MODERN ASTRONOMY:
FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES

Radio spectroscopy of the solar corona

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Abstract. The presence of continuous cooling and heating processes is a crucial condition that determines the existence of the solar corona. The defining aspects of the corona include the magnetic field, low plasma density, and high temperature of the corona. In this regard, the study of low-contrast structures in optical ranges is limited even with the use of large specialized telescopes. The radio range provides higher sensitivity, which can be used to detect very weak structures of emerging activity. However, the radio astronomical range also faces challenges in observation, both in terms of spatial resolution and the limitations of dynamic range due to the high temperature of the Sun's corona.

Observations show that the use of instruments with a large effective area allows us to overcome the main problem associated with the influence of powerful radiation from the quiet Sun, which amplifies equipment noise. The high sensitivity of the RATAN-600 reflector radio telescope to weak signals in radiation flux was used in the decimeter range for the detection of weak microwave bursts at a level of 10^{-3} s.f.u. Research and theoretical developments have shown that microwave bursts are caused by magnetic reconnection, which leads to the generation of accelerated particles that excite plasma waves at the second harmonic of the plasma frequency.

Due to significant changes in the concept of radio spectroscopy, work has begun on creating a series of broadband spectral complexes covering several octaves. The results of the first series of observations using the complex in the range of 1-3 GHz for searching for and studying quasi-periodic pulsations in the solar corona are presented here.

A by-product of these observations was the detection of narrow-band absorption in the frequency range 1560–1665 MHz, near the well-known OH absorption line (1612–1720 MHz).

Keywords: Sun: corona, radio radiation

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1 Introduction

Despite its proximity to the Earth, the corona of our star, the Sun, is difficult to study. This is due to its high temperature of about 1–2 MK, high transparency, and the complexity of its many structures. To study the activity of the corona by its radio emission, small radio telescopes without the spatial resolution are usually used to study the Sun as a star. On the other hand, to study the details of spatial structures, the use of solar radio interferometers (radio heliographs) has become more cost-effective than using radio telescopes with a single reflector. However, in large reflectors it is easier to achieve:

I) a large effective collecting area and consequently high sensitivity to radiation flux; II) octaval instant spectrum of intensity and polarization of radiation from individual solar objects to determine the mechanism of emission; III) high frequency and temporal resolution for studying dynamic and spectral structures (such as lines); IV) a large dynamic range to observe signals from nano-flares and powerful flares simultaneously, among others. The listed parameters are extremely important for solving problems related to the heating of the corona (model Parker 1988), searching for emission lines in the corona, constructing height magnetic maps of the corona, studying the flare process at both weak and powerful energy levels, etc.

In this work, we report a significant step in creating a tool suitable for many solar tasks using the existing RATAN-600 reflector. It is capable of covering a frequency range from 1 GHz to 18 GHz (in 2024 and up to 100 GHz in the future), with a sensitivity to radiation flux (down to 0.001 s.f.u.), a relative frequency resolution of up to 10^{-5}, a temporal resolution of about 1 ms, and a large dynamic range of at least 90 dB in regular observations (Ripak et al. 2023). The first test series of observations were carried out in the 1–3 GHz range, which demonstrates the high information potential of the combination of a reflector radio telescope and high-resolution spectroscopy.

2 Current Tasks in Solar Corona Physics

2.1 Temperature Inhomogeneity of the Corona at Radio Waves

The initial observations with the new spectral complex at RATAN-600 have detected the existence of thermal inhomogeneities with brightness oscillation amplitudes in the range of 0.001–0.002 s.f.u. in both emission and absorption. Since they are registered over a wide frequency range of 1–3 GHz, this indicates the presence of cold and hot layers larger than 150 Mm in the hot corona. The estimated brightness temperatures are from 3×10^3 to 10^5 K (Bogod et al. 2023). Multifrequency high sensitivity observations with a resolution of 4 MHz, conducted as one-dimensional scans of a quiet Sun, showed wide temperature fluctuations across the solar disk. Fluctuations occurred at a level of ± 1 s.f.u. relative to the calculated level of the quiet Sun, which was determined using the Principal Component method by Ovchinnikova et al. (2022). At $T = 1.0 \times 10^6$ K and a density of $N = 10^8$ cm^{-3}, at frequencies of 1–3 GHz, the temperature gradient was $dT/dz = 11$ K/km (i.e., 1100 K over a 100 Km interval) for both warm and cold temperature layers.

2.2 The Problem of Coronal Heating

Parker's theory of coronal heating is well known (Parker 1988). This theory remains unconfirmed, since observations are available only in X-ray and ultraviolet ranges from satellites, with energies 10^4 times higher than radio waves. However, detecting them in the radio range is also a difficult task. Our estimates indicate that RATAN-600 may register a set of nanoflares with energies up to 10^{21} erg, which may be a decisive fact for proving this theory. This will be tested during the upcoming minimum of solar activity.

