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Search for distant radio galaxies. Big Trio Project

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Distant radio galaxies as a population of galaxies with active nuclei are of particular interest for research, since current data indicate the presence of supermassive black holes with masses greater than $10^9 M_\odot$, already formed in these giant stellar systems in the first billion years of the existence of the Universe, and also due to the connection of such systems with protoclusters of galaxies.
For several years, within the framework of the Big Trio project, studies have been carried out on a sample of double radio sources with steep and ultra-steep spectra from the surveys of the Cold experiment on the search for distant radio galaxies. Optical candidates were found for 94% of the sample, and were not found for the rest of the sources, most likely due to the fact that the objects turned out to be weaker than the limit ($R \leq 25^m$) of the images obtained with the 6-m BTA telescope. Optical spectra were obtained for 68% of the sample, and no emission lines were found in 17 candidates, mainly due to the low brightness in the optics.
Three unique distant galaxies with redshift z>3 and high radio luminosity ($\log(L_{500\,MHz})>28$) have been discovered. For these objects, additional studies are still carried out using the MERLIN and EVN radio interferometers.
Additional studies using modern radio, optical, and infrared sky surveys, including archival data, made it possible to refine the radio structure, optical identifications, magnitudes, redshifts, and obtain information about the environment of the radio sources for 25% of the sample.

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1. Preparation and study of a sample of radio sources with steep spectra

In the early 1990s, SAO RAS began work on the Big Trio project [1, 2], which was aimed at searching for distant radio galaxies and their further study. For observations of the sample, three astronomical instruments were used – the RATAN-600 and VLA radio telescopes, and the 6-m BTA optical telescope. The final aim is to create a homogeneous sample of high-z radio galaxies in a 40′ wide strip around the sky, with a faint flux density limit. The implementation of the program included several stages, the first of which was the preparation of a list of candidates. As is known, the observed steepness of the radio spectrum correlates with the redshift [3]. The RC (RATAN Cold) catalog [4, 5] was used to prepare a steep spectrum (SS) sample. The catalog was obtained based on the material from the first cycles of the Cold experiment [6].

When compiling the SS sample of sources, we used the steepness of the radio spectrum as the main criterion. The spectral indices of sources were calculated using the data from the RC (3.94 MHz) and UTRAO (365 MHz) [7] catalogs. The SS sample included sources with α<–0.9 ($S_\nu \propto \nu^\alpha$). Some additional restrictions were also used, namely, the flux density (no brighter than a few hundred mJy at $S_{3.94\,GHz}$), double radio sources of the FRII type, and small angular size [8].

A preliminary study using the photographic Palomar Sky Survey made it possible to exclude radio sources identified with bright optical objects from the list under consideration, since they are not expected to be at extreme distances [9].

The next step was to obtain accurate radio coordinates, flux densities, structure and angular sizes. A search was made in the MIT–GB–VLA [9] archive, and VLA [10] observations were made. A total of 389 maps were obtained for 208 RC sources at a frequency of 1.4ĠHz with a resolution of 1.5″–4.5″, including candidates for the SS sample. Some of the unresolved objects were observed again at a frequency of 4.8 GHz with a resolution of 0.4″.

In total, about a hundred sources were selected for studies in the optical range (10% of the sources in the RC catalog). The 6-m BTA telescope was used for optical identification. In 1991–2003, about 80 observational nights were allocated for the optical identification of the SS sample on the 6-m BTA telescope. Direct images of subsecond (or close to it) seeing for 22 radio sources were also obtained with the 2-m Nordic Telescope [11]. For most of the sources (94%) of the sample, optical counterparts were found.

Photometric estimates of redshifts were carried out according to BVRI photometry with the 6-m telescope for 48% of the objects [12].

Further spectroscopy of optical candidates was carried out with the BTA. Spectra were obtained for 71 candidate host galaxies [13]. Half of these sources, according to the type of optical spectrum (narrow emission lines), were assigned to galaxies, and 50% of them have a redshift of z>1. A quarter of the candidates with broad spectral lines were assigned to quasars, 70% of which have a redshift of z>1. And for the remaining quarter of the candidates, no lines were found in the obtained spectra, mainly due to their low brightness.

Among the 54 studied radio sources with measured redshifts, we found 5 galaxies and 5 quasars with z>2, among them 2 sources with z>3 and one with z>4.

2. Additional studies of the most distant objects discovered

Additional observations of the most distant objects in the sample were carried out with MERLIN, EVN, and with the BTA and UKIRT telescopes [14]. Below, based on these observations, as well as on archival data and modern sky surveys, we present some results for these objects.

