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On the perspectives for separating the radio flux variations of the nucleus and the jet of active galactic based on data from monitoring programs and VLBI observations

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The subject and purpose of the work: the possibility of separating the spectral flux densities of the active core and the jet of sources (3C 120, 3C 273, 3C 345, 3C 454.3, 3C 446, Bl Lac, CTA 102, OJ 287, OT 081) is considered. The data of long-term monitoring of changes in the integral flux of extragalactic radio sources performed on the 26-meter telescope of the University of Michigan UMRAO (1969–2012) at frequencies of 14.5, 8, 4.8 GHz are used. Also, data on the core flux and images of active galactic nuclei at a frequency of 15–15.4 GHz VLBA monitoring MOJAVE are used. The subject of this work is to separate the jet flow from the integral flux from the source, as well as to compile the catalog of the quasi-periods of variability of nuclei and jets separately. Methods and methodology: Fourier-periodogram analysis is used to distinguish long-term and short-period variability of nuclei and jets of extragalactic sources. Autocorrelation calculations were carried out in order to confirm the periods of variability. Results: conclusions were made about the applicability of the described method for separating the jet flux, and a catalog of long-term and short-period variability of radio emission fluxes from nuclei and jets for the investigated radio sources was compiled.

Keywords: Fourier, periodogram, quasi-period, AGN, variability

1 Introduction

The flux of radio emission from active galactic nuclei and their jets, as well as its variability, carries important information about the physics of the processes occurring

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in them. This article presents a method for separation core and jet flux using VLBA observational data. From the archive of continuous monitoring of the University of Michigan Radio Astronomy Observatory (UMRAO), data on the integral flux from radio sources 3C 120, 3C 273, 3C 345, 3C 454.3, 3C 446, Bl Lac, CTA 102, OJ 287, OT 081 were taken. Observations with the RT-26 radio telescope were carried out at frequencies of 14.5, 8 and 4 GHz in the period from 1969 to 2012. This paper considers the Seyfert galaxies of the first type: 3C 120 ($z \sim 0.033$), 3C 273 ($z \sim 0.158$); quasars: 3C 345 ($z \sim 0.59$), 3C 454.3 ($z \sim 0.86$), 3C 446 ($z \sim 1.4$), CTA 102 ($z \sim 1.04$); lacertids: BL Lac ($z \sim 0.069$), OJ 287 ($z \sim 0.31$), OT 081 ($z \sim 0.32$). All sources have a spectral peak at low frequencies ($<10^5$ GHz) (according to MOJAVE data) (http://www.physics.purdue.edu/astro/MOJAVE/allsources.html).

For the selected sources, earlier investigations of quasi-periods in the integral flux were carried out using the methods of singular spectrum and wavelet analysis [1–5]. Also, forecasts of their integral flux were built in [5,6].

Based on the UMRAO observational data for selected sources, using the method of wavelet analysis, the presence of the main quasi-periods of variability and the time of their existence were revealed. The results of the research are presented in [5].

The results of VLBA observations at frequencies of 15–15.4 GHz are presented by the MOJAVE database, which contains data on the fluxes of the core and radio images of the objects under study since 1995.

The reasons for the variability are very diverse and are explained in different works by the spirality and inhomogeneity of the jet, as well as by the precession and changes of the Lorentz and Doppler factors, shock waves in the jet [7], accretion processes, interactions between the jet and the accretion disk [8], or perturbation of the accretion disk by a companion black hole [9]. Thus, the variability of the source as a whole consists of the variability of the flux separately from the core and the jet. The variability of the core flux is due to the manifestation of activity in the accretion disk. The observed variability of the jet flux is due to the passage of shock waves in the jet, the multilayer magnetic structure, relativistic effects, and the processes of its formation. Due to the considerable length of the jet, the processes occurring in it have a large delay time in relation to the activity of the nuclei.

The purpose of this work was to check the possibility of separating the flux of the core and the jet using VLBA observations for further construction of the catalog of jet variability and determination of the relationship with the variability of the core.

