Catalog of Radio Galaxies with \( z > 0.3 \). I: Construction of the Sample

M.L. Khabibullina\(^a\), O.V. Verkhodanov\(^a\)

Special Astrophysical Observatory of the Russian AS, Nizhnij Arkhyz 369167, Russia

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The procedure of the construction of a sample of distant \((z > 0.3)\) radio galaxies using NED, SDSS, and CATS databases for further application in statistical tests is described. The sample is assumed to be cleaned from objects with quasar properties. Primary statistical analysis of the list is performed and the regression dependence of the spectral index on redshift is found.

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1. INTRODUCTION

Radio galaxies, which are among the most powerful cosmic objects, allow us to study the evolution of matter and the dynamics of the expansion of the Universe at different cosmological epochs.

Investigations of these radio sources are linked to several cosmological tests, which permit estimating the parameters and evolutionary characteristics of the Universe. Radio galaxies are identified with giant elliptical galaxies with absolute magnitudes \( M \sim -26 \) and have black holes with masses on the of \( 10^9 \) \( M_\odot \) as their central engines. These facts allow the radio galaxies to be used as tools for the study of the parameters of the distribution of visible and dark matter, dynamics of the Universe, and the history of the formation of its structure. Let us point out various published methods developed to find cosmological parameters from the observed characteristics of radio galaxies \( 1, 2, 3 \), such as:

- “magnitude–redshift” Hubble diagrams (“K–z”) \( 4 \);
- the “size–z” diagram \( 5, 6, 7 \);
- the “age–z” diagram \( 8 \);
- the “source number–flux’ \( \log N - \log S \)’ distribution \( 9, 10 \);
- search for clustering and determination of the clustering parameter \( 11 \);
- search for gravitational lenses \( 12 \);
- investigation of the properties of the radio haloes of clusters of galaxies \( 13 \);
- cosmic background temperature variations caused by the interaction of the large-scale structure (clusters of galaxies) at different redshifts with cosmic microwave background and observed on small angular scales (the Sunyaev–Zel’dovich effect due to inverse Compton scattering) \( 14 \) and on large scales in variable gravitational potential—the Sachs–Wolfe effect \( 15 \). Radio galaxies can be used as a tool for searching for clusters of galaxies \( 16 \):
  - and a number of other methods (see, e.g., reviews \( 1, 2, 17 \)).

A striking feature of radio galaxies is that we observe them virtually from their formation epoch, i.e., their radio sources are so powerful that modern radio surveys have catalogued almost all objects of this type \( 3 \). Such objects can serve as good probes for the study of the formation of clusters of galaxies. Thus Venemans et al. \( 16 \) show that 75% of the radio galaxies with \( z > 2 \) are associated with protoclusters. Based on this fact, the above authors estimate that there are roughly about \( 3 \times 10^{-8} \) of forming clusters per comoving Mpc\(^3\) in the redshift interval \( 2 < z < 5.2 \) with an active radio source. They also estimate the density of protoclusters within the same redshift interval to be of the order of \( 6 \times 10^{-6} \) Mpc\(^3\).

Identification of radio galaxies with giant elliptical galaxies (gE) born as a result of mergers in the early epoch allows them to be used not only to probe the formation of the large-scale structure and test models of star formation. The (“K–z”) diagram confirms the age of the old stellar population in gE-type galaxies \( 4 \) and this fact can also be used to compute the ages of these galaxies \( 15, 19, 20 \) and perform quick photometric redshift estimates for these objects out to \( z \sim 4 \) \( 21 \).

Another important problem associated with the study of radio galaxies is the origin of supermassive black holes. The estimates of energy release in the central engines of radio galaxies at redshifts
4 < z < 5, when the Universe was slightly older than one billion years (in terms of the ΛCDM model), yield black-hole masses on the order of $10^9 M_\odot$, whereas it takes much more than one billion years for such black holes to form [22]. This paradox can be resolved in terms of the hierarchical formation model, but the actual number of such objects (black holes with masses on the order of $10^9 M_\odot$ in the redshift interval 4 < z < 5) in the Universe is not known with certainty.

