Multifrequency Study of GHz-peaked Spectrum Sources

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Abstract—Gigahertz-Peaked spectrum (GPS) sources are compact active galactic nuclei, presumably young precursors of bright radio sources. The study of GPS radio properties provides information about the features of synchrotron radiation in extragalactic sources. Also in applied research, GPS sources are useful as compact stationary radio sources in the sky for astrometric purposes. This paper presents the results of a multifrequency GPS study based on quasi-simultaneous measurements with the RATAN-600 radio telescope during the 2006–2017 period. A catalog of GPS spectral flux densities at six frequencies—1.1, 2.3, 4.8, 7.7/8.2, 11.2, and 21.7 GHz—is obtained. In addition, for the analysis of radio spectra, data from low-frequency surveys GLEAM (GaLactic and Extragalactic Allsky Murchison widefield array survey) and TGSS (Tata institute for fundamental research GMRT Sky Survey) and high-frequency measurements from Planck survey are used. A total number of 164 GPS and candidates have been identified (17 of them are new discoveries), which makes up a small fraction of GPS in the initial sample of bright AGNs—about 2%. The physical properties and formation conditions of synchrotron radiation are found to be quite different in GPS of different AGNs types. The deficit of distant GPS (z > 2) with low maximum frequencies (less than 1 GHz) has been confirmed. The existing “size–peak frequency” anticorrelation is continuous. The continuum radio spectra are found to become statistically steeper with increasing redshift.

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1. INTRODUCTION

Gigahertz-peaked spectrum (GPS) sources are compact extragalactic sources, distinguished by their convex radio spectra1 with peak at several GHz (in the reference frame). They believed to be young predecessors of massive radio loud radio galaxies [1–3]. There are two classes of objects with properties similar to those of GPS, but they differ in the peak frequency domain: Compact Steep Spectrum (CSS) sources have ν_{int} < 0.5 GHz and High Frequency Peakers (HFP) have ν_{int} > 5 GHz [4–7]. The above frequency boundaries are conventional, because the peak value may vary, and that is why in the literature these objects are often referred as GPS. All of them are distinguished by high radio luminosity L_{radio} \sim 10^{43–45} \text{erg s}^{-1} and compact size—less than 1 kpc [1] for GPS/HFP and about 20 kpc for CSS, low radio variability (a few percent) and small polarization [1, 8–10].

GPS and CSS sources are believed to account for 10% and 20% of the brightest representatives of active galactic nuclei (AGN), respectively. However, recent studies with RATAN–600 have revealed that the corresponding fractions are much smaller [11–15].

The shape of the spectrum after turnover frequency is often explained in terms of the synchrotron self-absorption or free-free absorption model [16]. The most commonly adopted model explaining the small sizes of such objects is the youth scenario [17–22]. The presence of dense environment surrounding their central regions can also hinder their active and rapid expansion [1]. The well-known “linear size–maximum frequency” anticorrelation [2] may also indicate of the young age of GPS/CSS sources [20].

The origin of some GPS (about 10%) is explained by the recurrent activity of radio galaxies [23, 24], when objects have a high radio luminosity for a long time. This hypothesis is confirmed by the discovery of diffuse radio-emission areas around some GPS,

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1Hereafter, the spectral flux density is related to the frequency as S_\nu \sim \nu^{\alpha}
which may be the remnants of previous periods of activity [23]. It was also suggested [25] that GPS quasars are blazars surrounded by a dense gas-and-dust medium. It can hide blazar properties during observations, despite the close line-of-sight location of the jet.

The observed radio spectra of GPS galaxies can be explained fairly well by projection effects [16]. There are few ready-made scenarios for GPS quasars, and the samples are significantly “contaminated” by variable objects with temporarily inverted radio spectra [26, 27]. GPS quasars are the most compact (with sizes from several parsecs to several hundred parsecs) and have complex structures with a core and an emitting jet. Their compact size is due to the orientation of the jet, which is aligned close to the observer line of sight [16].

GPS sources are obviously a heterogeneous group of extragalactic objects. The inclusion of a significant fraction of variable quasars in such samples affects the results of their analysis. An attempt of multidimensional ordering of the data about the various properties of GPS/HFP objects [28] revealed many subgroups (clusters), which differ significantly in their properties. All known GPS quasars were reasonably included into Roma-BZCAT [29] blazar catalog. It has now been established that there are two types of GPS sources: classic, non-variable young objects, we will designate them as type 1 GPS, and variable objects often associated with blazars, we will designate them as type 2 GPS. There is a slight difference in their spectra: the GPS of the first type have a narrower peak, whereas those of the second type usually has a wide peak [15, 30]. VLBI measurements are a reliable way to distinguish these objects [31, 32].

GPS sources are considered to be the predecessors of AGNs, as early stages of their evolution [1, 2, 7, 10]. Hence that it is interesting to study the possible connection of GPS with distant objects of the Universe [33–38]. The new measurements with high sensitivity at decimeter band [39–41] allowed the study of the compact objects with the peak in the spectrum below 1 Gz—Megahertz-Peaked Spectrum (MPS) objects. Nowadays, MPS are key objects for an alternative search for extremely distant objects [33, 36, 38] (z > 6), when spectroscopic redshift measurements are difficult due to the multiple Ly-α absorption lines on microwave background photons.

