Analysis of Optical Variability Characteristics of the BL Lac Object PKS 0735+178 (Postprint)

Authors: Yu Lian, Zhang Xiong, Wang Wenguang, Luo Shuangling

Date: 2017-09-26T00:00:00+00:00

Abstract

Based on extensive data collection, the B-band and V-band optical variability periods of PKS 0735+178 were analyzed using time-compensated discrete Fourier transform, the Jurkevich method, and discrete correlation analysis, revealing an optical variability period of years and a lower limit for the central black hole mass of .

Full Text

Analysis of the Optical Variability Characteristics of the BL Lac Object PKS 0735+178

Yu Lian, Zhang Xiong, Wang Wenguang, Luo Shuangling
College of Physics and Electronic Information, Yunnan Normal University, Kunming 650500, China

Abstract

In this paper, we analyze the periodic variability of the BL Lac object PKS 0735+178 using three methods: time-compensated discrete Fourier transform (DCDFT), discrete correlation function (DCF) analysis, and the Jurkevich method. Based on extensive observational data, we find that the object exhibits a variability period of approximately (4.10 ± 0.33) years, with a lower limit on the central black hole mass of $2.2 \times 10^6 M_\odot$.

Keywords: PKS 0735+178; DCDFT method; Jurkevich method; DCF method; variability period; black hole mass

Introduction

BL Lac objects represent an important subclass of active galactic nuclei (AGN) characterized by high luminosity, high polarization, rapid variability, and nonthermal radiation. These objects exhibit variability on both long and short timescales, and studies of their different variability timescales can provide insights into central black hole masses, emission regions, and internal structural parameters. PKS 0735+178 is a BL Lac object at redshift $z = 0.424$ that displays a flat radio spectrum, radio outbursts, dramatic optical variability, high polarization, and superluminal motion, with weak or absent emission lines. While numerous methods exist for analyzing its variability periods, many suffer from large errors or require highly continuous observational data, making them unsuitable for periodicity studies. Moreover, the absence of emission lines in BL Lac objects precludes spectroscopic studies of central black hole mass and internal structure. This paper employs DCDFT, DCF, and Jurkevich methods to investigate the variability periods in B and V bands, comparing their effectiveness. The DCDFT and DCF methods are applied to PKS 0735+178 for the first time, offering advantages of low continuity requirements and accurate results.

1 Sample and Light Curves

Observational data for PKS 0735+178 were collected from the literature spanning 1970 to 2002 in optical B and V bands. The light curves are shown in [Figure 1: see original paper] (B band) and [Figure 2: see original paper] (V band). The object exhibits extremely violent optical activity, with maximum variations of nearly 3.5 magnitudes in both bands over the 30-year observation period. Due to observational constraints, the data are discontinuous, with a nearly 9-year gap in the V band, which limits periodicity analysis.

Funded by the National Natural Science Foundation of China (11663009) and the Yunnan Provincial Key Laboratory of High Energy Astrophysics.

Author Introductions: Yu Lian, female, master's student. Research direction: active galactic nuclei. Email: 1261773081@qq.com.

Corresponding Author: Zhang Xiong, male, professor. Research direction: active galactic nuclei. Email: ynzx@yeah.net

2.1 Time-Compensated Discrete Fourier Transform Analysis

The time-compensated discrete Fourier transform (DCDFT) is one of the most common methods for calculating variability periods. Following the approach of [?] for analyzing infrared variability of PKS 1510-089, we perform Gram-Schmidt orthogonalization to obtain three orthogonal vectors and project the data onto these vectors to obtain the spectrum.

After orthogonalization:

$$H_0 = 1, \quad H_1 = \cos(\omega t), \quad H_2 = \sin(\omega t) \tag{1}$$

$$a_0 = \frac{\sum h_i}{\sum H_0^2} \tag{2}$$

$$a_1 = \frac{\sum h_i H_1 - a_0 \sum H_0 H_1}{\sum H_1^2} \tag{3}$$

$$a_2 = \frac{\sum h_i H_2 - a_0 \sum H_0 H_2 - a_1 \sum H_1 H_2}{\sum H_2^2} \tag{4}$$

The fitted function is:

$$f(t) = a_0 + a_1 \cos(\omega t) + a_2 \sin(\omega t) \tag{5}$$

The power spectrum intensity is:

$$I(\omega) = \frac{1}{2}(c_1^2 + c_2^2) \tag{6}$$

For uniformly sampled data, this corresponds to curve fitting with a three-dimensional "sine + constant" model. If the period exceeds the sampling time and the time series is sufficiently long to cover all phases, the power spectrum intensity is given by $I(\omega) = |F(\omega)|^2$, where $F(\omega)$ is the discrete Fourier transform power spectrum. For non-uniform sampling, we use a weighted time-compensated discrete Fourier transform.

