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

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Abstract

Based on extensive data collection, the optical variability periods in the B and V bands of PKS 0735+178 were analyzed using time-compensated discrete Fourier transform, the Jurkevich method, and discrete correlation analysis, revealing that the object has an optical variability period of (4.33±0.41) years and a lower limit for the central black hole mass of 0.22×106M .

Full Text

Preamble

Variability Analysis of the BL Lac Object PKS 0735+178

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Abstract

Based on extensive data collection, we analyzed the optical variability periods of PKS 0735+178 in the B and V bands using the time-compensated discrete Fourier transform (DCDFT) method, the Jurkevich method, and the discrete correlation function (DCF) method. We found that this object exhibits a variability period of years, and the lower limit of its central black hole mass is .

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) that observationally exhibit characteristics such as high luminosity, high polarization, rapid variability, and non-thermal radiation. These objects display both long-term and short-term optical variability. By observing and studying different variability timescales of BL Lac objects, we can obtain crucial parameters including central black hole mass, radiation region size, and internal structure. Therefore, investigating the variability periods of these objects is of great significance.

PKS 0735+178 is a BL Lac object with a redshift of 0.424. It possesses a flat radio spectrum, radio outbursts, dramatic optical variability, high polarization, and superluminal motion properties, while showing no or only weak and intermittent emission lines. Numerous methods have been employed to analyze the variability period of PKS 0735+178, though some suffer from large errors and require extremely high data continuity, making them unsuitable for periodicity studies. Moreover, since BL Lac objects characteristically lack emission lines, it is impossible to study central black hole mass and other internal structural parameters through spectroscopic observations.

This paper primarily utilizes three methods—time-compensated discrete Fourier transform, discrete correlation analysis, and the Jurkevich method—to investigate the variability periods in the B and V bands, with a comparative analysis of these approaches. The time-compensated discrete Fourier transform and discrete correlation analysis methods are applied for the first time to study the variability period of PKS 0735+178. These two methods have low requirements for observational data continuity and yield accurate results, while the Jurkevich method (previously used in reference [9]) requires long and continuous time series data.

1. Sample and Light Curves

The observational data for this study were obtained from references [11-18], comprising B-band and V-band photometric data for PKS 0735+178 spanning from 1970 to 2002. Figure 1 [Figure 1: see original paper] and Figure 2 [Figure 2: see original paper] display the light curves for the B and V bands, respectively. The light curves reveal that PKS 0735+178 exhibits extremely vigorous activity in the optical bands, with maximum variations of nearly 3.5 magnitudes in both B and V bands over the nearly 30-year observational period. However, due to observational constraints, the data are discontinuous, with the V band lacking data for nearly nine years, which limits the periodicity analysis.

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2.1 Time-Compensated Discrete Fourier Transform Analysis of PKS 0735+178 Variability Period

The time-compensated discrete Fourier transform method is one of the most commonly used techniques for calculating variability periods. Reference [19] applied this method to analyze the infrared variability period of PKS 1510-089. Through Gram-Schmidt orthogonalization of , , and , three orthogonal vectors are obtained. Projecting the data onto these three orthogonal vectors yields the spectrum:

, (1)
, (2)
. (3)

After orthogonalization:

, (4)
, (5)
. (6)

For uniformly sampled data, this process corresponds to curve fitting using a three-dimensional "sine plus constant" model. If the period is longer than the sampling time and the time series is sufficiently long to cover all phases, the power spectrum intensity is:

where represents the power spectrum of the discrete Fourier transform. In the case of non-uniform sampling, becomes the weighted time-compensated discrete Fourier transform.

In many BL Lac object observations, the precision of observational data varies. To address this issue, a weighting equation is introduced to redefine the inner product:

The intensity at frequency is given by:

From linear regression theory, we know that , where . Using this property, a normalization factor is introduced: the statistic is called the spectral correlation coefficient, and for all frequencies, .

Applying the above method to PKS 0735+178, we obtained periodograms for both B and V bands. As shown in Figure 3 [Figure 3: see original paper] and Figure 4 [Figure 4: see original paper], the B band exhibits periodicity information at 0.62 years, 1.01 years, 1.67 years, and 4.72 years, while the V band shows periods at 0.58 years, 1.07 years, 1.67 years, and 4.72 years. According to the criteria in reference [19], the most reliable periodicity signals are 1.01 years in the B band and 1.07 years in the V band, with the 4.72-year period being the next most significant in both bands. However, considering that periods with timescales of approximately one year are likely artifacts of Earth' s orbital motion around the Sun, the intrinsic variability period is determined to be 4.72 years in both the B and V bands.

