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Study of a bright sources sample in the RATAN-600 Western sector observations

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From June 2018 to May 2019, the 24 hours strip of the sky on the Crab nebula declination and from June 2020 to May 2021 the strip on the microquasar GRS 1915+105 declination were observed with a four-beam complex of four-channel sensitive radiometers, established in the focal line of the "Western sector" of the RATAN-600 radio telescope. The main aim of these surveys was to search for the fast radio bursts, but in the report we discuss the traditional blind survey with a high sensitivity. We averaged the data received in narrow channels to achieve total sensitivity of about ~ 5 mJy/beam for a total frequency band equal to 600 MHz at the frequency of 4.7 GHz. This value is only constrained by the effect of confusion for the antenna beam, having the angular sizes $1' \times 35'$. We obtained about 25 high-quality records of the 24 hour strip of the sky for every month of the observations and calculated 12 average drift scans. Here we considered a primary sample of 121 the most bright sources, detected in the both surveys. We identified these sources with the radio sources from different catalogs, collected in the CATS database. That allowed us to plot compiled radio spectra of the sources. We have analyzed spectra and light curves of all sources. Also we identified the sources with big optical and infrared catalogues, and found that sources are galaxies and quasars.

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1. Introduction

Blind sky radio surveys are the traditional method of the studies in radio astronomy from the pioneer (3C, 4C, Parkes, GB6) to modern surveys: TGSS [1], GLEAM [2], VLASS [3]. A significant contribution to the radio sources study was made by major high-precision VLA sky surveys NVSS [4] and FIRST [5].

Some large surveys were carried out with the RATAN-600 radio telescope: the Zelenchuck survey in the region $0° < \mathrm{Dec} < 14°$ [6], the "Cold" deep survey at 3.9 GHz [7]. The RATAN-600 Zenith Field (RZF) survey of the 2-degree (RA = 0h-24h, Dec = $+41°.5 \pm 1°$) strip of the sky at the declination of the source 3C84 was conducted for many years [8].

Since 2017 round-the-clock surveys with the Western sector of the RATAN-600 on a four-beam four-channel complex of radiometers at 4.3-4.9 GHz have been conducted. Main aim of this surveys has been to search for the fast radio bursts, but also data has been investigated as the data of usual blind surveys with high sensitivity.

In this report we discuss results of the investigation of a sample of two big surveys: from June 2018 to May 2019 the strip on the declination of the famous Crab nebula (Dec = +22°00′52") and from June 2020 to May 2021 on the declination of the microquasar GRS 1915+105 (Dec = +11°56′44"), receiving two strips on the sky with the areas about 180 square degrees.

We obtained about 25 high-quality daily drift scans for each RA-hour per a month, thus finally we obtained 12 average monthly records. On them, we detected bright 121 sources from both surveys. We analyzed light curves of the sources and identified them with a lot of radio data, using the CATS database [9] to plot compiled radio spectra of the sources. Sensitivity of the radiometer at 4.7 GHz reached 3 mK/s and with the effective area of 1200 m^2 a telescope sensitivity was about 5 mJy per beam.

2. Sample selection

Observations were carried out with the Western sector of the RATAN-600 radio telescope which was static during the surveys and at a fixed antenna elevation. Surveys were carried out with four 4.7 GHz frequency (λ 6.38 cm) receivers with 600 MHz bandpass divided for channels with a width of 150 MHz. We used four similar radiometers in the surveys and an additional 2.3 GHz radiometer.

Criteria for the bright sources sample selection were signal-to-noise ratio of $S/N > 100$ on average during the year of observations data and antenna temperature $T_a > 10$ mK.

The flux densities were higher than 40 mJy within the area $|\delta H| < 10$ arcmin. All detected sources have the NVSS[1] counterparts. It allowed us to define accurate coordinates of the sources.

There were 60 sources observed in the survey on the declination of the Crab nebula (RA = $0^h - 24^h$, Dec = +22°00′52") and 61 sources observed in the survey on the declination of the micro quasar GRS 1915+105 (RA = $0^h - 24^h$, Dec = +11°56′44") Observations were carried out from June 2018 to May 2019 and from June 2020 to May 2021 correspondingly.

