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New GPS sources candidates at high redshifts

Mufakharov T.,[a,b,*] **Sotnikova Yu.,**[a] **Mikhailov A.**[a] **and Mingaliev M.**[a,b]

[a] *Special Astrophysical Observatory of RAS, Nizhnij Arkhyz, Russia*
[b] *Kazan Federal University, Kazan, Russia*

E-mail: timur.mufakharov@gmail.com

GHz-peaked spectrum (GPS) objects are compact and powerful radio sources (galaxies and quasars) that have a maximum in the radio spectrum in the range from hundreds of MHz to several GHz. These sources are interesting as precursors of radio galaxies and, at high redshifts, also as active galactic nuclei of the early Universe. A monitoring of a sample of 101 bright (with a flux density of more than 100 mJy at a frequency of 1.4 GHz) quasars at high redshifts ($z > 3$) with the RATAN-600 radio telescope in 2017–2020 at six frequencies (1.2-22.3 GHz) has revealed that almost half of the objects (47%) have a radio spectrum with the maximum at GHz frequencies. We studied their radio properties and determined 10 new candidates for GPS sources based on their estimated peak frequencies, low variability, and radio morphology from the literature.

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*Speaker

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1. Introduction

The peaked radio spectrum (PS) indicates the presence of an underlying absorption mechanism of the radio emission: synchrotron self-absorption [1] or free-free absorption [2]. Based on the location of observed peak frequency $\nu_{\rm obs}$, PS sources are classified as MHz-peak sources (MPS) with $\nu_{\rm obs} \leq 1$ GHz, GHz-peaked sources (GPS) with $1 \leq \nu_{\rm obs} \leq 5$ GHz, and high-frequency peakers (HFP) $\nu_{\rm obs} \geq 5$ GHz.

About 10-20% of all radio-loud sources have PS [3]. Majority of them are blazars which have that shape of spectrum only temporarily. Only about 1-2% of all radio-loud sources are classified as *bona-fide* GPS sources, presumably radio galaxies at the early stages of evolution, characterised by low variability (see the review in [4]). These radio sources are powerful, but compact ($\leq$1 kpc) and according to the most popular theory, it is most likely due to their young age ($<10^4$ years). Thus, the GPS sources are important objects to study the early evolution of powerful radio-loud active galactic nuclei. A unification scenario assumes that HFP sources evolve into GPS/MPS sources, which in turn evolve into compact steep-spectrum sources (CSS) that later grow into extended radio sources (FR I/II galaxies) [5].

Obtaining broad-band radio spectra is crucial for identifying PS sources and further studying of their environment and compactness with interferometers. In our study we examine radio spectra of a sample of high-redshift radio-loud quasars, obtain their multifrequency radio properties, estimate their radio variability and reveal 10 new GPS sources candidates.

2. Sample of PS sources at high redshifts

The study of Sotnikova et al. (2021) [6] of the full sample of the radio-loud quasars with the flux density more than 100 mJy at 1.4 GHz in a declination range from -34° to +49° at the redshifts $z > 3$ contained 102 quasars with different radio spectrum types [6], where we discovered a fairly large fraction of peaked-spectrum sources, 47 to be precise. Twenty two of them were previously reported in the literature as having a peaked spectrum in [7–11]. We considered to analyse the rest 25 new PS objects for compliance to GPS sources criteria, they are listed in Table 1. There are 10 blazars among them, all classified as flat-spectrum radio quasars (FSRQ) [12, 13].

We used the available literature data from the astrophysical CATalogs support System (CATS database[1] [14]) along with the RATAN-600 measurements in 2017–2020 [6] to construct the radio spectra and estimate the parameters discussed below. The radio data for the objects are available since 1970s, but in some cases represented sparsely, especially it is relevant for the optically thick region below 1 GHz.

3. Parameters estimations

The rest-frame peak frequencies we determined as $\nu_{\rm rest} = \nu_{\rm obs}(1 + z)$.