Distant radio galaxies are selected by a criterion based on the spectral index of their continuum. To this end, lists of sources with ultrasteep spectra are compiled, where the parameters needed are the low–frequency data points on the continuum radio spectra. Among such objects a high percentage of distant radio galaxies is found [23, 24, 27, 28], including the most distant objects with redshifts $z > 4.5$: $z = 5.199$ [22] and with $z = 4.514$ [28].

Nowadays databases and identification techniques allow automating search and identification of distant radio galaxies. A number of authors [29, 30, 31, 32, 33, 34, 35] applied such approaches to study radio sources using CATS [36, 37] and NED [38] (NASA/IPAC Extragalactic Database) databases of astronomical catalogs and SkyView virtual telescope [39], which allow performing morphological analysis of objects.

The catalog of distant radio galaxies can be used not only to perform just purely cosmological studies, but also carry out statistical analyses of identification lists and of the corresponding populations of radio galaxies [42, 43, 44, 45, 35], and simulate radioastronomical surveys at RATAN–600 [46, 47, 48]. Organizing the databases and identifying the available heterogeneous measurements with particular objects are also tasks of great interest, and, as practical experience shows, such compiled catalogs are popular among the astronomical community [37, 49, 50].

Moreover, radio galaxies, as extended objects, may distort microwave background and bias the estimates of the angular power spectrum of CMB [51, 52].

In this paper we report a catalog of radio galaxies with spectroscopic redshifts $z \geq 0.3$ based on the data from the NED, SDSS [3, 53], CATS, and other databases and on an analysis of the corresponding bibliography, which allowed us to discard objects exhibiting quasar properties. There is no yet a consensus among the research community as to which radio galaxies should be considered “distant”, with different authors using this term to denote objects with redshifts above 0.3, 0.5, or 1.0. Based on observational data, one can set the boundary for distant radio galaxies at $z \sim 0.6 - 0.7$ (corresponding the age of the Universe of about 6.5 Gyr), when, according to ΛCDM cosmology, the domination of dark energy (DE) began. The lower redshift boundary can then be set at half this $z$ value. Such a choice permits the test to include the population of galaxies after the beginning of the DE domination.

This is the first publication of a series of three papers dedicated to the construction of the sample and statistical analysis of the catalog of radio galaxies, which contains objects with known spectroscopic $z$ and available radio data and optical photometry. In the future we plan to perform cosmological tests based on the physical parameters of the objects of our catalog.

2. THE CATALOG

2.1. Selection of Objects

To build our primary list, we use the NED database, where we select objects with the following parameters: redshift $z > 0.3$ and morphological type “radio galaxy”. The initial list contained a total of 3364 objects. This galaxy sample is polluted by objects with incomplete data or objects with different properties. Our next stage therefore consisted in cleaning the initial sample from wrong sources. To this end, we select the following objects to be removed from the initial list: (1) objects with photometrically determined redshifts; (2) objects with quasar properties. We performed an extensive scan of the literature including optical, infrared, and radio surveys represented both in the NED and CATS bases [53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114]. The complete catalog is available from the CATS database [55] and CDS ftp [56]. CDS database. Our sample also includes radio galaxies investigated within the framework of the “Big Trio” [26, 27, 115, 116, 117, 118, 119, 120] program, i.e., objects of the RC catalog [121, 122].

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1. http://cats.sao.ru
2. http://nedwww.ipac.caltech.edu
3. http://skyview.gsfc.nasa.gov
4. http://www.sdss.org
5. ftp://cats.sao.ru/pub/CATS/RGLIST
6. ftp://cdsarc.u-strasbg.fr/pub/cats/J/other/AstBu/64.123
7. http://cdsarc.u-strasbg.fr/cgi-bin/VizieR?-source=J/other/AstBu/64.123
with published redshifts and measured photometric magnitudes.

As a result, we compiled a catalog containing 2442 objects for further studies.

Figure 1 shows the location of selected radio galaxies on the sky.