2.3 Registration of Fine Frequency Structure (Lines)

Observations of the Sun at RATAN-600 using a spectropolarimetric complex in the range of 1–3 GHz revealed line radio emission from individual active regions of the Sun located in the cold filament or on the limb under the prominence, as well as during the observation of coronal rain. Absorption was found in the spectrum region of 1.5–1.65 GHz. The observed line structure corresponds to the hyperfine splitting frequencies in the ground state of $X^2\Pi_{3/2}$ hydroxyl (OH) 1612–1720 MHz. As the observed region passes through the antenna's beam pattern of the telescope, the absorption line shifts in frequency due to changes in the energy levels of the OH molecule in the magnetic field, the magnitude of which varies in the direction along the filament. A detailed description of the technique for detecting the hydroxyl absorption line in the range of 1.6–1.7 GHz is given in the work Ovchinnikova et al. (2024).

2.4 Registration of Frequency Structure of Radio Bursts

Due to the large dynamic range and high time resolution of the solar receiving equipment (about 119 spectra per second in the entire frequency range), scanning the Sun with the antenna beam directed along the declination parallel allows recording changes in the spectral density of the radio emission flux at a level of 0.1 s.f.u. (10^3 Jy) within the beam width. In the frequency range of 1–3 GHz, the beam width (BW) of the RATAN-600 antenna system (AS) South+Flat strongly depends on the wavelength, while the spatial resolution of the AS changes three times. Therefore, when operating over a wide frequency band, observational data undergo convolution with a theoretical horizontal BW calculated using aperture integration methods. During high-resolution observations (1 MHz) and in the mode of tracking a selected Active Region (AR), the horn of the complex is accurately positioned at the focus of the radio telescope, whereas during multi-azimuth observations in the standard mode with a resolution of 4 MHz, the horn is shifted from the focus by 430 mm (Fig. 1).

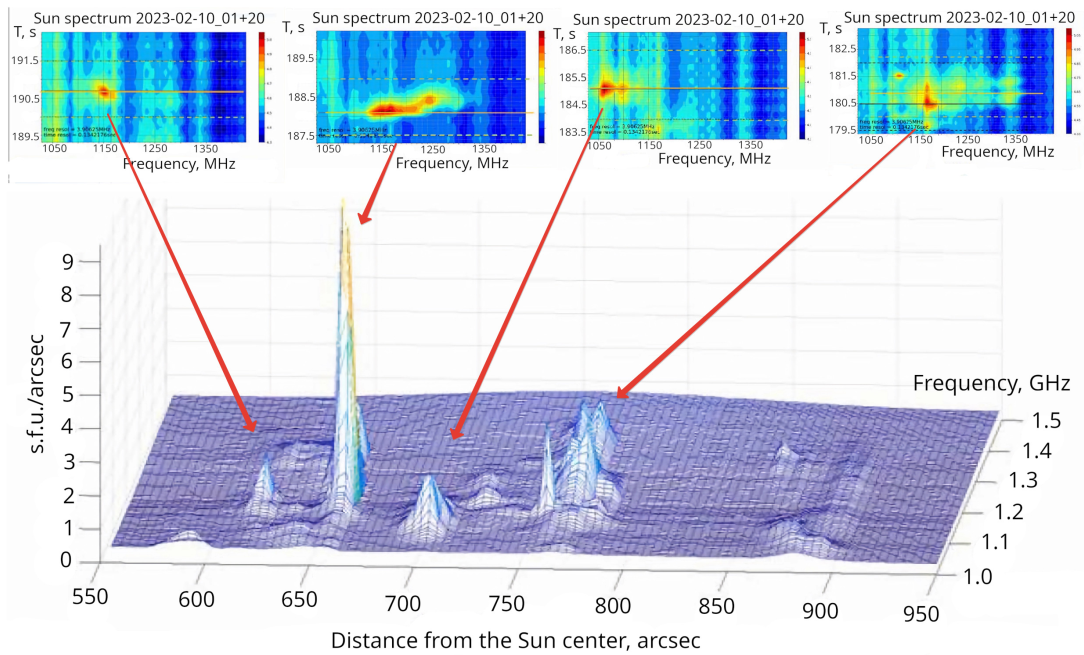

Fig. 1. A flare in the NOAA complex 13213 (13209) is presented as a multitude of individual radio sources with sizes ranging 10–15 arcseconds, with intensity levels 1–10 s.f.u., covering the frequency range 1.0–1.4 GHz, with bandwidths of individual radio sources ranging 20–50 MHz. At the top, frequency maps of the radio sources are shown with frequency and time axes. Below, the coordinate axis runs along the parallel of declination, and the other axes reflect intensity and frequency. The dotted envelope line indicates the scanning type without frequency resolution.

