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Study of the Radio Spectra Evolution of Narrow-Line Seyfert 1 Galaxies with RATAN-600

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We present the radio properties of narrow-line Seyfert 1 (NLS1) galaxies, obtained using quasi-simultaneous measurements with the radio telescope RATAN-600 in the frequency range 1.2–22.3 GHz. The sample of 95 NLS1s includes both galaxies emitting and not emitting γ-rays. Generally, γ-ray emitting NLS1s are more radio luminous and radio-loud than those not emitting γ-rays. The other difference is the more intensive spectral evolution for γ-ray emitters: the repetitive change of the spectral index sign on a time scale of months and a high level of variability, on average 26–37% at 4.7–11.2 GHz. The obtained differences between γ-ray emitting and non-emitting NLS1s can be caused by an evolving flare component in the γ-ray emitters, while for the NLS1s not emitting γ-rays a quiescent spectral component is predominant.

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1. Introduction

Narrow-line Seyfert 1 (NLS1) galaxies are a type of active galaxies without Doppler beaming in contrast to highly beamed and variable blazars. The distinct property of NLS1s is the relative narrowness of their permitted emission lines, unlike in typical type 1 Seyfert galaxies, $FWHM_{H_\beta} < 2000$ km/s [1]. NLS1 galaxies are seemingly very different objects from blazars; they have lower black hole masses, 10^5–10^8 $M_\odot$ [2], higher sub-Eddington accretion rates [3, 4], and a different host galaxy morphology: mostly spiral [5]. Most NLS1 galaxies are also radio quiet, only roughly 7% of the class are radio-loud [6]. A strong candidate to explain the radio loudness was, from the very beginning, relativistic beaming occurring in the jets [7–9]. Earlier, jets had been associated with elliptical host galaxies, while NLS1 galaxies were predominantly spiral, although elliptical and merger hosts had also been detected. Previous studies have shown that NLS1s have some properties of Flat Spectrum Radio Quasars (FSRQ): a two-humped shape of the broadband Spectral Energy Distribution (SED) and highly variable electromagnetic radiation on different time scales [10]. The obtained observational properties can mean that NLS1s are young precursors of blazars [11, 12].

The presence of relativistic jets in some NLS1 galaxies looks more likely, and the radio spectrum shape tells us about the emitting region conditions. In [6] proposed that some NLS1 galaxies have a steep spectrum similar to that of the compact steep spectrum sources, indicating a young age. Authors [10] found them to be predominantly flat spectrum sources, like blazars, which indicates a strong jet and possible particle-accelerating shock fronts moving in the jet flow [10]. They also found inverted spectra, where the self-absorption of synchrotron radiation indicates a dense environment and also possibly a young age [13].

An intriguing result of the last decade is the discovery of the γ-ray emitting NLS1 population with the satellite Fermi-LAT [14]. Thus, a new class of γ-ray emitting AGNs was found in addition to blazars and radio galaxies. Currently, there are 22 γ-ray emitting NLS1s (see [15] and references therein). In some NLS1s, jet-like structures were found on scales from pc to kpc [2, 16]. This fact motivates the following study of the broadband properties of NLS1s and the investigation of the relationship between the NLS1 radio and γ-ray emission properties. In this paper we present the multi-frequency observations of γ-ray NLS1s at frequencies of 1.2–22.3 GHz, which cover a long time period of 2014–2021.

