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Results of studying the radio and optical variability properties of MRK 501 active galaxy

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MRK 501 is a giant radio galaxy with an active core in the constellation Hercules. It is a powerful gamma source. MRK 501 has gamma cyclic variability as well as high X-ray and optical activity. MRK 501 is a quite powerful variable radio source, with a flux density at 15 GHz about 1.2 Jy. Of particular interest is the presence of cyclic brightness variations in gamma and optical ranges, which, according to modern models, may be caused by the presence of a supermassive double black hole in the core of the galaxy MRK 501. In this work, optical observatories of three countries, Ukraine (Mayaki, Heavenly Owl), Slovakia (Vihorlat) and Latvia (Baldone), took part in a joint project to study the rapid variability of AGN in radio and optical bands. The analysis of observations obtained from different observatories in V, R, I bands showed the presence of a wave-like, presumably cyclic, variability in the light curves with an average quasi-period of 46.7 days. Taking into account that a quasi-period of about 23 days was detected in the gamma range, it is most likely that we have found a harmonic (doubled value) of this period in the optical range, which is a new result. In addition, an analysis of long-term variability of MRK 501, from historical light curves of the AAVSO catalog, showed the presence of two longer cycles of variability with quasi-periods of about 1 year and about 5–6 years. It is shown that these quasi-periods, as well as their amplitudes, are unevenly distributed over an observation time interval from 2003 to 2021 (18 years) and change significantly over time.

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1 Introduction

The giant elliptical galaxy MRK 501, with an active nucleus, is located in the constellation Hercules, with right ascension $16^h53.9^m$ and declension $+39°45'$. Its active core has properties typical of BL Lac objects. The object MRK 501 was studied in detail and entered into the catalog of peculiar galaxies by the outstanding Soviet and Armenian astrophysicist Veniamin Markaryan in 1974. The apparent magnitude of MRK 501 is 13.29^m. The redshift Z is 0.0336 or 9915 kilometers per second. The distance to the galaxy MRK 501 is about 140 megaparsecs. This is one of the most powerful gamma-ray sources in the northern sky. In the range of very high energy gamma rays, with photon energies above 0.1 TeV, the galaxy is the brightest object in the sky. It has a characteristic gamma-ray flare activity, with flashes duration of about 20 minutes. Signal delay (approximately 4 minutes) was found between signals with energies of 1.2 TeV and 0.25 TeV. MRK 501 is part of a small galaxy cluster associated with the Abell 2199 cluster (in the constellation Hercules). There is some evidence that MRK 501 has absorbed a nearby satellite galaxy. This is one of the few objects where a quasi-period was confidently detected in long-term observations (with a duration of about 10 years) of gamma-ray variations with a value of 330 days. The radio galaxy, according to VLBI and VLA observations, has a one-way jet. Probably, there is a precession of the MRK 501 radio jet, but the precession period has not yet been determined [1–4].

In the optical range, there is a lot of information about the presence of intra-night optical variability (INOV) in the nucleus of the galaxy MRK 501, for example, in [5] it is noted that, according to observations in the R filter, there is "flare" variability with an amplitude, on average, about 0.03^m and completely irregular, without any quasi-periods. Longer "waves" of variability in the V and R filters were also found, with a characteristic time of about 100 days. The presence of rapid variability with a characteristic time of about 26–27 minutes is assumed. Similar results were obtained in [6], where the amplitude of variability about 0.05^m with a characteristic time of about 15 minutes was determined from observations in the R filter. It is noteworthy that V–R color index showed the presence of weak variability, which is quite rare for radio galaxies. An assumed source of such variability could be instabilities or pulsations in the accretion disk of MRK 501.

At the same time, MRK 501 also has a long-term optical variability, on time scales of several years, clearly visible on the historical light curves of this remarkable object. For example, it was found that the light curve of this source is well approximated by a fragment of a sinusoid with a period of about 5–6 years. Rapid brightness variations are superimposed on it, which also change quite rapidly over time, usually within 60–140 days. Based on the longest observational light curves with a duration of about 30 years, characteristic times of trend components in brightness changes were determined as 10 and 21 years. Such long-term variations reflect global processes both in the accretion disk and in the jet, since a significant part of optical radiation is of synchrotron nature [7].

In the gamma range, the day-to-day variability of MRK 501 is determined by flares, time intervals between which usually vary from 5 to 25 days. It is assumed that in MRK 501 day-to-day variability (in X-ray, gamma ranges) may be caused by precession of an accretion disk displaced relative to the rotation axis [8]. Variability within individual nights of observations of MRK 501, in the optical range (with a characteristic time of tens of minutes), was also observed in [9] and was explained by a change in the viewing angle between the line of sight and moving relativistic components in the jet.

Thus, the radio galaxy MRK 501 is an interesting and, in many ways, unusual object. High-quality observations of it in the optical and other electromagnetic ranges are extremely important for understanding the nature and refinement of some models of this object, based on the properties and features of emission variability, obtained from observations. This work is the next step in a series of articles about the main results from a joint study of rapid variability extragalactic radio sources, which is jointly carried out at the astronomical observatories of Ukraine, Slovakia and Latvia [10–13].

2 Observation technique and methods of their processing

For this work, the observations of the MRK 501 object were carried out in Ukraine, Latvia and Slovakia, using optical telescopes AZT-3 (Ukraine, Mayaki observatory), Schmidt camera (Latvia, Baldone observatory) and VNT (Slovakia, Vihorlat observatory). The diameter of the mirror of AZT-3 telescope is 48 centimeters, the diameter of the mirror of Schmidt camera is 1.2 meters, the diameter of the mirror of VNT telescope is 1 meter. B, V, R, I filters were used for observations. The duration of the observations was: at the Mayaki observatory, 25 Jun 2021 – 10 Oct 2021; at the Vihorlat observatory, 21 Jul 2021 – 15 Oct 2021; at Baldone Observatory, 4 Aug 2021 – 15 Aug 2021. Additionally, the observations of MRK 501 (9 Jul 2021 – 10 Oct 2021) in V and R filters were carried out at the Heavenly Owl private observatory (Odessa Region, Ukraine) on a fully automated Newtonian telescope with a mirror of 30 centimeters in diameter (observatory owner and observer – Valery Tsehmeistrenko).

At the Baldone Observatory, standard CCD processing was used, the exposure time was selected in such a way so as to suppress the diffuse halo of the host galaxy, to analyze the brightness variations of the MRK 501 core. In order to reduce CCD images, flats, bias, and dark calibration images were taken each night. The program Maxim DL was used to reduce and align CCD images. Flat-field images were taken against the twilight sky. The darks were exposed for the same time as the respective CCD images of MRK 501. After that, the program Canopus was used to perform differential photometry on reduced data sets. For each data set, six stars were used for brightness comparison to MRK 501. Aperture photometry using a differential photometry technique was done to determine the brightness of comparison stars and the object [14].