2 Data processing methodology

In this work, we used the observation data of the RT-26 UMRAO radio telescope at a frequency of 14.5 GHz, which were submitted under a cooperation agreement. The methodology for processing observational data at RT-26 is presented in [5], for data acquisition in [10]. To separate the fluxes of the core and the jet, the results of VLBA observations for the studied sources from the MOJAVE database in the time interval coinciding with the UMRAO observation data at frequency of 15 GHz were used. To prepare the data for the application of fast Fourier transform (FFT) and autocorrelation, the data was interpolated with an equal step, and a linear trend was subtracted from the data. The FFT procedure used a Hamming window (to reduce

distortion in large periods). To simplify the auto-correlation calculations, the data were reduced to the maximum value of the radio flux.

As part of this work, to automate its execution, we wrote a script in Wolfram Language which automated the analysis of the data.

2.1 Data processing of radio fluxes of investigated sources

The data from the MOJAVE Database were interpolated with an equal step of ∼5 days for 3C 120, 3C 273, ∼10 days for 3C 345, and ∼15 for 3C 454.3, ∼7.3 days for sources 3C 446, Bl Lac, CTA 102, OJ 287, OT 081 (Fig. 1).

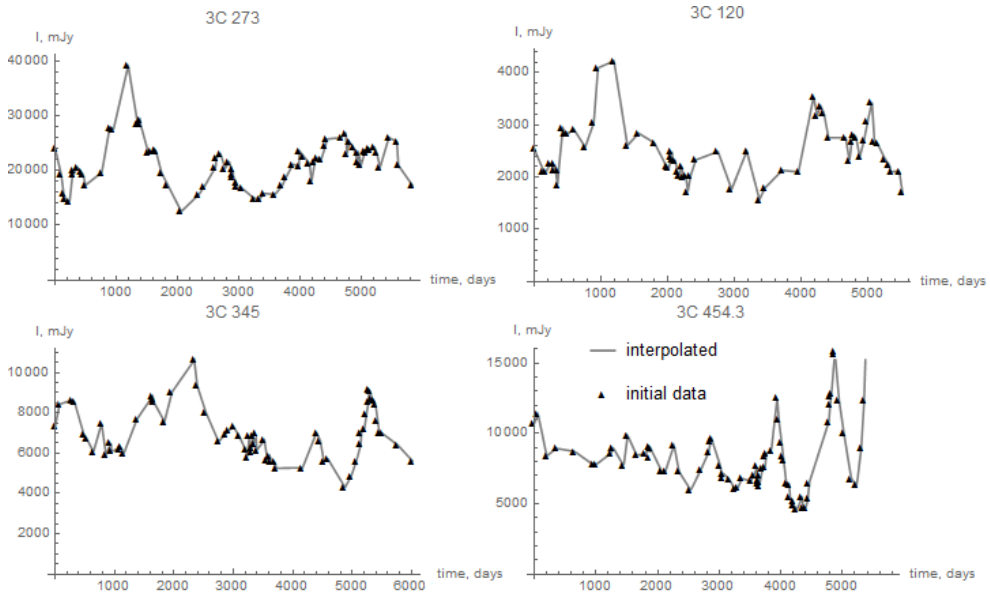


Figure 1 Comparison of the initial and interpolated data of core radio fluxes of sources 3C 273, 3C 120, 3C 345, 3C 454.3.

Further, the linear trend was subtracted and all data for autocorrelation were reduced to the maximum flux. Also, at the beginning and end of the data array, as many zeros were added as there are points in the signal (Fig. 2).

For continuous functions $f(t)$ of a real variable, the autocorrelation function $\Psi(\Delta t) = \int\limits_{-\infty}^{+\infty} f(t)f(t-\Delta t)\,dt$. For a discrete function, you can submit autocorrelation function in the form: $\Psi(\Delta t_j) = \sum\limits_i f(t_i)f(t_i - \Delta t_j)\Delta t_i$, Δt_i – the distance between the points at which the signal is defined. Δt_j – interval by which the initial signal is shifted. For a discrete signal, we can build an interpolation function and use the integral form.

As can be seen from the method of setting the autocorrelation function, for periodic signals, the autocorrelation function will be periodic with the same period. Thus, this will be another way to confirm the found periods (Fig. 3).

