Studies on slow radio transients.

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We present a brief overview of a very extensive studies of the group of active galactic nuclei (AGNs) that transitioned to radio-loud state over the past few decades. The sample consists of twelve sources, both quasars and galaxies, showing the characteristics of gigahertz-peaked spectrum (GPS) objects undergoing relatively rapid changes, due to the evolution of their newly-born radio jets. Discussed objects also show a wide range of physical parameters such as bolometric luminosity, black hole mass and jet power, suggesting a great diversity among young active galactic nuclei and their hosts. Furthermore, we introduce a new observational project, the aim of which will be to investigate and gain a more in-depth understanding of the phenomenon of slow radio transients.

KEYWORDS:
galaxies, quasars, galaxy-evolution, recurrent-activity

1 | INTRODUCTION

One of the main issues in modern research on active galactic nuclei (AGNs) is their evolutionary process. The proposed model, in which compact radio sources called the gigahertz-peaked spectrum (GPS) and compact steep spectrum (CSS) objects propagate their jets and enlarge their sizes to then develop into a large-scale FRI/FRII type radio galaxies (Fanti et al. 1990; O’Dea & Baum 1997; Readhead et al. 1996; Snellen et al. 2000) appears to be correct in principle. However, statistical studies show that we observe a surplus of compact, not fully developed sources, which in turn suggests that not every young radio galaxy will follow the evolutionary path described above. A few possible reasons for this phenomenon have been discussed in the literature. This is the presence of a dense environment suppressing the jets expansion (Mukherjee et al. 2016), the enhancement of radio emission in young sources due to their jet-environment interaction, resulting in their over-abundance in selected samples (Morganti et al. 2011; Tadhunter et al. 2011), and a short time scale ($10^4 - 10^5$ years) episodic activity of radio objects, causing them to alternately vanish and reappear as compact, young looking sources (Czerny et al. 2009; Kunert-Bajraszewska et al. 2010; Reynolds & Begelman 1997; Silpa et al. 2020; Wołowska et al. 2017). The studies of such transient phenomena have been recently performed by us using the high quality Caltech-NRAO Stripe 82 Survey (CNSS; Mooley et al. 2016, 2019). The CNSS was carried out with the Jansky Very Large Array (VLA) between 2012 December and 2015 May over five epochs at the S band (2-4GHz). The observations covered the Sloan Digital Sky Survey (SDSS) Stripe 82 region of the 270 deg$^2$ and resulted in the discovery, among others, of transient sources on timescales <20 years, presumably associated
TABLE 1 Basic properties of a selected sample.

| Name ID | ID | z | $S_{1.4}$ [mJy] | $S_{1.4}$ [mJy] | $S_{1.4}$ [W Hz$^{-1}$] |
|---------|----|---|-----------------|-----------------|----------------------|
| 221650.00 | G | 0.55 | 0.39 | 0.52 | 23.1 |
| 221812.01 | - | - | 0.51 | 1.60 | - |
| 223041.00 | G | 0.84 | 0.37 | 0.98 | 23.8 |
| 233001.00 | Q | 1.65 | 0.32 | 3.45 | 24.6 |
| 010733.01 | G | 0.12 | 0.47 | 3.03 | 22.9 |
| 013815.00 | Q | 0.94 | 0.32 | 1.48 | 24.5 |
| 015411.01 | G | 0.05 | 0.45 | 3.79 | 22.3 |
| 020827.00 | Q | 1.34 | 0.49 | 1.90 | 24.2 |
| 030533.00 | G | 0.42 | 0.41 | 0.88 | 23.4 |
| 030925.01 | G | 0.04 | 0.35 | 3.69 | 22.1 |
| 031833.00 | G | 0.40 | 0.34 | 0.79 | 23.2 |
| 034526.00 | G | 0.45 | 0.40 | 1.22 | 23.5 |

Note: (4) the 3σ noise level at the location of the source measured in the 1.4 GHz FIRST images in mJy; (5) the latest value of 1.4 GHz flux density measured based on our VLA observations in mJy. Taken from Wołowska et al. (2021).

