On the Spectral Index of Distant Radio Galaxies

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The problems of using the spectral index of radio galaxies in various tests, in particular, in selecting distant radio sources are considered. The history of the question of choosing a criterion of searching for distant radio galaxies based on the spectral index is presented. For a new catalog of 2442 radio galaxies constructed from NED, SDSS, and CATS data, an analytical form of the spectral index.redshift relation has been determined for the first time. The spectral index.angular size and spectral index.flux density diagrams have also been constructed. Peculiarities of the distribution of sources on these diagrams are discussed.

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1. Introduction

Radio galaxies are among the most powerful observed space objects, making it possible to use such radio sources to investigate the properties of the Universe at various cosmological epochs. Therefore, constructing samples of radio galaxies from various redshift ranges is one of the most important tasks in observational cosmology.

The sharp fall in the number of observed radio sources with increasing redshift forces us to seek for ways of rapidly selecting distant objects. One of the ways is selection by the spectral index $\alpha < -1.0$ ($S \sim \nu^\alpha$, where $S$ is the flux density and $\nu$ is the frequency). It is based on the fact that the farther the object, the more probable that it will have a steep spectrum. This is one of the first discovered and strongest criteria in searching for distant galaxies based on radio-astronomical data. It was established independently in several works devoted to the identification of radio sources and the analysis of radio-spectra statistics. Among the first papers, we will note the paper by Whitfield (1957), who pointed out a correlation of the spectral index for a radio source with its distance, and the papers by Dagkesamanskii (1969, 1970), who found that there were no distant objects with spectral indices $\alpha > -0.7$ for the 3C sources. Subsequently, Tievens et al. (1979) determined that the fraction of optically identified sources with ultrasteep spectra (spectral indices $\alpha_{178}^{5000} < -1$) decreased with decreasing $\alpha$. Following this work, Blumenthal and Miley (1979) showed the spectral index for 3C and 4C radio sources of various populations to depend on the properties of the objects: their apparent magnitude, redshift, radio luminosity, and angular size. The detected correlation suggested that the steep-spectrum sources were, on average, further away and more luminous than the sources with less steep spectra of the same populations (radio galaxies and quasars). Laing and Peacock (1980) investigated the relation between radio spectrum and radio luminosity for samples of extragalactic sources at 178 and 2700 MHz. The spectra were measured for the extended regions of the radio sources, which were classified by morphological types. At low frequencies, the degree of spectral curvature was found to correlate with the luminosity for sources with hot spots. At high frequencies, the correlation between spectral index and luminosity was confirmed. Laing and Peacock (1980) also confirmed the existence of a spectral index.redshift relation at 178 and 2700 MHz for FR II sources (Fanaroff and Riley 1974). At present, many groups and authors use such a selection of candidates for distant radio galaxies (see, e.g., Chambers et al. 1988; Wieringa and Katgert 1991; Soboleva and Temirova 1991; Röttgering et al. 1997; de Breuck et al. 2000; Pedani 2003; Verkhodanov et al. 2003; Gopal-Krishna et al. 2005; Kramer et al. 2006; Borrancini et al. 2006; Kopylov et al. 2006). Although the criterion based on the spectral index is very efficient, its explanation is not yet completely clear (De Young 2002). Three main, widely used ideas that explain this dependence can be highlighted:

- if the spectral steepness for many radio galaxies increases with frequency, then the spectra of distant objects must be steeper than those of near ones because of the factor $(1+z)$;
– the losses due to the Compton scattering of cosmic microwave background (CMB) photons by relativistic electrons grow, since the CMB radiation density increases as $(1 + z)^3$; these growing losses lead to an aging of the population of electrons, causing a cut-off or an increase in the steepness of the high-energy part of the spectrum where the losses are greatest;

– the selection effect: only bright sources are seen at high redshifts, and it can then be said that precisely these sources exhibit the greatest “depletion” in the high-energy part of the spectrum.