In assumption that mainly the synchrotron self-absorption mechanism is responsible for the forming of spectral peak, we calculated the apparent angular diameters of emitting regions (assuming

[1] https://www.sao.ru/cats

Table 1: The parameters of 25 new PS sources: NVSS name (Col.1), redshift (Col.2), peak frequencies calculated at observer's and rest-frame (Col.3), radio spectrum width at half maximum (Col.4), an angular size (Col.5), linear size (Col.6), variability index at 4.7 GHz (Col.7), PS type based on $\nu_{\mathrm{obs.peak}}$ and blazar identification (Col.8). Sources with low variability at the three frequencies ($V_S \leq 0.25$) marked with blue color.

NVSS name	z	$\nu_{\mathrm{obs.}}$ / ν_{rest} (GHz)	FWHM (dex)	θ (mas)	l (pc)	$V_{S_{4.7}}$	Type
1	2	3	4	5	6	7	8
000657+141546	3.2	1.5/ 6.3	7.7	0.98	7.6	0.10 ± 0.10	GPS
010012−270852	3.52	1.4/ 6.3	1.7	1.11	8.3	0.17 ± 0.04	GPS
021435+015703	3.28	0.5/ 1.9	1.9	2.87	22.1	0.13 ± 0.05	MPS
023220+231757	3.42	0.5/ 2.2	2.0	4.43	33.5	0.29 ± 0.01	MPS
024611+182330	3.59	1.8/ 8.3	1.8	0.99	7.4	0.29 ± 0.18	GPS-blazar
052506−334305	4.41	0.9/ 4.9	1.6	1.59	10.8	0.71 ± 0.01	MPS-blazar
053954−283955	3.10	7.0/ 28.7	1.8	0.76	5.9	0.59 ± 0.04	HFP-blazar(1)
062419+385648	3.46	0.3/ 1.3	2.5	9.80	73.8	0.30 ± 0.05	MPS-blazar
073357+045614	3.1	5.8/ 23.3	1.8	0.57	4.5	0.37 ± 0.05	HFP-blazar
083910+200207	3.3	1.8/ 7.7	2.0	0.75	5.7	0.29 ± 0.04	GPS
090549+041010	3.15	0.5/ 2.1	1.6	2.98	23.1	0.11 ± 0.08	MPS
093337+284532	3.42	1.7/ 7.5	1.5	0.71	5.4	0.25 ± 0.09	GPS
102623+254259	5.28	0.3/ 1.9	1.7	5.66	35.4	0.30 ± 0.01	MPS-blazar
104523+314232	3.23	0.9/ 3.8	2.3	1.52	11.7	0.11 ± 0.06	MPS
124209+372006	3.81	1.7/ 8.2	2.1	1.71	12.4	0.28 ± 0.05	GPS
130122+190353	3.1	1.7/ 7.0	1.9	0.76	5.9	0.05 ± 0.12	GPS
140135+151326	3.23	1.3/ 5.5	2.0	0.86	6.6	0.36 ± 0.01	GPS
140501+041535	3.20	8.3/ 34.9	2.1	0.58	4.5	0.25 ± 0.01	GPS-blazar(2)
141821+425020	3.45	0.9/ 4.0	1.5	1.46	11.0	0.02 ± 0.08	MPS
150328+041949	3.66	5.6/ 26.1	1.5	0.36	2.7	0.10 ± 0.03	HFP-blazar
152117+175601	3.6	3.5/ 14.2	1.4	0.55	4.1	0.32 ± 0.03	GPS
201918+112712	3.27	0.5/ 2.1	1.8	2.76	21.2	0.06 ± 0.05	MPS
204257−222326	3.63	3.5/ 16.2	2.1	0.55	4.1	0.27 ± 0.07	GPS-blazar
205051+312727	3.18	1.9/ 7.9	2.9	1.77	13.7	0.57 ± 0.02	GPS-blazar
231448+020151	4.11	1.7/ 8.7	2.1	0.76	5.3	0.20 ± 0.14	GPS

(1) J0539−2839 has a variable spectral shape.