2. Sample and observations

The sample consists of 95 NLS1 galaxies from the Metsähovi Radio Observatory observing list, studied at 37 GHz [17, 18]. Most of these sources are radio-loud, but the sample contains about 10% radio-quiet NLS1 galaxies. Broadband quasi-simultaneous measurements of individual NLS1s have been carried out with RATAN-600 at 1.2, 2.3, 4.7, 8.2, 11.2, and 22.3 GHz [19] in 2014–2021. There are 16 γ-ray emitting objects in the sample, thus the list includes about 70% of the currently known γ-ray emitting NLS1s (22 objects are listed in the review of Paliya [15]). For objective reasons the most intensive observations were made for 10–15 sources, among them about equal number of NLS1s emitting and not emitting γ-rays. We have been able to trace the evolution of their quasi-simultaneous radio spectra on a time scale of several years. Below we

Table 1: The mean (left) and median (right) radio luminosity and radio loudness for γ-ray sources and sources without γ-rays. N is the number of the sources, the standard deviations for the mean values are indicated in parenthesis.

type	$\log L_{4.7}$ erg/s		$\log R$		N
γ	42.10 (0.95)	42.39	2.76 (0.61)	2.76	16
no-γ	41.26 (0.83)	41.39	2.16 (0.76)	2.25	79

Table 2: Parameters of ten selected sources.

name	z	sp. type	$\log L_{4.7}$	$\log R$	$\alpha_{2.3-4.7}$	$\alpha_{4.7-8.2}$	$\alpha_{8.2-11.2}$	$\alpha_{11.2-22.3}$
				γ-ray emitting NLS1				
J0324+34	0.061	upturn	41.16	2.32	-0.17 (0.14) -0.13	-0.19 (0.22) -0.24	-0.16 (0.25) -0.19	-0.05 (0.24) -0.05
J0849+51	0.584	peaked	42.86	3.39		+0.17 (0.18) +0.18		+0.27 (0.10) +0.27
J0948+00	0.585	peaked	42.77	3.10	+0.35 (0.59) +0.21	+0.31 (0.44) +0.23	-0.25 (0.34) -0.13	-0.14 (0.23) -0.12
J1505+03	0.407	peaked	43.03	3.73	+0.52 (0.23) +0.54	+0.07 (0.14) +0.12	-0.54 (0.23) -0.62	-0.60 (0.16) -0.62
J1644+26	0.145	upturn	41.26	2.78	-0.06 (0.33) -0.09	+0.09 (0.20) +0.11	+0.04 (0.45) +0.16	+0.24 (0.26) +0.19
				non γ-ray emitting NLS1				
J0902+04	0.533	peaked	42.53	3.18	-0.30 (0.16) -0.26	-0.30 (0.07) -0.29	-0.60 (0.40) -0.65	
J1105+02	0.454	peaked	42.77	3.48	+0.32 (0.06) +0.32	+0.59 (0.46) +0.86	+0.30 (0.37) +0.36	+0.09 (0.30) +0.01
J1421+28	0.539	peaked	42.13	2.27		-0.15 (0.29) -0.12	-0.39 (0.51) -0.29	
J1548+35	0.479	flat	42.29	2.64	-0.47 (0.29) -0.59	-0.34 (0.15) -0.36	-0.31 (0.44) -0.36	
J1605+37	0.201	flat	41.46	2.22	-0.51 (0.05) -0.51	-0.33 (0.24) -0.31	-0.86 (0.13) -0.91	

present their radio properties and the features of the quasi-simultaneous radio spectra evolution for two γ-ray emitting NLS1s, J0948+00 and J1505+03, and two NLS1s not emitting γ-rays, J0902+04 and J1548+35.

3. Results

The radio luminosity $L_{4.7}$ and radio loudness R for the galaxies were estimated according to the conventional formulas [20], and their mean and median values over the entire sample are shown in Table 1. We found that γ-ray emitters are more luminous (about one order of magnitude), the median value of $\log L_{4.7}$ [erg/s] is 42.4, and their radio loudness is comparable to the galaxies without γ-rays. For the 10 systematically observed NLS1s (5 γ-ray emitters and 5 galaxies without γ-rays), their spectral indices calculated for quasi-simultaneous RATAN-600 radio spectra, spectral types, radio luminosity, and radio loudness are listed in Tables 2 and 3. The spectral indices are defined from the power-law $F_\nu \propto \nu^\alpha$, where F_ν is the flux density at a frequency ν. The spectral classification of flat, steep, peaked, upturn, and rising radio spectra is based on the generally accepted criteria [21].