Klamar et al. (2006) give yet another possible explanation for the $\alpha - z$ correlation. They noted that the steep-spectrum sources are rather rare among the nearest FR I radio galaxies, while those with such spectra are located in regions with a high baryon density. It can then be assumed that if there is evolution of the environment of powerful radio galaxies reflected in the richness of the surrounding cluster, then, on average, the radio galaxies are more likely located in regions with a higher ambient density than in less dense regions. Hence follows the observed redshift dependence of the spectral steepness. This can play its role when the gas density as one goes into the past increases as $(1 + z)^3$, while the injection of electrons with steeper spectra occurs naturally and is described as a function of the redshift in the first-order Fermi acceleration processes attributable to the decreasing expansion velocity of the hot spots in the denser and hotter intergalactic medium (Athreya and Kapahi 1998).

Other authors (Kharb et al. 2008), who studied a sample of 13 “powerful classical double” FR II radio galaxies, also analyzed this $\alpha - z$ correlation and pointed out the existence of a redshift dependence of the spectral index for both the hot spots and the core. From the presence of a correlation between the spectral indices for the hot spots and a core with a flatter spectrum, Kharb et al. (2007) drew the conclusion in favor of choosing the explanation of the effect by the electron aging model.

Although as yet there is no general, common consensus on clarifying the nature of the $\alpha - z$ correlation, the very fact that this empirical dependence exists is important for studies. Almost all of the distant radio galaxies found has passed through the stage of such a selection. An example of an object selected in this way is the radio galaxy that is the red-shift record-holder with $z=5.19$ and spectral index $\alpha = -1.63$ (van Breugel et al. 1999). Another example is the object RC 0311+0507 investigated in the “Big Trio” Program (Kopylov et al. 2006). Its redshift is $z=4.514$, it has the record radio luminosity for radio galaxies with $z > 4$, and its spectral index is $\alpha = -1.33$.

We prepared a sample of distant ($z > 0.3$) radio galaxies (Khabibullina and Verkhodanov 2009a, 2009b, 2009c) using the NED 1 CATS 2 (Verkhodanov et al. 2005), and SDS 3 (Schneider et al. 2007) databases for the subsequent application in various statistical and cosmological tests (Verkhodanov and Parijskij 2003, 2009; Miley and De Breuck 2008), in which a large number of objects of the same nature is required to carry out a study. To compile the primary list, we used the NED database, from which we selected objects with the following parameters: the redshift ($z > 0.3$) and morphological properties. Radio galaxies. The initial list contained 3364 object. This sample of objects is contaminated by objects with incomplete information or by objects with different properties. Therefore, the next stage was to clean the initial sample of superfluous sources. For this purpose, we selected the objects that were removed from the primary list (Khabibullina and Verkhodanov 2009a): (1) with photometrically determined redshifts and (2) with quasar properties based on available published data. The final catalog contains 2442 sources with spectroscopic redshifts, photometric magnitudes, radio flux densities, sizes of the radio sources, and radio spectral indices calculated from the results of the cross-identification of the list of selected radio galaxies with the radio catalogs stored in CATS in the frequency range from 30 GHz to 325 MHz. By default, the flux densities are given on the Baars scale. The data collected in the catalog can be used for cosmological luminosity-redshift, angular size-redshift, and age-redshift tests.

In addition, the statistical diagrams for the parameters of radio galaxies and their evolutionary properties can be investigated using the cataloged data.

The goal of this paper is to construct and analyze the spectral index-redshift, spectral index-angular size, and spectral index-flux density diagrams for a pure sample of radio galaxies, which can be used to estimate the redshifts of radio galaxies and to calculate their luminosity function.

2. CALCULATING THE SPECTRAL INDEX

To calculate the spectral indices, we performed cross-identification in the CATS database with a $200'' \times 200''$ identification window. To remove chance field radio objects in the specified box, we used a technique

\begin{itemize}
  \item \texttt{http://nedwww.ipac.caltech.edu}
  \item \texttt{http://cats.sao.ru}
  \item \texttt{http://www.sdss.org}
\end{itemize}
of data analysis similar to that described

in Verkhodanov et al. (2000, 2009). The essence of the method is to use a joint analysis of the data in coordinate and spectral spaces to separate out the probable identifications of specific radio sources at various radio frequencies. The spg program (Verkhodanov 1997a) of the RATAN-600 continuum data processing system is used for these purposes. In describing the spectra $S(\nu)$ of sources with available measurements at several frequencies, for the subsequent calculation of the spectral indices we used an automatic parametrization of $S(\nu)$ by the formula

$$\log S(\nu) = A + Bx + Cf(x),$$

where $S$ is the flux density in Jy, $x$ is the logarithm of frequency $\nu$ in MHz, and $f(x)$ is one of the following functions: $\exp(-x)$, $\exp(x)$, or $x^2$. For 91our sample, the spectra are linear. The accuracy of determining the coefficients of the least-squares fits varies from spectrum to spectrum, but it does not exceed 10\% given frequency was determined as the slope of the tangent to the spectrum at the specified point.

