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# The Optical Variability of the BL Lac AO 0235+164

Junhui Fan <sup>1,2,\*</sup>, Omar Kurtanidze <sup>3,4</sup>, Yi Liu <sup>1,2</sup>, Xiang Liu <sup>5</sup>, Gotthard M. Richter <sup>6</sup>,  
Maria G. Nikolashvili <sup>3</sup>, Sophia O. Kurtanidze <sup>3</sup>, Revaz Chanishvili <sup>3</sup>, Hongtao Wang <sup>7</sup>,  
Mahito Sasada <sup>8</sup>, Aiying Zhou <sup>9</sup>, Chao Lin <sup>1,2</sup> and Yuhai Yuan <sup>1,2</sup>

<sup>1</sup> Center for Astrophysics, Guangzhou University, Guangzhou 510006, China; pinux@gzhu.edu.cn (Y.L.); 374848511@qq.com (C.L.); yh\_yuan@gzhu.edu.cn (Y.H.Y.)

<sup>2</sup> Astronomy Science and Technology Research Laboratory of Department of Education of Guangdong Province, Guangzhou 510006, China

<sup>3</sup> Abastumani Observatory, Mt. Kanobili, Abastumani 0301, Georgia; O.Kurtanidze@lsw.uni-heidelberg.de (O.K.); mnik@abao.kheta.ge (M.G.N.); okur@abao.kheta.ge (S.O.K.); gmelik@dtapha.kheta.georgia.su (R.C.)

<sup>4</sup> Engelhardt Astronomical Observatory, Kazan Federal University, Tatarstan 420000, Russia

<sup>5</sup> Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011, China; liux@xao.ac.cn

<sup>6</sup> Astrophysikalisches Institut Potsdam, An der Sternwarte 16, Potsdam 14482, Germany; gmrichter@aip.de

<sup>7</sup> Faculty of Physics and Electronic Information, LangFang Teacher's College, China; htwtwang@126.com

<sup>8</sup> Department of Astronomy, Boston University, Boston, MA 02215, USA; sasada@kusastro.kyoto-u.ac.jp

<sup>9</sup> National Astronomical Observatory, Chinese Academy of Sciences, Beijing 100864, China; aiying@nao.cas.cn

\* Correspondence: fjh@gzhu.edu.cn

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**Abstract:** In this work, we present optical R band observations of AO 0235+164 carried out during the period of November 2006 to December 2012 using the Ap6E CCD camera attached to the primary focus of the 70 cm meniscus telescope at Abastumani Observatory, Georgia. It shows a large variation of  $\Delta R = 4.88$  mag (14.19–19.07 mag) and a short time scale of  $\Delta T_v = 73.5$  min during our monitoring period. When periodicity analysis methods are applied to the R-band data from both historic and our observations, periods  $P_1 = 8.26$  yr and  $P_2 = 0.54$  yr are found.

**Keywords:** galaxies; BL Lacertae objects; individual (AO 0235+164); photometry; variability

## 1. Introduction

Blazars are a special subclass of Active Galactic Nuclei (AGN) showing extreme observed properties such as high luminosity, strong and variable gamma ray emission, strong or no emission features, high and variable polarization, and superluminal motion. Blazars consist of two subclasses: BL Lacertae objects (BLs) and flat spectrum radio quasars (FSRQs). Physical classification of blazars is based on their peak frequency in their spectral energy distributions (SEDs) [1,2]. Abdo [3] extended the definition to all types of non-thermal dominated AGNs using new acronyms, such as low synchrotron peaked blazars (LSP,  $\log \nu_p < 14$  Hz), intermediate synchrotron peaked blazars (ISP,  $\log \nu_p = 14 \sim 15$  Hz), and high synchrotron peaked blazars (HSP,  $\log \nu_p > 15$  Hz). Quite recently, we calculated the SEDs for a sample of 1425 Fermi blazars and proposed classification as follows: LSP with  $\log \nu_p < 14$  Hz; ISP with  $\log \nu_p = 14 \sim 15.3$  Hz; HSP with  $\log \nu_p > 15.3$  Hz [4].

Variability is one of the most extreme observational properties of blazars, which show variability across almost all electromagnetic wavebands. The variations have been found to be over time scales from less than one hour to as long as years; see [5], who divided the time scales into three classes: micro-variability (intra-day variability, or IDV) with time scale  $\Delta T$  being less than one day; short-term variation (STV), with  $\Delta T$  being one day to several months; and long-term variation (LTV), with  $\Delta T$  being longer than one year. From observations, we can see that the short-term variations are

non-periodic, while the long-term variations in some cases are quasi-periodic, as discussed in the literature [6–17].

