PROCEEDINGS OF SCIENCE

Sources of the "Cold Experiment" surveys in different ranges of the electromagnetic spectrum

O.P. Zhelenkova,[a,*] **N.S. Soboleva,**[b] **E.K. Majorova,**[a] **A.V. Temirova**[b] **and N.N. Bursov**[a]

[a] *Special Astrophysical Observatory of RAS, Niznij Arkhyz, 369167, Russia*
[b] *SPb Branch of SAO RAS, Pulkovskoe sh., 65, Saint Petersburg, 196140, Russia*

E-mail: zhe@sao.ru, adelina_temirova@mail.ru

A study of the panchromatic properties of radio sources makes it possible to research the evolution of active galactic nuclei and their relationship with the environment. The study was made of a complete sample of radio sources in terms of flux density from surveys of the "Cold Experiment", carried out on the RATAN-600 radio telescope at a frequency of 3.94 GHz in 1980–2000. We have found hosts for 95% of these radio sources. According to the radio luminosity estimates, most of the sources are powerful FRII type radio sources. Based on photometric data and color indices among the hosts we have identified groups of quasars, early-type galaxies, and late-type galaxies. Additionally, the late-type galaxies are subdivided into a smaller group with a relatively low radio loudness index and a larger group with a high index.

Depending on the radio luminosity, the sources were divided into groups. In each group, the median of the ratio of the absolute magnitude to the radio luminosity was calculated, and the number of quasars and the number of galaxies were also calculated. Correlations are found whose behavior can be explained by a change in the screening properties of the torus. As the radio luminosity increases, the shielding properties of the torus decrease.

Long-term variability was found with varying degrees of confidence in 18% of the radio sources. The hosts of these sources with magnitude R$\leq 18^m$ exhibit variability in the optical range as well. According to the multi-frequency maps of the Planck mission, for 70% of the sources of the RCR catalog, at a level $\lesssim 4\sigma$, a positive signal was found at least at one frequency. The spectral studies confirm the connection of these positive spots with the radio sources. To search for the Sunyaev-Zel'dovich (SZ) effect, the studies of the properties of "hot" and "cold" spots near sources were carried out. 16% of the radio sources have signs of the SZ-effect at level $\lesssim 4\sigma$. One fifth of them are in the catalogs of galaxy clusters, which confirms the applicability of our technique for searching for the effect in faint sources.

The Multifaceted Universe: Theory and Observations - 2022 (MUTO2022)
23-27 May 2022
SAO RAS, Nizhny Arkhyz, Russia

*Speaker

PoS(MUTO2022)023

1. The "Cold Experiment"

In 1980, the RATAN-600 radio telescope was equipped with a cryoradiometer with a sensitivity of ~2 mK with an integration time of ≈1 s at a wavelength of 7.6 cm. And the "Cold Experiment" was launched as a series of surveys of about 40′-wide strip of the sky at declination of SS 433 ($\delta \approx 5°$). The main tasks of the experiment were the search for the 3°K background radiation, the study of weak sources and other tasks related to galactic radio emission.

The catalog of radio sources RC (RATAN Cold) was obtained from the data of the first cycles of the "Cold Experiment". The accuracy of the source coordinates in the central part of the survey is $5'' \times 45''$. The sources represent a complete sample in terms of flux density from 3.94 GHz to 10 mJy. Here we give only a very brief overview of the work that has long been carried out on the study of the panchromatic properties of the "Cold Experiment" sources.

2. Study of the RC radio sources

As planned, the studies of the radio sources of the "Cold Experiment" in the optical range began immediately after the first results were obtained. In 1984–1986, 16 nights were allocated for photographic observations on the 6-m optical telescope BTA. Also a search was made for optical counterparts using enlarged photographs of the Palomar Sky Atlas. As a result, including identification of the Big Trio project sources (see the paper Zhelenkova et al. in this volume), about 20% of the objects of the RC catalog were identified in the optical range before the era of modern digital surveys.