The standard reduction of the CCD frames was carried out using the MUNIPACK (http://sourceforge.net/projects/c-munipack) software. The procedures for an aperture photometry is composed of the dark-level and flat-field corrections, determination of the instrumental magnitudes and precision. The photometry was transformed to

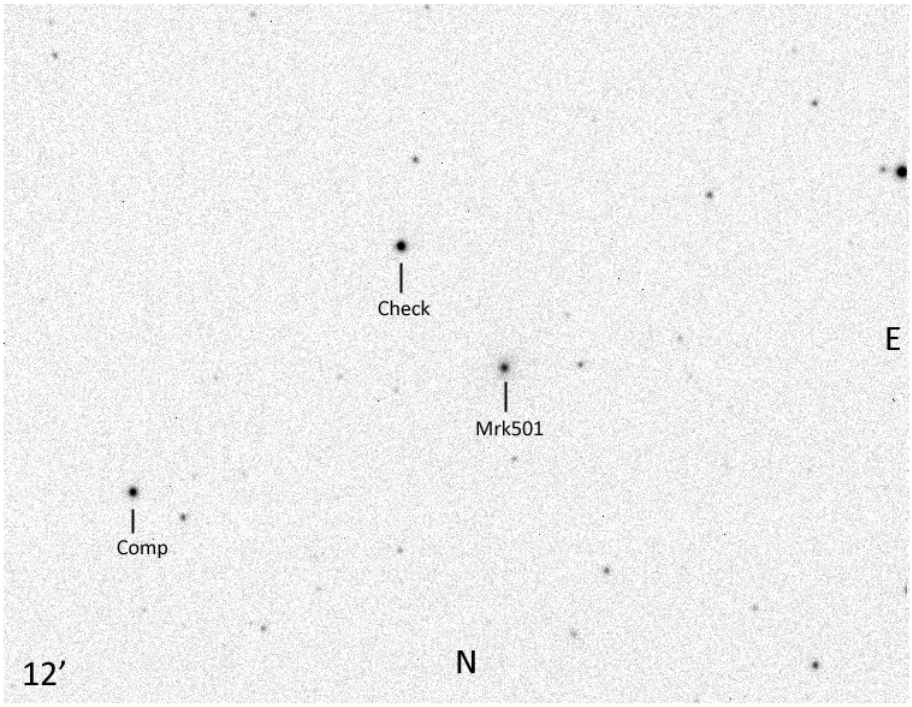


Figure 1 CCD image of the vicinity of the radio galaxy MRK 501. Both the object and the comparison stars are marked.

the standard V, R, I Johnson–Cousins system by means of the differential photometry method [15]. Observations from the AZT-3 telescope are reduced to a standard photometric system using the following formulas:

$$V_{st} = \Delta V_{inst} + \varepsilon_V \Delta(B-V) + V_{comp}, R_{st} = \Delta R_{inst} + \varepsilon_K \Delta(V-R) + R_{comp},$$

where V_{st}, R_{st} – stellar magnitudes in the standard system, $\Delta V_{inst}, \Delta R_{inst}$ – difference in magnitude of a variable star and a comparison star, $\varepsilon_V, \varepsilon_K$ – color transformation ratios, $\Delta(B-V), \Delta(V-R)$ – difference between the color indices of the variable star and the comparison star, V_{comp}, R_{comp} – magnitudes of the comparison star in the standard system [16]. The transformation coefficient was determined from observations of standard stars [17]. An example of a CCD frame with the vicinity of the radio galaxy MRK 501, which was obtained with the AZT-3 telescope, is shown in Figure 1.

At the Vihorlat Astronomical Observatory on Kolonica Saddle we used the Vihorlat National Telescope VNT 1000/9000 mm, equipped with FLI 1001E CCD camera and Johnson–Cousins photometric filters B, V, R_c, I_c. Acquired images were reduced in a standard way – corrected for darkframe and flatfield. Ensemble aperture photometry was performed using CoLiTecVS [18] software package. For differential photometry the following brightness values were taken from LONEOS catalogue [19]: $B = 12.99$; $V = 12.40$; $R_c = 12.05$; $I_c = 11.69$. It is very important to always use the

same size of aperture when comparing a diffuse object such as MRK 501, 3C 84, or other extra-galactic objects with point like sources. The FWHM of stars is changing according to the observing conditions, while the galaxy core remains almost the same size. We have selected the 5 pixels aperture radius which corresponds to 5.5 arcsec in the sky. For a comparative analysis of the long-term multiyear variability of the source MRK 501, we used the visual light curve from the AAVSO catalog (American Association of Variable Star Observers) (https://www.aavso.org/) received in the time interval 24 Jun 1998 – 6 Jun 2021. Additionally, we also analyzed light curves of the MRK 501 source from the AAVSO catalog, in optical bands B (22 Apr 2004 – 12 Sep 2015), V (24 Aug 2003 – 12 Sep 2021), R (12 Oct 2001 – 12 Sep 2015), I (22 Apr 2004 – 4 May 2019).

Search for the presence of quasi-periodicities was carried out using the following approach. At the first stage, the Lomb–Scargle periodograms were calculated using a modified method described in [20], which provides a more accurate determination of periods and spectral intensity (power) of harmonics. It is also less prone to periodogram distortion due to spectrum leakage and data noise for estimates of periods of quasi-sinusoidal components in the light curves data. At the second stage, a linear approximation of light curves (using the least squares method) was performed to determine the amplitude and phase values of one dominant variability component. These results were used as initial parameter estimates for the third stage of optimization – iterative fitting by the least squares method of approximating the curve, in the form of a single sinusoid, to real data by choosing optimal values of initial parameters of frequency, amplitude and phase for approximating the sinusoid. This allows us to slightly refine initial values of periods for each light curve making their assessment more meaningful and believable. This typical procedure is presented in more detail, for example, in [21]. Light curves were smoothed and noise in optical observation data was reduced using a polynomial moving average [22]. Individual outliers-points that were in light curves were removed manually. Also, in this work we used the method of constructing periodograms ANOVA (this method uses orthogonal periodic polynomials to approximate the data and statistics of analysis of variance to estimate the quality of the approximation), which provides good sensitivity of the method to weak periodic signals, and also gives significantly lower false peaks on the periodogram than some other methods, and is especially good for analyzing non-sinusoidal but quasi-periodic light curves [23]. In the task of determining characteristic times of intra-night optical variability (INOV), the ANOVA method of periodogram analysis, for two harmonics in the model, showed a good result.

3 Fast optical variability of MRK 501

As a result of the observations, the V, R, I light curves were obtained at the Mayaki and Vihorlat observatories, and additionally, the B light curve was obtained at the Baldone observatory. Images of the obtained light curves are shown in Figs 2 and 3.

Statistical parameters of the light curves from the four observatories Mayaki, Heavenly Owl (Ukraine), Vihorlat (Slovakia) and Baldone (Latvia) are summarized in the resulting Table 1. It can be seen from the table that the light curves show a pronounced low-amplitude variability characteristic of the core of the radio galaxy MRK 501.