The aim of this work is to study the GPS radio properties over a wide frequency range (0.075–857 GHz) on time scales longer than 10 years. We analyze the properties of objects depending on the AGN class. Our analysis is based on measurements made with RATAN-600 (1.1,2.3,4.8,7.7/8.2,11.2 and 21.7 GHz) during the 2006–2017 period of time. A significant amount of additional measurements consists of the data from the CATS astrophysical catalogs support system [42, 43]. Additionally, the millimeter- and submillimeter-band flux densities were estimated for bright objects based on the analysis of the Planck survey map images. In our computations we adopted the following values of the cosmological constants: \( \Omega_m = 0.27 \), \( \Omega_A = 0.73 \), \( H = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. THE SAMPLE PROPERTIES AND OBSERVATIONS

We study the complete sample of GPS source and candidates \( S_{5\text{GHz}} \geq 200 \text{ mJy} \) from [15]. In that work, a total number of 467 radio sources with the spectral maximum were selected and 112 of them were considered as GPS sources according to classical criteria [1]. GPS objects and candidates from this list were measured with the RATAN-600 within the framework of a planned research program in 2006–2017. Intermediate results of the monitoring for the 2006–2011 period were published in [12, 13, 15]. The observations were carried out at the frequencies of 1.1, 2.3, 4.8, 7.7/8.2, 11.2, and 21.7 GHz. We selected GPS sources based on the criteria from [1, 44, 45], according to the properties their radio spectrum which should coincide with the theoretical spectrum of a homogeneous self-absorbed synchrotron source with a power law electron energy distribution. These criteria include: spectral indices of the optically thick and thin emission regions \( \alpha_{\text{below}} = +0.5 \) and \( \alpha_{\text{above}} = -0.7 \), respectively [45]; the full width of the spectra at half maximum \( FWHM \) is about 1.2 frequency decades [1, 46], and the variability index \( V_{\text{radio}} \leq 25\% \). The redshift values for objects of research are from 0.01 up to 4.5 and are known for almost half of the sources (Fig. 1).

Spectral flux densities were measured with two continuum radiometers (Table 1): (1) using secondary mirror No. 1 at the frequencies of 1.28, 2.25, 4.8, 7.7/8.2, 11.2, and 21.7 GHz (designated as “1” in the table) and (2) with the three-frequency continuum radiometer using secondary mirror No. 2 (designated as “2” in the Table) at the frequencies of 4.8, 11.2, and 21.7 GHz. The RATAN-600 continuum radiometers are the direct amplification receivers with a square-law detection. All the radiometers were designed as the “total power radiometer” mode. We use the standard data acquisition and control system based on the ER-DAS (Embedded Radiometric Data Acquisition System) [47]. The current level of the receiving equipment is provided by low-noise uncooled amplifiers based on high-electron mobility transistors (HEMT).
The redshift distribution for GPS (type 1 and type 2). The dashed line indicates the median redshift values.

Fig. 1. The redshift distribution for GPS (type 1 and type 2). The dashed line indicates the median redshift values.

Table 1. The RATAN-600 continuum radiometers

| $f$, GHz | $\Delta f$, GHz | $\Delta S$, mJy/beam | $FWHM$, $''$ |
|---------|-----------------|-----------------------|------------|
| 1       | 2               | 1                     | 2          |
| 21.7    | 21.7            | 2.5                   | 50         |
| 11.2    | 11.2            | 1.4                   | 10         |
| 7.7/8.2 | ...             | 1.0                   | ...        |
| 4.8     | 4.8             | 0.6                   | 5          |
| 2.25    | ...             | 0.06                  | 200        |
| 1.28    | ...             | 0.06                  | ...        |

Designations: $f$—central frequency, $\Delta f$—bandwidth, $\Delta S$—flux density detection limit per beam, $FWHM$—angular resolution in RA.

and digital signal processors in the data acquisition system.

The observations were made using two- and three-mirror antenna configurations. The angular resolution of the radio telescope depends on the declination of a source being observed, and due to the knife-edge shape of beam, the angular resolution in declination is three to four times worse than in RA. The detection limit for the RATAN-600 is approximately 5 mJy (3 s integration time) under good conditions at the frequency of 4.8 GHz and at an average antenna elevation.

The data were processed using an automated system for the reduction for the RATAN-600 continuum observations based on the modules of the standard FADPS (Flexible Astronomical Data Processing System) [49] package and designed for a mass interactive processing of output RATAN-600 data. Estimates of measurement errors and the flux density calibration procedure are described in [12, 13, 48, 50–52]. The information on secondary calibration standards is taken from [53–56]. The total fluxes measurement error is determined by the calibration error and the antenna temperature error. The systematic uncertainty of the absolute flux density scale (3–10% at different frequencies) has not been included in the flux density error:

$$\left(\frac{\sigma_s}{S_\nu}\right)^2 = \left(\frac{\sigma_c}{g_\nu(h)}\right)^2 + \left(\frac{\sigma_t}{T_{ant,\nu}}\right)^2.$$  

where $\sigma_s$ is the total standard flux error; $\sigma_c$ is the standard error of calibration; $T_{ant,\nu}$ is the antenna temperature at the frequency $\nu$; $\sigma_t$ is the error of antenna temperature $T_{ant,\nu}$; $S_\nu$ is the spectral flux density; $g_\nu(h)$—calibration coefficient that reflects the total dependence of the atmospheric absorption instability and effective area on the angle $h$ above the horizon (for real aberrations due to transverse movement of a primary feeds from the electrical axis of the antenna). The elevation of the antenna is $h = 90^\circ - \phi + \delta$, where $\delta$ is the declination of the object and $\phi = 43^\circ.653$ is the telescope site latitude. The average spectral flux density measurement error for the sample is 15%, 7%, 6%, 5%, 7%, and 12% at 21.7, 11.2, 8.2, 7.7, 4.8, 2.3, and 1.2 GHz, respectively.

The continuum radio spectra of GPS sources are presented in electronic form in VizieR catalog database and a fragment is shown in Fig. 2. Some of them can be analyzed in the interactive RATAN–600 BL Lac’s catalog [58]. The crosses with downward arrows show the estimated fluxes of the “hot” spots (positive response) on Planck maps. The spectra were analyzed using spg module of FADPS package.

The results of the GPS measurements during the 2011–2017 period are presented at the site of Strasbourg Astronomical Data Center (CDS)\(^3\). In this paper, we provide a fragment in Table 2. Column 1 is the object name in accordance with NVSS catalog; Column (2)—the mean observational epoch, and Columns (3–8) are the RATAN-600 spectral flux densities values with their errors at six frequencies (in the table header).