(2) J1405+0415 has a two-component spectra.

spherical source visible as a disk) using the formula adopted from [15]:

$$\theta \approx 1.345 \frac{\sqrt{S_{\max}}(1+z)^{1/4}}{\nu_{\max}^{5/4}}, \tag{1}$$

where z is the redshift, $S_{\max}$ is the flux density value at the maximum of the radio spectrum in Jy, θ is the angular size in mas, and $\nu_{\max}$ is the observed frequency of the spectral peak in GHz. Then we used the ΛCDM cosmology with H_0 = 67.74 km s^{-1} Mpc^{-1}, Ω_m=0.3089, and Ω_Λ=0.6911 [[16] to calculate projected linear sizes (l) based on our estimates of angular sizes.

For the classical GPS sources the width of the radio spectrum at half maximum level (FWHM) in an observer's frame was found to be 1-1.5 in units of decades of frequency (dex) in [3]. In [10] authors found that the radio spectrum of GPS-quasars is on average wider (FWHM~1.6) than for the GPS-galaxies (FWHM~1.4) when comparing samples of GPS sources classified as galaxies and quasars (diverse sample with redshift values spanning from 0 to 5). In our sample of new GPS candidates FWHM varies from 1.4 to 7.7 dex with the mean value of 2.1, demonstrating the broadening of radio spectra.

We estimated the variability index [17] to assess variations of flux density as:

$$V_S = \frac{(S_{\max} - \sigma_{S_{\max}}) - (S_{\min} + \sigma_{S_{\min}})}{(S_{\max} - \sigma_{S_{\max}}) + (S_{\min} + \sigma_{S_{\min}})}, \tag{2}$$

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. We used both RATAN-600 and external catalogs measurements to calculate V_S on a timescale of up to 30 years at the frequencies of 4.7, 8.2, and 11.2 GHz. All of the calculated parameters listed in Table 1: peak frequency at the rest-frame, FWHM, angular size, linear size, and variability index (we show only at 4.7 GHz for brevity).

Among 10 blazars in the sample, two tend to demonstrate the low variability: J1045+3142 with $V_{S_{4.7}}$=0.25 (26 measurements in 53 years) and J1503+0419 with $V_{S_{4.7}}$=0.10 (9 measurements in 39 years). We note that the radio spectrum of J1503+0419 lacks the data, with currently only two measurements at one epoch being represented above 10 GHz. Thus, its spectral shape might change significantly if the new data is available at high frequencies. The J1045+3142 has a compact core and bending jet in VLBI image at 5 GHz [18]. Hence we do not consider them as GPS candidates.

4. Summary

A relatively low level of radio variability ($\lessapprox$ 25%) is proposed as a characteristic for the classical GPS sources (e.g., [7,8]). We found 12 PS sources fitting that criteria in our high-redshift bright quasars sample: J0006+1415, J0100−2708, J0214+0157, J0905+0410, J0933+2845, J1045+3142, J1301+1903, J1405+0415, J1418+4250, J1503+0419, J2019+1127, and J2314+0201. Their variability indices of less than 0.25 at the three frequencies (4.7, 8.2, and 11.2 GHz), are calculated based on the data spanning for more than 30 years. Their angular sizes vary from 0.36 to 2.98 mas (linear sizes from 2.7 to 23.1 pc). We suggest to further consider these sources, except for two FSRQ blazars (J1045+3142 and J1503+0419), as the candidates to new GPS sources, see their radio spectra in Fig. 1. More detailed analysis of the candidates and comparison of their properties with properties of known GPS sources will be presented in forthcoming paper, as an extension of study in [6].