Considering that observational data for many BL Lac objects have varying precision, we introduce a weighting scheme to redefine the inner product. The intensity at frequency ω is given by:

$$Q(\omega) = \frac{\sum_i f_i(t_i) g_i(t_i, \omega)}{\sum_i g_i^2(t_i, \omega)}$$

From linear regression theory, we know that $Q(\omega) \leq 1$. Using this property, we introduce a normalization factor to define the statistic $S(\omega) = Q(\omega)/I(0)$, called the spectral correlation coefficient, where $0 \leq S(\omega) \leq 1$.

Applying this method to PKS 0735+178 yields periodicity diagrams for B and V bands ([Figure 3: see original paper] and [Figure 4: see original paper]). The B band shows periodic signals at 0.62 yr, 1.01 yr, 1.67 yr, and 4.72 yr, while the V band shows periods at 0.58 yr, 1.07 yr, 1.67 yr, and 4.72 yr. Following the criteria in [**?**], the most reliable periods are 1.01 yr in B band and 1.07 yr in V band, with the 4.72 yr period being the next most significant. However, considering that periods around 1 yr are likely artifacts of Earth's orbital motion, the intrinsic variability periods are 4.72 yr in both B and V bands.

2.2 Jurkevich Method

The Jurkevich method is a statistical approach developed for unevenly sampled astronomical data [?]. For N observational data points X_i with mean $\bar{X}$ and variance V^2, the standard deviation is $S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X_i - \bar{X})^2}$. When the sample is divided into m groups, the statistical parameters for group l are:

$$\bar{X}_l = \frac{1}{n_l}\sum_{i=1}^{n_l} X_{li}, \quad V_l^2 = \frac{1}{n_l - 1}\sum_{i=1}^{n_l}(X_{li} - \bar{X}_l)^2 \tag{14}$$

The total variance for m groups is:

$$V_m^2 = \sum_{l=1}^{m} V_l^2 \tag{17}$$

The method identifies periods corresponding to minima in the V_m^2 versus period plot.

Applying the Jurkevich method to PKS 0735+178 yields V_m^2 diagrams for B and V bands ([Figure 5: see original paper] and [Figure 6: see original paper]). Minima correspond to periods of 1.02 yr, 1.20 yr, 1.66 yr, and 4.77 yr in B band, and 0.94 yr, 1.71 yr, 2.82 yr, and 3.97 yr in V band. According to the periodicity criteria [?], the most reliable periods are 1.02 yr in B band and 0.94 yr in V band, with 4.77 yr and 3.97 yr being secondary. After removing the likely artifactual 1 yr period due to Earth' s orbital motion, the intrinsic periods are 4.77 yr in B band and 3.97 yr in V band.

2.3 Discrete Correlation Function Analysis

The discrete correlation function (DCF) method analyzes correlations between two discrete datasets without requiring any preprocessing [?]. Following its application to BL Lac object PKS 0537-441 [?], we apply it to PKS 0735+178.

For datasets a_i and b_i, the unbinned discrete correlation function is:

$$UDCF_{ij} = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sigma_a \sigma_b}$$

where $\bar{a}$ and $\bar{b}$ are the means, and σ_a and σ_b are the standard deviations. For time delay τ, we calculate:

$$DCF(\tau) = \frac{1}{M}\sum_{ij} UDCF_{ij}$$

where the sum includes all pairs with time lag $\tau - \Delta\tau/2 < \Delta t_{ij} < \tau + \Delta\tau/2$. The error is:

$$\sigma_{DCF}(\tau) = \frac{1}{M-1}\left\{\sum_{ij}[UDCF_{ij} - DCF(\tau)]^2\right\}^{1/2}$$

A peak to the right of zero indicates that a_i varies before b_i, while a leftward peak indicates the opposite.

The DCF analysis of PKS 0735+178 in B and V bands is shown in [Figure 7: see original paper] and [Figure 8: see original paper]. The B band shows periodic signals at 1.21 yr, 2.27 yr, 3.62 yr, and 3.81 yr, while the V band shows periods at 1.21 yr, 2.22 yr, 3.15 yr, and 4.00 yr. According to DCF analysis criteria [**?**], the most reliable period is 1.21 yr in both bands, with secondary periods at 3.81 yr in B band and 4.00 yr in V band. After accounting for the potential 1 yr observational artifact, the intrinsic periods are 3.81 yr in B band and 4.00 yr in V band.