2.2 Jurkevich Period Analysis

The Jurkevich method is a statistical approach developed to address non-uniform measurement problems in astronomical observations. For a dataset with N observations, where represents individual measurements, is the mean of all measurements, is the variance, and is the standard deviation, we have:

. (14)

If the sample data are divided into m groups, the statistical parameters for the l-th group are:

. (17)

The total variance for the m groups is:

Applying the Jurkevich method to PKS 0735+178, we obtained diagrams for both B and V bands. As shown in Figure 5 [Figure 5: see original paper] and Figure 6 [Figure 6: see original paper], corresponding to minima in , the B band exhibits periodicities at 1.02 years, 1.20 years, 1.66 years, and 4.77 years, while the V band shows periods at 0.94 years, 1.71 years, 2.82 years, and 3.97 years. According to the periodicity criteria [20], the most reliable signals are 1.02 years in the B band and 0.94 years in the V band, with 4.77 years in the B band and 3.97 years in the V band being the next most significant. However, after accounting for the one-year artifact period likely caused by Earth' s orbital motion, the intrinsic periods are determined to be 4.77 years for the B band and 3.97 years for the V band.

2.3 Discrete Correlation Function Analysis

The discrete correlation function method is used to analyze correlations between two discrete datasets without requiring any preprocessing, enabling direct assessment of their relationship. Reference [24] applied this method to analyze the variability characteristics of the BL Lac object PKS 0537-441. The specific procedure is as follows:

First, calculate the discrete correlation function values for two datasets, such as arrays and :

. (19)

Here, and are the means of the two datasets, and and are their corresponding standard deviations.

Second, calculate the DCF( ) values. The two datasets are related through time delays. If the time delay is and there are M data points in the interval , then the DCF( ) value is:

. (20)

Third, the error of the discrete correlation function is:

. (21)

For the resulting discrete correlation plot, if the peak appears to the right of zero, it indicates that array varies earlier than array ; conversely, array would vary later than array .

Applying the discrete correlation function to analyze the B and V band data for PKS 0735+178 yields the results shown in Figure 7 [Figure 7: see original paper] and Figure 8 [Figure 8: see original paper]. The analysis reveals periodicity information in the B band at 1.21 years, 2.27 years, 3.62 years, and 3.81 years, while the V band shows periods at 1.21 years, 2.22 years, 3.15 years, and 4.00 years. According to the periodicity analysis criteria for discrete correlation functions [21-23], the most reliable periodicity is 1.21 years in both bands, with 4.77 years in the B band and 3.97 years in the V band being the next most significant. After removing the one-year artifact period likely caused by Earth's orbital motion, the intrinsic periods are determined to be 3.81 years for the B band and 4.00 years for the V band.

3. Discussion and Conclusions

This paper collected optical variability data for PKS 0735+178 and analyzed its variability periods using three methods: time-compensated discrete Fourier transform, Jurkevich method, and discrete correlation analysis. The DCDFT method yields periods of approximately days for the B band and days for the V band. The Jurkevich method gives periods of approximately 1740 days for the B band and 1450 days for the V band. The DCF method produces periods of approximately 1390 days for the B band and 1460 days for the V band. From these results, we conclude that the BL Lac object PKS 0735+178 has a variability period of days, which is consistent with previous studies using other methods [25, 11].

Based on the derived period for PKS 0735+178, we employ thin accretion disk theory [3] to analyze the central black hole mass and the region where thermal instability occurs in the thin disk. Generally, the thermal timescale of the limit cycle depends on the viscosity parameter , the central black hole mass , and the generalized stress tensor parameter , with the outburst time given by:

, (22)

where is the viscosity coefficient, is expressed in units of solar mass, and is the central black hole mass of PKS 0735+178.

Since the origin and characteristics of accretion disk viscosity remain unclear, magnetohydrodynamics provides a common approach for discussion. Reference

[26] suggests that if the magnetic field escape rate is relatively low, we can assume . Using this parameter value, the long-period outburst time is approximately , that is:

, (23)

For PKS 0735+178, if and , and the analyzed period is , we derive a central black hole mass of . This mass appears too small for PKS 0735+178. Since the thin accretion disk theory analysis does not account for black hole spin, the derived mass is underestimated. Nevertheless, given that BL Lac objects characteristically show no emission lines in spectroscopic observations [10], providing a lower limit for the black hole mass represents a meaningful contribution to the deep study of this class of objects. Future CCD photometric observations searching for short-timescale variability will help obtain more accurate central black hole masses for further comparison.

The periodograms also reveal that different methods show varying degrees of periodicity significance. The time-compensated discrete Fourier transform method can be effectively applied to astronomical data processing, handling unevenly sampled data and overcoming false periods introduced by traditional Fourier transforms. Through Gram-Schmidt orthogonalization, this method effectively solves the problem of spurious signals caused by the non-orthogonality of the three vectors , , and [27]. The discrete correlation function analysis of the B and V bands for PKS 0735+178 shows strong correlation between them, indicating similar radiation origins [24].

Additionally, in the periodicity analysis, we note that the one-year result may be related to the annual observational cycle, possibly arising from regular observational time intervals [28]. Periods with average timescales of one year are likely artifacts of Earth' s revolution around the Sun [29], though they could also represent real variability periods of PKS 0735+178, with other periodic signals being integer multiples (N=1,2,3,···) of this fundamental period [30]. Further investigation of this period [30] will guide future observational campaigns. Additional observations and measurements will confirm the true variability period of PKS 0735+178.

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