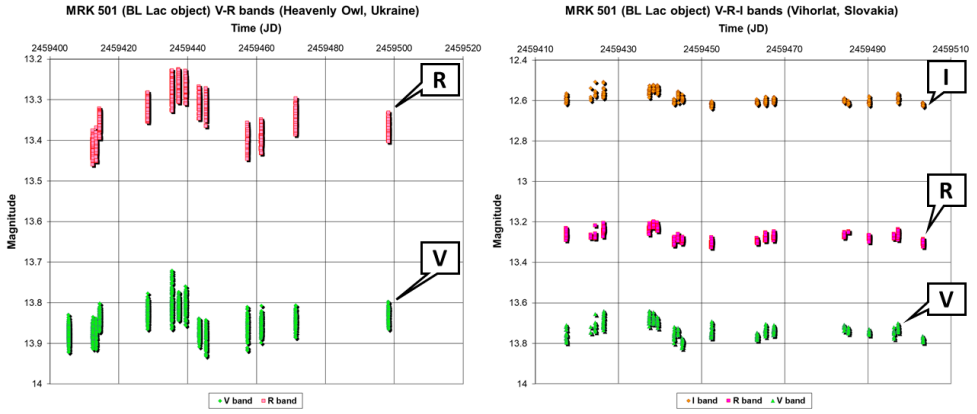


Figure 2 Light curves of the core of the radio galaxy MRK 501 obtained at the Heavenly Owl private observatory (left) in optical bands V, R, and light curves obtained at the Vihorlat observatory (right) in optical bands V, R, I.

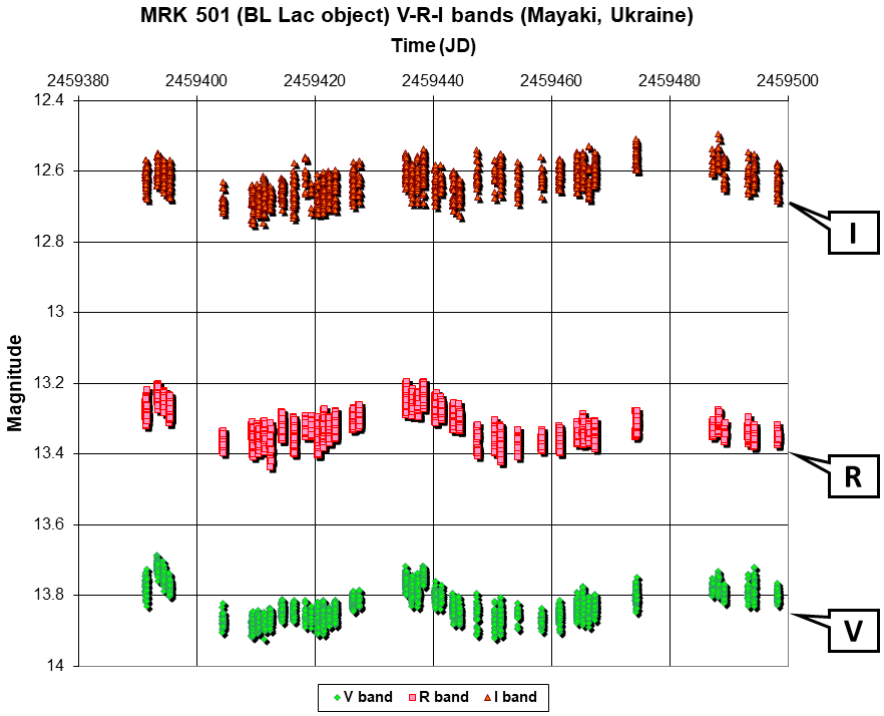


Figure 3 Light curves of the core of the radio galaxy MRK 501, obtained at the Mayaki observatory in optical bands V, R, I.

Now consider the periodograms of light curves, examples of which are shown in Figure 4. Based on the results of periodogram analysis, the value of the main, most

Table 1 The table shows some descriptive statistics of the light curves of radio galaxy MRK 501, obtained in optical bands B, V, R, I at the observatories of Ukraine, Slovakia and Latvia. The table uses the following notation: Mean – average value of stellar magnitude; StdDev. – standard deviation; MeanDev. – mean deviation, as well as standard deviation, shows scatter of data points relative to the mean value, but is calculated as $\hat{x} = \frac{1}{n}\sum_{i=1}^{n}|x_i - \overline{x}|$, where n – number of elements in a time series, x_i , where $i = 1, 2, 3, \ldots n$ – time series element values, $\overline{x}$ – sample mean of a time series; Ampl. – greatest amplitude of the brightness change in the light curves of MRK 501; Max., Min. – highest and lowest magnitude values in light curves; Aver.G. – the average Gini difference characterizes scatter of time series values relative to each other and does not depend on any central value, for example, on mean or median values; the average Gini difference is calculated using the formula $g = \frac{1}{n(n-1)}\sum_{i=1}^{n}\sum_{i=1_{i\neq j}}^{n}|x_i - x_j|$, where n – data sample size, x_i , $i = 1, 2, 3, \ldots, n$ – time series element values; Q 25% and Q 75% – quartiles showing important information about the structure of time series, the upper quartile is 75% percentile of data sample and the lower quartile is 25% percentile of data sample; Ampl.Q. – interquartile range, characterizes the amplitude of data points scatter in absolute numbers, here in stellar magnitudes, interquartile range is a more presentable estimate scatter of sample values compared to the estimate of standard deviation; N.points – number of data points.

Statistical	Mayaki			Vihorlat			Heavenly Owl		Baldone
parameters	V	R	I	V	R	I	V	R	B
Mean	13.822	13.314	12.631	13.735	13.271	12.591	13.848	13.340	14.462
StdDev.	0.0473	0.0471	0.0445	0.0348	0.0275	0.0273	0.0340	0.0561	0.0309
MeanDev.	0.0395	0.0391	0.0366	0.0275	0.0221	0.0220	0.0280	0.0479	0.0248
Ampl.	0.237	0.240	0.253	0.184	0.128	0.130	0.210	0.234	0.156
Max.	13.686	13.195	12.495	13.639	13.198	12.507	13.720	13.225	14.424
Min.	13.923	13.436	12.749	13.824	13.326	12.637	13.931	13.459	14.580
Aver.G.	0.0537	0.0536	0.0509	0.0391	0.0312	0.0300	0.0384	0.0648	0.0307
Q 25%	13.788	13.279	12.598	13.716	13.254	12.574	13.823	13.292	14.442
Q 75%	13.859	13.350	12.667	13.759	13.292	12.612	13.875	13.389	14.459
Ampl.Q.	0.0712	0.0712	0.0676	0.0429	0.0383	0.0373	0.0519	0.0967	0.0170
N.points	2718	2596	1192	402	392	397	2322	1935	145

probable quasi-period ranges from 40 to 48 days, depending on the light filters and the observatories where the MRK 501 observations were made, are in good agreement between the light curves obtained at the Mayaki, Vihorlat and Heavenly Owl observatories.

The next step was to refine the values of main quasi-periods obtained from periodogram analysis. We used the method of approximating the data with a single sinusoid, the initial values of the period, amplitude and phase of which were taken from periodogram analysis, iteratively fitted to the data using the least squares method. This makes it possible to obtain a more meaningful estimate of the quasi-periods. Examples of such an approximation of light curves (with a pre-subtracted mean value) are shown in Figures 5, 6 and 7.