2.2. Description of the Catalog

The catalog of radio galaxies consists of three parts with each dedicated a separate paper. Here we give the list of the objects with the names of the source catalogs (and, in the case of the 3C and 4C surveys, with the source names): equatorial coordinates (J2000.0); spectral indices for the 325, 1400, and 4850 MHz frequencies, and spectroscopic redshifts. No spectral indices are given for galaxies with the fluxes measured only at a single frequency (e.g., SDSS objects with the data from the FIRST catalog [84]).

We compute the spectral indices based on the results of cross identification in the CATS database with a $200'' \times 200''$ identification box. To remove spurious field radio sources within the given box, we apply the technique of data analysis similar to that described by Verkhodanov et al. [29, 34].

The central idea of the method consists in performing joint analysis of the data in the coordinate and spectral spaces in order to identify likely identifications of particular radio sources at different radio frequencies. To this end, we use the 'spg' program [123] of the system of the reduction of continuum data at RATAN-600 radio telescope. To represent the spectra ($S(\nu)$) for the subsequent computation of spectral indices we parameterize them by the following formula $\lg S(\nu) = A + Bx + Cf(x)$, where $S$ is the flux in Jy; $x$, the logarithm of frequency $\nu$ in MHz, and $f(x)$ is one of the functions $\exp(-x)$, $\exp(x)$, or $x^2$.

We collected the optical (DSS2) and radio images (mostly from the NVSS [96]) of the galaxies and their spectra into an atlas, which is available at http://sed.sao.ru/~rita/Atlas_RG.html.

2.3. Statistical Analysis of the Sample

Figure 1 shows the locations of the selected galaxies in the sky. The list as a whole is by no means complete or homogeneous, since the sample contains objects brought from different catalogs and located in mutually unconnected sky areas. The most complete and homogeneous subsample of our list contains SDSS objects, which are indicated by white circles in Fig. 1. Among the SDSS radio galaxies (with the data from the NVSS and FIRST radio surveys) there are many objects with small redshifts ($z < 0.5$) and small fluxes ($S < 15$ mJy), making the subsample in question stand out qualitatively against other subsamples.

We nevertheless view the list reported here as a tentatively pure catalog of radio galaxies suitable for testing cosmological relations. We call this list only tentatively pure, because we cannot say with certainty that selected objects would not be found to exhibit properties typical of another class. The list remains open with both some objects to be possibly removed or new objects added.

The Table and Figs. 2–6 give the primary statistical parameters for the resulting catalog.

Figure 2 shows the histogram of spectral indices at
Table 1: Table. Parameters of the sample of the first part of the catalog of distant radio galaxies \((z > 0.3)\): the median redshift, minimal, median, and maximum 1400 MHz flux in mJy, the minimum, median, and maximum spectral index at 1400 MHz.

| \(z_{med}\) | \(S_{min}\) | \(S_{med}\) | \(S_{max}\) | \(\alpha_{min}\) | \(\alpha_{med}\) | \(\alpha_{max}\) |
|------------|-----------|-----------|-----------|-------------|-------------|-------------|
| 0.5        | 3.5       | 31.6      | 22720     | -2.22       | -0.63       | 1.85        |

Figure 2: Histogram of spectral indices at 1400 MHz. 1400 MHz. We fitted the spectra of the sample mostly by linear functions, resulting on almost wavelength independent distribution. The median of the distribution of the spectral indices for the entire sample is equal to –0.63. Figure 3 shows the distribution of fluxes at the same frequencies\(^8\), and Fig. 4 shows the distribution of redshifts.

Figures 5 and 6 show the “flux–redshift” and “spectral index–redshift” diagrams, respectively.