BL Lac AO 0235+164 shows variability timescales from less than one hour to several years [9,18–25]. In our previous paper, variations in the UBVRI bands are  $\Delta U = 4.26$ ,  $\Delta B = 5.47$ ,  $\Delta V = 4.74$ ,  $\Delta R = 4.18$ , and  $\Delta I = 3.85$  mag [26].

Raiteri et al. [27] analyzed about 25 years of observational data in optical and radio bands during the period from 1975 to 2000, and found a quasi-periodicity of the main radio (and optical) outbursts on a 5.7-year time scale. A period of  $5.87 \pm 1.3$  years was found in our previous work based on 16 years of optical observations [9], but  $5.8 \pm 0.3$  years (based on 14.5 GHz light curve),  $5.7 \pm 0.3$  years (based on 8.0 GHz light curve), and  $10.0 \pm 1.3$  years (based on 4.8 GHz light curve) are found in its radio bands [13]. This perhaps suggests the existence of a binary black hole system at its center [28,29]. It is one of the objects in our monitoring programme at Abastumani Observatory, Georgia [30–34].

In Section 2, we describe the observations; in Section 3, we show period analysis results; and in Section 4, we give discussions and conclusions.

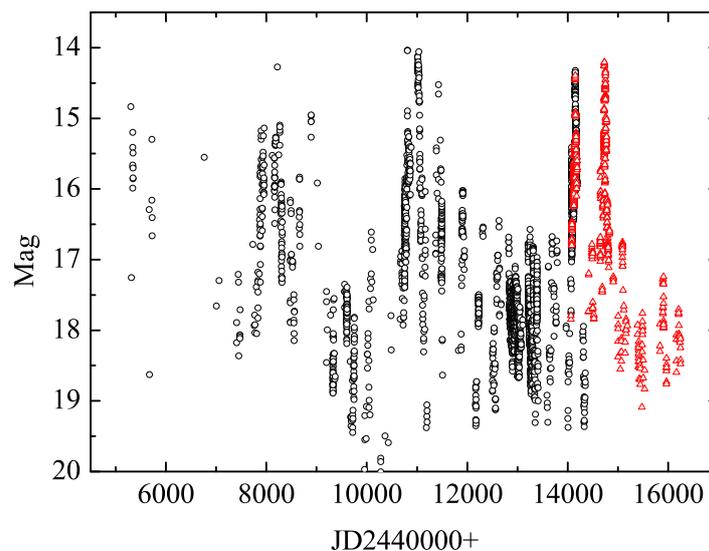
## 2. Observations

All our observations were made using a 70 cm meniscus telescope at Abastumani Observatory. The observations and data reduction were described in our recent work [34]. The R-band light curve for AO 0235+164 is shown in red in Figure 1.

From the red points in Figure 1, we can see that AO 0235+164 is extremely variable. It shows a variation of  $\Delta R \sim 4.88$  mag from  $R = 14.19$  to  $R = 19.07$  mag, and a short time scale of  $\Delta T_v = 73.5$  min during the whole observing period [34].