432 radio sources of the RC catalog fell into the region of intersection of the SDSS DR3 [1] and FIRST [2] surveys in the right ascension interval 8^h11^m<R.A.<16^h25^m. Due to the insufficient coordinate accuracy, we first refined the coordinates of the RC radio sources [3], identifying them with the radio catalogs with higher coordinate accuracy and angular resolution. For 75% sources, we found radio counterpats in the NVSS [4] and FIRST surveys. Optical hosts were found for 80% of the radio sources at the limiting magnitude of the SDSS survey r≈22.6^m [5]. The ratio of galaxies and stellar objects among the identified sources turned out to be 2:1.

3. Study of the RCR catalog radio sources

To refine the coordinates and flux densities of the radio sources of the RC catalog, the surveys of 1987–2000 were processed, and the surveys of 1980–1981 were re-processed. As a result, for the right ascension interval 2^h<R.A.<17^h, the RCR catalog was obtained, which included about 850 objects [6, 7]. Fluxes, the right ascension coordinates and spectral indices were determined for these sources.

Flux-density-complete samples of radio sources can include different populations of objects, depending on the frequency at which and with what flux-density limit they were obtained due to the different redshifts of objects, the contributions to the integrated observed spectrum are obtained from various physical components of the source [8].

The spectral characteristics of the RC sources have been repeatedly determined both from multi-frequency observations, carried out with the RATAN-600 radio telescope, and using data from well-known catalogs. With the advent of more flux-sensitive TGSS and GLEAM surveys, it became possible to refine the spectra of bright sources in the low-frequency range, as well as more confidently determine the spectra of half of the RCR sources for which flux density data are known only at two frequencies.

For each of the objects of the RCR catalog, radio spectra were built and spectral indices were calculated at 0.5 and 3.94 GHz, as well as two-frequency spectral indices at 74 and 150 MHz, 1.4, 3.94 and 4.85 GHz. We investigated the relationship between two-frequency spectral indices and integrated flux density for various combinations of indices and flux densities for the above frequencies. An appreciable correlation between α_{150} and F_{150} is found for both the sources with steep spectra (SS) and the sources with flat spectra (FS). As the flux density increases, the radio spectrum becomes steeper. In general, FS sources are weaker in flux density than SS sources, as can be seen from the graph in Figure 1 (left). We believe that this is due to the different brightness

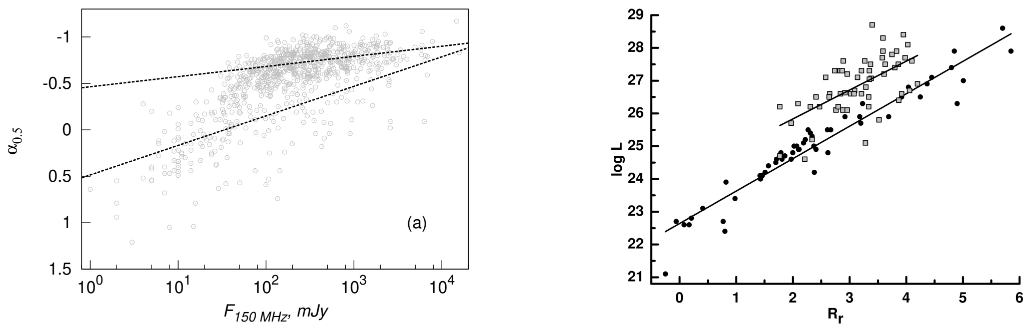

Figure 1: *Left*: the diagram of scattering of spectral indices at the frequencies of 0.5 GHz and the flux density at the frequencies of 150 MHz for 830 RCR-sources. The upper dashed line is a regression line over all points for the sources with steep spectra ($\alpha \leq$–0.5, filled circles), bottom line is for the sources with flat spectra (empty circles). *Right*: the relation between the radio loudness index R_{r} and $\log(L_{1.4})$ for galaxies (circles) and quasars (squares) with known spectroscopic redshifts. The lower and upper lines show the linear dependencies of $\log L_{1.4}$ on R_{r} for radio galaxies and quasars, respectively.

of the extended components in the SS and FS sources. At the frequencies of 3.94–4.85 GHz, where the contribution of the nuclear part predominates, there is no such noticeable difference. It can be assumed that SS ans FS sources belong to types of objects with different jet energies, which may be due to different types of accretion. However, the environment and evolutionary stage of a radio source can also have an impact.