In the examples shown above, 95% confidence intervals and prediction intervals are given for approximating sinusoids. Here, the 95% confidence interval is the Y range for a given X value, which has a 95% probability of containing the true Y value. The 95% prediction interval is the Y range for a given X value, where there is a 95% probability that the following experiments will have a Y value, based on

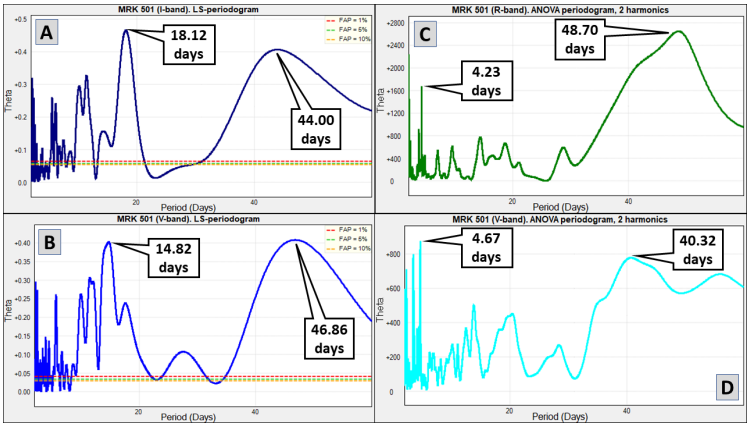


Figure 4 Example of modified Lomb–Scargle and ANOVA periodograms for the light curves of MRK 501. Sections of the figure show: A) periodogram for light curve in I band (Vihorlat); B) periodogram for V-band light curve (Vihorlat); C) periodogram (for comparison, constructed by ANOVA method, approximation by two harmonics) for light curve in R-band (Heavenly Owl); D) periodogram for V-band light curve (Heavenly Owl). As can be seen from the example, in addition to the main quasi-period, data sets from the Vihorlat and Heavenly Owl observatories also contain harmonics with periods of about 14 and 18 days (Vihorlat) and with periods of about 4 days (Heavenly Owl). There is a high probability that harmonics with periods of about 4 days are false, and their appearance is associated with discontinuities gaps in the observational data. Harmonics with periods of around 14 and 18 days are most likely also false, but this requires additional verification.

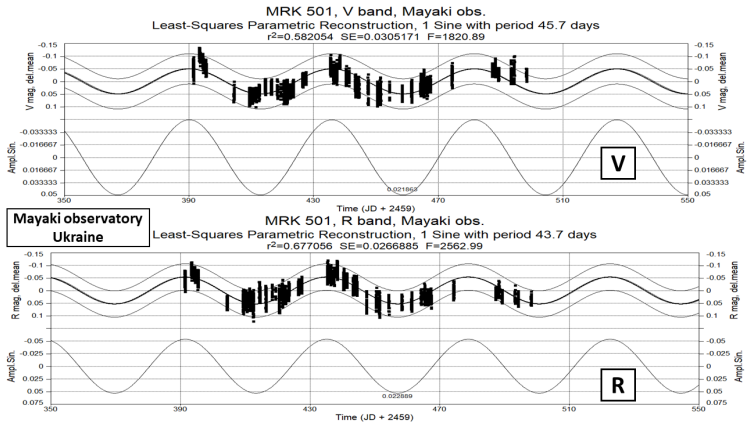


Figure 5 Results of inscribing and fitting single sinusoids (Mayaki observatory) to light curves of MRK 501 (with subtracted mean value) in the V (upper part of the figure) and R (lower part of the figure) bands. The refined values of quasi-periods were 45.7 days (V band) and 43.7 days (R band).

an approximation of current experimental data. All refined values of obtained quasi-periods for the light curves in V, R, I bands, as well as parameters for approximating initial data sets by single sinusoids, are summarized in Table 2.

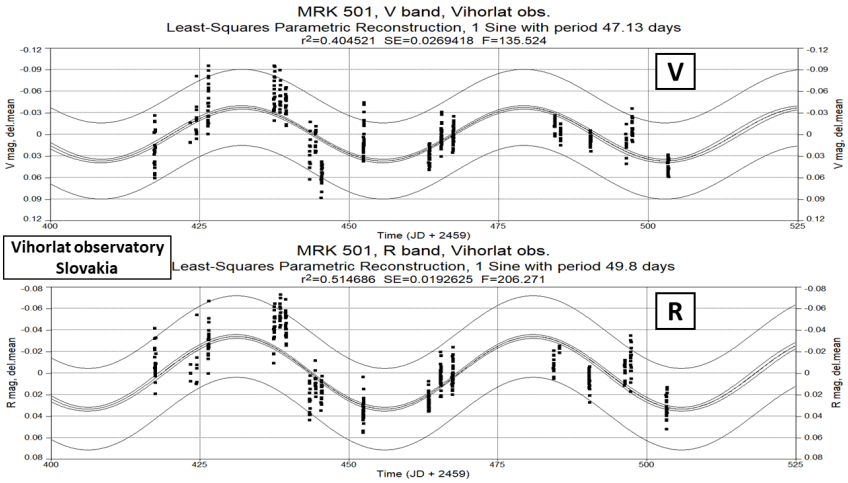


Figure 6 Results of inscribing and fitting single sinusoids (Vihorlat observatory) to the light curves of MRK 501 (with subtracted mean value) in the V (upper part of the figure) and R (lower part of the figure) bands. The refined values of quasi-periods were 47.1 days (V band) and 49.8 days (R band).

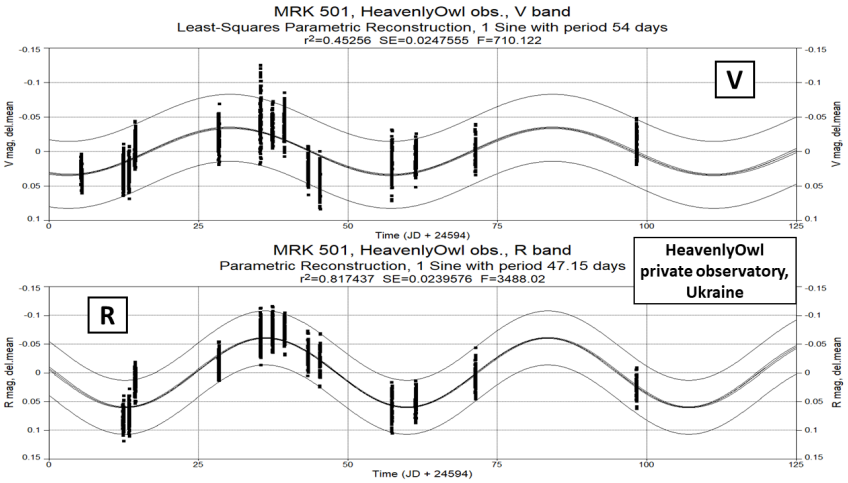


Figure 7 Results of inscribing and fitting single sinusoids (Heavenly Owl observatory) to the light curves of MRK 501 (with subtracted mean value) in the V (upper part of the figure) and R (lower part of the figure) bands. The refined values of quasi-periods were 54.0 days (V band) and 47.1 days (R band).

As can be seen from the table, the values of the quasi-periods of brightness variations of the active galaxy MRK 501 core, according to V, R, I photometry data, performed at three different observatories and at three different telescopes, are in quite good agreement with one another. They are confirmed by two methods of analyzing the light curves for the presence of quasi-periodic variations. The greatest differences

Table 2 Table of the main quasi-periods found in the light curves of the core of the active galaxy MRK 501, according to periodogram analysis data, and refined values of quasi-periods, obtained by approximating the data by single sinusoids using the least squares method. The table uses the following notation: R^2 – coefficient of determination, SE – standard error, F_{stat} – Fisher's F-statistic, P_{ref} – refined value of quasi-period by the method of approximating data by a sinusoid, P_{LS} – initial value of the quasi-period obtained from the periodogram method, Obs. – observatory where the light curves were obtained.