RC J0105+0501 (Z=3.138[1]). The object is classified as a core-lobe source [13]. The redshift was determined from the narrow Lyα emission line in the spectrum of the object with coordinates α=01^{h}05^{m}34.09^s, δ=+5°01′13.0″ (J2000)[2], which practically coincides with the brighter northern radio lobe (01:05:34.15 +05:01:13.1). It has the maximum brightness in the V-band, probably due to the contribution of the Lyα envelope. Another object (01:05:34.03 +05:01:11.7) practically merges with it. The photometric redshift from the Legacy Surveys catalog [15] z_{LS}=0.684±0.574 most likely refers to this faint galaxy. Two other neighboring objects, one of which falls on the southern radio lobe, are galaxies at $z_{LS}\approx$0.5. Photometric redshift data show that the source is behind a group of foreground galaxies. This complicates identification and most likely affects the shape of the radio source due to possible gravlensing. The assumption that these are two different radio sources is not ruled out.

RC J1740+0501 (Z=3.570). According to the new data for RC J1740+0502 obtained with the MERLIN radio interferometer (JBO, UK) at the frequencies 1.7 and 5 GHz with an angular resolution of 0.1″ [14], the source uniquely corresponds to a double source of the FRII type, and not the core-lobe morphology as previously defined. The optical object (17:40:33.95 +05:02:42.1, r_{PS}=22.81^m±0.04^m) almost coincided with the northern lobe, judging by the maps with lower resolution. On the new map, this object is displaced from the radio source position and, most likely, is not an optical counterpart. The optical spectrum has a broad Lyα(5560Å) line, and is classified as a faint quasar spectrum. We believe that due to the favorable location of the slit, the light from the $Ly\alpha$ emitter (LAE) falls on the spectrum of the optical object, which was considered as an identification. This faint LAE cannot be detected with certainty with the BTA and the NOT frames, as well as in the J-filter cutout from the UHS survey [16]. Strong Lyα emission is often observed in radio galaxies, and is used as a technique of searching for distant objects.

RC J0311+0507 (Z=4.5141). As is shown by the MERLIN and EVN maps, RC J0311+0507 (4C 04.11) has a multi-component structure, with each component having a very high luminosity [17]. The nature of the small size sub-components shows that it is possible that the jet is propagating through and interacting with a dense environment. Interestingly, Wang et al. [18] found eight HI absorbing systems in spectroscopic observations (VLT/MUSE) for mapping the emission and kinematics of the Lyα halo (~70×30 kpc) around RC J0311+0507. In that paper [18], the redshift of the galaxy is refined as Z=4.5077.

Using deep frames in the R, I and SED665 filters (BTA/SCORPIO), we estimated the surface density of the objects in a 2.5′×2.5′ area (at z=4.51 this corresponds to ~1×1 Mps) centered on RC J0311+0507. An excess of 2–3σ was found compared to areas of the same size, but taken elsewhere in the same frames [19]. During visual inspection of Subaru archival data [20] in the ~1′×1′ vicinity of the host galaxy, several objects were found that are absent in the B-band, but are present in the R and/or I filters (B-dropout). Moreover, some of them are in the narrow NL671

[1]We designate the spectroscopic redshift with a capital letter Z, and the photometric redshift with a small letter z.
[2]Hereafter, the source coordinates are given in sexagesimal form hh:mm:ss.ss sdd:mm:ss.s for epoch J2000.

filter centered on the $Ly\alpha$ line for z=4.51 and are possible $Ly\alpha$-emitters (LAE). However, Kikuta et al. [21] report that the radio galaxy was found to be near a void of LAEs.

We performed astrometric re-calibration for $5' \times 5'$-sized cutouts centered on the host position for the images from the BTA (R and SED665 filters), Subaru (R, NL671), UKIRT (K), and Spitzer (3.6 and 4.5 μm bands) telescopes. SDSS objects with minimal coordinate errors were selected as reference sources. The spread of the coordinate errors of the reference objects on these frames ranged from 0.060″ to 0.096″. We then measured the position of the galaxy in each used cutout. The coordinates of the host in the K filter and in the 3.6 and 4.5 μm bands are located near the radio core, while in other filters they are located along the jet and farther from the core. The difference between the end positions is 0.890″, which is higher than the 3σ confidence level for the coordinate errors [22]. The shift of the host coordinates in the R, SED665, NL671 filters, where Lyα radiation predominates, relative to the measured position on the K, 3.6 and 4.5 μm frames, where the main contribution comes from the stellar population, can be explained by the presence of a cloud of ionized gas [23] in the southern hotspot, where the jet has stopped propagating, as well as the UV contribution of the jet with an accelerating effect, since it is directed sufficiently close to the line of sight [24]. Note that the presence of a gas cloud is probably confirmed by the discovery of the largest absorbing structure in the halo of the galaxy [18], which is a leaky shell generated by a previous AGN or star formation episode, now captured by a radio jet, which leads to the interaction of the jet with gas.