3.1 Optical counterparts

The studied part of the RCR catalog overlaps with the SDSS optical survey, the UKIDSS and WISE infrared surveys in the right ascension interval 07^h<R.A.<17^h[1]. If the object was not detected from the optical or infrared image in one filter, we analyzed the cutouts in all available filters, and also analyzed the co-added frames to get a deeper image. The final decision on the optical candidate was made after analyzing all available information, taking into account coordinate coincidence, radio structure, photometric and spectroscopic data, and data on proper motion. With

[1]For our calculations, we take the following cosmological parameters: H_0=73 km s^{-1}Mpc^{-1} and Ω_Λ=0.73.

the help of software tools and resources of the virtual observatory, 94% of 550 radio sources [9, 10] were identified. 48% of the sources were identified for the first time, and for 52%, the identification made by us earlier or available in databases was confirmed.

For 440 RCR-sources, the radio loudness index R_r[2] was calculated. It turned out that 2.5% of the sources in the RCR-catalog, mostly galaxies with z≈0.1, have R_r<1. We found a correlation berween R_r and log($L_{3.94}$), both for galaxies and quasars (see Fig. 1, right). We used the obtained relations to estimate the radio luminosity of the sources with unknown redshifts[3]. It was learned that 60% of RC objects in terms of radio luminosity are powerful FRII-type radio sources.

Using color index constraints from SDSS, 2MASS, UKIDSS, and WISE photometric data [12–14], 52% of the identified hosts are classified as galaxies, 24% as quasars. The remaining 24% of the objects we could not attribute to any type, since they are weak in optics. 217 (52%) of the studied sources (r≤21.5^m) are divided into four groups according to available photometric data SDSS, colour and concentration indeces correlations of the «red» and «blue» sequences[4]: (I) quasars (43%), (II) late-type galaxies (16%), (III) early-type galaxies (22%) with a relatively low radio loudness index with an average R_r≈1.8, and (IV) early-type (19%) galaxies with a high index R_r≈3.1.

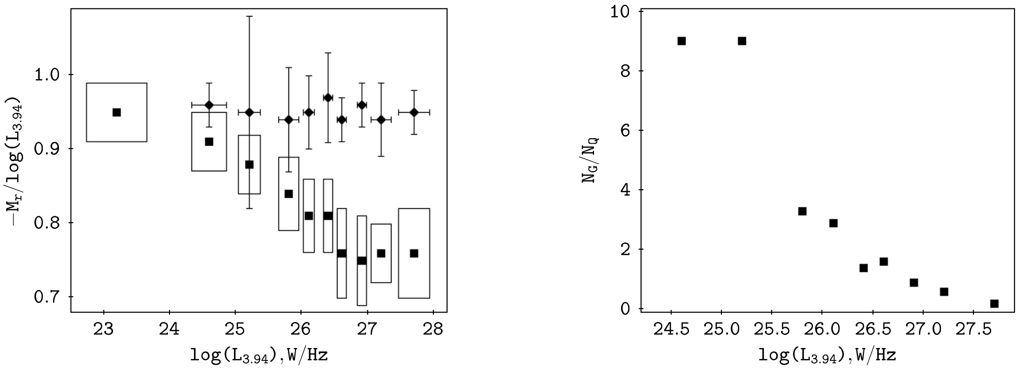

Figure 2: *Left*: the dependence of the ratio k = $-M_r/\log(L_{3.94})$ on the logarithmic radio luminosity at a frequency of 3.94 GHz for galaxies and quasars from the RCR catalog. Squares denote the median value of the k parameter for each bin of the logarithmic radio luminosity for galaxies, circles – for quasars. *Right*: the ratio of galaxies to quasars in each group by radio luminosity at the frequency of 3.94 GHz.

