Study of the population of the steep-spectrum compact radio sources (filler)

1 Motivation

Analysis of early single dish radioastronomy blind surveys revealed that the source distribution over spectral index defined as $S \sim f^{+\alpha}$ is bi-modal with peaks at around -0.9 (steep spectrum population) and -0.2 (flat spectrum population). This is generally accepted that sources from the second population, also known as flat spectrum radio sources or flat spectrum radio quasars (FSRQ), are compact AGNs powered by the synchrotron emission. VLBI surveys of flat-spectrum radio sources with $\alpha > -0.5$ showed that most of them have high compactness defined as the ratio of the correlated flux density at milliarcsecond resolutions from flux density at 10–100″ resolutions. But then a curious student may ask: what about steep spectrum sources with $\alpha < -0.5$? Are they AGNs? Deep VLA surveys, f.e. Condon et al. (2012) provides the answers: the vast majority of observed radio sources, regardless of their spectral index, with flux densities down to 1 mJy are mainly AGNs. Are they compact? We can answer this question: some of them have compact core. How many? And then we stumble. Known VLBI surveys have a heavy bias towards flat spectrum sources selected from parent single-dish or connected array catalogues. The VLBI surveys were optimized to provide the highest yield of detections, and flat spectrum sources were considered low hanging fruits. By 2014 the pool of known flat spectrum sources was mainly depleted. When we lifted selection of targets by the spectral index, we found that the detection rate was still around 50%. Now we know that detection of compact emission of steep spectrum sources from surveys with 10–100″ resolutions is not an exception. But we still cannot answer even a simple question — how many steep spectrum sources are compact — due to a heavy bias in known VLBI samples. Do flat spectrum sources form a distinct population in the AGNs zoo, or steep spectrum is just an indicator of the significant emission from the jet and extended radio lobes *in addition to* the flat spectrum emission from the core?

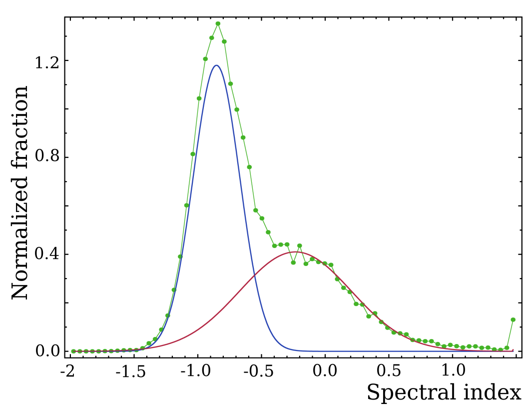

Fig. 1: The distribution of spectral indices between 4.85 and 1.4 GHz from GB6 and NVSS catalogues with resolutions 210″ and 40″ respectively (**green line**). **The blue line** shows the contribution of the steep spectrum source population, and **the red line** shows the flat spectrum source population.

2 Problem statement

It is not practical to conduct an unbiased all sky survey. However, it is within an arm reach to get a complete, unbiased flux limited sample in two relatively large areas. First, a zone with ecliptic latitude $\beta \in [-7.5°, 7.5°]$ was observed with the VLBI ecliptic plane survey (Shu et al. 2017). The

Table 1: Source count among the GB6+PMN sample $|\beta| < 7.5°$, $F_{4.85\ GHz} > 70$ mJy and AT20G sample $-40° < \delta < 0°, F_{20\ GHz} > 40$ mJy.

Sample	# Tot	# Obs	# Det	# Non-det	# Targets
GB6+PMN	5756	5140	1958	3182	616
AT20G	3572	3830	2543	287	742
Total					1358

parent catalogue is GB6+PMN and the detection limit of the survey was 13–18 mJy. By 2019 only 616 sources brighter 70 mJy have not been not observed. Second, a zone with $\delta \in [-40°, 0°]$ was observed in a number of VLBI surveys with a detection limit of 10–12 mJy. Only 742 sources from the AT20G catalogue brighter 40 mJy have not been observed with VLBI. Among them, 8 sources are in both list.

VLBA observations of missing 1350 sources will make two unbiased flux-limited samples of over 2000 sources each.

