics of microwave emission of active regions in the Sun.

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