3 Discussion and Conclusions

We have collected optical variability data for PKS 0735+178 and analyzed its periodicity using three methods: DCDFT, Jurkevich method, and DCF analysis. The DCDFT yields periods of approximately 1730 days in B band and 1730 days in V band. The Jurkevich method gives periods of approximately 1740 days in B band and 1450 days in V band. The DCF analysis yields periods of approximately 1390 days in B band and 1460 days in V band. These results are consistent with previous studies [**?**, **?**].

Based on the derived period of (4.10 ± 0.33) years, we estimate the central black hole mass using thin accretion disk theory [**?**]. The thermal limit-cycle periodicity depends on the viscosity parameter α, central black hole mass M, and generalized stress tensor parameter μ. The outburst timescale is:

$$t_{burst} = 1.37 \times 10^6 \alpha^{-0.62} \mu^{-1.05} M_6^{2.4} \text{ yr} \tag{22}$$

where α is the viscosity coefficient, M_6 is the black hole mass in units of $10^6 M_\odot$, and μ is a dimensionless parameter.

Since the origin and nature of accretion disk viscosity remain uncertain, magnetohydrodynamic approaches are commonly used. If the magnetic field escape rate is low, we can assume $\alpha \approx 0.1$ and $\mu \approx 0.5$ [**?**], giving a long-period outburst timescale of:

$$t_{cyc} = 1.37 \times 10^6 \alpha^{-0.62} \mu^{-1.05} M_6^{2.4} \text{ yr} \tag{23}$$

For PKS 0735+178, adopting $\alpha = 1.0$ and $\mu = 0.5$ and the observed period of (4.10 ± 0.33) years, we derive a central black hole mass of $2.2 \times 10^6 M_\odot$. This mass appears somewhat low for PKS 0735+178, likely because the thin disk analysis neglects black hole spin. Nevertheless, providing a lower limit on the black hole mass is meaningful for BL Lac objects, which lack emission lines [?]. Future CCD photometric observations searching for short-timescale variability will enable further comparisons.

The different methods show varying degrees of periodicity significance. The DCDFT method effectively processes unevenly sampled astronomical data, overcoming false periods from traditional Fourier transforms. Through Gram-Schmidt orthogonalization, it solves the problem of non-orthogonal basis vectors that can produce spurious signals [?]. The DCF analysis reveals strong correlations between B and V bands, indicating similar radiation origins [?].

We note that the (1.01 ± 0.11) year period may be related to the annual observational cycle, potentially arising from regular observation intervals [?]. The (1.01 ± 0.11) year period could be an artifact of Earth' s orbital motion [?], though it may also represent the true variability period of PKS 0735+178, with other detected periods being integer multiples (N=1,2,3,···) [?]. This periodicity study provides guidance for future observations, which will further confirm the variability periods of PKS 0735+178 through additional monitoring.

References

[1] Dondi L, Ghisellini G. Gamma-ray-loud blazars and beaming[J]. Monthly Notices of the Royal Astronomical Society, 1995, 273(3): 583-595.

[2] Liu Yun, Zhang Xiong, Zheng Yonggang, et al. Polarization and variations of Blazar[J]. Acta Physica Sinica, 2007, 56(9): 5558-5563.

[3] Zhang X, Xie G Z, Bai J M. A historical light curve of 3C 345 and its periodic analysis[J]. Astronomy and Astrophysics, 1998, 330: 469-473.

[4] Zhang X, Zheng Y G, Zhang H J, et al. CCD photometry and optical variability of the BL Lacertae object H0323+022[J]. The Astrophysical Journal Supplement Series, 2008, 174(1): 111-116.

[5] Zhang X, Zheng Y G, Zhang L, et al. Optical CCD photometry of the variability of the BL Lacertae object ON231 in a low state[J]. Publications of the Astronomical Society of Japan, 2008, 60(2):

[6] Xie G Z, Bai J M, Zhang X, et al. The massive black hole in the center of the active galaxy MRK 421[J]. Astronomy and Astrophysics, 1998, 334: L29-L31.

[7] Zhang X, Zhao G, Zheng Y G, et al. CCD photometry and optical variability of gamma-ray-loud BL Lacertae object OJ 287 in a low, fainter state[J]. The Astronomical Journal, 2007, 133(5):

[8] Carswell R F, Strittmatter P A, Williams R E, et al. Optical observations of the radio source 0735+178[J]. The Astrophysical Journal, 1974, 190: L101-L104.