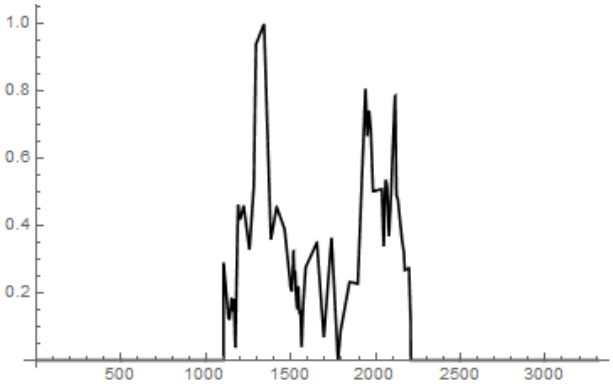


Figure 2 An example of substracting a linear trend and reducing the signal to one for a 3C 120 source.

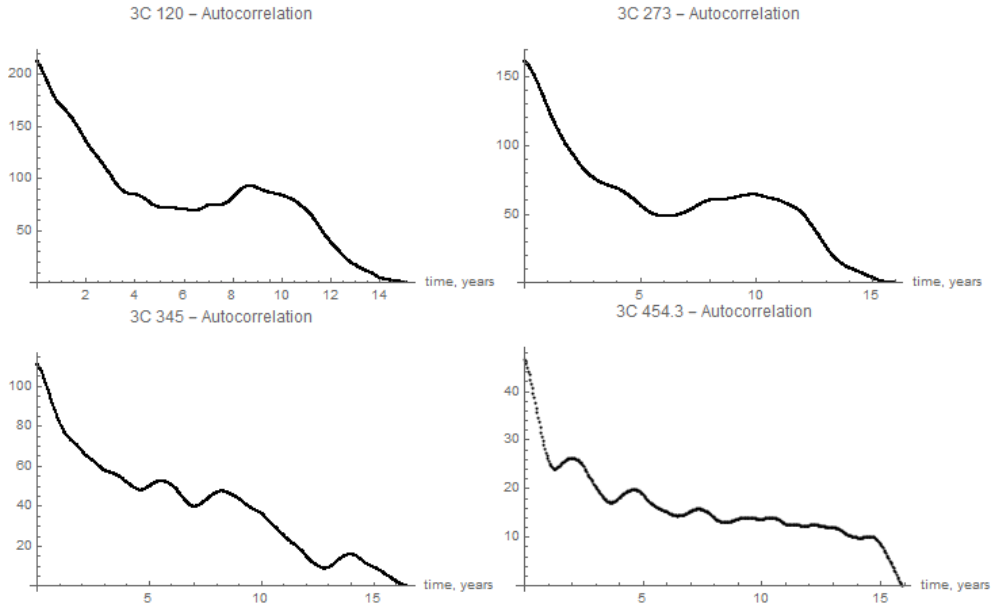


Figure 3 Autocorrelation of the radio flux of nuclei of sources 3C 120, 3C 273, 3C 345, 3C 454.3.

Next, the Hamming window functions were applied (Fig. 4) to the signal with subtracted trends and the fast Fourier transform was performed (Fig. 5).

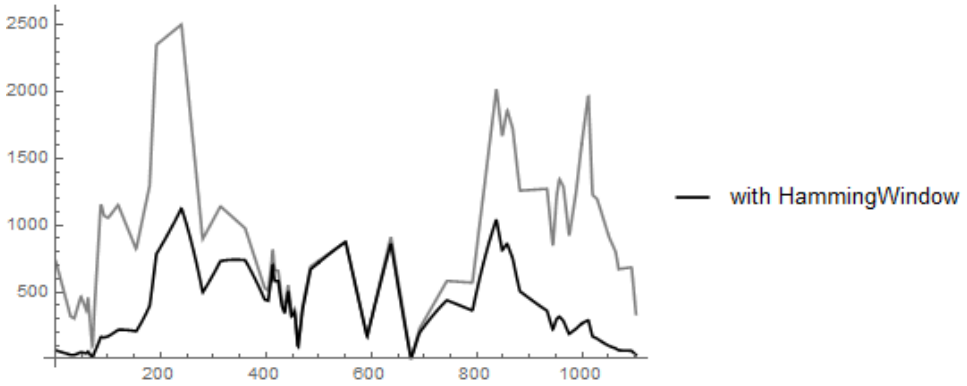


Figure 4 Applying a window function to interpolated trend-subtracted data for source 3C 120.