3 Prior observations

We ran a campaign of VLBA observations of a small complete flux-limited sample of radio sources the past: the Northern Polar Cap Survey (BK130). All the sources with declination $> +75°$ with flux density > 200 mJy at 1.4 GHz from the NVSS were observed at X and S bands in that projects, namely 502 objects. The detection limit of the survey was around 25 mJy. Analysis of these data and their comparison with single-dish broad-band spectra made it possible to study the relation between the source compactness and spectral index within an unbiased sample (Popkov et al. (2019), in preparation). Firstly, we confirmed statistically that flat spectrum sources are compact: nearly all targets with spectral index $\alpha > -0.5$ were detected by VLBA. That means their compactness defined as the ratio of NVSS flux density to VLBI flux density was over 0.1. Gigahertz-peaked spectrum sources, as well as flat spectrum ones, show 100% detectability. This was known. Meanwhile, more than 90% of the sample are the sources with steep spectrum ($\alpha < -0.5$). Among them, 25% were detected in S band and 14% in X band. It means that the fraction of compact steep spectrum sources is significant, and their number in a complete sample is even higher than the number of flat spectrum sources. This was not known. That means the statement: *"if a radio source has flat spectrum, it is compact"* is not reversible. This result shows that a population study of compact radio sources based on the current list of known VLBI sources may results in wrong conclusion due to a heavy selection bias.

4 The goal of the project

The main goal of the project is to investigate the relationship between compactness, spectral index at kiloparsec scale (angular size at aresecond level), spectral index at parsec scale (angular size at milliarcsecond level), source size and its morphology at parsec scales from VLBA images and kiloparsec scales using VLA images from NVSS and VLASS. The key scientific questions are

- Which parts of an AGN dominates in emission at different frequencies and different resolutions?
- Can the spectral index be used as a discriminator of radio source properties? If yes, which properties and what are the eliminations?

- ◦ How different the statistics of VLBI detected sources drawn from flat-spectrum biased parent samples are different from the statistics drawn from unbiased samples? How many compact sources do we miss? For instance, CGRaBS catalogue of flat specrtum sources (Healey et al. 2017) was used by *Fermi* mission for associations of γ-rays sources with AGNs. How many AGN associations were missed due to the selection bias?

This will be achieved by the following way:

- We will produce images of proposed target sources at 4.3 and 7.6 GHz and compute the total VLBA flux density, the median flux density at baseline projections shorter 900 km, and the median flux density at baseline projections longer 5,000 km. These flux density estimates will augment information collected from dual-band images of other sources of the sample that have been previously observed.
- We will determine the fraction of compact sources as a function of spectrum among AGNs for each of three complete flux-limited samples, the sample drawn from the NVSS at 1.4 GHz (see Sec. 3), from the GB6+PMN at 4.85 GHz, and the sample draw from AT20G at 20 GHz. These samples are complimentary to each other.
- We will analyze the physical differences between flat and steep spectrum radio sources by correlating the flux density, angular size, and spectral index of the compact component with single-dish total flux spectra of the sources integrated over 10–100$''$ area. We have collected information about single-dish flux densities and spectral indies of our samples from literature and we will run RATAN-600 observations to collect missing information for the rest of the target sources. We will also compute spectral indices over 2–4 GHz from VLASS observations over entire source and over the central pixels of VLASS images.

A by-product of this campaign will be a list of new calibrators near the ecliptic plane that are used for space navigation and VLBI observations of interplanetary spacecrafts. The newly detected sources from AT20G will be useful as ALMA calibrators since they are brighter than 40 mJy at 20 GHz. We will determine absolute positions of all detected sources with accuracies better 1 mas.

5 Proposed VLBA observations

Analysis of prior VLBA surveys, such as VCS9 program for observing 10766 sources showed that the overall efficiency is about 17 sources per hour, including overheads for slewing and observations of atmospheric calibrators. Therefore, we request in total 84 hours at wide C-band receiver, at 4.3 and 7.6 GHz sub-bands simultaneously for observing 1350 targets mentinoed above in one scan of 60 seconds at 2048 Mbps in a mode used in VCS7–9 surveys (Petrov in preparation 2019[1]. In order to optimize the use of the VLBA, we request 60 hours in the filler mode and six 4 hour blocks in the non-filler mode. The filler time schedules will be generated by the array operators on-demand using the web-based tool that we have developed and used in past filler projects. The targets are uniformly distributed over right ascensions, but according to our experience, available filler time in not uniformly distributed. Requested six 4-hour blocks are intended to cover the area that is inaccessible for the filler time. Since we do not know beforehand which area will not be covered with the filler time, we are going to schedule six 4-hour blocks after we use of 60 hours of filler time. Therefore, we ask to extend the project over two semesters.

[1]See the on-line project report at http://astrogeo.org/vcs9

6 Data release plan

We wave the proprietary period. Images and source positions will be available from the project web site immediately upon processing, typically with a lag of one month of observations. Upon completion the project the positions will augment the Radio Fundamental Catalogue and the images will be be submitted to the the Astrogeo VLBI FITS image database.

References

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