The measured flux densities of 51 sources were 40 mJy < S_ν < 100 mJy and for 13 sources they were $S_\nu > 500$ mJy. Figure 1 (left) shows how the sources are distributed for their flux (right):

[1] https://www.cv.nrao.edu/nvss/

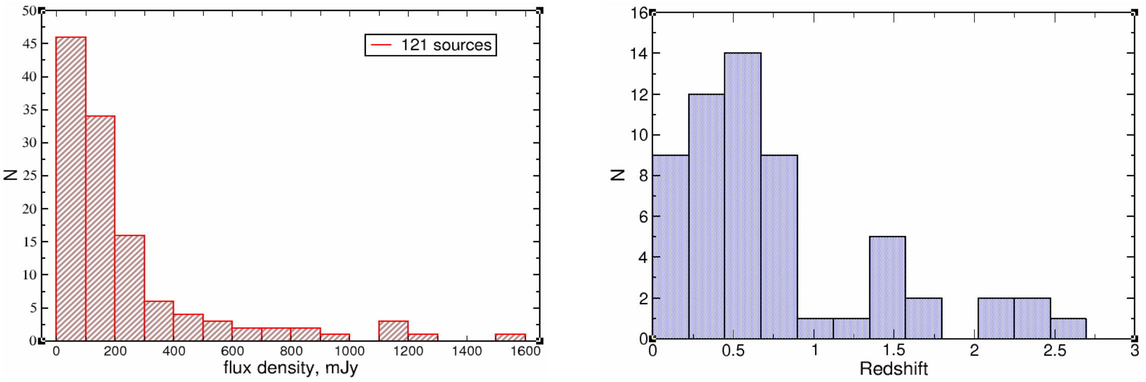

Figure 1: *Left*: Sources flux density distribution of 121 radio sources, 2/3 of the sources had the flux density S_ν < 200 mJy; *right*: 66 sources redshift distribution. Half of the sources have redshift z < 1. The optical data were used from the SDSS catalogue and Simbad data base.

shows how the sources are distributed for their redshift: from 66 sources 44 sources have redshift z < 1 and four sources have redshift z > 2.

Estimations of beam pattern for the antenna of the Western sector of the RATAN-600, data processing, continuum radio spectra of sampling radio sources analysis were made with help of the standard data processing package FADPS [10] for each receiving horn of the radiometers.

3. Sources properties

Properties of all individual sources: sources size, sources continuum radio spectra, sources variability, radio luminosity and radio loudness were studied.

3.1 Continuum radio spectra of the sources

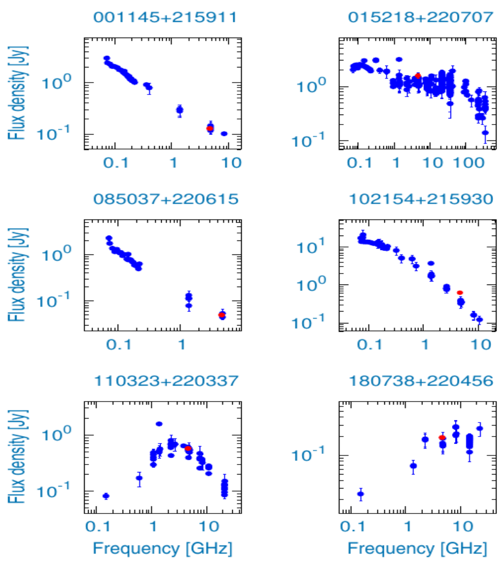

Figure 2: Different types of continuum spectra of the sources. *Blue*: the CATS data; *red*: obtained in this work estimations of flux density at 4.7 GHz.

When we identified the detected sources with VLASS survey sources, distribution of the sources size was obtained. 63 detected sources have a single-component, and 46 sources have an angular size less than 4 arcsec.

Using data from the CATS astrophysical catalogue database, radio spectra of all sampling sources were constructed and spectral indices at the frequency of 4.7 GHz were calculated. The distribution of values of spectral indices shows that 60 sources have steep spectrum (-1.1 < α < -0.5, $S_\nu \sim \nu^\alpha$), 18 sources are Gigahertz Peaked Spectrum sources (GPS sources, where the maximum of radiation lies at 1–5 GHz), four sources are Ultra Steep Spectrum sources (USS sources) (α < -1.1), 21 sources are flat spectrum (-0.5 < α < 0.5), four sources have inverted spectrum ($\alpha > 0.5$), 15 sources have turnovers at the lower frequency spectrum.