Parameter	V	R	I	V	R	I	V	R
R^2	0.582	0.677	0.286	0.404	0.514	0.444	0.452	0.817
SE	0.0305	0.0267	0.0376	0.0269	0.0192	0.0204	0.0247	0.0239
F_{stat}	1820.890	2563.00	239.240	135.524	206.271	157.552	710.122	3488.020
P_{ref}	45.700	43.700	44.063	47.130	49.811	42.586	54.000	47.150
P_{LS}	45.689	43.664	33.165	46.862	49.398	43.976	40.567	48.701
Obs.	Mayaki			Vihorlat			Heavenly Owl	

between the results of periodogram analysis and refined quasi-periods appeared for the I band (Mayaki) and the V band (Heavenly Owl). In the first case, this is probably due to a large scatter of data, which reduced the sensitivity of the periodogram method. In the second case, differences can be associated with quite large gaps in the observational data. In general, we can conclude that observations at the three observatories gave close results, and the true value of the quasi-period is in the range from 42 to 54 days. The average value of the quasi-period for three observatories was 46.767 days. These are the most statistically significant results. Thus, in the radio galaxy MRK 501, a quasi-periodic brightness variation with a period of about 46–47 days was reliably recorded.

Since, in the B band, the duration of the observations was shorter and filling of the observation time interval by points was shorter, the observations at Baldone were used only to estimate characteristic times of brightness variations within individual nights. Optical intra-night variability is one of the most mysterious and little-studied phenomena of active galactic nuclei. Usually this is a fairly infrequent phenomenon, possibly somehow related to the phases of long-term nuclear activity of galaxies. In the case of the core of the radio galaxy MRK 501, significant optical variability within individual nights of observations was noted in many works (examples were given above). Nevertheless, these are mainly irregular variabilities, as shown, for example, in [24]. Considering that the observations of MRK 501 obtained at the Heavenly Owl and Mayaki observatories contain about 2 thousand measurements, we can try to determine the characteristic intra-night times of the brightness variations of this object. The B-band light curve obtained at the Baldone Observatory (Latvia) is shown in Figure 8.

To estimate the characteristic intra-night variability time of MRK 501, periodograms were constructed by the ANOVA method using two harmonics to approximate the data, in the period range of 0.03–0.45 days (0.72–10.80 hours). Thus, the 12-hour diurnal harmonic was excluded from the analysis. Further, in the same way, ANOVA periodograms were constructed for the light curves obtained at the Mayaki and Heavenly Owl observatories (Ukraine). An example is shown in Figure 9.

As can be seen from the above examples, in the period interval 0.03–0.45 days, in the data obtained at the Mayaki, Baldone and Heavenly Owl observatories, there are

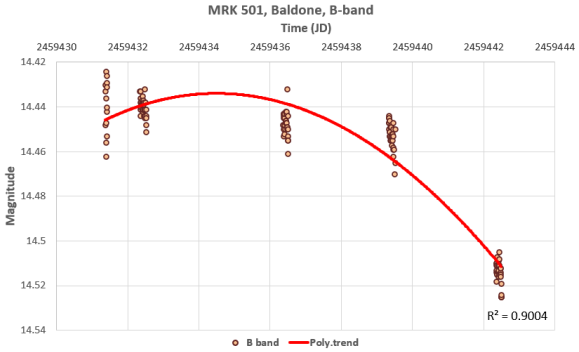


Figure 8 Light curve of MRK 501, B-band, according to the Baldone observatory. The plot also shows a polynomial trend of second degree, which well describes the decrease in brightness of the radio galaxy core. Perhaps this is part of a cyclical wave of brightness change, clearly visible in the V, R, I filters.

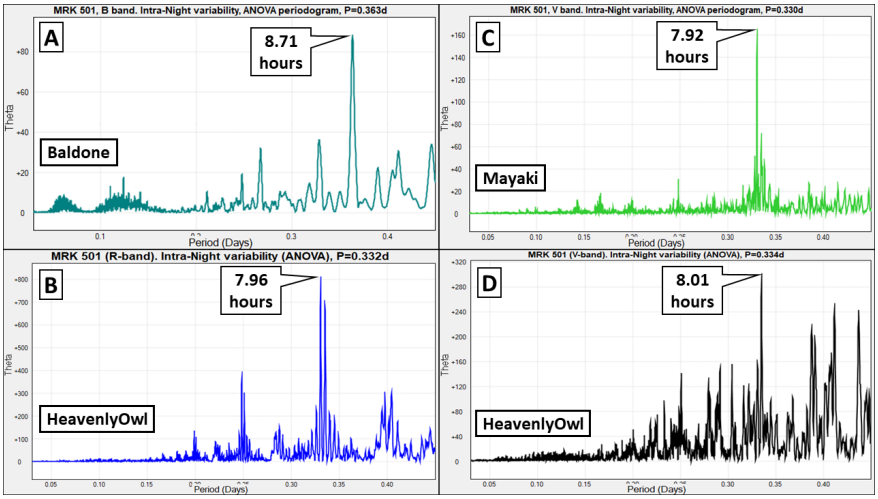


Figure 9 Periodograms ANOVA of the active galaxy MRK 501, plotted in the period interval of 0.03–0.45 days. Fragments of the figure show: A) periodogram for the B-band light curve (Baldone observatory), quasi-period of 8.71 hours; B) periodogram for the R-band light curve (Heavenly Owl observatory), quasi-period of 7.96 hours; C) periodogram for the Mayaki observatory light curve, quasi-period of 7.92 hours; D) Periodogram for the Heavenly Owl observatory light curve, quasi-period of 8.01 hours.

clear brightness variations with a period very close to 8 hours. However, this is most likely not a real quasi-period, but an 8-hour diurnal harmonic, which appears as a result of discontinuity in the data, and is not a real, physical quasi-period. Based on this, we can conclude that the periodogram analysis in order to search for intra-night variability in MRK 501 did not show the presence of significant brightness variations within individual observation nights. Only noise irregular variability is present here. This is fully consistent with the previously published results of other authors.

4 Long-term optical variability of MRK 501

In addition to a rapid variability, MRK 501 also exhibits a long-term variability. It is clearly visible on the historical light curves of this object, in the optical range, with a characteristic time of brightness variations of about 1.5–2 years, and possibly even longer. A graph of the historical light curves of the radio galaxy MRK 501 (from the AAVSO catalog) in the optical range (bands B, V, R, I plus visual light curve) is shown in Figure 10.

Historical light curves were analyzed using the standard VStar application, optimized for working with AAVSO data and freely available for download (https://www.aavso.org/vstar). Light curves were preliminarily smoothed by a moving average with a window width of 6 days. Periodogram construction method – Date Compensated Discrete Fourier Transform (DC DFT). This method is effective for studying long-term periodicity in low-noise light curves and is described in detail in [25]. Search for periods was carried out in a range from 100 days (0.273 years) to 2555 days (7 years). Taking into account the duration of analyzed observations, it makes no sense to look for periods longer than 7 years. Examples of DC DFT periodograms for V and R light curves are shown in Figure 11.

