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Recent results of studies of radio galaxies

H. V. Abrahamyan [*], A. M. Mickaelian[†], G. A. Mikayelyan[‡] and G. M. Paronyan[§]

NAS RA V. Ambartsumian Byurakan Astrophysical Observatory (BAO), Byurakan, Armenia

Abstract

The investigation of the physical properties of Active Galactic Nuclei is one of the most important tasks in astronomy. Until now, the properties of AGN have not been fully studied. Therefore, we have studied a number of important properties of AGN. For example, one of the main properties of AGN is variability. We have studied samples of AGN derived from different methods. For these sources, we have identified some properties of activity in the radio and optical ranges. These properties provide us with insight into active galaxies.

Keywords: *Active Galactic Nuclei, QSO, radio spectral index, cross-correlations*

Introduction

Many active galaxies, especially Active Galactic Nuclei (AGN), are strong in radio wavelengths (e.g., many objects in Véron-Cetty & Véron (2010) have strong radio; the catalogue of Blazars by Massaro et al., 2015 is compiled exclusively from objects having radio detection); hence, studying radio emission from galaxies may be key to identifying the active ones among them. Radio galaxies, quasars, blazars, megamasers and other classes of objects are strong radio emitters. Radio galaxies and their relatives, radio-loud quasars and blazars, are types of AGN that are very luminous at radio wavelengths, with luminosity up to 10^{39} W in the range of 10 MHz to 100 GHz. This radio emission is due to the synchrotron process; the observed radio structure is determined by the interaction between two opposite jets and the external medium, affected by relativistic beaming. The host galaxies are almost exclusively giant elliptical galaxies and radio galaxies can be detected at large distances, making them valuable tools for observational cosmology. Recently, much work has been done related to the effects of these objects on the intergalactic medium as well, particularly in galaxy groups and clusters.

Radio variable sources at 1400 MHz and their optical variability

NVSS and FIRST radio catalogues have been cross-matched. Our principle is to consider positional errors for individual sources, and we have applied a similar approach to our previous research method (Abrahamyan et al. (2015)). In the FIRST catalogue, there is no information on positional errors for each source, that is why 5 arcsecond as the error for all sources. In NVSS catalogue, each source is provided with its individual positional error. We have created software through which cross-correlations are conducted. This software allows for the consideration of positional errors for each source individually, and we have taken associations having coordinate differences between counterparts not exceeding 3 sigma (calculated using both sigma-s from NVSS and FIRST). As a result, we have obtained 556,282 associations between NVSS and FIRST (Abrahamyan et al. (2018)).

Our main task is the revelation of the variability of radio sources in radio wavelengths. For variability criteria, we will consider those radio sources that have associations within less than 3 sigma of the positional errors, and for which the second association is 2 times farther than the first one. The systematic shift (SS) between the fluxes of the NVSS and FIRST catalogues was considered. We counted SS between these

[*]abrahamyanhayk@gmail.com
[†]aregmick@yahoo.com
[‡]gormick@mail.ru
[§]paronyan_gurgen@yahoo.com

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Table 1. Activity types of 6301 radio sources having radio variability.

N_o	Activity Type	Numbers
1	Blazar (BZB, BZG, BZQ, BZU)	308
2	QSO	639
3	Sy 1.0 / Sy 1	19
4	Sy 1.2	2
5	Sy 1.5	6
6	Sy 1.9	2
7	Sy 2.0 / Sy 2	9
8	AGN	97
9	Starburst	1
10	FSS (Flat-Spectrum radio source)	87
11	USS (Ultra-Steep-Spectrum radio source)	36
	Known (total)	**1206 (19%)**
	Unknown	**5095 (81%)**
	Total	**6301 (100%)**

Table 2. Activity types of 2425 radio sources having both radio and optical variability.

N_o	Activity Type	Numbers
1	Blazar (BZB, BZG, BZQ, BZU)	176
2	QSO	333
3	Sy 1.0 / Sy 1	9
4	Sy 1.5	6
5	Sy 2.0 / Sy 2	5
6	AGN	45
7	FSS (Flat-Spectrum radio source)	41
8	USS (Ultra-Steep-Spectrum radio source)	4
	Known (total)	**619 (25.5%)**
	Unknown	**1806 (74.5%)**
	Total	**2425 (100%)**

catalogues to get rid of systematic errors that could appear due to different flux calibration. As FIRST accuracy is higher, we have shifted NVSS using SS. The First step that was accomplished is computing systematic shift (SS) for fluxes between NVSS and FIRST (SS=-0.765 mJy).

$$\Delta F = |F_{FIRST} - (F_{NVSS} - SS)| - 3\sigma \quad (1)$$

Where σ is the combined error of radio fluxes:

$$\sigma = \sqrt{\sigma^2_{FIRST} + \sigma^2_{NVSS}} \quad (2)$$

We have carried out a cross-correlation of NVSS and FIRST catalogues to distinguish sources that have large differences of fluxes at 1400 MHz. We have selected 6301 radio sources with a flux difference of at least 15 mJy. Further investigation of these radio sources led to a new sample of radio sources, which also exhibit high optical variability.