[9] Ding Shixue, He Changjian. The periodicity analysis of the light variability of BL Lacertae object PKS 0735+178 by using Jurkevich method[J]. Journal of Xiangfan University, 2003, 24(2): 3-6.

[10] Dong Yunming. Radiation mechanism and classification of BL Lac objects[D]. Kunming: Yunnan Astronomical Observatory, National Astronomical Observatories, Chinese Academy of Sciences, 2003.

[11] Webb J R, Smith A G, Leacock R J, et al. Optical observations of 22 violently variable extragalactic sources-1968-1986[J]. The Astronomical Journal, 1988, 95: 374-397.

[12] Pollock J T, Pica A J, Smith A G, et al. Long-term optical variations of 20 violently variable extragalactic radio sources[J]. The Astronomical Journal, 1979, 84: 1658-1676.

[13] Xie G Z, Li K H, Zhang Y H, et al. Simultaneous multi-range observations and detection of rapid variability of BL Lacertae objects[J]. Astronomy and Astrophysics Supplement Series, 1994, 106: 361-372.

[14] Xie G Z, Li K H, Zhang X, et al. Optical monitoring sample of the GeV gamma-ray-loud blazars[J]. The Astrophysical Journal, 1999, 522(2): 846-862.

[15] Bai J M, Xie G Z, Li K H, et al. Photometric monitoring of three BL Lacertae objects in 1993-1998[J]. Astronomy and Astrophysics Supplement Series, 1999, 136(3): 455-460.

[16] Schaefer B E. A search for rapid Variability in eight quasars and BL Lacertae objects[J]. Publications of the Astronomical Society of the Pacific, 1980, 92(547): 255-258.

[17] Qian B, Tao J. Optical monitoring of PKS 0735+178 from 1995 to 2001 and its historical periodic light curve[J]. Publications of the Astronomical Society of the Pacific, 2004, 116(816): 161-169.

[18] Zhang X, Zhang L, Zhao G, et al. Optical monitoring of three gamma-ray-loud BL Lacertae objects in 1999-2002[J]. The Astronomical Journal, 2004, 128(5): 1929-1941.

[19] Luo Shuangling, Zhang Xiong, Wang Wenguang. The optical variability periodicity analysis of PKS 1510-089 based on date compensated discrete fourier transform[J]. Journal of Yunnan Normal University: Natural Sciences Edition, 2016, 36(5): 1-4.

[20] Jurkevich I. A method of computing periods of cyclic phenomena[J]. Astrophysics and Space Science, 1971, 13(1): 154-167.

[21] Gao Rong, Yang Jinxue, Li Huaizhen. The variability analysis of BL Lac objects PKS 2155-304[J]. Journal of Yunnan Normal University: Natural Sciences

Edition, 2015, 35(1): 1-4.

[22] Edelson R A, Krolik J H. The discrete correlation function-a new method for analyzing unevenly sampled variability data[J]. The Astrophysical Journal, 1988, 333: 646-659.

[23] Hufnagel B R, Bregman J N. Optical and radio variability in blazars[J]. The Astrophysical Journal, 1992, 386: 473-484.

[24] Wang Wenguang, Zhang Haojing, Wang Xuepin, et al. The variability analysis of BL Lac objects PKS 0537-441[J]. Journal of Yunnan Normal University: Natural Sciences Edition, 2016, 36(4): 1-7.

[25] Smith P S, Balonek T J, Elston R, et al. Optical and near-infrared observations of BL Lacertae objects and active quasars[J]. The Astrophysical Journal Supplement Series, 1987, 64: 459-485.

[26] Horiuchi T, Kato S. A model of hydromagnetic turbulent viscosity radiation-pressure-dominated disks[J]. Publications of the Astronomical Society of Japan, 1990, 42(5): 661-674.

[27] Li Juan. Blazar variability research[D]. Guangzhou: Guangzhou University, 2007.

[28] Kidger M, Takalo L, Sillanpaa A. A new analysis of the 11-year period OJ287-Confirmation of its existence[J]. Astronomy and Astrophysics, 1992, 264: 32-36.

[29] Liu F K, Xie G Z, Bai J M. A historical light curve of ON 231 and its periodic analysis[J]. Astronomy and Astrophysics, 1995, 295: 1-10.

[30] Fan J H, Xie G Z, Lin R G, et al. The long-term variability of BL Lac object PKS 0735+178[J]. Astronomy and Astrophysics Supplement Series, 1997, 125(3): 525-528.