Based on the GPS selection criteria (see [1, 12, 13, 15, 45]), we selected 164 GPS objects and candidates (Table 3). Seventeen among them (marked with “*”) are identified for the first time. We also marked with asterisks “**” 30 more objects, which we identified for the first time as GPS candidates in our earlier paper [15]. Table 3 provides the following data:

\(^3\)http://vizier.u-strasbg.fr/viz-bin/VizieR

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Fig. 2. Radio continuum spectra of GPS and candidates. The filled and open circles show the 2006–2017 RATAN-600 measurements and CATS archival data, respectively, and the crosses show the upper flux limit estimates based on Planck maps [57].
### Table 2.
The flux densities of GPS sources and candidates for several epochs (RATAN-600 observations 2006–2017). Full catalog is available at the VizieR database

| NVSS name | JD      | \( S_{21.7}, \sigma, \text{Jy} \) | \( S_{11.2}, \sigma, \text{Jy} \) | \( S_{7.7/8.2}, \sigma, \text{Jy} \) | \( S_{4.8}, \sigma, \text{Jy} \) | \( S_{2.3}, \sigma, \text{Jy} \) | \( S_{1/1.3}, \sigma, \text{Jy} \) |
|-----------|---------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| 032957+275615 | 0.196 ± 0.03 | 0.384 ± 0.04 | 0.488 ± 0.04 | 0.686 ± 0.04 | 1.027 ± 0.1 | 1.206 ± 0.10 |
| 034729+200453 | 0.172 ± 0.02 | 0.259 ± 0.02 | 0.349 ± 0.02 | 0.354 ± 0.02 | 0.404 ± 0.04 |
| 040305+260001 | 1.490 ± 0.09 | 1.894 ± 0.05 | 2.194 ± 0.07 | 2.460 ± 0.06 |
| 040922+121739 | 0.815 ± 0.10 | 1.044 ± 0.10 | 1.448 ± 0.10 | 1.834 ± 0.10 |
| 040922+121739 | 0.856 ± 0.10 | 1.191 ± 0.10 | 1.479 ± 0.10 | 1.663 ± 0.10 |
| 040922+121739 | 0.609 ± 0.10 | 1.057 ± 0.10 | 1.306 ± 0.10 | 1.461 ± 0.10 | 1.521 ± 0.02 | 1.395 ± 0.10 |
| 2457033 | 0.383 ± 0.05 | 0.280 ± 0.03 | 0.218 ± 0.01 |
| 2457090 | 0.179 ± 0.02 | 0.219 ± 0.02 | 0.303 ± 0.02 |
| 2457124 | 0.272 ± 0.03 | 0.250 ± 0.01 |
| 2457214 | 0.223 ± 0.03 | 0.235 ± 0.02 | 0.248 ± 0.01 |

### Table 3.
Parameters of GPS sources and candidates which were obtained with the RATAN-600 in 2006–2017. Full catalog is available at the VizieR database

| NVSS name | sp.type | opt type | \( z \) | \( \nu_{\text{obs}}, \text{GHz} \) | \( \nu_{\text{int}}, \text{GHz} \) | \( \alpha_{\text{below}}, \sigma \) | \( \alpha_{\text{above}}, \sigma \) | \( \alpha_{353-857} \) | \( FWHM \) | \( Var_{11.2}, \% \) | morph. | AGN type |
|-----------|---------|----------|------|-------------------|-------------------|------------------|------------------|------------------|------------------|------------------|--------|----------|
| 000319+212944 | GPS | QSO | 0.45 | 2.3 | 3.3 | 0.429 ± 0.006 | −0.948 ± 0.013 | 2.7 ± 1.3* | 1.5 | 3.0 | cso | FSRQ |
| 000346+480703 | – | – | 1.9 | – | 1.037 ± 0.1 | −1.004 ± 0.023 | 1.3 | – | cd | – |
| 000520+052410 | HFP | QSO | 1.89 | 2.0 | 5.7 | 0.189 ± 0.027 | −0.473 ± 0.010 | 1.8 | 25.0 | cso | FSRQ |
| 000800–233917* | HFP | QSO | 1.41 | 3.4 | 8.1 | 0.450 ± 0.004 | −0.550 ± 0.007 | 1.6 | 3.4 | – | FSRQ |
| 001610–001512 | GPS | – | 1.57 | 0.9 | 2.3 | 0.488 ± 0.003 | −0.309 ± 0.002 | 2.0 | – | – | FSRQ |
maps of the microwave emission components obtained by Planck satellite, and the Planck source catalogs, which are available from the Planck Legacy Archive—PLA7.

There is a hypothesis about the increased likelihood of a positive response ("hot" spots) on microwave background maps if a radio galaxy located there. It was shown [57, 63] that a fairly large number of extragalactic point sources with different spectral properties are detected at the level below 4σ on Planck maps containing signals of both the frequency channels and the cleaned CMB. We used Aladin application [64, 65] to identify the spots with the objects studied and to measure the distance from the source to the center of the spot. We selected spots with the centers located no farther than 2′5 and 3′−5′ from the sources at frequencies above 100 GHz and below 70 GHz, respectively.

We used Source Extractor program8 (SExtractor) [66] for photometric measurements of the signals from spots and to determine the integrated brightness of spots on Planck maps. Then we converted the inferred brightness temperatures into fluxes using the [57] calibration curves, which relate flux densities of the sources (in Jy) with the microwave background temperature on Planck maps (in kelvins).

In this work, we followed the procedure to determine the calibration curves using objects with known flux densities as calibrators from [13, 15]. We compare the fluxes obtained using our technique with those presented in the Planck catalog to verify our estimations of the flux densities. The mean ratio \( \bar{T} \) of the fluxes determined using the above technique to the fluxes given in the Planck catalog and the standard deviation of this mean ratio, \( \sigma_\bar{T} \), for the calibrators [13, 15] lie in the \( \bar{T} = 0.97 - 1.05 \) and \( \sigma_\bar{T} = 0.2-0.4 \) intervals depending on the frequency.

The obtained upper flux limits for spots in Planck maps located in the vicinity of GPS sources were also included into the spectra of the objects (Fig. 2, downward-pointing arrows), and constructed their distributions. The histograms are shown in Fig. 4. The hatched areas present the distributions of Spectral indices based on Planck measurements exclusively, and the white areas correspond to all data including both direct measurements from the Planck catalog and the estimated fluxes of "hot" spots with the coordinates matching those of the sources.