Optical variability of blazars

To understand some properties of blazars, we used the Roma Multifrequency Catalog of Blazars (BZCAT) 5th version. Altogether, 3,561 objects are classified as BZB, BZQ, BZG, or BZU, corresponding to BLL, FSR quasars, galaxies, and blazars of uncertain/transitional type (Abrahamyan et al. (2019)).

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Having 3,561 blazars that exhibit radio variability, we aim to determine how many of these sources are optically variable. We cross-correlated these radio sources with POSS1-based and POSS2-based optical catalogs: APM, USNO A2.0, USNO B1.0, and GSC 2.3.2. In Figure 1, we present graphs of absolute magnitude versus redshift. Essentially, the objects are grouped into three loci (BZB, BZG, and BZQ).

Three types of blazars (BZB, BZG, and BZQ) are mostly separated, but there is some overlap among them to some extent.

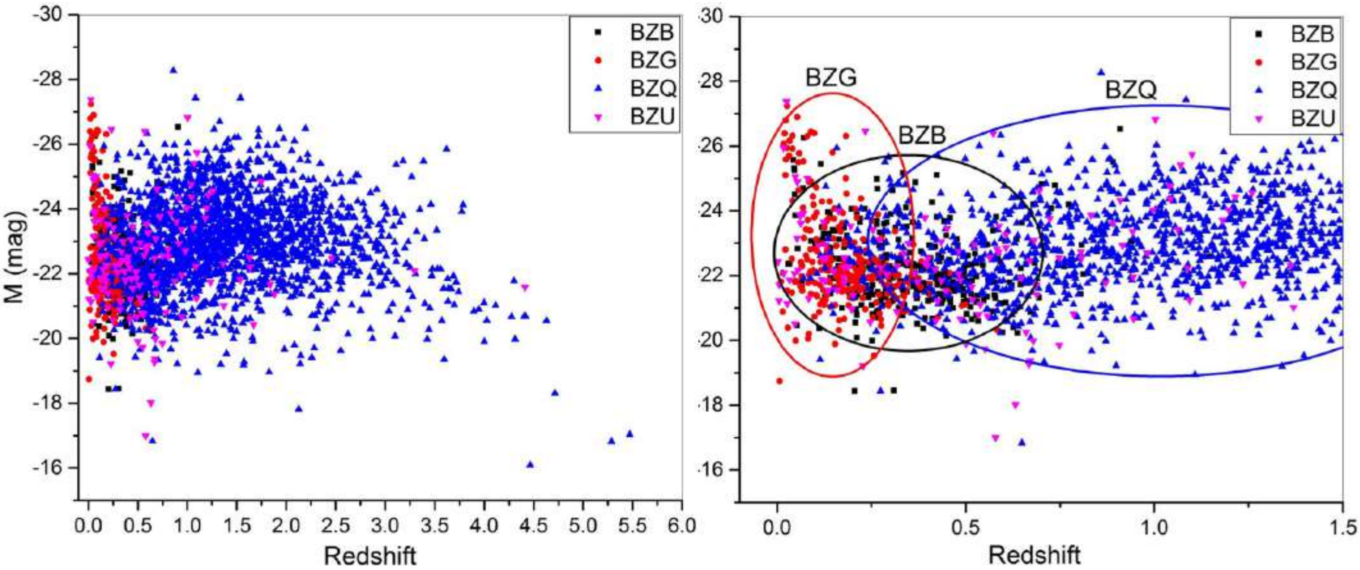

Figure 1. Absolute magnitude vs. redshift.

We have obtained 2,121 blazars that exhibit optical variability using POSS1 and POSS2 epoch measurements. We have compared our work with the one reported by Hovatta et al. (2014). In this work, the authors investigated optical data from the PTF and the CRTS to study the variability of gamma-ray-detected and non-detected objects within a large population of AGN selected from the Candidate Gamma-Ray Blazar Survey and Fermi Gamma-Ray Space Telescope catalogs. Their samples include 714 sources with PTF data and 1,244 sources with CRTS data. We compared our list with the list by Hovatta et al. (2014). As a result, we identified 704 sources.