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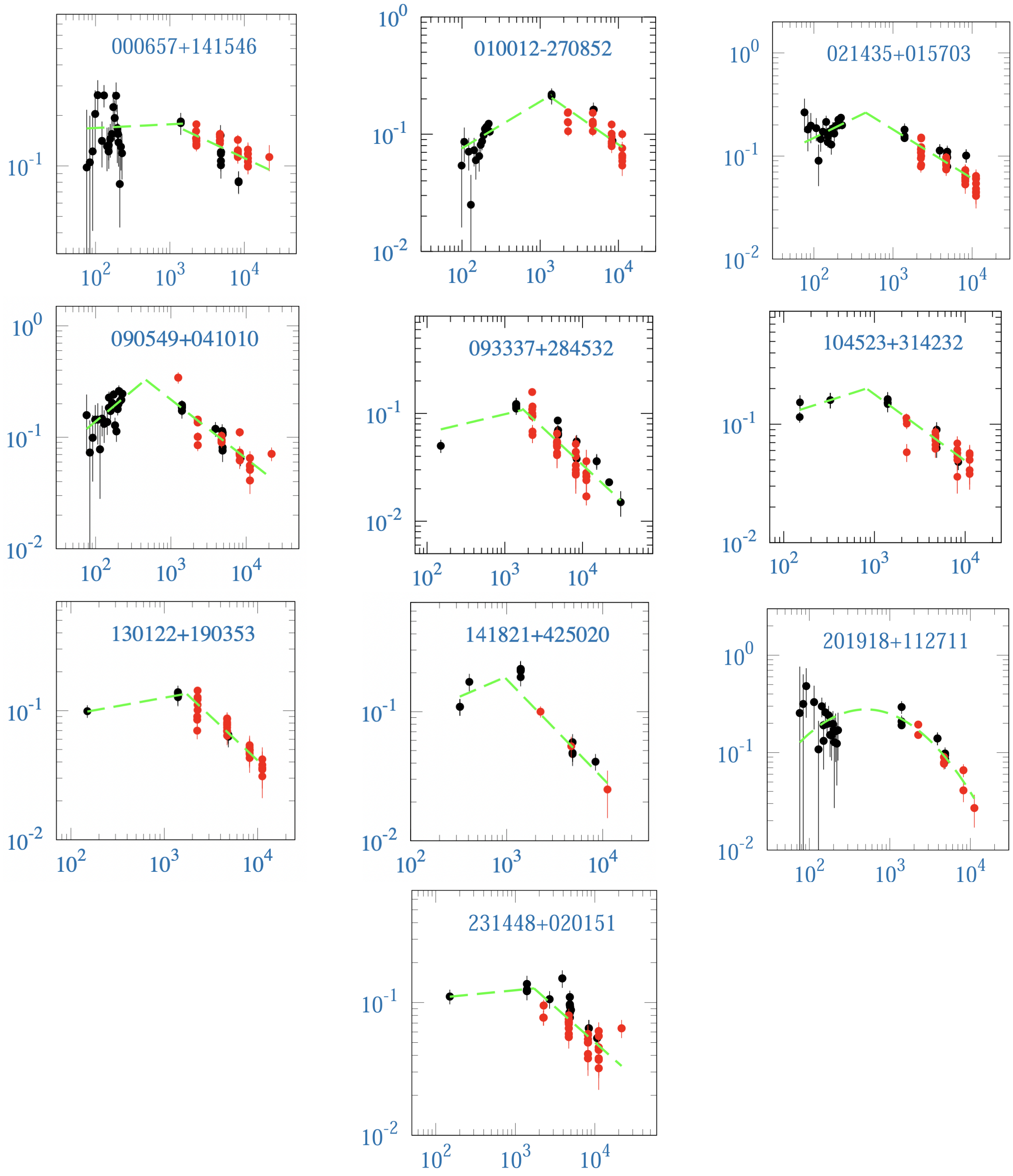

Figure 1: Radio spectra of 10 new GPS sources candidates from [6]. Frequency (x-axis) in units of MHz and flux density (y-axis) in units of Jy. RATAN-600 measurements shown with red color and data from the literature shown with black color.