Thus, the analyzed light curves of the active galaxy MRK 501 from the AAVSO catalog contain the following values of main quasi-periods and their amplitudes: 378 days, amplitude 0.12^m (Visual data); 391 days, amplitude 0.34^m (I-band data); 397 days, amplitude 0.32^m (R-band data); 398 days, amplitude 0.52^m (B-band data); 387 days, amplitude 0.17^m (V-band data). In all five light curves, the main quasi-period is very close to 1 year, which may be due to annual modulation due to the Earth's orbital motion. However, as noted above, in the gamma range, a quasi-period of 330 days was recorded with high reliability, from the source MRK 501, using several

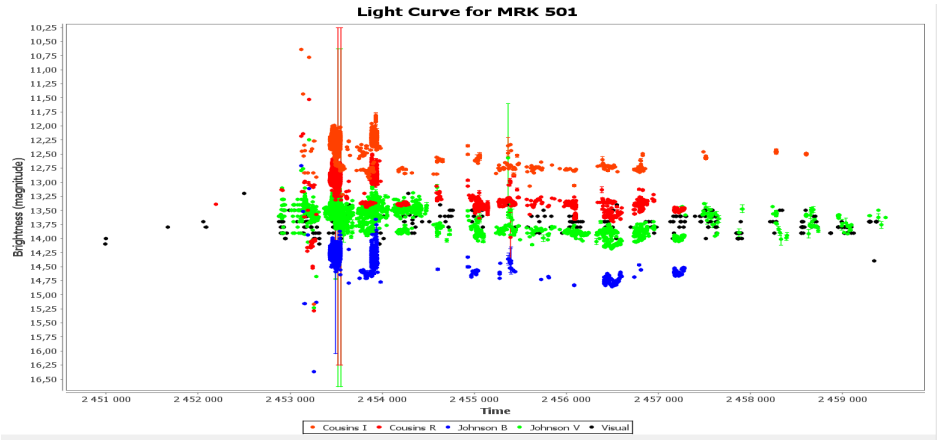


Figure 10 Light curves of MRK 501 in bands B, V, R, I, Visual, were taken for this study from the AAVSO catalog. Average brightness values: 14.390^m (B), 13.637^m (V), 13.361^m (R), 12.373^m (I). Standard deviation values: 0.225 (B), 0.243 (V), 0.315 (R), 0.250 (I). Duration of observations: B (2004–2015, 11 years), V (2003–2021, 18 years), R (2001–2015, 14 years), I (2004–2019, 15 years).

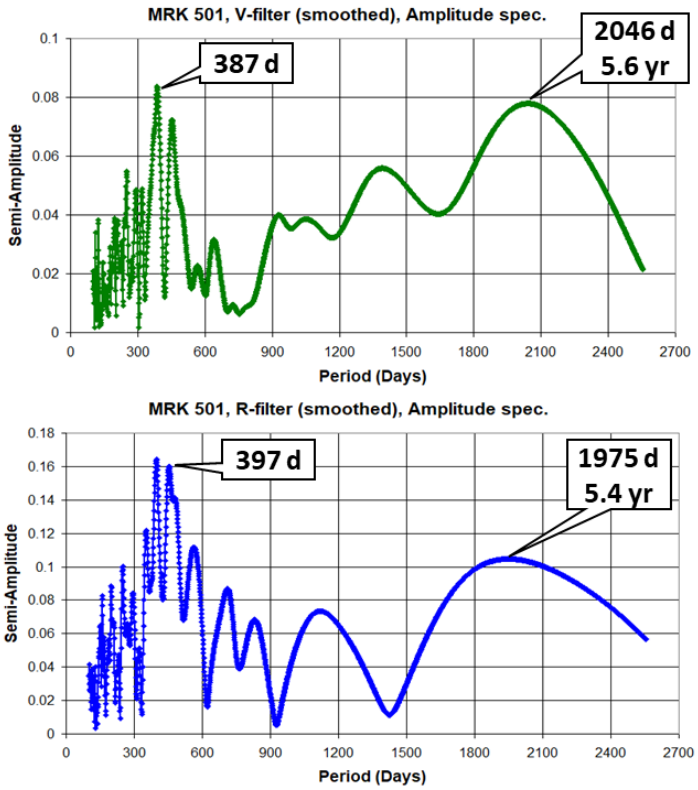


Figure 11 Examples of periodograms (Y-axis is the half-amplitude of brightness variations) for the light curves of the active galaxy MRK 501 (AAVSO data) in the optical bands V (upper graph) and R (lower graph). These light curves were preliminarily smoothed with an averaging window of 6 days. The example shows that the data contains clear cyclical variations in the MRK brightness with a quasi-period of about 1 year. It is also possible that there are longer, trendy, brightness variations with a characteristic time of about 5–6 years (in the V, R, I bands).

methods of data analysis [4]. Therefore, it may well be that the quasi-period of about one year, found in the historical optical light curves of MRK 501, is not only real, but also reflects the same physical process. For example, the presence of a double black hole in the active nucleus of this galaxy is likely.

5 Long-term variability of MRK 501 in the radio range

While many long-term monitoring observations of the active galaxy MRK 501 have been carried out in the optical range and a lot of information has been obtained about the variability of this object at different time scales, the situation is different in the radio range. Unfortunately, there are very few works about the search for quasi-periodic properties of both fast and long-term variability of MRK 501 in the

radio range. There are also few radio monitoring observations of this object with good time resolution. For this reason, in 2019–2020, the search for fast variability on intra-day time scales was carried out with the Ventspils International Radio Astronomy Center (Latvia) radio telescopes, at frequencies of 1.6 and 6.7 GHz. However, at that time radio intra-day variability was not reliably recorded. As a result of more than 20 observation sessions, only irregular manifestations of ionospheric scintillations of