2 TRANSITION EVENTS FROM CNSS

All sources we discuss here are transient with respect to the FIRST survey (1995-2011) where they were undetected at the sensitivity level of <0.5 mJy at 1.4 GHz. However, their detection in the CNSS survey (2012-2015) showed a significant increase in their brightness on a scale of several decades and therefore now they can be classified as radio-loud objects (log$_{10}$[L$_{1.4 \text{GHz}}$/W Hz$^{-1}$] > 22.5, Tab.1). The studied sample contains both quasars and galaxies in a wide range of redshift values (0.04 < z < 1.7) hence it is very diverse in terms of radio luminosity. However, their placement on a luminosity vs. redshift plane shows, that the group consist mainly of low-power sources with quasars being brighter than galaxies (Fig.2 right).

The rich observation material (multi-frequency and multi-epoch) that we managed to collect allowed for a detailed description of our sources and for tracing the changes that have occurred in them since the ignition of radio emission. And thus the VLA spectroscopic studies revealed that all the transient sources have convex spectra peaking in the range 2–12 GHz at rest-frame. However, the radio spectra of quasars are changing rapidly with time. It is manifested by a flattening in the optically thin part of the spectrum. An example of such behavior are the changes seen in the spectrum of the quasar 013815+00 in Fig.2. As a result, after a few years of radio activity the quasars start to look like flat-spectrum objects, while galaxies keep their convex shape of the spectra. The phenomenon responsible for this characteristics is the birth of a new radio jet and the observed rapid changes are associated with its expansion and dissipation of energy. The differences in the behavior of the spectrum of galaxies and quasars over time are probably related to their different orientation in relation to the observer. And indeed the high-resolution 4.5 and 7.5 GHz VLBA images show the presence of small jets in case of some of our objects (see example in Fig.2). Nevertheless, these jets are not very prominent, and most of the objects remained unresolved in these observations. We argue that this may be due to the fact that the VLBA observations were carried out about 3 years after the ignition of radio activity in these sources, which in the case of weak jets may be enough time for the emission to fade out.

In order to test the hypothesis that our transient sources are the new born radio objects we placed them on the peak (turnover frequency) $\nu_p − l$ linear size plane (Fig.1). This relationship shows that the there is a continuous distribution of young AGNs with GPS sources evolving into CSS objects (O’Dea & Baum 1997). We found that indeed the properties of our sources are similar to those of high-power GPS and CSS radio objects. They follow the established relationship quite accurately, with slight discrepancy visible in the case of the weakest sources. This may suggest a slower development of the source in terms of size and therefore the object will remain compact even for most of its life. We marked this as an alternative development path in Fig.1 (left). Nevertheless, this hypothesis requires further research on weaker radio objects in the early stages of evolution which is our research plan now (see the next section).

Attempts to detect our sample in the X-ray range resulted in three detections (two galaxies and one quasar) and the estimation of upper limits for six other sources. We then used the correlation between X-ray and radio luminosity to preliminarily classify them as low- and high-excitation radio galaxies. However, in general, the observational results of our sample in terms of X-ray show that the emission is weak, especially in the case of galaxies, and does not exceed the value of $10^{42}$ erg s$^{-1}$. This, in turn, is consistent with the presence of a radiatively inefficient accretion onto a black hole with a mass within $10^6 - 10^8 M_\odot$. And indeed the black hole mass estimations we performed for our galaxies are in agreement with the suggested values (Wołowska et al. 2021). In the case of quasars the black hole masses are higher, of the order of $10^9 M_\odot$. 