Different examples of spectra are shown on figure 2. The radio source 001145+215911 is a steep-spectrum source, 015218+220707 is a flat-spectrum radio source, 085037+220615 is an ultra-steep-spectrum radio source, 102154+215930 is a steep-spectrum radio source with a flattering on a lower frequency, 110323+220337 is a GPS radio source, 180738+220456 is an inverted-spectrum radio source.

3.2 Sources variability

We obtained about 25 high-quality daily drift scans for each RA-hour per a month, thus finally we obtained 12 average monthly records.

The sample sources in each of the annual surveys were divided by months of observations with following averaging. Calculation of the variability index showed that for the most of the sources change in their flux density estimations does not exceed 20%.

The variability index was calculated using the formula from [11]:

$$Var = \frac{(S_{\max} - \sigma_{S_{\max}}) - (S_{\min} + \sigma_{S_{\min}})}{(S_{\max} - \sigma_{S_{\max}}) + (S_{\min} + \sigma_{S_{\min}})}, \quad (1)$$

where $S_{\max}$ and $S_{\min}$ are the maximum and minimum values of the flux density at all epochs of observations; $\sigma_{S_{\max}}$ and $\sigma_{S_{\min}}$ are their errors.

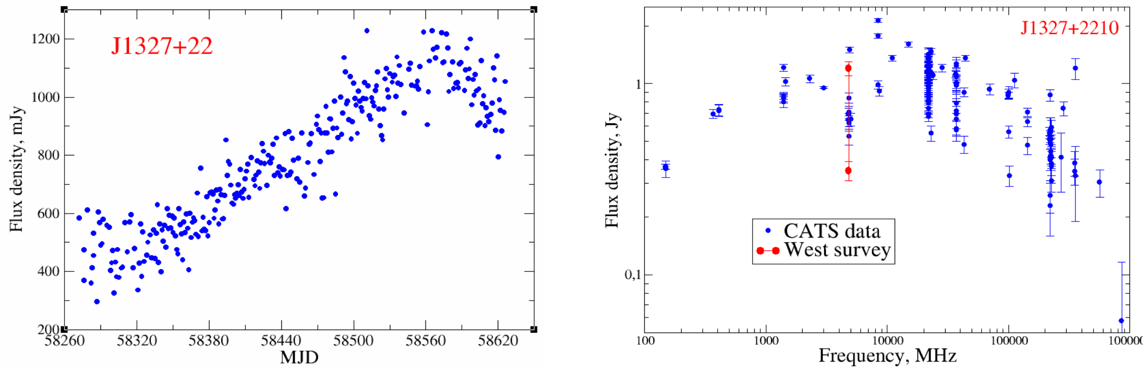

Figure 3: Variable blazar B1324+22 at redshift $z = 1.4$; *left:* daily flux density during the year of observations; *right:* its radio spectrum. Blue points: CATS data, red points: obtained in this work.

The blazar B1324+224 (J132700+221050) was the only radio source detected with a significant (2.4 times) variability in the flux density estimations during the year of the observations ($Var = 0.33$, $S_{avr} = 655$ mJy, $z = 1.4$). Figure 3 shows a slow variation of flux density of the blazar B1324+224 during all observations.

3.3 Radio luminosity and radio loudness of the sources

Optical counterpart candidates were found for 109 sources of the sample using optical SDSS (DR16)[2] and infrared 2MASS [12] surveys, as well as the Simbad database[3]. Measured

[2]http://www.skyserver.sdss.org/dr16/
[3]https://simbad.u-strasbg.fr/simbad/

redshift values were found in optical catalogues for 66 of sampling sources. According to this data 43 sources are extended and 66 are point sources. Figure 1 shows the redshift distribution of 40 galaxies and 26 quasars.