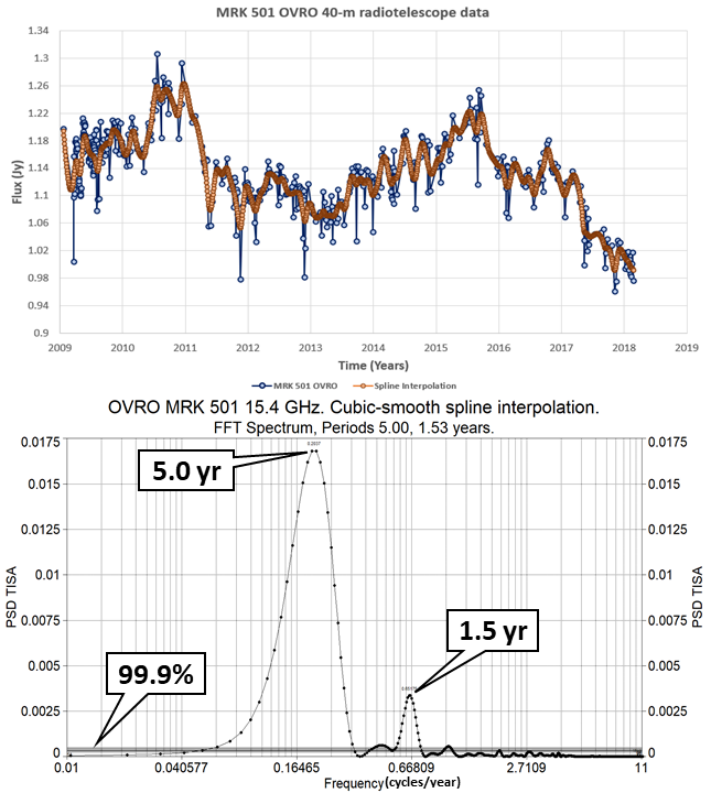


Figure 12 Upper part of the figure shows initial data of the multi-year flux density change of the radio source MRK 501, at a frequency of 15 GHz, and the solid line shows interpolated and smoothed cubic spline data. X-axis – time in years, Y-axis – flux density in Jansky. Lower part of the figure shows FFT periodogram (for data with a subtracted mean value), on which two highs are clearly distinguished peaks, corresponding to periods of 5 and 1.5 years. The X-axis of the periodogram is frequency in cycles per year, the Y-axis is spectral power in the form of TISA (time-integral squared amplitude power). This is actually integral under curve defined by square of original data. In this case, spectral power is calculated as: $2 \cdot dx \cdot \left(Re^2 + Im^2\right)/n$, where Re, Im – real and imaginary part of FFT, respectively, dx – sampling interval of data, n – size of data set, for a given frequency. Accordingly, TISA values are calculated for each frequency on the FFT periodogram. In the figure, flag marks the critical level of 99.9%, which corresponds to the level at which only in 1 out of 1000 separate sets of random noise, the largest peak will reach this height only by chance. The two peaks on periodogram are significantly above the critical level, which indicates their good significance.

MRK 501, with characteristic times of several minutes, were obtained. As for long-term variability of the MRK 501 radio flux, the unique monitoring at the 40-m Owens Valley Radio Observatory (OVRO) radio telescope in California, USA at a frequency of 15 GHz began in 2008 and was discontinued in 2020. Within the framework of this monitoring, in addition to MRK 501, long-term observations of several dozen active galactic nuclei were carried out, and unique data were obtained (for a more detailed description of this monitoring, see [26]). In this article, we will consider the long-term flux density record of MRK 501, at a frequency of 15 GHz, which was obtained at the OVRO observatory during the time interval 2009–2018. The radio data was freely available in 2019 on the website OVRO 40-m radiotelescope (https://sites.astro.caltech.edu/ovroblazars/).

The purpose of analyzing the OVRO monitoring radio data was an attempt to compare the characteristic times of long-term variability of MRK 501 at a frequency of 15 GHz with the characteristic times of variations in optical light curves from the AAVSO catalog, which were considered above. The following approach was used to analyze radio variability. At the first stage, the time series of MRK 501 flux density was interpolated by a smoothing cubic spline (in order to remove noise, outliers points and convert the data to a uniform time grid). At the second stage, classical FFT periodogram was built (for uniform time series). The plot of original and interpolated data, as well as the periodogram (plotted after subtracting the average value from the smoothed data), for the radio source MRK 501 are shown in Figure 12.

As can be seen, the characteristic times of flux density variations (1.5 and 5 years) in the radio range are in good agreement with the optical data, where variations with characteristic times of about 1 and 5–6 years also prevail. This additionally shows that the variability is caused by one global process in the core of the galaxy MRK 501.

6 Discussion

The BL Lac object MRK 501 is an extremely active object, from the radio to the gamma range. Since it is located in the constellation Hercules, it is convenient for long-term optical observations. Its relatively high brightness allows monitoring even with small telescopes with a mirror diameter of 30 centimeters or little more, and therefore MRK 501 is very popular among researchers. As in many active galactic nuclei, long-term variability has been studied best in MRK 501. A quasi-period of about one year obtained in our work in the B, V, R, I bands plus the visual light curve from the AAVSO catalog confirms the earlier result (333 days) described in [27]. Thus, a clear connection between the gamma and optical ranges is seen for MRK 501. BL Lac objects, which include the MRK 501 source, have a contribution to optical emission from both the accretion disk and the synchrotron component of the relativistic jet (for BL Lac objects, the jet is often one-sided due to the very strong Doppler amplification of signals). Here, at different time scales of variability, different mechanisms for generating cyclic variations can operate. In the case of MRK 501, it is interesting to consider the dependence of the quasi-period on time, that is, the change of the dominant quasi-period over time. For this, the wavelet transform was calculated for non-uniform time series, for the light curve from AAVSO in the V band (in range

of periods 100–2555 days), as the highest quality light curve MRK 501 available in AAVSO. The "classic" WWZ method (Weighted Wavelet Z-Transform) was used, described in detail in [28], which is implemented in the Vstar (AAVSO) application. The WWZ method performs a wavelet transform using an analysis test function that includes both a periodic sinusoidal function and a Gaussian window function. The width of the window is determined by damping constant and time divisions. Then the method makes optimal the wavelet function by fitting it into the observations. In doing so, it weighs observations by applying a sliding window function to them. Observations in the center of the window have the greatest weight in the data fit. The window iteratively slides over the observations, producing a representation of spectral composition of signal, at times corresponding to the center of this window. Figure 13 shows a plot of the maxima of WWZ transform, which shows the change in the main quasi-period over time.

The figure shows that the quasi-period was stable (close to 6 years). Then, there was a transition to a period of 5 years. Subsequently, there is a jump in period up to about 7 years. Finally, there is a transition to a quasi-period of about 1 year (390 days) with a slight increase to 652 days (1.8 years) at the end of the light curve. It can also be seen that the amplitude of brightness variations decreased significantly by the end of 2014, and then began to increase again to the initial level. Of course, this result is somewhat conditional, because the quality of the light curve is not quite good. According to better data, the result of WWZ may turn out to be slightly different. Nevertheless, in general, it can be seen that the observed variability in the light curve is the superposition of two phases of activity with slow and fast variability, with a fairly fast transition between them.

The observed long-term variability of the active galactic nucleus can be the result of changes in the accretion disk (perturbation of viscosity, change in accretion rate, turbulence) on the corresponding characteristic time scales. In BL Lac objects, the flux variability arising in the disk can be changed by the Doppler effect emission from the relativistic jet as it propagates along the jet. Nevertheless, it is possible that modulation should propagate along the jet through the disk-jet interaction mechanisms [29, 30]. As shown in [31], the variability of blazars, correlated between different ranges, can also be provided by moderately relativistic shock waves. They are formed by colliding magnetohydrodynamic flows and are the main centers of acceleration of relativistic particles and creation of highly variable polarized multiwave emission from relativistic jets in blazars.

In our work, a new result was obtained (by two different methods of analysis), specifically, the variability of MRK 501 with a characteristic time between 42 and 54 days (depending on optical bands and observatory) was found. It is present on the V, R, I light curves (total average value of quasi-period is 46.767 days for all light curves used in this work). Taking into account the overlapping time observations of different observatories in Ukraine and Slovakia and use of different optical telescopes, it is highly likely to be reliable.

