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TOOLS AND METHODS OF LOW-FREQUENCY RADIO RECOMBINATION LINES INVESTIGATIONS

A.A.Konovalenko, S.V.Stepkin, D.V.Mukha, E.V.Vasilkovskiy

Institute of Radio Astronomy of the National Academy of Sciences of
Ukraine, 4, Mystetstv St., 61002, Kharkiv, Ukraine, *vasylkivskyi@mail.ua*

ABSTRACT. In the report the tools and methods of observations of radio recombination lines which are carried out at Institute of Radio Astronomy of the National Academy of Sciences of Ukraine using the world's largest decameter radio telescope UTR-2 (arrays "South – North" and "East – West") are described. The low-frequency radio recombination lines can be used as effective means of the low-density partially ionized interstellar medium diagnostic. However, low intensities of the lines and high level of interferences makes such investigations very difficult and impose high requirements to equipment. Observations are carried out with the 4096-channel digital correlometer and new generation digital spectral processors with 8192 spectral channels. Currently, the systematic observations of radio recombination lines have been carried out in the directions of remnants of supernova stars, Galactic plane, nebulas and dust clouds. Experiments aimed to finding the redshifted line of neutral hydrogen HI which arises in the cosmological epochs of reionization in the range 8 – 32 MHz are carried out. The carbon radio recombination lines have been detected in the direction of Cassiopeia A in the broad range of frequencies from 20 to 32 MHz. The carbon radio recombination line, corresponding to the transitions to atomic level with number of 1009 (these corresponds to the Bohr size of atom near 0,1 mm) have been registered.

Keywords: Radio recombination lines: UTR-2 radio telescope: spectral equipment: data processing

1. Introduction

Radio recombination lines (RRLs) are produced by transitions of recombining electrons between two atom levels in ionized gas. Their frequencies can be calculated using Rydberg's formula:

$$\nu_n = cZ^2R\left(1-\frac{m_e}{M_a}\right)\left(\frac{1}{n^2}-\frac{1}{\left(n+\Delta n\right)^2}\right), \tag{1}$$

where c is speed of light, Z is the nuclear charge of the ion, R is the Rydberg constant for the taken species, m_e and M_a are electron and nuclear mass, n and Δn are principal quantum number and its change respectively.

The possibility of the RRLs observations was predicted by Kardashev in 1959. They were detected in 1963-1964 by Sorochenko and Borodzich at 8.9 GHz ($n = 90$) and by Dravskikh and Dravskikh at 5.7 GHz ($n = 104$). A lot of high frequency RRLs has been observed towards classical hot HII regions. Also, for example, they have been detected in planetary nebulae, external galaxies, and in some circumstellar envelopes (Gordon & Sorochenko, 2002).

2. Detection of RRLs at Extremely Low Frequencies

The first detection of carbon RRLs was made at high frequencies. After that they were observed in the directions of a number of HII regions simultaneously with corresponding *Hnα* lines. As follow from the atomic physics the mechanism of the carbon line formation is similar to that of hydrogen lines.

RRLs of high-excited interstellar carbon atoms opened in decameter range by means of radio telescope UTR-2 about 40 years ago gave a new method of cold partially-ionized plasma diagnostic. High-precision determination of fundamental parameters of the medium – temperature, density, pressure, ionization rate, movements, mechanisms of ionization and recombination and other became possible (Konovalenko & Sodin, 1980; Konovalenko & Sodin, 1981). Detection of largest bound Rydberg atoms states up to levels of the main quantum numbers 1009 in the range 10-30 MHz is important not only for an astrophysics, but also for physical science as a whole (Stepkin et al., 2007).

3. Equipment for Low-Frequency Radio Spectroscopic Observations

The radio telescope UTR-2, the world's biggest decameter wavelengths radio telescope (situated near Kharkiv, Ukraine), remains to the most efficient for radio spectroscopy investigations owing to a set of its merit (Braude et al., 1978). UTR-2 is a T-shaped antenna which consists of 2040 "fat" dipoles. It has an effective area of about $140000\,m^2$, the angular resolution is high for a telescope of the decameter range (~30′ at 25 MHz). The telescope has an electronic beam steering which can track up to ±70° from zenith.

3.1. Digital autocorrelometer

Spectral lines at decameter range have very low relative power $s = \Delta\nu \times \Delta T_L / T_C \sim 0.1 s^{-1}$. It creates certain difficulties for their search and research. The strictest requirements

Figure 1: Appearance of 4096-channel autocorrelometer which used at observations in UTR-2

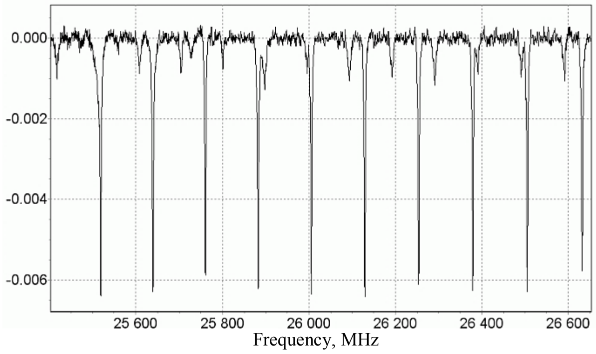

Figure 2: Spectrum obtained in the direction of Cas A with UTR-2 using autocorrelometer

are imposed to sensitivity of the radio spectrometer (not worse than 0.01%) in case of very big time of averaging. In this connection it is most suitable spectrum analyzer based on the digital sign correlometer, wherein the correlation function is determined first and then the power spectral density is determined by it. Similar multi-channel analyzers possess high stability of the operation peculiar to single-channel devices, in case of almost unlimited time of observations. Differing in simplicity of the construction connected to extremely small number of levels of quantization, such analyzers are very safe and easy-to-work. Bulky operations of Fourier transform can be executed once at the end of observations. Now on observatory of UTR-2 it is used 4096-channel correlometer (see Figure 1).