The nature of active galaxies based on their radio properties

We use data from Véron-Cetty & Véron (2010). This catalog includes 133,336 quasars, 1,374 BL Lac objects, and 34,231 active galaxies (including 16,517 Seyfert 1.0). We have considered 34,231 active galaxies for our research (Abrahamyan (2020) and Abrahamyan et al. (2020)).

For investigation, galaxies with magnitudes in the range of 12^m-19^m have been selected. In the next step, we have cross-correlated (Abrahamyan et al. (2015)) these objects with radio catalogs: FIRST, NVSS, 87GB, GB6, 3C, 4C, 7C, 8C, 9C, 10C, SUMSS, WISH, WENSS, Molonglo Reference Catalogue of Radio Sources, Texas Survey of radio sources at 365 MHz, Miyun 232 MHz survey, CLASS survey of radio sources, 74MHz VLA Low-frequency Sky Survey Redux, and the GMRT 150 MHz all-sky radio survey. As a result, we have 4,437 objects that have been radio-identified. 4,437 objects have 1-10 radio fluxes at different wavelengths. In this work, radio catalogs that cover the 38 MHz to 15.7 GHz frequency range have been used. For our investigation, we have taken objects that have six or more radio fluxes at different wavelengths, in total 198 objects. With six and more radio fluxes, there is an opportunity to better understand some physical properties in radio, namely the radio indices.

Active galaxies are very interesting objects in the Universe. In order to understand some physical properties, we must identify which properties our objects have in the radio range. We have 198 active galaxies with six or more radio fluxes at different wavelengths. A very important radio property for radio objects is the radio spectral index. Using six or more frequencies, we have developed a graph for all 198 galaxies (lg[flux] vs. lg[frequencies]). Using an lg[flux] versus lg[frequencies] graph for each source, we have made linear fitting. The software "Origin" gives the formula for each linear fit, and using that, we have measured the radio spectral index for each source.

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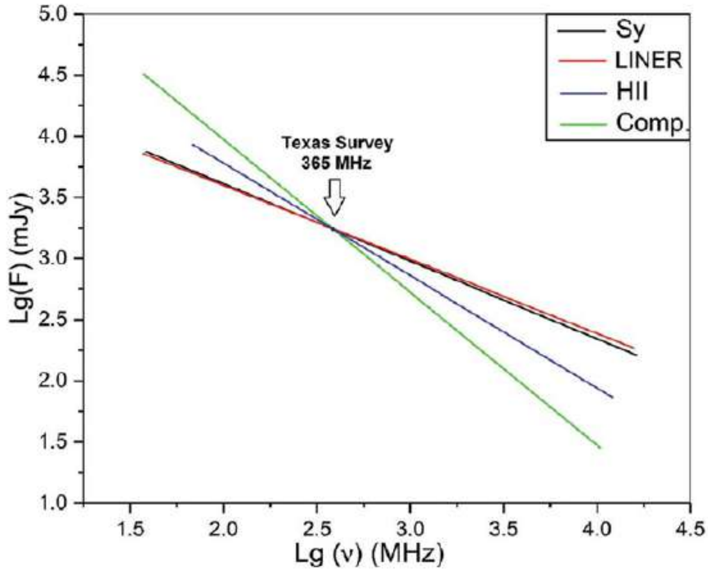
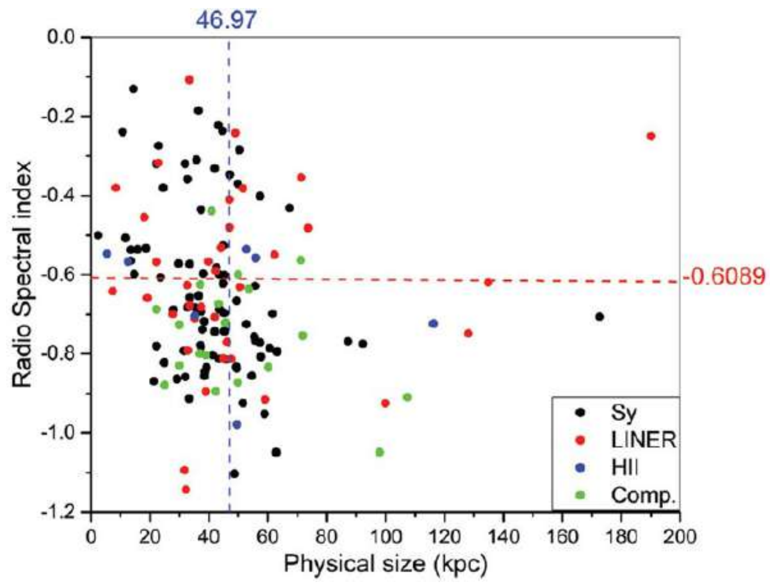


Activity type	Average radio spectral index
Seyfert	-0.6013 ± 0.027
Low-ionization narrow emission-line region	-0.5955 ± 0.025
HII	-0.6672 ± 0.039
Composite	-0.7128 ± 0.043
All	-0.6089 ± 0.056

Figure 2. Average radio spectra for our objects.

