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Multi-band variability of the blazar AO 0235+164

V. Vlasyuk[1], Yu. Sotnikova[1,2], A. Volvach[3], T. Mufakharov[1,2], Yu. A. Kovalev[4,5], O. Spiridonova[1], M. Khabibullina[1], Yu. Yu. Kovalev[6], A. Mikhailov[1], V. Stolyarov[1,7], D. Kudryavtsev[1], M. Mingaliev[1,2,8], T. Semenova[1], A. Kudryashova[1], N. Bursov[1], S. Trushkin[1], A. Popkov[9,4], A. Erkenov[1], I. Rakhimov[8], M. Kharinov[8], M. Gurwell[10], P. Tsybulev[1], A. Moskvitin[1], T. Fatkhullin[1], E. Emelianov[1], A. Arshinova[11], K. Iuzhanina[1,2], T. Andreeva[8], and L. Volvach[3]

[1] SAO RAS, Nizhny Arkhyz, 369167 Russia
[2] Kazan Federal University, 18 Kremlyovskaya St, Kazan, 420008 Russia
[3] Crimean Astrophysical Observatory of the RAS, Nauchny, 298409 Russia
[4] Astro Space Center, Lebedev Physical Institute of RAS, Moscow, 117997 Russia
[5] Institute for Nuclear Research of RAS, 60th October Anniv.Prosp. 7a, Moscow, 117312 Russia
[6] Max Planck Institute for Radio Astronomy, Auf dem Hugel 69, Bonn, 53121 Germany
[7] Astrophysics Group, University of Cambridge, Cambridge, CB3 0HE UK
[8] Institute of Applied Astronomy of RAS, Kutuzova Emb. 10, St. Petersburg, 191187 Russia
[9] Moscow Institute of Physics and Technology, Institutsky per. 9, Dolgoprudny, 141700 Russia
[10] Center for Astrophysics, Harvard & Smithsonian, 60 Garden Str., Cambridge, MA 02138 USA
[11] St. Petersburg State University, 7/9 Universitetskaya Emb., St Petersburg, 199034 Russia

Abstract. We present a study of the multiwavelength (MW) variability of the blazar AO 0235+164 based on the radio-to-γ-ray data covering a period from 1997 to 2023. The radio data are represented by the measurements from the SAO RAS, IAA RAS, and CrAO RAS telescopes. The optical measurements were collected with the SAO RAS 1-m and 0.5-m reflectors. The archive data at 230 GHz from the Submillimeter Array and the γ-ray data from the Fermi-LAT mission were used too. A significant correlation between different spectral bands is found with time delays up to 1.7 years. The relation between time delay and frequency is well described by a linear law. The revealed features of MW variability for the quiet period and for flaring states suggest that the mechanisms dominating the radio–γ-ray variations are not substantially different. AO 0235+164 shows a total variability period of $\sim$6 years for all wavelength bands, and 1.4–2.3 years during the low state, which may reflect its general properties.

Keywords: galaxies: active; BL Lacertae objects: individual (AO 0235+164)

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1 Introduction

Blazars are a specific type of active galactic nuclei (AGN) known for their relativistic jets aligned with the observer's line of sight, which causes the radiation to be highly Doppler boosted (Urry & Padovani 1995). Blazars include two types of AGN: BL Lacertae objects (BL Lacs) and Flat Spectrum Radio Quasars (FSRQs). BL Lacs display a continuous, featureless emission or weak narrow emission lines in their optical/UV spectra, while FSRQs exhibit prominent broad emission lines. The fluxes over various ranges, polarization, and spectra of blazars are strongly variable from radio to γ-rays on different time-scales, ranging from minutes to several decades (e.g., Miller et al. 1989; Gupta et al. 2004 and references therein). The jet, presumably originating from accretion onto a supermassive rotating black hole (SMBH) surrounded by an accretion disk, contains relativistic electrons, which produce soft photons from radio up to UV (or even soft X-rays) through synchrotron emission and high-energy photons up to GeV and TeV energies.

One of the effective ways to understand relativistic jet emission is studying the changes in the blazar physical properties that cause the observed multiwavelength (MW) light-curve variations (e.g., Krishna Mohana et al. 2024).

The BL Lac blazar AO 0235+164 at $z = 0.94$ (Cohen et al. 1987) is a good candidate for a MW study of variability processes in AGNs, exhibiting extreme variability of non-thermal radiation across all EM spectrum at time-scales from less than tens of minutes to several years (Volvach et al. 2015; Fan et al. 2017 and references therein). The Very Long Based Interferometric observations indicate on extreme compactness of blazar nuclei on submilliarcsecond scales with superluminal apparent speeds and on a broad projected jet opening angle (Jorstad et al. 2017; Kutkin et al. 2018).