Luminosity and radio loudness were calculated at the frequency of 4.7 GHz for the sources of the sample. We used the ΛCDM cosmology with $H_0 = 67.74$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3089$, and $\Omega_\Lambda = 0.6911$ [13] to estimate the radio luminosity:

$$L_\nu = 4\pi D_{\rm L}^2 \nu S_\nu (1+z)^{-\alpha-1}, \quad (2)$$

where ν is the frequency, S_ν the measured flux density, z is the redshift, α is the spectral index calculated at 4.7 GHz , and D_L is the luminosity distance [14]. The radio loudness is defined as

$$R = \frac{S_{\nu,\rm radio}}{S_{\nu,\rm opt}}, \quad (3)$$

where $S_{\nu,\rm radio}$ is the estimated radio flux density at 4.7 GHz and $S_{\nu,\rm opt}$ is the optical flux density corresponding to the filter B or g. We adopted $S_{\nu,\rm opt} = 3631$ Jy for $g = 0$[4], $S_{\nu,\rm opt} = 4260$ Jy for $B = 0$ [15], and the optical spectral index α = -0.3 [16]. Quasars at the redshift $z > 1$ have the greatest luminosity ($L_\nu > 10^{44}$ erg/s). The highest radio loudness is showed by galaxies.

Figure 4 shows the luminosity and radio loudness distribution of the sources depending on redshift.

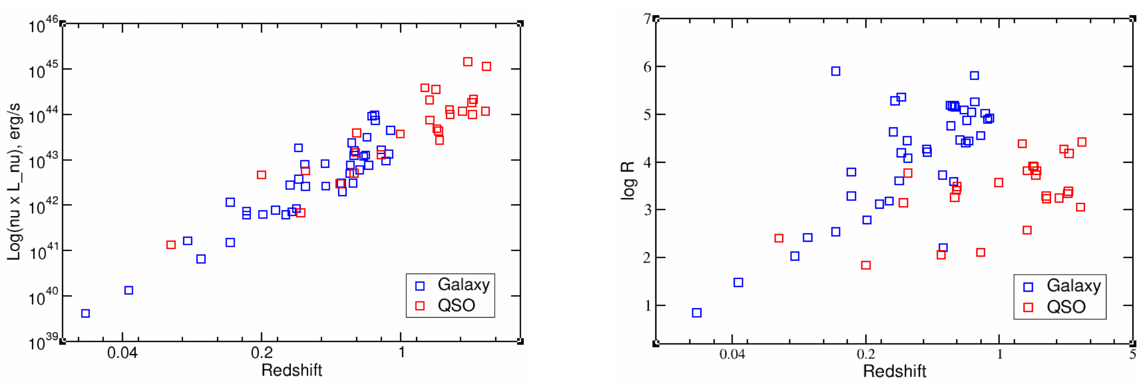

Figure 4: *Left:* radio luminosity of the sources at 4.7 GHz depending on redshift; *right:* radio loudness of the sources.

4. Conclusion

1. The sample of 121 bright sources from the surveys on the Western sector of the RATAN-600 radio telescope on the Crab nebula and the declination of the GRS 1915+105 was studied.

2. From the VLASS radio catalogue, distributions of the sources sizes and number of components were obtained: 63 detected sources are single-component and 46 sources size is less than 4 arcsec.

[4] https://www.sdss.org/dr12/algorithms/fluxcal/#SDSStoAB

3. Spectra of all 121 sources were constructed. 60 of the sources are steep-spectrum (-1.1 < α < -0.5, $S_\nu \sim \nu^\alpha$), 18 sources are GPS sources, 4 sources are USS sources (α < -1.1), 21 sources are flat spectrum (-0.5 < α < 0.5), 4 sources are inverted spectrum (α > 0.5), 15 sources have turnovers at the lower frequency.

4. The estimation of the sources variability showed that there were not significant variability(more than 20%) of flux density. However, the blazar B1324+224 showed increase for the flux density during one year.

5. From the SDSS(DR16) and 2MASS catalogues and the Simbad database, 109 sources have optical counterparts: 43 sources are extended and 66 sources are point objects in optical and infrared bands. There are published redshift measurements of 66 sources in the literature: for 40 galaxies and for 26 quasars radio luminosity and radio loudness were calculated. The luminosity of quasars is higher for quasars than of galaxies. Radio loudness of the galaxies is higher than of quasars.

5. Acknowledgements

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