The plot shows steep radio spectra for each line, which is considered the radio spectral index. As examples, we present average radio spectra for our objects in Figure 2.

Using redshift information, we have estimated the physical sizes of our objects. We have eight objects that exhibit HII activity. For these sources, we have also estimated physical sizes, and for one of them, we have obtained a very large physical size (832.2 kpc) compared to the other HII objects, which are up to 116.35 kpc. With the purpose of calculating the average size and drawing other comparisons, we have excluded this object. Therefore, using physical sizes, we have developed the dependence of the radio spectral index on physical size (Figure 3).



Activity type	Range of sizes (kpc)	Average size (kpc)	RMS (kpc)
Seyfert	$2.39 \div 305.46$	44.88	35.62
Low-ionization narrow emission-line region	$7.36 \div 190.19$	50.15	36.14
HII	$5.4 \div 116.35$	46.81	33.81
Comp.	$22.27 \div 107.51$	50.23	22.46
All	$2.39 \div 305.46$	46.97	32.26

Figure 3. Radio spectral index versus physical size.

Results and Conclusions

We have cross-correlated NVSS and FIRST radio catalogues having radio flux measurements at the same 1.4 GHz frequency. This way we benefit from repeated observations from both catalogues, as they give more accurate positions and fluxes and more important, reveal large differences between the two measured fluxes, thus allowing to establish radio variability. As a result, 79,382 radio variables have been revealed, including 6301 with flux differences at 1.4 GHz larger than >15 mJy, 1917 with flux differences >45 mJy and 260 with flux differences >200 mJy. By using a special technique, 2425 optically variable objects out

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of 6301 radio sources have been revealed. 2425 radio sources with both high radio and optical variability were grouped into four categories. 1206 (19%) out of 6301 radio sources have activity types from available catalogues and 619 (25.5%) out of 2425 radio sources with at the same time radio and optical variability have activity types from available catalogues. In addition, 279 radio sources out of 2425 have high variability in the optical range. We have established their activity types when available. The IR fluxes and colors for the 6301 variable radio sources have been studied. Color-color diagrams show that most of the "unknown" sources are galaxies. The activity types for 110 (42%) out of 260 extremely high variable radio sources have also been retrieved (Abrahamyan et al. (2018)).

The analysis of blazars' parameters from BZCAT leads to a conclusion that they do not have the same properties. The preliminary criterion for including an object in the catalog was strong radio emission; however, two types of radio sources were selected: BL Lacertae (BLL) objects and Flat Spectrum Radio Quasars (FSRQ). As a number of properties are typical of blazars (strong radio emission, optical variability, continuum optical spectra without lines, polarization, high luminosity, etc.), using the optical data, we investigate them to clarify which property plays the most significant role in their classification as blazars. We found that 60% of blazars have optical variability. We use a technique developed based on POSS1 and POSS2 photometry and group the variability into extreme, strong, medium, and low classes. In the optical range, 51 blazars have powerful variability (extreme variables), and 126 are high variables. In addition, 63% of blazars have detected radiation in X-ray and 28% have detected radiation in gamma rays. We give the average statistical characteristics of blazars based on our analysis and calculations in Abrahamyan et al. (2019).

In the next work we investigate radio properties of active galaxies taken from Véron-Cetty & Véron (2010) catalogue. The galaxies are limited to magnitudes in the range of 12^m-19^m. We have cross-correlated the list with radio catalogues and selected those galaxies, which have data on 6 or more radio fluxes at different wavelengths. As a result, we have 198 galaxies, which satisfying these conditions. Using SDSS DR15, we have obtained 96 spectroscopic identifications out of the 198 objects. After the classification, 85% of 96 objects have changed their types. Available data on the classification of these objects and our classification showed that 56.7% of them are Seyfert galaxies. For all the objects we have built radio spectra and estimated radio spectral indices. As a result, we obtain α_{ave}= -0.6089±0.056 ($\alpha_{Seyfert}$ =-0.6013±0.027, α_{LINER}=-0.5955±0.025, α_{HII} =- 0.6672±0.039, α_{Comp} =-0.7128±0.043). We discuss the radio properties of active galaxies based on their radio spectral indices. Using the spectra from the SDSS catalog, 96 objects were studied and detailed types of activity were given for them. For more confident classification we used three diagnostic diagrams and direct study of the spectra. As a result, we have changed classification for 85% of these objects (Abrahamyan (2020) and Abrahamyan et al. (2020)).

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