3. The SS sample of the RC catalog and modern sky surveys

Observations for 112 objects were carried out with the BTA telescope under the Big Trio project. With the advent of deeper optical sky surveys such as Pan-STARRS [25] (PS), the DESI Legacy Imaging Surveys [16] (LS), DES [26] optical surveys, we have refined the identification of the sample. Archival data from the NOAO observatory [27] were also used, which are available to the user through the NOIR DataLab system. In some cases, we used archival data from the Hyper Suprime-Cam Subaru Strategic Program [28] (HSC SSP DR3). To refine the structure of radio sources, in addition to the already available radio maps, the VLASS survey was used. We used infrared surveys conducted with the 4-m UKIRT telescope – LAS, GPS, and UHS [29], as well as WISE mission data [30].

We revised the optical identifications for 112 radio sources of the SS sample. For 11 objects we added new z from LS and SDSS. We refined the optical identifications and radio structure for 16 radio sources (15%) from the SS sample. These new identifications, since the counterparts turned out to be weaker in optics, are most likely located at higher z.

10 quasars and one galaxy have confirmed SDSS spectroscopic redshifts, including a quasar from a quasar-galaxy pair RC J0213+0516.

Table 1 lists the median values for the whole SS sample (**all**), for the subsample with spectroscopic redshifts (**spz**), the subsample with photometric redshifts (**phz**), and the subsample of optically faint objects (**noz**) for which redshifts are unknown. Also presented is a sample of sources with redshift **z>1**, which includes objects with photometric (46%) and spectral redshifts, where z was first obtained for 77% of the objects in the Big Trio project, as well as a sample with **z>2**, which contains only the objects with spectral z obtained with the BTA. Also shown are the subsamples of galaxies (**G**) and quasars (**Q**) with known redshifts. The columns show: **name** – name of the sample, **n** – number of objects, **r** – r-band magnitude, **z** – redshift, **las** – the largest angular size (in arcseconds), **sp** – spectral index (365–3940 MHz), **S14** – integral flux density in mJy at 1.4 GHz, **S39** – integral flux density in mJy at 3.94 GHz.

Optical candidates were found for 16 of the 30 sources with no redshift data that are most suitable

Table 1: Median characteristics of the SS sample radio sources

name	n	r	z	las	sp	S14	S39
all	112	22.5	0.968	11.0	-1.00	194	55
spz	52	21.2	0.913	10.4	-0.96	213	68
phz	30	23.0	1.072	17.5	-1.02	155	63
noz	30	24.0	>1.5	5.8	-1.06	82	29
z>1	39	22.8	1.272	6.3	-1.03	165	66
z>2	10	22.8	2.463	4.0	-1.09	168	37
G	63	22.4	0.870	12.0	-0.97	200	66
Q	19	20.0	1.189	10.0	-0.99	203	90

in terms of positional coincidence in accordance with the radio structure. They are listed in the catalogs mentioned above. The rest of the candidates were found only in sky survey cutouts, and 6 of them are absent from optical surveys but are present in the WISE catalog. There are still 6 very faint objects for which there are no sufficiently reliable data in the survey cutouts.

According to new data, the SS sample radio sources are often found in groups of galaxies, clusters, and even in close pairs. Thus, 30% have close neighbors, confirmed by spectral or photometric redshifts, 30% are close in angular distance. More than 10% of the hosts are in a pair where the distance between the objects is 1–3″. Such a pair includes two galaxies, or a quasar and a galaxy, with redshifts confirmed in half of these pairs.

The environment of the source can also be judged from the morphological features of the radio structure. According to the deformed structure, about 20% of the sources can be attributed to the WAT (Wide-Angle Tail) type. Usually such sources are considered as indicators of galaxy clusters [31]. 25% of the objects have a double-double (DDRS) or core-dominated triple (CDT) radio structure, which indicates a re-start of the radio source phase [32]. 6% of the radio sources are X-shaped (XRG) or S-shaped, which indicates a reorientation of the jet [33].

5 pairs of nearby radio sources were found, of which two pairs were confirmed by redshift data, one radio source overlaps in the picture plane, which is also confirmed by z, and one possible pair and one possible overlap of two radio sources.

4. Conclusion

The Big Trio program, in terms of the applied candidate selection methods, the use of allocated instrument observation time, and the use of archival data has shown a high efficiency in its approach to solving the problem, eventually obtaining world-class results. Russian, German, American and British researchers took part in the joint work.

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