### Period Analysis

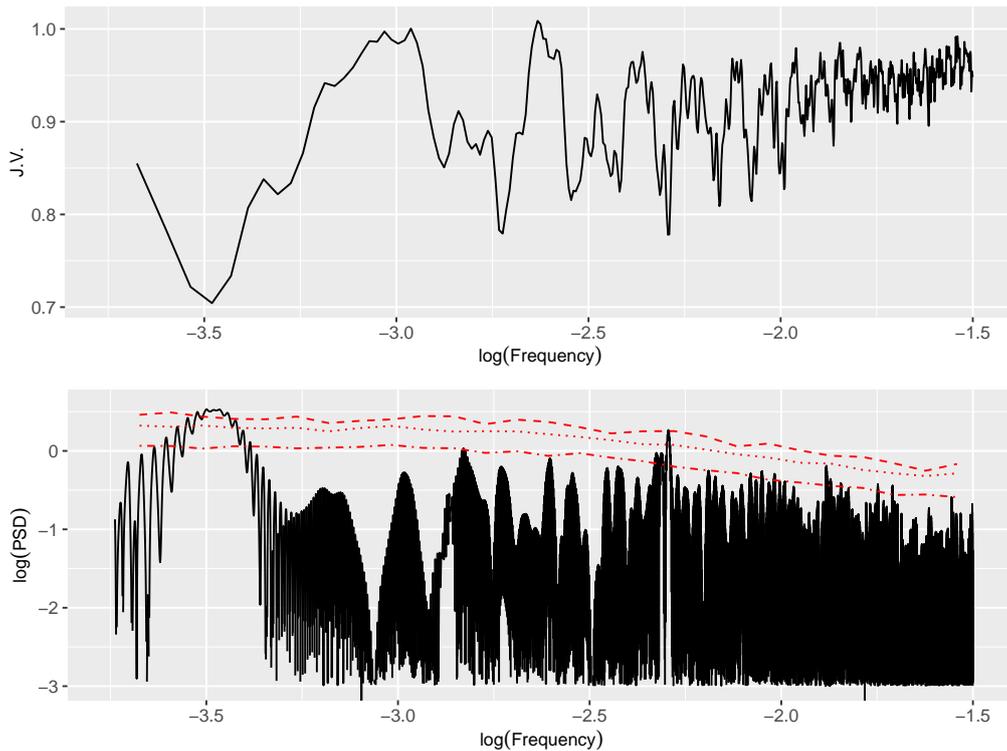
We have compiled the optical data from the literature [9,24], and constructed an optical light curve covering a time span of 30 years, as shown in Figure 1. It is clear that the light curve is not evenly sampled. In the case that data are unevenly sampled in time series (as we have done in [33]), the Jurkevich (JV) method [6] and improved power spectral analysis (PSA) will be adopted for the possible periodicities.



**Figure 1.** Historic light curve of AO 0235+164 during JD 2445300 to JD 2456247. The open circles are from the literature and the triangles are from our own observations.

The JV method is based on the expected mean square deviation. The deviation  $V_m^2(\tau)$  of a given period  $\tau$  for a light curve  $X(t_i), i = 1, 2, \dots, N$  can be calculated, as described in [33,35]. If a frequency  $f = 1/\tau$  is equal to the true frequency, then  $V_m^2(\tau)$  reaches the minimum. The plot of  $V_m^2(f)$  against  $f$  is shown in the top panel of Figure 2.

Many attempts of power spectral analysis have been made to investigate the periodicity. An improved technique is the date-compensated discrete Fourier transform (DCDFT)+ the CLEANest algorithm [36,37], a least-square regression on  $\sin(\omega t)$ ,  $\cos(\omega t)$ , and constant function. The DCDFT is a powerful method for unevenly spaced data, so we adopted it to the Figure 2 light curve [37].



**Figure 2.** Top panel: Periodicity analysis results of AO 0235+164 obtained by Jurkevich (JV) method. Bottom panel: results for AO 0235+164 by power spectral analysis (PSA) method. The curves of the false alarm probability by using the continuous autoregressive process (CAR1) method are also plotted. Two signals,  $P_1 = 8.26$  yr and  $P_2 = 0.54$  yr, can be found with the threshold that false alarm probability ( $FAP$ )  $\geq 3\sigma$ .

We assume that there are seven independent frequency components to clean the observational data; the CLEANest spectrum is shown in Figure 2. There are signs of periods:  $P_1 = 8.26$  yr,  $P_2 = 0.54$  yr,  $P_3 = 0.85$  yr,  $P_4 = 1.99$  yr, and  $P_5 = 0.56$  yr in the optical light curve.

We also use the first order continuous autoregressive process (CAR1) to estimate the false alarm probability (FAP) of red noise, which CAR1 process  $Y_t$ , a model of red noise, can be given by the stochastic difference function :

$$Y_t = -\frac{1}{\tau}Y_t dt + dW_t.$$

Here,  $\tau$  is the timescale of the CAR1 process, and  $W_t$  is the Weiner process. The value of  $\tau$  can be obtained from the light curve [38],  $\tau = 377_{-17}^{+54}$  days. The simulated  $FAP$  curves are also shown in Figure 2. We can find only two possible periods,  $P_1 = 8.26$  yr and  $P_2 = 0.54$  yr, which show that threshold  $FAP \geq 3\sigma$  [34].