The “flux–redshift” relation shows a well-defined upper flux envelope (at 1400 MHz, NVSS data), which gives the maximum luminosities of observed radio galaxies at different \(z\), and apparently is due to the dynamics of cosmological expansion. We fit linear regression to the maximum values of the distribution in \(\Delta z = 0.5\) wide bins. Our choice of the \(\Delta z = 0.5\) bin width was determined by the following reasons: it must be (1) small enough (\(\Delta z \leq 1.0\)) to take the differential properties of the population into account and (2) big enough (\(\Delta z \geq 0.1\)) for the bins to contain sufficient number of objects. We adopted \(\Delta z = 0.5\), which is, on the one hand, halfway between the two extremes, and, on the other hand, ensures that bins at \(z > 3\) contain a comparatively large number of objects. The regression relation is given by the formula \(\log S_{1400} = p + rz\), where \(S_{1400}\) is the 1400 MHz flux; \(p = 4.16\) is a constant intercept, and \(r = -0.45\) is the slope of the line. The objects of this sample are to be divided by morphological type and luminosity for further analysis. Here we point out the especially powerful radio galaxies with fluxes lie by more than half a magnitude above the regression boundary: 3C 295 \((z=0.464)\) \(^{102}\), PKS 0742+10 \((z=2.624)\) \(^{124}\), 8C 1435+635 \((z=4.261)\) \(^{125}\). We will analyze the properties of these objects in the third paper dedicated to the catalog. We also do not plot the data point for the radio galaxy VLA J123642+621331 \((z=4.424)\) \(^{126}\), which is included into the catalog, but is absent in the NVSS list (be-

\(^8\) We will report the fluxes in the third paper of this series. The plots here are based on the data adopted from the NVSS survey.
cause of its weak flux (0.5 mJy)).

The “spectral type–redshift” diagram (Fig. 6) shows a well-defined trend—spectral index decreases with increasing $z$ and fits linear regression relation $\alpha = a + bz$, where $a = -0.73 \pm 0.02$ and $b = -0.15 \pm 0.01$ are the intercept and slope, respectively. Some objects exhibit peaks near 1 GHz and at lower frequencies, which result in positive spectral indices at low frequencies. In cases of negative $\alpha$, with steep source spectra, we fitted the spectrum by a linear relation. The spectral indices in the diagram is computed at 1400 MHz. Selection of objects by the steepness of their spectra has been used extensively by a number of authors [24, 26, 27, 25], but we are the first to derive an analytical regression formula for such a large sample of radio galaxies. We compute the regression relation for the median of spectral indices in $z$ bins with a bin width of $\Delta z = 0.5$, which we adopt based on the same considerations as in case of “flux–redshift” diagram (see above), thereby making the inferred regression parameters stable against the eventual future enlargement of the sample. The slope can, in principle, be explained by two selection effects, although physical causes cannot be ruled out:

(1) We adopt the lists of distant radio galaxies from the catalogs compiled by selecting objects with steep spectra. The only way to avoid this effect is to use complete samples of radio galaxies with measured redshifts, which are few.

(2) When we select the most powerful radio sources at large $z$ the radio flux is contributed by hot spots, which have steep spectra. And the farther is the radio source, the more likely for it to be more powerful compared to the surrounding sources and to have a steep radio spectrum. We plan to verify this fact in our future studies by analyzing subsamples of radio galaxies of different luminosities. However, despite the scatter of spectral indices, the analytical form of the regression can be used for preliminary selection of radio galaxies and obtaining preliminary distance estimates, the regression yields a median estimate for a large number of objects.

3. CONCLUSIONS

We report the first part of the catalog of radio galaxies with $z > 0.3$ with complete information on the coordinates of the objects, their spectral indices at radio frequencies, and redshifts. We constructed our catalog based on the lists of objects from the NED...
Figure 6: The “spectral index–redshift” diagram (the spectral indices are computed at 1400 MHz). The triangles and circles indicate the SDSS data and objects of all other catalogs, respectively. The regression fit is drawn for the median spectral indices inside the bins with a redshift bin size of $\Delta z = 0.5$.

and CATS databases. Our sample includes objects of the SDSS survey and of the “Big Trio” program. We perform preliminary statistical analysis and compute the distributions of spectral indices and fluxes and plot diagrams of parameters as functions of $z$. The catalog forms a basis for further study of the objects and of the properties of distant radio galaxies population. For our objects we construct the spectra and the “flux–redshift” and “spectral index–redshift” diagrams. On the former diagram we determine the upper boundary of the dependence of flux on $z$, which can be described by the regression relation $\log S = 4.16 - 0.45z$. The latter diagram yields the regression relation $\alpha(z) = -0.73 - 0.15z$.

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