Figure 1 presents a histogram of the spectral-index distribution at 1400 GHz.

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Figure 1: Histogram of the spectral-index distribution at 1400 GHz.

3. STATISTICAL DIAGRAMS

Using the list of selected radio galaxies (Khabibullina and Verkhodanov 2009a), we constructed the spectral index-redshift ($\alpha - z$), spectral index-angular size ($\alpha - \theta$), and spectral index-flux density ($\alpha - S$) diagrams.

The spectral index-redshift diagram is shown in Fig. 3. It has a clear tendency for the spectral index to decrease with increasing $z$ and satisfies a linear regression $\alpha = a + bz$, where $a = -0.7 \pm 0.02$ is the regression constant and $b = -0.15 \pm 0.01$ the slope. Some of the objects have peaks in their spectra at a frequency near 1 GHz and lower, giving a positive spectral index at low frequencies. In the

Figure 2: Histogram of the redshift distribution for the catalog.

Figure 3: Spectral index-redshift diagram. The spectral indices were calculated at 1400 MHz. The triangles and circles indicate the SDSS objects and the objects from all the remaining catalogs, respectively. The regression line was drawn using the median spectral indices within bins with a step $\Delta z = 0.5$. 

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case of negative $\alpha$, when the source has a steep spectrum, a straight line was used to fit. The diagram was constructed for the spectral indices at 1400 MHz. The presented boundaries of the parameter estimates correspond to the statistical ones determined by the least-squares method from the median values. The accuracy of determining the regression parameters can be discussed in terms of sample completeness. However, as the above estimates show, the extrapolation prediction gives a difference in the right boundary value of less than 13 from the first half of the bins. The selection of distant objects by the steepness of their spectra has been widely used in a number of papers (Blumenthal and Miley 1979; Parijskij et al. 1996, 1999; de Breuck et al. 2000), but the analytical form of the regression for such a large sample of radio galaxies has been determined for the first time. The regression was calculated from the median spectral indices at zintervals with a step (bin) $\Delta z = 0.5$. The choice of the bin size $\Delta z = 0.5$ was dictated by two factors: it should not be (1) large, $\Delta z \leq 1.0$, in order to take into account the differential peculiarities in the behavior of the population and (2) small, $\Delta z \geq 0.1$, in order that there be a sufficient number of objects in the specified bins. We chose $\Delta z = 0.5$ on the one hand, as the mean size and, on the other hand, as a bin that allowed a comparatively large number of objects to be obtained at $z > 3$. The chosen bin size makes the regression parameters very stable against an increase in the number of objects during a further possible expansion of the sample.

In principle, the existence of a slope can be explained by two selection effects, although it does not rule out physical causes either.

1. The lists of distant radio galaxies were taken from the catalogs that were compiled by taking into account the selection by a steep spectrum. This effect can be avoided only based on complete samples containing radio galaxies with measured redshifts. There are very few such samples. (2) When we choose the most powerful radio sources at high z, hot spots with steep spectra contribute to the radio emission. The farther the radio source, the more probable that it will be more powerful than the surrounding ones and will have a steep radio spectrum. We are planning to verify this fact in our subsequent paper by studying subsamples of galaxies with different luminosities.

The analytical form of the regression can also be used to preselect objects at given z, to estimate the distances to radio galaxies in the first approximation, and to analyze and model the distributions of the number of sources (Condon 1984; Gorshkov, 1991), which are used to study the luminosity function. The estimate of the regression parameters is stable, because it was made using the median values of large subsamples of radio galaxies. It should be noted that when the spectral indices of radio sources from samples including both radio galaxies and quasars are analyzed, the regions of $z$ with low $z$ are filled (Vollmer et al. 2005). This shifts greatly the dependence $\alpha(z)$ toward larger spectral indices. In addition, to check the stability of the slope, we limited the data used by redshift intervals with $z < 2.5$ (where more than 15 objects fell within the bins being analyzed) and reconstructed the observed regression for them. As a result, the value of $\alpha$ predicted by the regression with incomplete data for $z=5.2$ was -1.34, in contrast to -1.54 obtained for the complete set of bins, i.e., the relative error in the extrapolation to high z is within 13.