As is known from earlier works, for the MRK 501 source, the cyclical variability of flux in the gamma range was confirmed by observations on Cherenkov telescopes with a period of about 23 days (for more details, for example, in [32]) and considered in detail in [33]. One of the most logical explanations for interrelated variability, with close characteristic times on small- and medium-time scales, in the gamma and optical

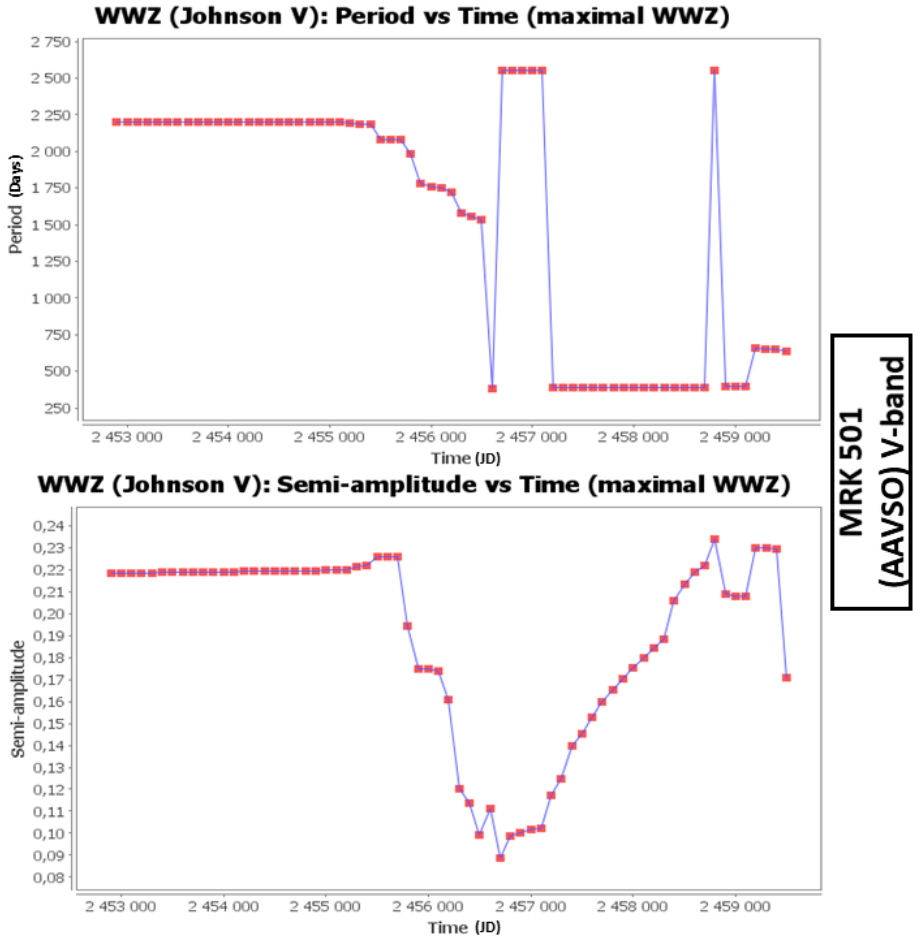


Figure 13 Plots of WWZ transform maxima, period vs time (upper figure) and half-amplitude vs time (lower figure) for the V-band light curve of the source MRK 501 from AAVSO. In the figures, the horizontal axis is time in Julian days, the Y axis is the period of brightness variations in days (upper figure) and the half-amplitude of brightness variations (lower figure). Here, one can clearly see the transition between quasi-periods over time and a quite significant change in the amplitude of optical brightness variations of MRK 501.

data, is the model of a binary black hole in the active core of MRK 501. The orbital motion of a satellite black hole can cause regular perturbations in the accretion disk and in the base of the jet, which is observed in the form of a fairly stable variability. The new result obtained in our work for the quasi-period in the optical range, 46.767 days, is very close to the doubled value of 23 days $\cdot$ 2 = 46 days, i.e. the harmonic of the 23 days visible period in the gamma range. In the same paper [33], a hypothesis is presented about the possibility that periodicity arises from the orbital motion of a companion, a less massive black hole with relativistic jets. It should be noted that for BL Lac objects, value of quasi-period from observational data will be significantly less than the value of this quasi-period in the reference frame associated with the source,

due to a relativistic decrease in the period of brightness variations. For example, for the observed quasi-period of 23 days in the gamma range, the real orbital period will be much longer, about 6 years [33]. Thus, the presence in the optical range of a quasi-period almost equal to the doubled quasi-period from the gamma range, discovered in our work, indirectly confirms the hypothesis that the core of the MRK 501 galaxy may contain a double supermassive black hole, the orbital motion component of which provides the observed fast variability of MRK 501. At the same time, the long-term variability of MRK 501 in the optical range is not stable and probably contains a long-term change in quasi-periods of brightness variations, and their amplitude, over time. This was shown in Figure 13 using the example of WWZ diagram of the maxima of WWZ coefficients for the V band.

Analysis of long-term radio data MRK 501, obtained at the OVRO observatory at a frequency of 15 GHz, shows the presence of cyclic variations, the quasi-periods (1.5 and 6 years) of which are very close to those obtained (about 1 year and 5–6 years) from the analysis of optical light curves of MRK 501, according to data from the AAVSO catalog. This is an additional factor that confirms the interrelation between the variability of MRK 501 in different wavelength ranges, which is caused and maintained by one global process, most likely a binary system of supermassive black holes in the core of the galaxy MRK 501. This is quite likely because MRK 501, in the past, possibly interacted with and absorbed, a nearby satellite galaxy [34].

Conclusions

As a result of joint work on studying the rapid variability of the core of the active galaxy MRK 501, which was carried out in 2021 at the observatories Mayaki (Ukraine), Vihorlat (Slovakia), Baldone (Latvia) and the private observatory Heavenly Owl (Ukraine), the following results were obtained:

Quasi-periodic brightness variation of MRK 501 was found in the form of a quasi-sinusoidal wave in the optical bands V, R, I, with average period of 46.767 days. This quasi-period is confirmed by observations at different observatories that participated in this study. This is a new result, which, judging from the analysis of the literature, has not been previously published in articles of other authors.

The quasi-period of about 46 days found in the optical range is very close to the doubled value of a quasi-period of 23 days, previously found in the gamma range and described in detail in [33]. Thus, we have found the second harmonic of 23 days period, which can be associated with the orbital motion of black hole-companion in the system of double supermassive black hole in the core of the active galaxy MRK 501.

A search for intra-night optical variability (INOV) showed that in the range of periods 0.72–10.80 hours there is no significant variability in the light curves of MRK 501 (except for 8-hour daily harmonic), and the observed intra-night brightness variations are irregular.

An analysis of the long-term variability of MRK 501 in the optical range using historical light curves from the AAVSO catalog, showed the presence in B, V, R, I bands a clear main quasi-period of about 1 year and a long, trend cycle with a characteristic time of about 5–6 years. Calculation of the WWZ transform (for V-band from AAVSO) in the range of periods from 100 to 2555 days, showed that the

long-term variability of MRK 501 is unstable over time, and brightness variations with a quasi-period of about 6 years are replaced by variations with a period of about 1 year (after 2014). In this case, the amplitude of brightness variations gradually decreases until 2014, and after that, it also smoothly increases to initial values. Analysis of the long-term radio data of MRK 501 at a frequency of 15 GHz, which were performed at the OVRO observatory, showed the presence of regular flux variations with quasi-periods of 1.5 and 5 years, which is very close to the quasi-periods of 1 and 5–6 years, found in the optical range from AAVSO data. This confirms the good consistency of the MRK 501 variability in different wavelength ranges, and also shows the high relevance of performing coordinated radio-optical monitoring of MRK 501.

This object is of particular interest and we will continue our observations in the radio and optical ranges.

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