Figure 2 shows the resulting spectrum measured in the direction of Cassiopeia A (Cas A) in the frequency band around 26 MHz with UTR-2 and 4096-channel autocorrelometer, integration time is 504 hours.

3.2. Digital spectral processors

In recent years with the progress of digital and computer technologies made possible the creation and application of multi-bit wide-band digital receivers (Konovalenko et al., 2016). Figure 3 shows control center of UTR-2 observatory, DSPZ-receivers (Digital Spectro-Polarimeter Z-type) are assembled within standard desktop PC cases.

The digital receiver can operate in three qualitatively different regimes: waveform, full power and correlation mode. The modes are mutually exclusive. For radio spectroscopic observations correlation mode is typically used. In this mode two input signals are converted into a single output, the value of coherence between the two input signals (Ryabov et al., 2010).

Figure 3: The UTR-2 control center with new-generation back-end facilities

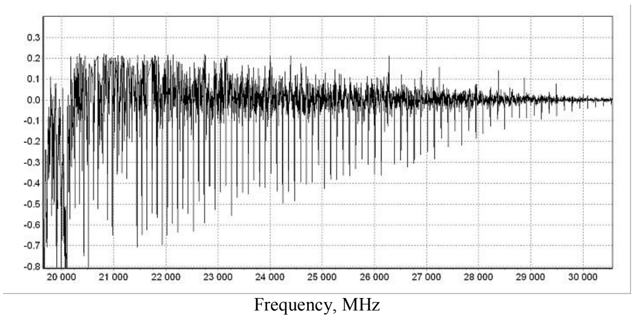

Figure 4: Carbon RRLs towards Cas A measured with the North-south arm of the UTR-2 array (using DSPZ)

Figure 4 shows the spectrum measures at UTR-2 using DSPZ in the direction of Cas A in the range 20-30 MHz. Clearly visible absorption lines in a series of about 100.

4. Methodology of Data Processing and Interpretation

After the observations were carried out observational data must be properly processed for their subsequent interpretation.

4.1. Doppler shift determination

The only ultimate criterion of the natural origin of the spectral lines in the decameter range is determination of Doppler shift of the spectral line frequency due to the orbital rotation of the Earth:

$$f = f_0\left(1-\frac{v_x}{c}\right), \tag{2}$$

where f is observed frequency, f_0 is the central frequency of generation, c is speed of light, and v_x is the speed of the line of sight.

If the source of monochromatic radiation is a subject that is far enough away from the Sun, the frequency of the line will change due to periodic changes in the Earth's velocity component directed to the object, due to the annual motion of the Earth around the Sun. This criterion is often used in radio astronomy for observations of pulsars and spectral lines. The maximum value of the Doppler shift plays the pipe in the directions lying in the plane of the ecliptic. At a frequency of 25 MHz, the assumption of a circular orbit

Earth at a linear speed of about ~30 km/s camping maximum velocity differences (frequency) at times separated by an interval of 6 months, is 5.8 kHz.

4.2. Interference reduction

Usually spectroscopic observations at UTR-2 are carried out using four minute frames, which are stored in computer.

In order to remove hindering signal from processed spectrum we subtract from measured autocorrelation function a model of interference. It described by

$$R[i] = \frac{2A}{r_1}\exp\left[-\sqrt{\frac{i\pi\Delta f}{(2\ln 2)^2 f_d}}\right]\cos\left(2\pi(f_0 - f)\frac{i-1}{f_d}\right), \qquad (3)$$

where $R[i]$ is the autocorrelation function of hindering signal, A is the amplitude of hindering signal, r_1 is the autocorrelation function point number, Δf is the bandwidth of hindering signal, f_d and f_0 are the sampling frequency and the frequency of the local oscillator respectively.

5. Experiment to Detect 21-cm Cosmological Line Using UTR-2

The great interest in the scientific world is caused by radio astronomical investigations of physical processes taken place in the distant cosmological epochs. At least three distant epochs have been identified which have corresponding spectral windows for the redshifted HI signal (Peters et al., 2011):

1. The Dark Ages: $100 < z < 30$ (15 MHz $< \nu < 50$ MHz);
2. First star formation: $30 < z < 15$ (50 MHz $< \nu < 90$ MHz);
3. Epoch of Reionization: $15 < z < 7$ (90 MHz $< \nu < 200$ MHz).

For the use of the radio telescope UTR-2 and new generation radio telescope GURT (Konovalenko et al., 2016) these epochs are of particular interest.

Observations began to be conducted from January 2015. Search the spectral lines in the observational data obtained during the daytime, it is possible only o relatively narrow frequency band. The different interfering signals will not only pose a significant challenge to detect this effect, but also RRLs arising in the interstellar medium in our epoch.

6. Conclusions

Observations of low-frequency RRLs are promising means of the tenuous ISM diagnostics. Improvement of the existing low-frequency radio telescopes, spectral analyzers and methods of observation as well as the creation of new tools will open new opportunities in space plasma spectroscopy. Long-term successful observations with Ukrainian radio telescope UTR-2 gave new information about fundamental properties of the interstellar medium. Presently investigations of low-frequency RRLs with UTR-2 are continuing for many galactic objects and data processing is progressing. It is clear that RRLs studies will be important part of the scientific programs of new generation and future giant low-frequency instruments such as GURT, LOFAR, SKA, LRA.

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