FIGURE 1 Left: the intrinsic turnover frequency vs. linear size relationship. The CSS/GPS comparison sample taken from the literature are indicated with circles and the transient GPS sources presented in this work are marked as squares (see Wołowska et al. [2021] for more details). The sizes of the circles/squares correspond with the k-corrected radio luminosity at 5GHz, and arrows indicate maximum linear sizes for unresolved sources. The blue solid line indicates the linear relationship updated by Orienti & Dallacasa [2014]. The dashed green line indicates a separate development path for weak radio sources (green points) discussed in this article. Right: redshift vs. luminosity at 5GHz for the comparison sample combined with the low-luminosity CSS sources from Kunert-Bajraszewska et al. [2010] (empty points), and transient objects presented in this work (filled points). The blue dots indicate the estimated position of the sources from the new VLASS sample.

The optical spectroscopic data collected both from the SDSS archives and from our Southern African Large Telescope (SALT) project allowed for the estimation of a few more parameters of the discussed sources like bolometric luminosities, Eddington ratios and jet powers. Additionally, the detailed study of one of our quasars (Fig.2) led us to the conclusion that the ignition of radio activity coincides with relatively small changes of bolometric luminosity and hence Eddington ratio. We have observed that the burst of radio emission in 013815+00, recorded for the first time in December 2013, coincides with an increase in the brightness of the accretion disk (Fig.2 SDSS 2015). However, within the next two years, the disk brightness returns to its original state (SDSS 2018), which shows how fast changes occur in this new source. We estimated that the change in the bolometric luminosity of quasar 013815+00 was by a factor of just 1.4. Summarizing, a wide range of values of the physical parameters that we have obtained for our transient sources suggest that they belong to several different sub-classes of young radio objects.

3 NEW VLASS SAMPLE

The objects described above constitute the first unbiased sample of 12 transient sources discovered in the CNSS survey [Kunert-Bajraszewska et al. 2020, Wołowska et al. 2021]. However, the slow radio transient observations are continued thanks to the new ongoing Very Large Array (VLA) Sky Survey (VLASS, Lacy et al. 2020). Very recently the detection of changing-state quasars has been reported by Nyland et al. (2020) as a result of VLASS survey. However, a much larger population of such radio sources exists, and has been uncovered in the first epoch of VLASS survey, which we plan to explore further.

Our new sample consists of 24 newly-born candidates for short-lived radio AGN (Fig.1 blue dots), undetected in the NVSS survey (1995), but discovered in VLASS to have brightened in the past ~25 years. Selection criteria assumed point-like sources that were >8 mJy, coincident within 2 arcsec with the nuclei nearby galaxies having r<20 mag based on visual inspection of a Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) optical images. The VLA archival sensitivity limits and new VLASS detections of these sources at 1.4 GHz implies spectral indices between 1.4 GHz and 3 GHz to be $a > 2$ ($S \propto \nu^a$). The sources are therefore either highly synchrotron self-absorbed GPS sources or are completely new bright sources in the radio sky. To better understand their nature, we have started a multi-frequency observation campaign for these objects with the use of radio and optical instruments.
FIGURE 2: Left: Radio spectrum of "switched-on" radio AGN/quasar J013815+00 (z = 0.94) from 0.5–18 GHz (red arrow is the upper limit from the FIRST survey from 1997). Inset shows the optical image cutout. Middle: The optical spectra across different epochs indicate accretion state changes over ~years timescale. Right: The VLBA image reveals the young jet (core-jet morphology). Taken from Kunert-Bajraszewska et al. 2020.

4 | SUMMARY AND FUTURE PLANS

We summarized here the first such extensive research of a sample of newly discovered radio sources. They have been detected by CNSS survey between 2007 and 2013 on the level of a few mJy and higher. Based on their radio properties they can be classified as GPS objects, at least in the initial phase of radio activity. They might have transitioned from radio-quiet to radio-loud state either as a result of the increase in radio power or its ignition.

However, thanks to the new and ongoing VLASS survey of the sky, new discoveries and studies of transient sources continues. Our new research is now focused on 24 VLASS detections of candidates for young radio galaxies. These are nearby objects with a redshift <0.3. Their radio luminosities at 3 GHz, >10^{39} erg s^{-1}, suggest that they are most likely "switched-on" AGN jets. These sources give us an excellent opportunity to study a fairly uniform sample of young AGN in the "local" Universe and will be published soon.

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