For the γ-ray emitting NLS1s we found greater average and median spectral indices at 1.2–22.3 GHz than for the subsample of NLS1s not emitting γ-rays (Table 3). The peaked radio spectrum shape is often found for γ-ray emitting NLS1 galaxies: 5 out of 16 in the entire sample (about 30%). For the remaining 79 NLS1s not emitting γ-rays, we found eight galaxies with the peaked spectra (∼10%).

Table 3: The mean and median spectral indices calculated at different frequency intervals for ten NLS1 sources.

	type	mean (sd)	median
$\alpha_{2.3-4.7}$	γ	0.13 (0.44)	-0.06
	no-γ	-0.32 (0.31)	-0.38
$\alpha_{4.7-8.2}$	γ	0.06 (0.32)	0.00
	no-γ	-0.16 (0.39)	-0.28
$\alpha_{8.2-11.2}$	γ	-0.19 (0.38)	-0.14
	no-γ	-0.36 (0.52)	-0.38
$\alpha_{11.2-22.3}$	γ	-0.17 (0.35)	-0.10
	no-γ	0.09 (0.30)	0.01

Figures 1 and 2 show quasi-simultaneous radio spectra for four NLS1s at different observing epochs, from 7 to 10 in number (the inset shows the date as JD – 2450000), and their parameters are presented in Table 2. Despite these sources have close redshifts, radio luminosity, and radio loudness (differences are within one order of magnitude), the shapes of their quasi-simultaneous spectra are different. The sources without γ-ray emission, J0902+04 and J1548+35, have falling spectra with a decrease in flux density as the frequency increases. The γ-ray emitting sources J0948+00 and J1505+03 have an inverted and convex spectral shape. The spectral index α of γ-ray NLS1s changes its sign, and this is typical for the γ-ray sources, while such a behavior is not common for the sources without γ-rays. The mean and median variability indices at 4.7, 8.2, and 11.2 GHz are listed in Table 4. The variability index V_S was calculated using the formula from [22]. The γ-ray NLS1 galaxies are statistically more variable than the NLS1s not emitting γ-rays. At 11.2 GHz the mean variability index of γ-ray emitters is 0.30±0.16, while for the sources without γ-rays V_S=0.16±0.19. Thus, the γ-ray NLS1s demonstrate significant radio spectrum evolution on a time scale of several years (about 5).

Angelakis et al. [23] described a phenomenological classification of continuum radio spectrum variability patterns of blazars. This classification was constructed based on the synthesis of the multi-frequency monitoring of Fermi blazars within the F-GAMMA program [24]. According to [23], most types of variability can be described as a superposition of two components: a steep quiescent spectral component (probably related to a large-scale jet) and a time-evolving flare component following the “shock-in-jet” model evolutionary path [25]. In the framework of this model, the sources not emitting γ-rays are characterized by the predominance of the quiescent spectral component, while for the γ-ray sources the evolving flare component is typical.

4. Summary

The multi-frequency quasi-simultaneous measurements of a large sample of NLS1 galaxies with RATAN-600 revealed the following: 1) γ-ray emitting NLS1s are more radio-luminous compared to those not emitting γ-rays; 2) γ-ray emitters have more flat and often peaked radio spectra than galaxies without γ-rays, which have steeper radio spectra; 3) γ-ray emitting NLS1s are characterized by intensive spectral evolution, apparent spectral shape variation, and a larger