The distributions of the spectral indices \( \alpha_{30-44} \), \( \alpha_{44-70} \), \( \alpha_{70-143} \), and \( \alpha_{143-217} \) based on our upper

| GPS | \( S_{21.7} \) | \( S_{11.2} \) | \( S_{8.2} \) | \( S_{4.8} \) | \( S_{2.3} \) | \( S_{1.1} \) |
|-----|----------|----------|----------|----------|----------|----------|
| type 1 | 0.19 | 0.21 | 0.28 | 0.41 | 0.66 | 0.62 |
| type 2 | 0.42 | 0.58 | 0.72 | 0.84 | 0.87 | 0.61 |

(2)—radio source type depending on the peak frequency value: CSS, GPS, or HFP, and candidate “g” for objects with unknown \( z \);
(3)–(4)—Optical type and redshift taken from NED3 database;
(5)–(6)—The \( \nu_{\text{obs}} \) and \( \nu_{\text{int}} \) values;
(7)–(8)—The spectral indices \( \alpha_{\text{below}} \) and \( \alpha_{\text{above}} \);
(9)—The spectral index \( \alpha_{353-857} \);
(10)—The FWHM of the spectrum in the units of frequency decades;
(11)—Spectral flux density variability at 11.2 GHz (%);
(12)—Morphology [? ? ?];
(13)—AGN type according to the Roma-BZCAT4.

The asterisks near the values of spectral index \( \alpha \) indicate those presented in the Planck catalog to verify our estimations of the flux densities. The mean ratio \( \bar{T} \) of the fluxes determined using the above technique to the fluxes given in the Planck catalog and the standard deviation of this mean ratio, \( \sigma_\bar{T} \), for the calibrators [13, 15] lie in the \( \bar{T} = 0.97 - 1.05 \) and \( \sigma_\bar{T} = 0.2-0.4 \) intervals depending on the frequency.

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3. FLUX DENSITIES ESTIMATION AT MILLIMETER AND SUBMILLIMETER BANDS

We derived the spectra of the sources in the millimeter- and submillimeter-bands based on WMAP 5 (23–94 GHz) [60] and Planck (30–847 GHz) [?] surveys. Planck measurements have a three times higher resolution and 10-times higher sensitivity compared to the data of WMAP. The WMAP and Planck observational data have been obtained quasi-simultaneously with the Ratan-600 data during the GPS monitoring program (in 2006–2017).

For faint objects, which have no Planck measurements we estimated the upper flux-density limit using the technique proposed in [57]. We used the
flux estimates show the same pattern as the corresponding distributions based on Planck catalog data. This pattern also agrees well with the results based on two releases of the Planck catalog [67–69]. Thus the behavior of the spectral indices distributions reported in [67, 68] and our distributions (from $\alpha_{30–44}$ to $\alpha_{143–217}$) shows appreciable shift of the histograms toward lower $\alpha$, which is due to the steepening of the spectral indices of the sources. Such a distribution of indices at low frequencies is due to the predominance of sources with synchrotron radiation.

The histograms of the distributions of $\alpha_{217–353}$ differ from those reported in [67, 68]. Most of the sources in our list, including those that have flux densities in the Planck catalog, have a spectral indices in the $-2 < \alpha_{217–353} < 1$ interval, and this fact also confirms the predominance of sources with synchrotron radiation. When going to frequencies above 217 GHz, a small fraction of the GPS objects shows a rise of the spectrum at 353–857 GHz, and the two-frequency spectral indices $\alpha_{545–857}$ and $\alpha_{353–545}$ become greater than $+1$. According to the classification proposed in [69], such sources can be considered as belonging to the “intermediate synchrotron” type. These are sources with signals detected at the frequencies of 545 GHz and 857 GHz and exhibiting both a strong synchrotron component and a significant dust component. Objects of this type were discovered, for example, when studying the spectra of extragalactic sources in [70].

Less than 10% of the sources analyzed in [69] were classified as “intermediate”. Their fraction increases substantially if we remove the condition of the completeness of the sample in terms of the high level of photometric noise in the signal and include the sources with lower fluxes.

If we consider only distributions of two-frequency spectra based on the Planck catalog data exclusively with a detection threshold of more than 4$\sigma$ (Fig. 4, the shaded bars), when this sample consists practically of purely “synchrotron” objects. Of the 10 objects with the 857 GHz available in the Planck catalog, only four have measurements for the spectral indices $\alpha_{545–857} > 1$, which make up about 8% of the sample. Lowering the detection threshold down to about 1–3$\sigma$ increases the number of objects near which spots were found in Planck maps at the frequencies of 545 GHz and 857 GHz.

Fig. 3. The flux densities distribution at 1.2–21.7 GHz (RATAN-600) for GPS type 1 and 2 (hatched and gray, respectively). Objects with the flux densities exceeding 8 Jy were excluded for readability.
The two-frequency spectral indices distributions (from 30 up to 857 GHz). Spectral indices $\alpha$ were obtained from the Planck catalog fluxes measurements (hatched) and were computed based on entire data set including both Planck measurements and our upper fluxes limit estimates (white).

The rise of spectra at high frequencies can be due to the signal from cold Galactic dust present in Planck maps, although we cannot rule out the contribution of the proper internal dust of the sources. We cannot make more specific conclusions because the $\alpha_{353-857}$ spectral indices were inferred based on estimated data.

4. ADDITIONAL MEASUREMENTS

Table 5 presents additional measurements from the CATS database in the form of a catalogs list. It was mostly used low-frequency and simultaneous multifrequency measurements. We used low frequency measurements from GLEAM survey which was conducted in 2013–2014 [40] at the 72–231 MHz band at 20 frequencies with an angular resolution of 2$'$ and with a flux density detection limit of 50 mJy. Our analysis also includes TGSS survey measurements, which is conducted with GMRT (Giant Metrewave Radio Telescope) telescope at 150 MHz [39]. The first data release of the TGSS, ADR1 (Alternative Data Release) [39], is based on 2010–2012 observations. The catalog includes 620 thousand objects discovered with the flux detection limit and with angular resolution of 7$\sigma$ and 2$''$, respectively. Both catalogs complete the objects spectral information at the frequencies below 1.1 GHz. In addition, the analysis also includes the low-frequency measurements used in [13].