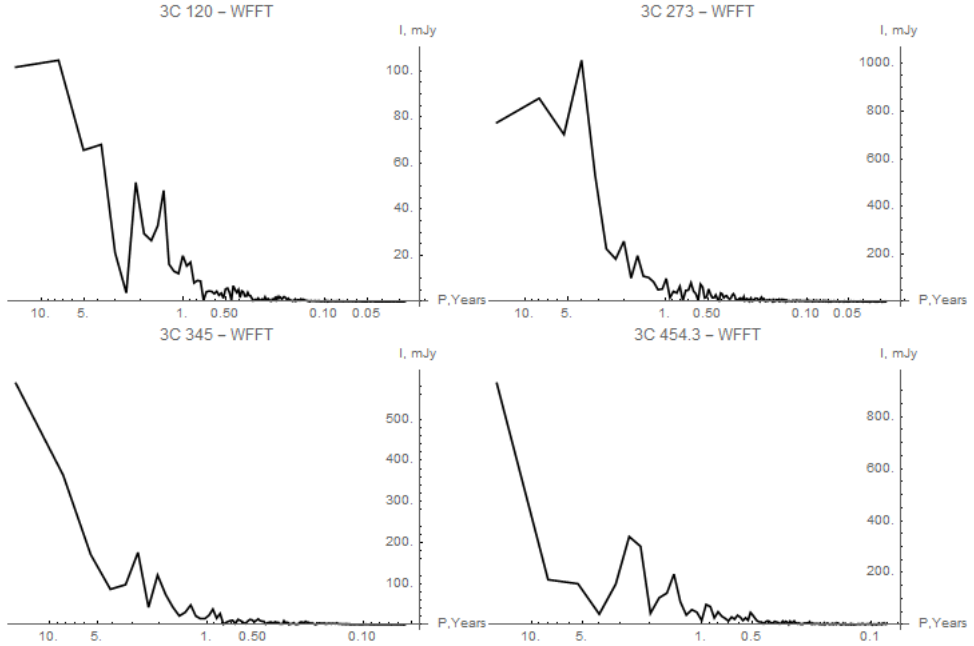


Figure 5 Fourier spectra (amplitude – period) of sources 3C 273, 3C 120, 3C 345, 3C 454.3, abscissa axis is in logarithmic scale.

2.2 Extraction of the jet radio flux and processing of the received data

The time intervals were selected, at which observations were carried out both on the RT-26 UMRAO (Fig. 6) and the VLBA MOJAVE program (Figs 1, 7) for the sources

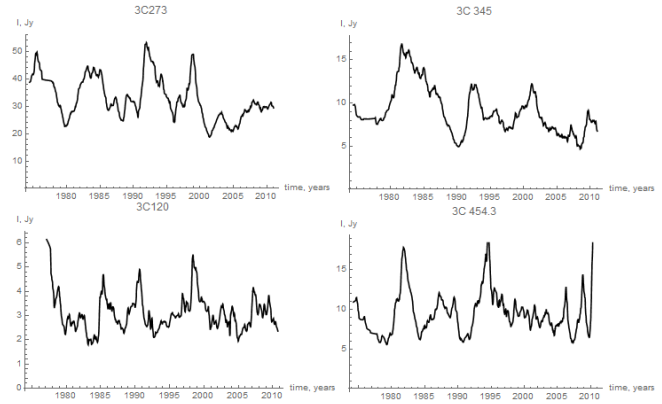


Figure 6 Observational data of UMRAO sources 3C 120, 3C 273, 3C 454.3, 3C 345 from 1974 to 2011 at a frequency of 14.5 GHz.