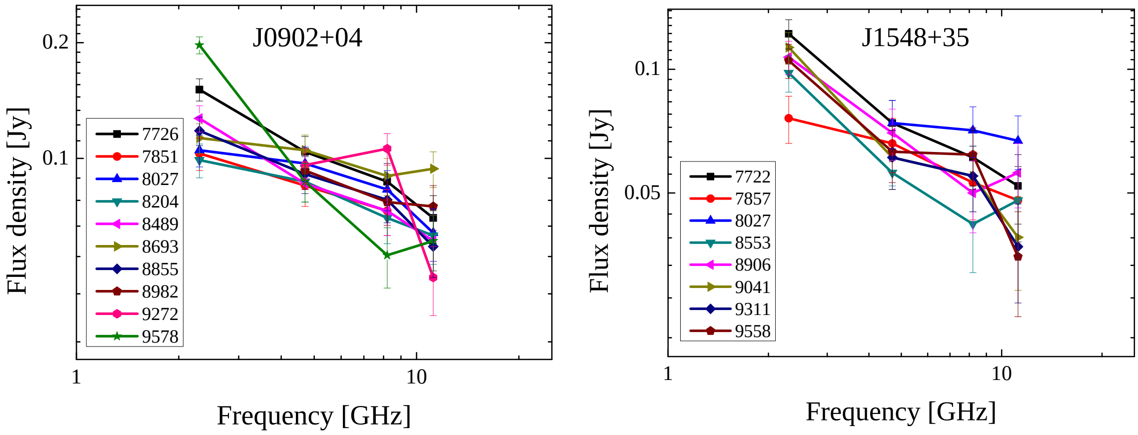

Figure 1: Radio spectrum evolution of two NLS1s not emitting γ-rays: J0902+04 (left) and J1548+35 (right).

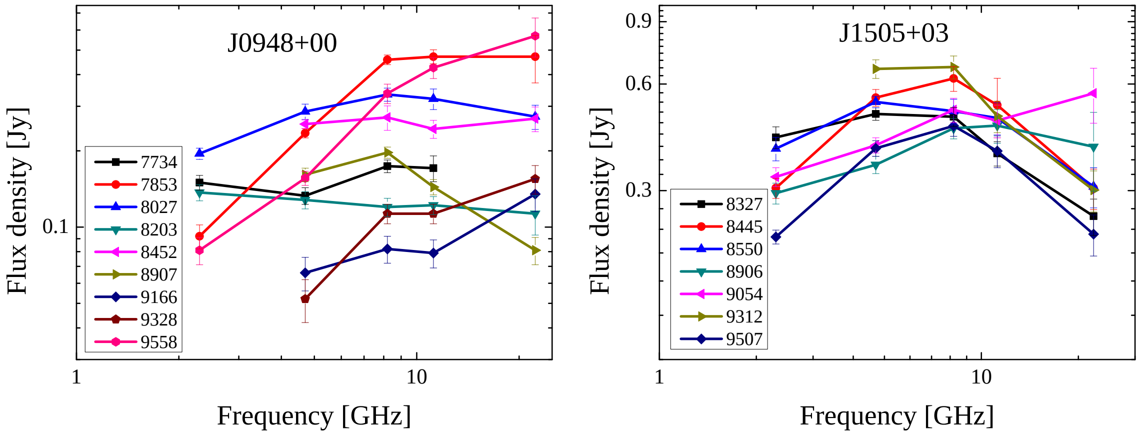

Figure 2: Radio spectrum evolution of two γ-ray emitting NLS1s: J0948+00 (left) and J1505+03 (right).

Table 4: The mean and median V_S for γ-ray sources and sources without γ-rays, the standard deviations for the mean values are indicated in parenthesis.

ν, GHz	type	V_S	
		mean	median
4.7	no-γ	0.20 (0.16)	0.20
	γ	0.37 (0.28)	0.30
8.2	no-γ	0.13 (0.13)	0.08
	γ	0.26 (0.16)	0.21
11.2	no-γ	0.16 (0.19)	0.11
	γ	0.30 (0.16)	0.23

variability index, 26–37% at 4.7–22.3 GHz. The obtained results may indicate that γ-ray emission generation processes are linked to the non-stationary events (e.g., instabilities and shocks) in the jet.

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