Additional low- and high-frequency measurements allowed us to determine a more reliable spectral classification, highlighting compact objects subclasses: CSS, GPS and HFP (Table 3).

5. ANALYSIS OF GPS RADIO SPECTRA

As a result of the combined radio spectra analysis we determined the following parameters: the peak frequency $\nu_{\text{obs}}$ and $\nu_{\text{int}}$ in the observer’s and reference frames, respectively; the spectral index $\alpha_{\text{below}}$ and $\alpha_{\text{above}}$ of the optically thick and optically thin emission region, and the $\text{FWHM}$ (in decades of frequency), and the variability index $V_{\text{radio}}$ [13, 15].

Classification of the objects by type of their spectra, AGN type and morphology are given in the Table 6. About 40% of the objects are type-2 GPS...
Table 5. Additional measurements (catalogs from the CATS database)

| Catalog     | Frequency, MHz | Reference |
|-------------|---------------|-----------|
| GLEAM       | 72–231        | [40]      |
| VLSS        | 74            | [71]      |
| TGSS        | 150           | [39]      |
| TXS         | 365           | [72]      |
| Kuehr       | 318–750       | [73]      |
| PKS90       | 80–2700       | [74]      |
| WENSS       | 325           | [75]      |
| MIYUN       | 232           | [76]      |
| WISH        | 352           | [77]      |
| MRC         | 408           | [78]      |
| NAIC        | 611           | [79]      |
| GPSDa       | 1365, 1665    | [80]      |
| GPSTi       | 1365, 1665, 2300 | [10]  |
| GPSSr       | 325, 608, 1380, 1630, 2300, 2695 | [81]  |
| NVSS        | 1400          | [82]      |
| QORG        | 1400          | [83]      |
| MSL         | 1415, 2700    | [84]      |
| PKSFL       | 2300, 2700    | [85]      |
| VCS         | 2300          | [86–88]   |
| KOV97       | 1000–21 700   | [89]      |
| NCPMi       | 1100–21 700   | [50]      |
|             | 1100–21 700   | [51, 52]  |
| GPSRa       | 1100–21 700   | [13]      |
| SRCAT       | 1000–21 700   | CATS      |
| SRCKi       | 960–21 700    | [90]      |
| WMAP        | 22 000–94 000 | [60]      |
| PCCS1       | 30 000–857 000 | [61]  |
|             | 30 000–857 000 | [70]  |
| VLAC        | 43 000        | [91]      |

Sources [29] with the spectral peak mostly at frequencies of $\nu_{\text{int}} > 5$ GHz (HFP). The information about VLBI morphology is available for one third of the sources—mostly compact symmetric objects (‘cso’), ‘core-jet’ objects, ‘cd’ (compact double) objects, and

Table 6. General classification of the GPS sample

| Spectral type | $N$ | GPS type 1 | Morphology  |
|---------------|-----|------------|-------------|
|               |     | $\nu_{\text{int}} > 5$ GHz | cso | cj | un | cd |
| HFP           | 71  | 14         | 57          | 10 | 6  | 11 | – |
| $\nu_{\text{int}} \geq 0.5$ GHz | 40 | 27 | 13 | 8  | 3  | 1  | 7 |
| undefined     | 51  | 50         | 1           | 4  | 2  | 1  | 2 |

Total: 164

5.1. Spectral Indices

The distributions of the spectral indices for GPS sources type 1 and type 2 are shown on Fig. 5. According to the values of spectral indices and the Kruskal–Wallis criterion ($p \leq 0.005$), the subsamples of these two GPS type do not belong to the same distribution (Table 7). Type 2 GPS objects have statistically flatter spectra in the optically thick and thin emission regions, which are usually considered in terms of the standard assumption about additional synchrotron radiation compact components [30]. For type 1 GPS, the distributions of the indices $\alpha_{\text{below}}$ and $\alpha_{\text{above}}$ have a wider shape and may exhibit more varied properties of the emission medium in them or a heterogeneity of the sample.

There are statistical differences between the distributions of all measured quantities for type 1 and type 2 GPS objects ($z$, $\nu_{\text{obs}}$, $\nu_{\text{int}}$, $FWHM$, angular size $\theta$, and radio luminosity $L_{5\text{GHz}}$). The average value $\alpha_{\text{below}}$ for both GPS types differs significantly from the theoretical limit for a homogeneous synchrotron radiation source, $\alpha_{\text{below}} = 2.5$, and this fact has been confirmed repeatedly by observations [92]. Only five objects have spectral indices $\alpha_{\text{below}}$ of about 2 or greater (Table 8). This value is reliably determined for the galaxy 1447–34 due to the large number of RATAN multifrequency measurements [13, 15] and low flux densities variability.

We determined 32 GPS objects with an ultra-steep radio spectra $\alpha_{\text{above}} < -1$ (Table 9). There are no redshift measurements for 11 of them and five objects have redshifts greater than 3. The sample contains a total of 17 objects with $z > 3$. We have
Table 7. Some parameters for GPS type-1 and type-2 (average values)

| Type  | N    | $z$  | $\alpha_{\text{below}}$ | $\alpha_{\text{above}}$ | $\nu_{\text{int}}$, GHz | FWHM  | $\theta$, mas | $L_{5\text{GHz}} \times 10^{13}$, erg s$^{-1}$ |
|-------|------|------|--------------------------|--------------------------|--------------------------|--------|-------------|--------------------------|
| type 1| 93   | 1.3  | +0.99 (0.5)              | –0.80 (0.3)              | 4.3 (0.6)                | 1.4    | 2.2 (0.6)   | 14 (3.2)                 |
| type 2| 71   | 1.8  | +0.71 (0.2)              | –0.66 (0.2)              | 14.1 (1.4)               | 1.5    | 0.6 (0.2)   | 56 (13.5)                |

Fig. 5. The high-$\alpha_{\text{above}}$ and low frequency spectral indices ($\alpha_{\text{below}}$) distributions for GPS objects. Statistically, second-type GPS objects (solid gray) have flatter spectra both before and after the maximum. The dotted and dashed lines show the median values of spectral indices for type 1 and type 2 GPS objects, respectively.