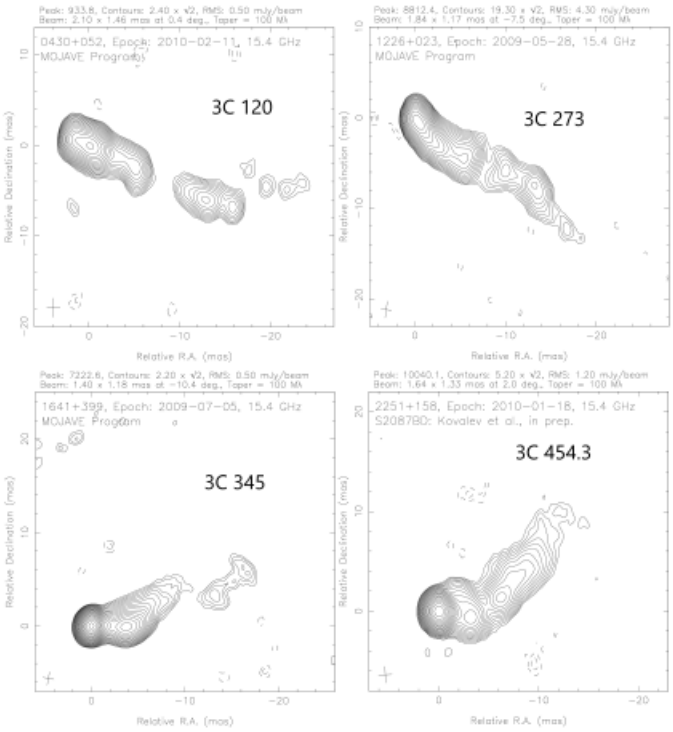


Figure 7 Radio maps provided by the MOJAVE project for sources 3C 120, 3C 273, 3C 454.3, 3C 345.

under study. The data of two series of observations were interpolated with an equal step at the same time points (Fig. 8), after that, from the integral flux over the entire source, measured by RT-26 UMRAO, the core flux, which was obtained from the MOJAVE database, was subtracted. As a result, a series of data was obtained that contained a jet flux (Fig. 9) and Fourier spectra of jet fluxes (Fig. 10).

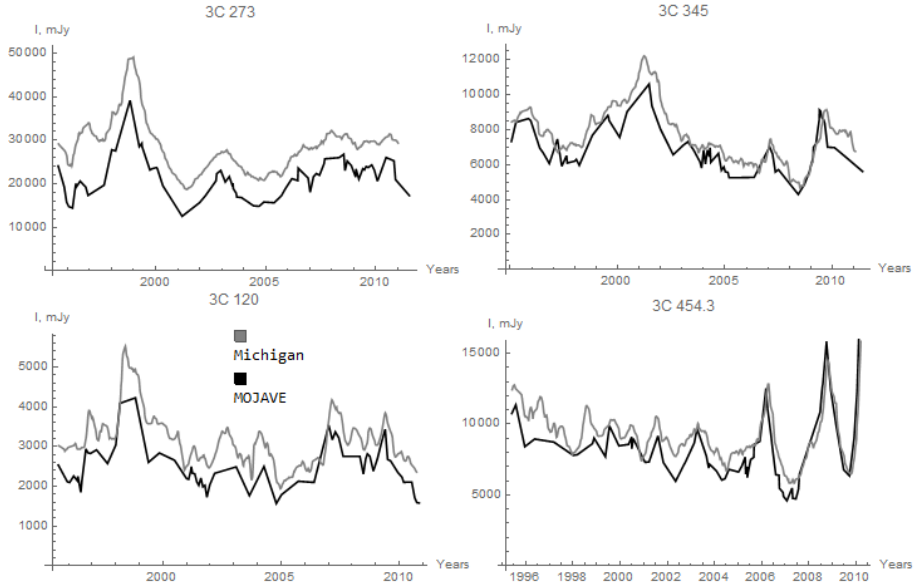


Figure 8 Comparison of data series, core fluxes provided by MOJAVE and UMRAO integral fluxes from sources 3C 273, 3C 120, 3C 345, 3C 454.3).