To estimate the sensitivity, we will calculate the conditions for registering a single flare with a brightness temperature of about 10^6 K and dimensions of $1'' \times 1''$. For a wavelength of 20 cm, the parameters chosen are: $S = 1000\,\mathrm{m}^2$, $\Delta f = 10\,\mathrm{MHz}$, $\tau = 10\,\mathrm{s}$, and $T_{\rm sys} = 150\,\mathrm{K}$. The estimated noise sensitivity of the radiometer in the absence of a solar signal gives $\delta T = (1.5 \times 10^{-2})\,\mathrm{K}$, while in the presence of the solar signal ($T_{\odot} = 6000\,\mathrm{K}$), it is about $0.6\,\mathrm{K}$. Thus, the sensitivity for the flux density ΔF

in the antenna + radiometer system, considering $S = 1000\,\mathrm{m}^2$ and $T_\odot = 6000\,\mathrm{K}$, will be $\Delta F = 2 \times 10^{-3}$ s.f.u..

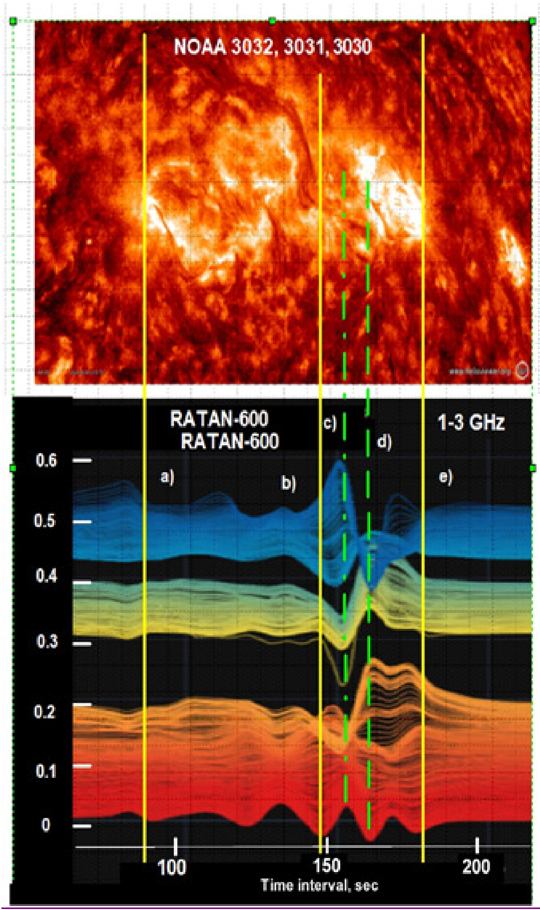

Fig. 2. Radio Registration of the Phenomenon of "Coronal Rain" on June 18, 2022. The horizontal axis represents the time scale of scanning at a speed of 15″/sec. The scale of the vertical axis is shown in s.f.u. At the top, a representation of the active region complex consisting of AR 3032, 3031, and 3030 is shown based on data from the SDO satellite. Below, spectral scans in the range of 1–3 GHz with a frequency resolution of 4 MHz are presented. Frequency gaps correspond to bands of suppressive anti-interference filters. Yellow vertical lines denote the boundaries of the active region complex along the scanning longitude. Green vertical lines mark the locations of the highest frequency activity, where regions c) with a double change in signal intensity predominately occur. This interesting phenomenon indicates thermal turbulence in the coronal plasma, which is characteristic of the "coronal rain" phenomenon. Outside the active region, the radio frequency response stabilizes, and temperature effects gradually fade. The labels a), b), c), d), and e) indicate different activity levels within the active complex, with c) and d) being the most active. This observation refers to the "coronal rain" on the solar disk, whereas this phenomenon is usually observed on the solar limb in the X-ray and extreme ultraviolet ranges.

2.5 Registration of the "Coronal Rain" Phenomenon in Radio Waves

The phenomenon of "coronal rain" has long been known from observations in the Hα and Ca II H lines as well as in the EUV range on satellites such as Hinode, SDO, and others (Antolin 2020). It is characterized by the presence of dense and cold plasma, primarily found in prominences. The large effective area of RATAN-600 (about 1000 m^2 on average across the range from 1 GHz to 40 GHz) allows achieving high parameters in the dynamic range (more than 90 dB), which distinguishes it from existing instruments on a global scale. New spectral observations have shown for the first time the existence of such a structure in coronal altitudes in the decimeter wavelength range (Fig. 2).

3 Conclusions (Summary)

The review is devoted to the work dedicated to the creation of a new method for analyzing radio emission from the solar corona. Thanks to modern technologies, new receiving equipment with exceptional parameters has been created for analyzing the properties of the high-temperature and optically thin corona using spectral analysis on a new high-resolution spectral complex in the 1–3 GHz range on the RATAN-600 radio telescope. Its high sensitivity is confirmed by measuring weak signals on the disk at the level of 0.01–0.001 s.f.u. in a wide frequency range. A number of new phenomena have been registered, including various depressions in the AR emission spectra, uneven thermal distribution in detailed temperature spectra, and the behavior of flare plasma with high frequency resolution. Unique registrations of the coronal rain phenomenon on the disk and on the limbs of the Sun have also been obtained. Preliminary interpretations have been proposed, which require further development.

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