Table 8. List of objects with $\alpha_{\text{below}}$ values of approximately 2 or greater

| Name | $z$  | $\alpha_{\text{above}}$ | Opt. type |
|------|------|--------------------------|-----------|
| 0029–34 | – | +2.1 (0.02) | –         |
| 0806–29 | – | +1.9 (0.01) | –         |
| 1447–34 | 0.85 | +2.5 (0.04) | G         |
| 1845+35 | 0.76 | +2.2 (0.04) | G         |
| 2330+31 | – | +1.8 (0.01) | –         |

We subdivided the initial sample into redshift bins $\Delta z = 0.2$ and determined the median $\alpha_{\text{above}}$ value in each bin (Fig. 6b). To find a statistically significant correlation ($k_{sp} = -0.59, p < 0.005$), which is indicative of the average spectral index steepening with increasing $z$ within the adjusted cosmological intervals.

5.2. FWHM of the Spectra

One of the common GPS selection criteria is based on the full width of the spectrum at half maximum level FWHM (in the frequency decades). The authors of [1, 45, 46] set it equal to 1.2 for the classical case. However, the measured FWHM are greater than 1.2 almost always [13, 15]. We obtained an average FWHM = 1.5 for type 2 GPS objects, which is somewhat greater (broader) than for type 1 GPS objects (Fig. 7), which is equal to 1.4 frequency decades.

The full width FWHM is related to the steepness of the spectrum and to the features of its flat part, where $\alpha \sim 0$. For some objects, this part is quite broad, as, e.g., for the blazar 2022+s61, or, on the contrary, very narrow (1340+37) (see the catalog of spectra). A broad spectrum is often associated with the variability of radio emission; in this case we observe superpositions of several time-varying radio spectra. Such spectra are more commonly found in blazars. The presence of several compact components also plays a crucial role. Narrow spectrum can be found in the case of the lack of measurements. To see whether the slopes of the spectra are consistent with the width, we analyzed the relation between $\alpha_{\text{below}}$ and $\alpha_{\text{above}}$, and obtained a statistically significant linear trend (Fig. 8) with a regression coefficient of $k = -0.4 (p < 0.005)$. There is no dependence between spectral indices for the type 1 GPS sample under investigation.

5.3. Estimation of Linear Size

We determined the linear sizes of the emitting regions by the following formula [44, 94]:

$$\nu_{\text{max}} = 8B^{1/5}S^{2/5}_{\text{max}}\theta^{-4/5}(1 + z)^{1/5}. \quad (2)$$
Fig. 6. Left: The “z–α_{above}” relation for all objects of the initial sample (triangles and crosses); with additionally plotted galaxies from [93] (circles); the dashed and solid lines show the linear interpolations of the formulas given in this paper and in [93]. Right: the same obtained by binning with Δz = 0.2; here α_{above} is computed as the median value in each redshift bin.

Fig. 7. Distribution of FWHM for GPS objects of both types. The dotted and dashed lines show the median FWHM values for type 1 and type 2 GPS objects.

Fig. 8. Relation between the spectral indices α_{below} and α_{above} for GPS objects of both types. The sizes of the symbols correspond to radio luminosity L_{5GHz} values.

It follows from

\[ \theta \approx 1.345 \sqrt{S_{\text{max}}(1 + z)^{1/4} \nu_{\text{max}}^{5/4}}, \]  

(3)

where \( B \) is the magnetic field strength in Gauss (we adopt the value of 100 \( \mu \)G for compact extragalactic sources with homogeneous distribution of magnetic field and relativistic particles [95]); \( S_{\text{max}} \) is the flux density value at the maximum of the radio spectrum in Jy; \( \theta \) is the angular size in mas, and \( \nu_{\text{max}} \)—the observed frequency of the spectral peak in GHz.

The angular size estimates are made for a radio source with a homogeneous magnetic field and a power-law distribution of emitting particles with the self-absorption at the frequencies below \( \nu_{\text{obs}} \). In the case where the object is a point source for the beam pattern the registered emission is a sum of the emission of the source components. Therefore formula (2) can be used to estimate the upper limit of the emitting region angular size of the emitting region. On the whole, for the sample, angular size \( \theta \) does not exceed 10 mas (Fig. 9). It is evident from Fig. 10 that bright type 2 GPS objects (with the average \( L_{5GHz} \sim 56 \times 10^{43} \) erg s\(^{-1}\)) have a more compact sizes statistically (0.6 mas).

The peak frequency \( \nu_{\text{int}} \) in the reference frame is related to the peak frequency in the observer frame as \( \nu_{\text{int}} = \nu_{\text{obs}}(1 + z) \). The additional measurements used in this paper allowed us to extend the range of \( \nu_{\text{int}} \) values and analyze the “z–\( \nu_{\text{int}} \)” relation (Fig. 11). Our result is in good agreement with earlier results, e.g., those reported in [9, 45], extending the range of \( \nu_{\text{int}} \) from 0.2 up to 20 GHz. At the redshifts of \( z > 2 \) a deficit of objects with low \( \nu_{\text{int}} \) less than 1 GHz...
Table 9. Objects with ultra-steep spectra (α_{above} < −1)