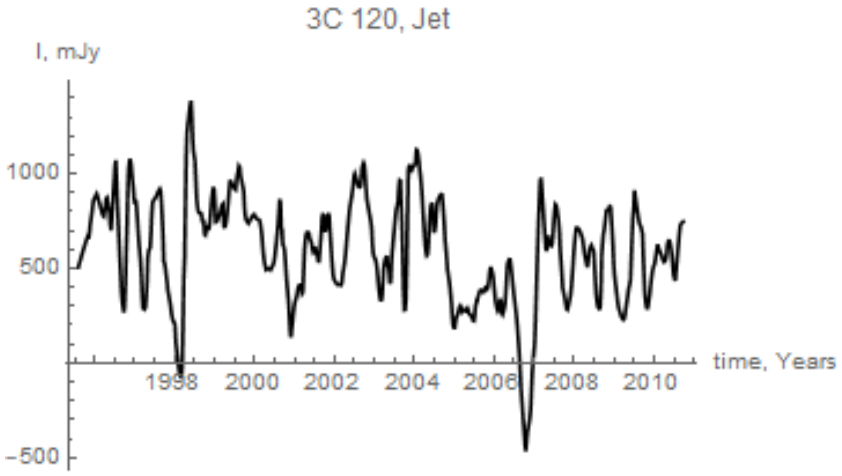


Figure 9 Jet flux extracted from the integral flux by subtracting the core flux for the 3C 120 source.

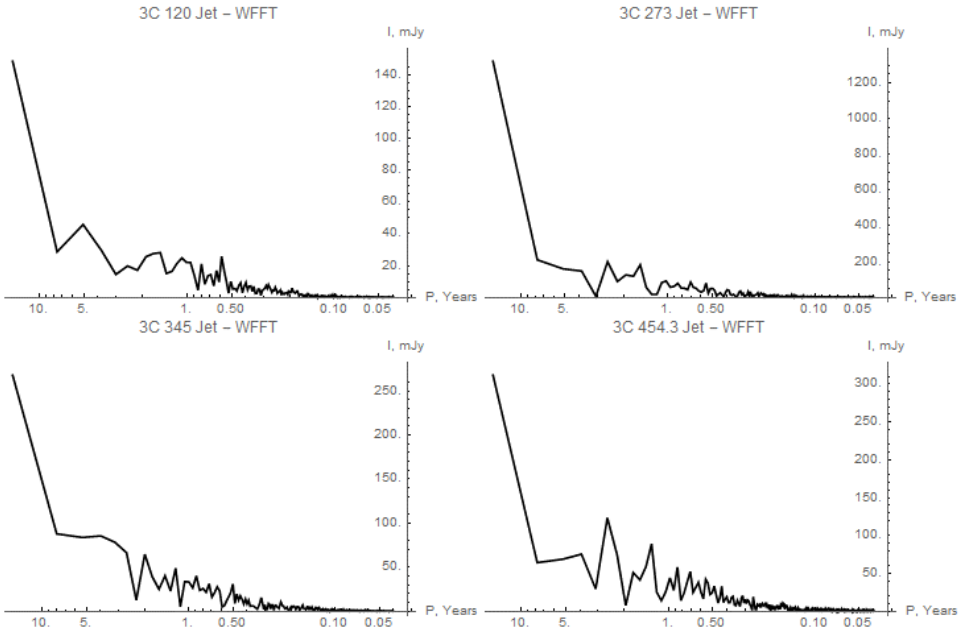


Figure 10 Fourier spectra of jet fluxes (amplitude – period) of sources 3C 273, 3C 120, 3C 345, 3C 454.3, abscissa axis is in logarithmic scale.

3 Variability catalogs

The work [5] presents the results of the analysis of the variability of the integral flux from sources, which are considered in this work. The singular spectrum method was used to determine the quasi-periods of variability of these sources. The results are presented in Table 1. The singular spectrum method, unlike the Fourier transform,

Table 1 The catalog of the variability of the integral flux of radio sources obtained by the method of analysis of the singular spectrum.