Consider satisfactory.

For the angular size.redshift.spectral index diagram (Fig. 4), we made the spectral index.angular size (Fig. 5) and spectral index.flux density (Fig. 6) projections; we presented the former in two forms, highlighting in one case the SDSS objects by symbols and in the other case the objects from different redshift ranges by different symbols: $0.3 < z < 0.7$ (circles), $0.7 \leq z < 1.5$ (squares), and $1.5 \leq z$ (asterisks).

The angular sizes were taken from the NVSS catalog (Condon et al. 1998). The last diagram demonstrates the existing relation between the redshift of a radio galaxy and the radio spectral index. In addition, the expected relation where larger sources have steeper spectra due to synchrotron radiation in extended components is observed in Fig. 5. Note that for the distribution of radio galaxies observed in SDSS, there is a shift toward smaller spectral indices for the case where the distributions of sources in size for the
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SDSS and non-SDSS subsamples do not differ in form.

The difference in the data shown in Fig. 5 can be explained by the selection effect attributable to the existence of a spectral index-redshift relation. The latter is demonstrated in Fig. 5b, where the region of high zis marked by light gray.

On the spectral index-flux density diagram (Fig. 6), we marked galaxies with redshifts in different ranges by different symbols: \(0.3 < z < 0.7\) (circles), \(0.7 \leq z < 1.5\) (squares), and \(1.5 \leq z\) (asterisks). The flux densities were taken from the NVSS catalog (1400 MHz). As we see from the figure, objects from all redshift ranges are encountered in the entire range of flux densities; most of the objects with large spectral indices (\(\alpha > -0.3\)) are the objects with the lowest redshifts in our sample. In addition, a correlation \(\alpha(S_{1400})\) between the spectral index and flux density is observed for all three ranges. We drew linear regressions in the form \(\alpha = d + k\log S_{1400}\) using the median values of \(\alpha\) calculated in logarithmic intervals of flux densities. The regressions for different ranges are indicated in Fig. 6 by the solid line \((d = -0.60; k = -1.8 \times 10^{-4})\) for \(0.3 < z < 0.7\), the dashed line \((d = -1.03; k = -3.7 \times 10^{-5})\) for \(0.7 \leq z < 1.5\), and the dotted line \((d = -1.04; k = -9.2 \times 10^{-5})\) for \(1.5 \leq z\). They confirm the apparent effect of a change in the slopes of the correlations for different redshifts.

4. CONCLUSIONS

We presented the results of our investigation of the \(\alpha - z\), \(\alpha - \theta\), and \(\alpha - S\) diagrams for a sample of radio galaxies containing 2442 objects (Khabibullina and Verkhodanov 2009a, 2009b, 2009c) and constructed from the spectroscopic data collected in NED, SDSS, and archives of the Big Trio program (Parijskij et al. 1996, 1999). For the objects of our list, we found the existence of a regression \(\alpha(z)\) and established its analytical form: \(\alpha(z) = -0.75 - 0.15z\). The estimate of the regression parameters is stable, since is was made using the median values of large subsamples of radio galaxies. This dependence can also be used to pres-
elect objects at given $z$, to estimate the distances to radio galaxies in the first approximation, and to study the luminosity function. Nevertheless, when using the derived relation $\alpha(z)$, we should take into account the fact that the detected regression was obtained from an incomplete sample.

For the correlation $\alpha(S_{1400})$, the regression parameters were found to evolve with increasing $z$. Since correlations (Disney et al. 2008) suggesting the existence of a multiparameter fundamental plane of radio galaxies are found for a number of their physical parameters (total mass, baryon fraction, luminosity, etc.), it may be concluded that the evolution of the dependence $\alpha(S_{1400})$ is also indicative of the possible evolution of the fundamental plane. In turn, the existence of a correlation between the variations in parameters of the fundamental plane and spectral indices argues for the explanation of the dependence $\alpha(z)$ by the electron aging model, which complements the conclusions by Kharb et al. (2007).

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