| Name        | z  | α_{above} | Opt./AGN type |
|-------------|----|-----------|---------------|
| 0003+48     | −  | −1.0(0.02)| −             |
| 0048+06     | 3.58| −1.0(0.01)| QSO           |
| 0108−12     | 1.54| −1.2(0.01)| G            |
| 0111+39     | 0.7 | −1.2(0.01)| G/Blazar.un.type |
| 0204+09     | −  | −1.1(0.01)| −             |
| 0210−22     | 1.49| −1.1(0.01)| G            |
| 0318+16     | 0.91| −1.2(0.01)| QSO           |
| 0557+24     | 3.2 | −1.1(0.01)| FSRQ          |
| 0906+03     | 0.83| −1.2(0.01)| G            |
| 1009+06     | −  | −1.3(0.01)| −             |
| 1122−27     | 0.65| −1.2(0.01)| −             |
| 1227+36     | 1.97| −1.3(0.01)| QSO           |
| 1237+20     | −  | −1.0(0.01)| −             |
| 1340+37     | 3.11| −1.1(0.02)| QSO           |
| 1407+28     | 0.07| −1.3(0.01)| QSO/BLac     |
| 1555−25     | −  | −1.5(0.08)| −             |
| 1600−00     | −  | −1.7(0.04)| −             |
| 1609+26     | 0.47| −1.1(0.01)| G            |
| 1753+27     | 0.86| −1.2(0.01)| G            |
| 1819−02     | −  | −1.0(0.01)| −             |
| 1826+27     | −  | −1.1(0.01)| −             |
| 1929+23     | −  | −1.4(0.02)| −             |
| 2022+61     | 0.2 | −1.2(0.01)| FSRQ          |
| 2052+36     | 0.35| −1.1(0.02)| G            |
| 2131−12     | 0.5 | −1.1(0.01)| FSRQ          |
| 2139+14     | 2.4 | −1.2(0.02)| FSRQ          |
| 2143+33     | −  | −1.1(0.02)| −             |
| 2148+02     | −  | −1.0(0.03)| −             |
| 2208+18     | 3.14| −1.1(0.04)| QSO           |
| 2237−25     | 1.28| −1.3(0.02)| G            |
| 2316−33     | 3.1 | −1.6(0.04)| QSO           |
| 2325−03     | 1.5 | −1.2(0.01)| G            |

Fig. 9. Angular sizes θ of emitting regions for type 1 (squares) and type 2 (circles) GPS objects at different redshifts. The sizes of the symbols correspond to the radio luminosity of L_{5GHz}.

Fig. 10. The radio luminosities L_{5GHz} distributions for type 1 (hatched) and type 2 (gray) GPS objects.

is observed. Here the solid line corresponds to the minimal value of ν_{int} in the sample at a certain redshift. For comparison, we also show the ν_{int} values from the low-frequency (0.74–210 MHz) GLEAM survey [41]. Starting with z > 2, our sample is dominated by HFP objects (ν_{int} > 5 GHz). The GLEAM sample (110 sources) contains six sources for this redshift interval, with ν_{int} spanning from 0.2 to 1 GHz. Fig. 12 shows the well-known θ−ν_{int} anticorrelation [2]. Also, these quantities are linearly related in logarithmic scale:

\[
\log \nu_{\text{int}} = 0.56(±0.03)−0.68(±0.01)\log \theta \quad (4)
\]

or ν_{int}≃θ^{−0.68}.

We found a significant anticorrelation for the entire sample (k = −0.8, p < 0.005), which is strong for type 1 GPS objects (k = −0.86, p < 0.005), and a little bit weaker for type 2 GPS objects (k = −0.63,
to the minimum value of the frequency \( \nu \) for \( \nu_d \). Dashed lines show the evolutionary curves of the reference peak frequencies, and the luminosity decreases ("negative luminosity evolution" [96]). That is why it is interesting the presence of low-luminosity compact objects with a high-frequency peak. This fact indicates that the initial luminosity plays the crucial role in the morphological evolution of extragalactic radio sources.

6. DISCUSSION

A multifrequency study of a complete sample of GPS objects at radio wavelengths revealed that this morphological AGN type is a heterogeneous group of compact extragalactic objects [30]. On the whole, they can be subdivided into two large groups. The first group is associated with classical GPS representatives and includes young objects with low variability. The second group is associated with beamed jet objects, mostly blazars [30]. The results of this paper revealed that type 1 GPS objects are much rarer than it had been previously believed [1, 9], and their fraction in the bright radio sources sample is less than 2%. The sample under study contains GPS objects of first ("classic") and second ("blazar") type in the proportion of 60% to 40%.

Simultaneous multifrequency measurements of GPS objects performed with the same instrument over a long time period allowed us to eliminate the effects due to the variability of the objects. Almost one third of the objects of the initial sample exhibited activity at the radio frequencies over long time scales (\( \text{Var}_{\text{radio}} > 35\% \)). Many objects demonstrate the relatively quiet behavior in the radio domain. Strong fluxes variations exceeding level of 50% appear in the form of rare irregular bursts.

The investigated GPS objects are bright radio sources—the average radio luminosity for them is about \( 10^{43-44} \text{ erg s}^{-1} \), the average radio luminosities of type 1 and type 2 GPS objects are equal to \( 1.4 \times 10^{44} \text{ erg s}^{-1} \) and \( 5.6 \times 10^{44} \text{ erg s}^{-1} \), respectively.

Statistical differences in the distribution of spectral values for two types of GPS objects reveal a variety of ambient conditions for the propagation of radio waves. In general, type 2 GPS objects have narrower distributions of all spectral parameters, making up a more homogeneous sample with common influence of relativistic effects. The distributions of spectral parameters for type 1 GPS sources reveal the objects with a heterogeneous morphology. This result is consistent with that obtained in [28, 97], where cluster analysis algorithms applied to GPS properties failed to reveal any specific morphological classification.

For most GPS objects, the spectral index of the optically thick emission region, \( \alpha_{\text{below}} \), is far from the theoretical limit of 2.5 [98]: the average values type 1 and 2 GPS objects reach the value of +0.99

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\( p < 0.005 \). The simple relation between the peak frequency and angular size in Fig. 12 appears continuous for whole \( \nu_{\text{int}} \) and radio luminosity \( L_{5\text{GHz}} \) range.

The existing anticorrelation often implies an evolutionary connection between HFP, GPS, and CSS [2, 20]. Young bright compact objects have a spectral peak at high radio frequencies; in the process of their evolution they expand, the peak shifts toward lower frequencies, and the luminosity decreases ("negative
and $+0.71$, respectively. This spectral index reflects the self-absorption mechanisms in a relativistic electron gas. We found three GPS sources with the spectral index of the optically thick emission region $\alpha_{\text{below}} \geq 2$: J1447–34 (2.5), J0029–34 (2.1), and J1845+35 (2.2).