For AO 0235+164 the quasi-periodic oscillations (QPO) at 3–6 year time-scale on base of data taken between 1975–2000 in the radio and optical light curves were found by Raiteri et al. (2001). Roy et al. (2022) present a comprehensive analysis of a long-term optical light curve from 1982 to 2019, revealing a periodicity of $\sim$8 years. The five major flares were followed by minor flares roughly after ~ 2 years. This double-peaked periodicity is consistent with the hypothesis of a binary supermassive black hole system, proposed by Volvach et al. (2015).

One of the main goals of this study is checking of QPO presence in MW emission of AO 0235+164—from γ-rays to centimeter radio range on maximal time interval.

2 Observations of AO 0235+164

We have collected MW datasets from three Russian radio telescopes: RATAN-600 (SAO RAS), RT-32 (IAA RAS), RT-22 (CrAO RAS) and 1-meter Zeiss-1000 and

0.5-m AS-500/2 optical reflectors of SAO RAS. Part of the data are from public archives, and most recent results are published for the first time.

At 230 GHz (1.3 mm) we utilized measurements from the Submillimeter Array[1], obtained in the period from October 2002 to December 2023. We have made use of the γ-ray light curves available in the Fermi Large Area Telescope (Fermi-LAT) public Light Curve Repository (LCR)[2]. We adopted the 7-day binned light curves for γ-rays with energies between 100 MeV and 100 GeV to have more evenly-sampled time series with higher time cadence in the period from August 2008 to end of 2023.

2.1 Radio data

Flux densities for AO 0235+164 at 1–22 GHz were obtained with the RATAN-600 radio telescope in 1997–2023. Broad-band radio spectra at six frequencies from 1 to 22 GHz were measured within 3–5 minutes. The flux densities were measured with a standard error of about 10–30%. The descriptions of the RATAN-600 antenna, its radiometers, and data reduction are given by Sotnikova (2020).

Flux densities of blazar radio emission at frequencies of 4.8 and 8.6 GHz were measured at several observing epochs using three RT-32 radio telescopes of IAA RAS: Svetloe, Zelenchukskaya and Badary (Shuygina et al. 2019). All the antennas and receivers have similar parameters: bandwidth = 900 MHz for both ranges; beam width at half-power level $7'$ and $3.'9$, respectively; flux density limit — about 20 mJy per scan with a time constant of 1 s for both frequencies. Observations were performed in the elevation or azimuth drift scan mode.

The data on the flux densities at the 36.8 GHz frequency for AO 0235+164 were obtained with the 22-metre RT-22 radio telescope (CrAO RAS). The beam-modulated receivers were used to acquire the data. Observations of the blazar consisted of 5–20 measurements to achieve a required signal-to-noise ratio. Details of the observations and data reduction are presented in Volvach et al. (2023). The period of observations with the RT-22 spans the time interval since February 2002 till October 2023.

2.2 Optical measurements

The optical study (mainly in the R-band) was carried out with the 1-metre Zeiss-1000 (August 2002—December 2023) and 0.5-metre AS-500/2 (January 2021—December 2023) optical reflectors of SAO RAS.

[1] http://sma1.sma.hawaii.edu/callist/callist.html
[2] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/about.html

The main observations with the optical telescope Zeiss-1000 were conducted with CCD photometer in the Cassegrain focus, equipped with a 2048 × 2048 px back-illuminated E2V chip CCD 42-40. Details of the instrumental setup are described in our paper Vlasyuk et al. (2023). The main characteristics of the instrumental complex of an AS-500/2 reflector are presented in Valyavin et al. (2022). In order to improve the system parameters we installed in July 2023 a smaller but more sensitive detector: the back-illuminated electron-multiplying CCD camera Andor IXon^{EM}+897.

The typical integration time for observations of the blazar was 300 s for Zeiss-1000 and 120 s for AS-500/2 (or 30 s for the period of high intensity of the object for better time cadence). The optical data are collected from 568 observing nights spanning between August 2002 and December 2023.

3 MW light curves

Figure 1 shows the MW light curves of AO 0235+164 collected from March 1997 to December 2023.