### 3. Discussions and Conclusions

Variability is one of the extreme properties of BL Lacertae objects. A variation can be taken as a real one if the variability shows up in simultaneous multiwavelength observations. However, most monitoring programs are performed at a certain waveband. Romero et al. [39] introduced a variability parameter  $C$  to justify a variation to be strong or not. Heidt & Wagner [40] proposed a method to obtain a variability amplitude  $A$ . We also proposed that a variation can be taken as a real one if the variability is three times greater than the deviation; namely,  $\Delta m_{12} = m_1 - m_2 \geq 3\sqrt{\sigma_1^2 + \sigma_2^2}$ , where  $\sigma_1$  and  $\sigma_2$  are the uncertainties corresponding to  $m_1$  and  $m_2$ . The corresponding time interval is adopted as the time scale  $\Delta T = t_{m2} - t_{m1}$  [41]. The time scale is also defined to be  $\Delta T_v = \Delta F / (dF/dt)$ .

AO 0235+164 is a well-studied object. Although it was classified as a BL Lac object, the equivalent width (EW) of emission lines varies from one observational epoch to another. It is violently variable in all wavebands from radio through high-energy  $\gamma$ -rays [23].

At the optical bands, rapid variability was reported by many authors [20,40,42]. Schramm et al. [42] reported extreme optical variability of 1.6 mag within 48 h. Heidt & Wagner [40] found a variation amplitude of 6.33% per day. Romero et al. [20] reported intra-night variability with amplitudes of  $A \sim 100\%$  over 24 h, variations of  $\Delta m = 0.5$  mag were detected in R and V bands within a single night, and variations up to 1.2 magnitudes occurred from night to night.

In the soft X-ray region, ROSAT detected an increase by a factor of 1.7 in about 3 days, and a decrease of a factor of 3.5 in about 13 days [43], which suggests doubling time scales of  $\Delta T_D = 1.76$  and 3.71 days, respectively.

*Variability:* For AO 0235+164, its historic variation amplitude is as large as  $\Delta m \sim 5.0$  mag [26,44,45]. In our monitoring period, the light curve shows a variation amplitude of  $\Delta R \sim 4.88$  mag, which is similar to the historically largest amplitude.

*Periods:* Periodicity analysis is also interesting in active galactic nuclei (AGNs). AO 0235+164 has been observed and periodicity analyzed in many works (see [34]).

Using discrete Fourier transform (DFT), Webb et al. [46] analyzed the optical light curve of AO 0235+164 and found periods of 2.79, 1.53, and 1.29 years. Later on, we removed a linear trend from the light curve and adopted unequal-interval Fourier transform and CLEAN techniques to its normalized data, and obtained periods of 2.7 and 1.2 years. Smith & Nair [47] found periods of 2.7 and 3.6 years in the optical band. Raiteri et al. [27] reported a 5.67 year period in the R optical light curve and 1.8, 2.8, and 3.7 years in radio bands.

In our previous papers [9,13], we found periods of 2.0 years,  $2.95 \pm 0.15$  years, and  $5.87 \pm 1.3$  years in the optical light curve, and periods of  $10.0 \pm 1.3$  years,  $5.7 \pm 0.3$  years, and  $5.8 \pm 0.3$  years at 4.8 GHz, 8.0 GHz, and 14.5 GHz.

Raiteri et al. [27] claimed a possible quasi-periodic occurrence of the major radio and optical outbursts of AO 0235+164 every  $5.7 \pm 0.5$  years, which resulted in the Whole Earth Blazar Telescope WEBT campaign observing the source [48,49]. The period analysis based on the historic and the campaign observations suggests that the period for the large outburst is  $8 \sim 8.5$  years [48–51]. It is clear that the periodicity analysis results depend on the observations, which is why different works give different results.

In this work, we find that two periods— $P_1 = 8.26$  yr and  $P_2 = 0.54$  yr—have  $FAP \geq 3\sigma$  in the optical light curve. Our period of  $P_1 = 8.26$  yr with high confidence is consistent with the results of [48–51]. However, the periods of  $P_3 = 0.54 \sim 0.56$  yr and  $P_5 = 0.85$  yr have not been claimed in the literature.

The long-term period maybe caused by a binary black hole system [7,8,14,33,34].

### 4. Summary

In this work, we have presented the R optical observations during the period of November 2006 to December 2012. The following results are obtained:

- (1) The largest variation  $\Delta R = 4.88$  mag is detected from our observations.
- (2) There are two periods in the light curve,  $P_1 = 8.26$  yr and  $P_2 = 0.54$  yr.

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**Conflicts of Interest:** The author declares no conflict of interest.

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