Source	Observation interval, years	Long-term variability, years	Short-period variability, years
3C 120	1974.6–2011.1	∼9.7, 6.5, 4.1	∼2.5, 2.0
3C 273	1974.4–2011.1	∼8, 5.2, 4	∼3.5
3C 345	1974.4–2011.1	∼15.6, 11, 9.9, 5.1, 4.2	∼3.3, 2.7, 2.0
3C 454.3	1974.2–2011.1	∼6.2	∼3.5, 2.7, 2.3
3C 446	1979.9–2011.1	∼8.6, 6.5	∼3.5, 2.8
BL Lac	1974.2–2011.1	∼7.3, 4.5	∼3.8, 2.7, 2.4, 1.9
CTA 102	1999.1–2011.1	–	∼3, 0.8
OJ 287	1974.5–2011.1	∼6.0	∼2.4, 2.1, 1.9, 1.6
OT 081	1999.1–2011.1	–	∼2.6, 1.1, 0.6

does not have an analyzing function. The analysis of the singular spectrum consists in the decomposition of the original signal into frequency components: trend, harmonic components and noise components. A description of this method is presented in [6]. This method, like FFT, does not provide the ability to analyze changes in quasiperiodic components over time.

Further, the most significant and large in amplitude quasi-periods of variability of the nuclei and jets of sources were identified (Tables 2, 3).

Table 2 The catalog of variability of source core fluxes.

Source	Observation interval, years	Long-term variability, years	Short-period variability, years
3C 120	1995.6–2010.7	∼3.8, 8	∼0.8, 0.9, 1, 1.4, 2.2
3C 273	1995.6–2011.5	∼4	∼0.5, 0.7, 0.8, 1, 1.6, 2
3C 345	1995.1–2011.6	∼2.7	∼0.8, 0.9, 1.3, 2
3C 454.3	1995.1–2011.9	∼2.7	∼0.5, 0.8, 0.9, 1.1, 1.5
3C 446	1995.6–2011.0	∼4.5, 9	∼0.7, 1–1.2, 3
BL Lac	1995.3–2011.0	∼2.4–3	∼0.5, 1.1–1.3
CTA 102	1999.2–2011.1	∼3.7	∼1.2–2.7
OJ 287	1995.3–2011.1	∼6.0	∼0.7, 1–1.4
OT 081	1999.1–2011.1	∼4.2	∼0.66, 0.9, 1.2

Table 3 The catalog of variability of source jet fluxes.

Source	Observation interval, years	Long-term variability, years	Short-period variability, years
3C 120	1995.7–2010.7	∼5	∼0.6, 0.8, 1.1, 1.5–1.9
3C 273	1995.7–2011.0	∼2.6	∼0.4, 0.5, 0.7, 0.8, 1, 1.5
3C 345	1995.0–2011.0	∼–	∼0.5, 0.6, 0.7, 0.9–1.1, 1.2, 2
3C 454.3	1995.5–2011.0	∼2.6	∼0.6, 0.7, 0.9, 1.3, 2.6
3C 446	1995.6–2011.0	–	∼0.7, 1–1.2
BL Lac	1995.2–2011.0	∼2.6-4	∼0.5, 0.7–1.1
CTA 102	1999.2–2011.1	∼3	∼0.7, 1
OJ 287	1995.3–2011.1	–	∼0.8, 0.9, 1.3, 1.8
OT 081	1999.1–2011.1	∼2.4, 4	∼0.66–0.75, 0.9–1.5

4 Conclusions

In the course of the work, using the UMRAO and MOJAVE observational data, the method of separating the fluxes of the nucleus and jet of the AGN was tested. Based on the data on the integral AGN flux of the UMRAO program, from which the AGN core flux was subtracted (from the MOJAVE database), time series were obtained that represent the jet fluxes. Using the FFT analysis method, the most significant quasi-periods of variability of jets and nuclei of AGN were obtained. A general analysis of the quasi-periods of variability of the integral flux of the sources under consideration

is presented in [1–5]. For all sources, the values of the short-term quasi-periods of the core and the jet turned out to be comparable. At the same time, the long-period components for the nuclei and jets for some sources of this group are different enough (3C 120, 3C 273, 3C 446, OJ 287, OT 081). But for BL Lac and CTA 102, as well as for 3C 454.3, the long-period components of the nucleus and the jet have similar values. In general, the tendency is that the periods of jets are shorter than the periods of nuclear activity. This may indicate the characteristic size of the region of activity in the jet compared to the AGN nucleus. In the future, for a more detailed analysis, the wavelet spectra will be calculated, which make it possible to determine the lifetime of variability periods in the core and jet of the AGN, on the basis of which we can try to explain the evolution of the sources on the radio images obtained by the VLBI.

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