The ratio k=$-M_r/\log(L_{3.94})$ can be considered as a characteristic of the shading of the nucleus by the torus, if one follows the unified model [16, 17]. As such characteristic, we took the ratio of the r-band absolute magnitude M_r to log($L_{3.94}$) and compared it for hosts for which the type was

[2] R_r=0.4(m_r–t_N), where m_r is the deredded magnitude in the r-band; t_N is the NVSS flux density expressed in the magnitude of the AB-system by the formula: t_N=–2.5log(F_N/3631 Jy) [11]. Radio sources with R_r>1 are radio loud sources.

[3] Photometric or spectroscopic redshifts are known for half of the parent objects.

[4] Strateva et al. [15] found that SDSS galaxies (g<21^m) can be subdivided into early-type galaxies (E, S and Sa or «red» sequence) with u–r≥2.22 and late-type galaxies (Sb, Sc and Irr or «blue» sequence) others.There is also a correlation between the colour of the galaxy and its radial profile, measured by a concentration index C. If C > 2.6, the galaxy belongs to the early types.

determined – a galaxy or a quasar. For quasars, this ratio does not depend on the radio luminosity, but for galaxies it has a minimum value for the radio sources with a maximum luminosity and, with decreasing radio luminosity, grows to the level characteristic of quasars. The sources were divided into bins according to their radio luminosity, the number of quasars and galaxies in each group was calculated. It turned out that in each bin, with increasing radio luminosity, the number of quasars increases. These results can be explained by the fact that the shielding properties of the torus depend on the power of the radio source.

3.2 Search for long-term variability

The search for the variability of radio sources and radio transients is carried out both on the basis of archival data [18, 19] and in the course of monitoring programs [20, 21]. Based on the "Cold" surveys 1980–1999, we tried to discover sources with long-term radio variability and transient events as well. We made a careful selection of calibration sources to build calibration curves for determining the flux density. To test for probable variability, we used several common statistical tests of variability [21]. 73 sources turned out to have positive variability indices, which suggests their possible variability [22]. Almost half of these sources are bright objects with the flux density $F_{3.93}$>100 mJy. The parent objects of candidate variable sources are both galaxies and quasars. 18% of the surveyed sources can be attributed to long-term variables in the radio range, which is comparable with the estimates given in other works [21].

For optical counterparts of the radio sources, we have up to five epochs of observations in the optical and infrared ranges according to USNO-B1, GSC, SDSS, 2MASS and UKIDSS catalogs. The hosts with R$\lesssim$18^m can be suspected of having optical and/or infrared variability due to significant magnitude variations (Δm>0.7^m), as well as positive values of the variability index, which we used. About 40% of the radio sources, for which there are data in two or more catalogs, have brightness variations in the range 0.7^m–1.0^m and higher [10].

4. Study of RCR sources in sub-mm and mm ranges

The energy distribution in the spectra of radio sources is marked by a rise in the submillimeter range and indicates the presence of a dust component in active galactic nuclei. We have studied the maps of the microwave background radiation near the radio sources of the RCR [23] catalog. We tested the areas with the radius of 1.5 beamwidth (~7′) at Planck frequencies for searching for a signal at a signal-to-noise ratio of $\lesssim 4\sigma$. We found a positive signal in 70% of the sources at least at one frequency of the Planck mission, according to the measurements of multi-frequency maps, and estimated the flux densities of the RCR sources[5]. The weak sources that we study are difficult to remove from maps due to the low intensity of the radiation flux, which makes it difficult to statistically analyze the cosmic microwave background on Planck maps at scales less than 7′.

We searched for the Sunyaev-Zeldovich effect in the direction of the radio sources [23, 24]. The detection of low intensity spots that satisfy the conditions of the SZ-effect near radio sources can be regarded as evidence of the manifestation of the effect and its connection with clusters.

[5]The calibration curves needed to determine the flux densities were constructed based on measurements of compact sources from the Planck catalogue. The data published in Vizier database in the next tables: J/AZh/93/616, J/other/AstBu/76.109.