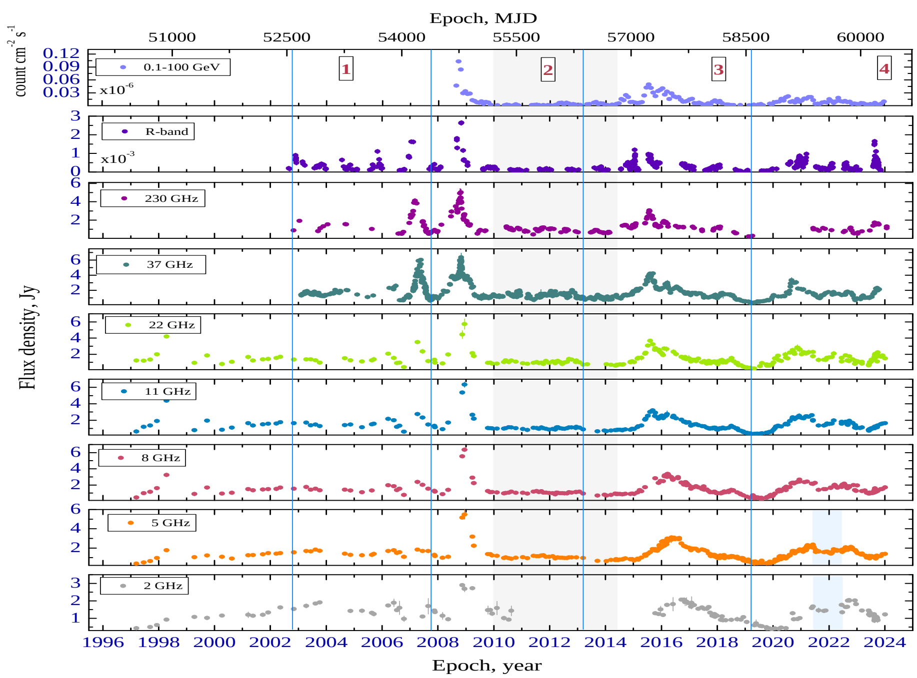

Fig. 1. Multiband light curves of AO 0235+164 in 1997–2023: radio data at 230, 37, 22, 11, 8, 5, 2 GHz, optical data (R-band) and γ-rays (from bottom to top).

The most complete light curves covering this period are those at radio frequencies of 5–22 GHz. The data for 37 GHz, 230 GHz, and the R-band span a shorter interval: between 2002 and 2023. The low-frequency radio curve at 2 GHz contains extended gaps due to strong radio interference.

The light curves show continuous flux density variations with four prominent flares at the epochs near 2006, 2008, 2015 and 2020, respectively. Most of them are well modeled by exponential laws with common maximum. During the years 2009–2014, AO 0235+164 has been showing quiescent broadband behaviour with a remarkable feature: very low activity lasting over 4.5 years.

4 Studies of AO 0235+164 MW properties

To analyze properties of multi-wavelength variability we apply some statistical instruments, which are well adapted for search specific features. There are: calculation of a fractional variability, structure functions method, pairwise cross-correlation method, the Lomb–Scargle method of periodicity searches. Application of these method both to total time interval and to individual epochs allow us to make the following conclusions about variability features of AO 0235+164:

1. The pairwise cross-correlation analysis of light curves has shown that time lag decreases with frequency in the range from 0 to 450 days. The relation between lag and frequency is described by a linear fit with a negative slope of -10 day GHz^{-1} for the pairs of most radio frequencies versus high-energy emission.
2. A smooth decrease of variability time-scale from radio waves to γ-rays is observed for all the epochs, as it follows from structure function analysis. During the low state, the variability time-scale practically does not vary with frequency, suggesting a similar size of the non-thermal emission region for all the bands.
3. For four years of low activity in 2009–2014, we have measured clear variability throughout the electromagnetic spectrum. The highest flux density variations occurred in the R-band and γ-rays. This variability might be caused by interaction between the remnants of the shocks followed from major outbursts.
4. The Lomb–Scargle periodogram method reveals significant peaks with close values, near 6 years, for all the wavelengths (see, for example, periodogram for optical light curve Fig. 2, left). For the low state in 2009–2014, a shorter period of ~ 2 years was revealed (see periodogram at Fig. 2, right).

The quasi-period of 6 years reflects the time between the most prominent outbursts in the light curves. These flares have probably a stochastic nature, and the detected quasi-periodicity does not have tight connection with the characteristics of the active nucleus and relativistic jet. On the other side, we suppose that the periodicity found for the low state reflects general AGN properties.

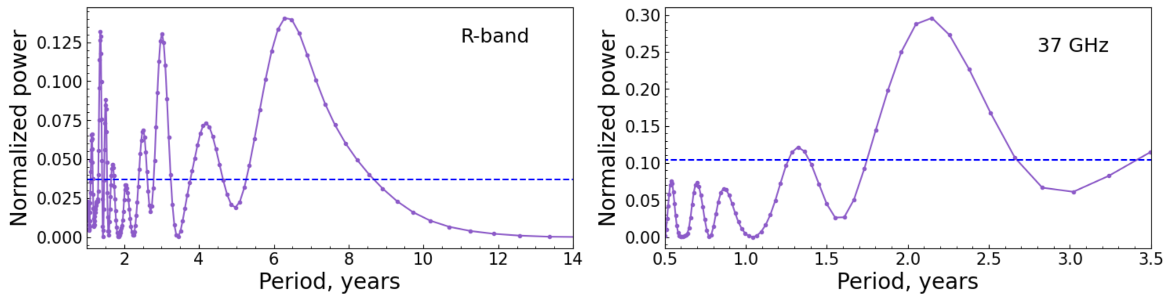

Fig. 2. The L–S periodograms for the total flux variations in the optical R-band (left) and for total flux variations at 37 GHz during the low activity state in 2009–2014. The most significant peaks correspond to components with periods of 6.4±0.1 and 2.1±0.1 years, respectively. The dashed lines show the FAP = 1 per cent (false alarm probability) level accordind to Baluev (2008).

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