The obtained relation “$\theta - \nu_{\text{int}}$” agrees well with the results of a number of studies, e.g., [2, 9, 59], where the relation between the sizes and the internal peak frequency can have the form $\nu_{\text{int}} \approx \theta^{-0.59}$. According to our results, the type 2 GPS sources are massively associated with the HFP objects and they are localized in the more compact sizes and high peak frequencies area. GPS sources with low radio luminosity may be of particular interest. They are massively associated with GPS of the type 1 and should be targets of the high-sensitive multi-frequency surveys. There are objects with the small angular sizes, with high values of $\nu_{\text{int}} > 5 \text{ GHz}$ and low radio luminosity ($10^{10–42} \text{ erg s}^{-1}$) in both GPS samples.

The study and simulations of the morphological evolution of radio sources [99–101] have provided several scenarios of the relation between the size and luminosity of extragalactic objects. The evolutionary differences are based on the initial conditions: properties of the environment and the behavior of the jet activity (ongoing, discontinuous and recurrent). As the result, the simple “young-age” scenario is not always evident, but is just one of the possible ones.

Some GPS studies [15, 45] found a deficit of GPS objects with peak frequencies lower than 1 GHz at high redshifts. In this study the deficit is evident despite the use of low-frequency measurements (see Fig. 11). A comparison of the “$\theta - \nu_{\text{int}}$” relation for the our sample with the corresponding relation for a 110-object sample of the GLEAM survey [41] revealed their overall similarity at $z > 2$: in both cases the number of objects with $\nu_{\text{int}} < 1 \text{ GHz}$ sharply decreases. The lack of large-scale components of synchrotron radiation during early Universe epochs is considered to be one of the possible causes of such deficit [45].

On the whole, type 1 GPS objects are less bright than type 2 objects and therefore the mean redshift of the former averaged over the sample is smaller and their contribution to the “$\theta - \nu_{\text{int}}$” distribution at high $z$ weaker than for type 1 GPS objects. On the other hand, there is a sharp drop of the type 2 GPS objects with low-frequency peak at high redshifts.

We found a statistical steepening of radio spectra of objects with redshift increasing. Such a correlation is expected for distant galaxies and has been found and discussed repeatedly [1, 35, 37, 102]. A comparative analysis of our sample and the sample of 108 USS (ultra-steep spectrum) galaxies [93] revealed a similar linear regression “$z - \alpha_{\text{above}}$”, however, in the case of our sample we found no significant correlation between these quantities (Fig. 6). Taking into account that sample [93] consists of galaxies and our sample is a mix both galaxies and quasars, such result can be explained by the effect of objects with different morphology at relatively close redshifts. This is clearly seen in the in Fig. 6a: we can see mostly powerful GPS objects with increasing $z$. Subdividing our sample into small $dz = 0.2$ bins allowed us to reveal a trend of spectral steepening (median values). The variety of the objects properties at relatively low $z$ shows up as the large scatter of $\alpha_{\text{med}}$ values, whereas starting with $z > 2$ we observe a well-defined linear trend.

Estimates of the hot spot flux densities on the Planck mission microwave background maps provided information about the behavior of the GPS spectra at millimeter- and submillimeter-wave frequencies ranges in addition to the data available from the Planck catalog. Deriving two-frequency spectra of sources in this range showed that part of the GPS objects can be classified as “intermediate”, synchrotron-type objects, which, along with synchrotron radiation, may suggest the presence of a dust component. The rise of the spectra at high frequencies may be an indicator of both the presence of a signal from cold galactic dust on Planck maps and of the contribution of the internal dust contribution of the sources. Taking into account that the spectral indices are based on the estimated data, more accurate conclusions are impossible.

It has been rightly noted [96] that GPS studies are often based on classic bright samples, which rely on selection according to the shape of the spectrum without taking into account the physical features. A conservative approach leads to the absence of agreed criteria, such as compact structure (< kps), polarization and variability, and the presence of relativistic effects. Measurements of these values are available for a limited number of candidates; thus the samples are initially heterogeneous.

It is necessary to note the selection effects that affect our results: the absence of systematic decimeter-wave measurements during the initial selection of GPS objects [15], the lack of a wide approach to the construction of the sample [15] (the selection was made at the same frequency—5 GHz), the lack of measurements of the faint GPS objects. It is evident that during the initial selection a fraction of objects was lost due to the lack of measurements and the inability to classify them as GPS objects. The number of such objects is not known, they are the faint radio sources and there are no systematic measurements for them.
GPS objects are also of practical interest as bright compact sources with a stationary radio emission—the so-called flux standards. The knowledge of the flux densities with a certain accuracy for such objects allows us to use them in applied tasks outside the field of astrophysics, for example, for astrometric purposes. The classical GPS sources (“type 1”) can be the good candidates for calibration tasks in radio astronomy.

7. RESULTS

We obtained the following main results based on the GPS objects monitoring with the RATAN-600 radio telescope in 2006–2017:

The quasi-simultaneous measurements of flux densities at 1.1, 2.3, 4.8, 7.7/8.2, 11.2, and 21.7 GHz obtained with the RATAN-600 have been collected into the catalog; the broad band radio spectra have been constructed for the sample in the range of 0.072–857 GHz, based on RATAN-600 data with additional measurements from the GLEAM, TGSS and Planck surveys.

We selected 164 GPS objects and candidates, 17 of them have been classified as GPS for the first time. The radio luminosity average value for GPS sample is $L_{5GHz} \sim 10^{43–44}$ erg s$^{-1}$. We confirm the relatively small proportion of GPS objects (1–2%) among bright AGNs. The sample contains GPS objects of first (“classic”) and second (“blazar”) type in the proportion of 60% to 40%. The statistical difference between the spectral parameters of two types GPS objects can reveal the heterogeneity of the physical conditions of the synchrotron emission formation in compact extragalactic objects.

The deficit of GPS objects with low peak frequencies (less than 1 GHz) at high redshifts ($z > 2$) have been confirmed. The statistical steepening of the GPS spectra with the redshift have been found in the considered cosmological epochs. At redshifts $z = 1.5$ the contribution of the objects of different morphology is clearly noticeable, and at $z > 2$, the contribution of GPS objects with steeper spectra in optically thin emission regions increases.

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CONFLICT OF INTEREST

The authors declare the absence of conflict of interest.

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