About 270 radio sources fall in areas of about 1.5 the beam size of the Planck antenna, where the SZ-effect is detected with varying degree of confidence. Near most of the spots, which are possible SZ-candidates, clusters with z>0.10 are located. In 9% of SZ-candidates and clusters of galaxies in the immediate vicinity, redshifts coincide, which indicates that the sources belong to these clusters. It was found that near the spots with the topology of the SZ-effect, clusters of galaxies with different redshifts or a radio source (often more distant) can be located. It can be assumed that for several clusters of galaxies or a cluster and a radio source located along the line of sight, the SZ-effect may become weaker or blurred.

5. Conclusion

For a number of years, the studies of the radio sources of the "Cold Experiment" were carried out. These surveys serve as an intermediate link between deep VLA surveys and low-sensitivity all-sky surveys. One of the important results is that we haven't found objects at the 10 mJy level that were not previously included in the catalogs of decimeter waves.

Examining this sample, complete in terms of flux density, we found that the vast majority of sources are powerful radio sources with the radio luminosities at the level of FRII-type radio sources. Among the parent objects of the radio sources, in addition to quasars and early-type galaxies, late-type galaxies account for an unexpectedly large proportion, previously not noted in publications. We have revealed a relationship between torus geometry and radio luminosity – the sources of higher luminosity have a thinner torus.

In conclusion, we note that sufficiently representative and complete samples of objects, like the RCR catalog, turn out to be an optimal and effective tool for studying the properties of radio sources, including the search for and discovery of new patterns.

References

[1] K. Abazajian, J.K. Adelman-McCarthy, M.A. Agüeros, S.S. Allam, K.S.J. Anderson, S.F. Anderson et al., *The Third Data Release of the Sloan Digital Sky Survey*, *Astron. J.* **129** (2005) 1755 [astro-ph/0410239].

[2] D.J. Helfand, R.L. White and R.H. Becker, *The Last of FIRST: The Final Catalog and Source Identifications*, *Astrophys. J.* **801** (2015) 26 [1501.01555].

[3] O.P. Zhelenkova and A.I. Kopylov, *Analysis of the RC catalog sample in the region overlapping with the regions of the FIRST and SDSS surveys: I. Identification of sources with the VLSS, TXS, NVSS, FIRST, and GB6 catalogs*, *Astrophysical Bulletin* **63** (2008) 346 [0901.2248].

[4] J.J. Condon, W.D. Cotton, E.W. Greisen, Q.F. Yin, R.A. Perley, G.B. Taylor et al., *The NRAO VLA Sky Survey*, *Astron. J.* **115** (1998) 1693.

[5] O.P. Zhelenkova and A.I. Kopylov, *Analysis of a sample of RC catalog objects in the region overlapping with the areas covered by FIRST and SDSS surveys. II: Optical identification*

with the SDSS survey and USNO-B1 and 2MASS catalogs, Astrophysical Bulletin **64** (2009) 109 [0906.1731].

[6] N.S. Soboleva, E.K. Majorova, O.P. Zhelenkova, A.V. Temirova and N.N. Bursov, *RATAN-600 7.6-cm deep sky strip surveys at the declination of the SS433 source during the 1980-1999 period. Data reduction and the catalog of radio sources in the right-ascension interval* $7^h \leq$ *R.A.* $< 17^h$, Astrophysical Bulletin **65** (2010) 42 [1003.0829].

[7] O.P. Zhelenkova and E.K. Majorova, *Study of RCR Catalogue Radio Source Integral Spectra*, Astrophysical Bulletin **73** (2018) 142 [1805.05656].

[8] L.M. Ker, P.N. Best, E.E. Rigby, H.J.A. Röttgering and M.A. Gendre, *New insights on the* z–α *correlation from complete radio samples*, Mon. Not. R. Astron. Soc. **420** (2012) 2644 [1111.5244].

[9] O.P. Zhelenkova, N.S. Soboleva, E.K. Majorova and A.V. Temirova, *Multiband Study of Radio Sources of the RCR Catalogue with Virtual Observatory Tools*, Baltic Astronomy **21** (2012) 371.

[10] O.P. Zhelenkova, N.S. Soboleva, E.K. Majorova and A.V. Temirova, *Identification and properties of host galaxies of RCR radio sources*, Astrophysical Bulletin **68** (2013) 26.

[11] A.E. Kimball and Ž. Ivezić, *A Unified Catalog of Radio Objects Detected by NVSS, First, WENSS, GB6, and SDSS*, Astron. J. **136** (2008) 684 [0806.0650].

[12] Ž. Ivezić, K. Menou, G.R. Knapp, M.A. Strauss, R.H. Lupton, D.E. Vanden Berk et al., *Optical and Radio Properties of Extragalactic Sources Observed by the FIRST Survey and the Sloan Digital Sky Survey*, Astron. J. **124** (2002) 2364 [astro-ph/0202408].

[13] K.R. Covey, Ž. Ivezić, D. Schlegel, D. Finkbeiner, N. Padmanabhan, R.H. Lupton et al., *Stellar SEDs from 0.3 to 2.5* μ*m: Tracing the Stellar Locus and Searching for Color Outliers in the SDSS and 2MASS*, Astron. J. **134** (2007) 2398 [0707.4473].

[14] X.-B. Wu, G. Hao, Z. Jia, Y. Zhang and N. Peng, *SDSS Quasars in the WISE Preliminary Data Release and Quasar Candidate Selection with Optical/Infrared Colors*, Astron. J. **144** (2012) 49 [1204.6197].

[15] I. Strateva, Ž. Ivezić, G.R. Knapp, V.K. Narayanan, M.A. Strauss, J.E. Gunn et al., *Color Separation of Galaxy Types in the Sloan Digital Sky Survey Imaging Data*, Astron. J. **122** (2001) 1861 [astro-ph/0107201].

[16] C.M. Urry and P. Padovani, *Unified Schemes for Radio-Loud Active Galactic Nuclei*, Publ. Astron. Soc. Pac. **107** (1995) 803 [astro-ph/9506063].

[17] M. Elitzur, *On the Unification of Active Galactic Nuclei*, Astrophys. J. **747** (2012) L33 [1202.1776].

[18] N. Thyagarajan, D.J. Helfand, R.L. White and R.H. Becker, *Variable and Transient Radio Sources in the FIRST Survey*, Astrophys. J. **742** (2011) 49 [1107.5901].

[19] E.O. Ofek, D.A. Frail, B. Breslauer, S.R. Kulkarni, P. Chandra, A. Gal-Yam et al., *A Very Large Array Search for 5 GHz Radio Transients and Variables at Low Galactic Latitudes*, *Astrophys. J.* **740** (2011) 65 [1103.3010].

[20] K.W. Bannister, T. Murphy, B.M. Gaensler, R.W. Hunstead and S. Chatterjee, *A 22-yr southern sky survey for transient and variable radio sources using the Molonglo Observatory Synthesis Telescope*, *Mon. Not. R. Astron. Soc.* **412** (2011) 634 [1011.0003].

[21] A.G. Gorshkov, V.K. Konnikova and M.G. Mingaliev, *Long-term variability of a complete sample of flat-spectrum radio sources at declinations of 4° 6° (B1950)*, *Astronomy Reports* **52** (2008) 278.

[22] E.K. Majorova and O.P. Zhelenkova, *Search for variable sources using data of "Cold" surveys*, *Astrophysical Bulletin* **68** (2013) 418.

[23] O.V. Verkhodanov, E.K. Majorova, O.P. Zhelenkova, M.L. Khabibullina, D.I. Solovyov and Y.N. Parijskij, *Investigation of the RCR catalog sources in the millimeter and submillimeter ranges based on the Planck mission data*, *Astrophysical Bulletin* **70** (2015) 156.

[24] E.K. Majorova, O.V. Verkhodanov and O.P. Zhelenkova, *Search for Candidate Objects with the Sunyaev-Zeldovich Effect on Planck Maps in the Neighborhood of RCR Catalog Radio Sources*, *Astrophysical Bulletin* **75** (2020) 77.