Lomb-Scargle Periodogram Study of Long-period Optical Variability Characteristics of Blazar 3C 454.3 (Postprint)

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Abstract

This study collected data for the blazar 3C 454.3 in the optical bands B, V, R and infrared bands J, K from the SMARTS database and previous literature, spanning nearly ten years from June 2008 to July 2017. A total of 4,234 data sets were obtained, comprising 891 sets in the optical B band, 855 sets in the V band, 877 sets in the R band, 860 sets in the J band, and 751 sets in the K band. Using these observational data, the periodicity in each band was investigated using the Lomb-Scargle Periodogram (LSP) method and the Weighted Wavelet Z-transform (WWZ) method. The results indicate that: (1) 3C 454.3 exhibits periodic optical and infrared variability with a period of 454 days; (2) A long-term periodic variability of 454 days exists across all five bands, from which the central black hole mass of 3C 454.3 is derived as: and the radiation region radius as: ; (3) Based on the analysis of long-term periodic variability, the blazar 3C 454.3 is expected to undergo another outburst around June 2021.

Full Text

Studying the Long-Period Light Variation Characteristics of Blazar 3C 454.3 Using the Lomb-Scargle Periodogram Method

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Abstract

This paper collects optical B, V, R and infrared J, K band data for the blazar 3C 454.3 from the SMARTS database and previous literature, covering nearly a decade from June 2008 to July 2017. The dataset comprises 891 groups in the B band, 855 groups in the V band, 877 groups in the R band, 860 groups in the J band, and 751 groups in the K band, totaling 4,234 data points. Using these observations, we employ the Lomb-Scargle Periodogram (LSP) method and the Weighted Wavelet Z-Transform (WWZ) to investigate periodicities in each band. The results demonstrate that: (1) 3C 454.3 exhibits a 454-day periodic light variation in both optical and infrared bands; (2) Based on this 454-day long-period variation, we derive the central black hole mass and radiation region radius of 3C 454.3 as: $M \approx 6.24 \times 10^8 M_\odot$ and $R \approx 3.68 \times 10^3 R_g$; (3) Through analysis of the long-period light variation, we predict that the blazar 3C 454.3 will undergo another outburst around June 2021.

Keywords: Monte Carlo simulation; Weighted Wavelet Z-Transform; black hole mass; radiation region radius

0 Introduction

The multi-band variability timescale of blazars represents an important physical parameter, with long-period light variations providing crucial insights into central black hole masses, internal structures, and radiation regions of these objects. Numerous methods have been developed to study such phenomena, including structure function analysis, the period4 method, power spectral density (PSD), the Jurkevich method, the Weighted Wavelet Z-Transform (WWZ), and the Lomb-Scargle Periodogram (LSP). However, optical and infrared observations of celestial objects are often affected by weather, equipment, and other factors, resulting in temporally discontinuous data that introduces significant errors into period studies. The precision of results has remained a central challenge in this research field.

In previous work [5], PSD analysis was applied to optical and infrared data for this object, yielding results consistent with our current study. Nevertheless, the PSD method requires uniformly spaced data, necessitating averaging and interpolation of adjacent data points in [5]. Such processing may compromise the authenticity of the original data, introduce subjective human factors, and potentially create additional periodic interference. In this paper, we collect nearly ten years of quasi-simultaneous optical and infrared data for the blazar 3C 454.3 from SMARTS and literature [5]. We apply the LSP method to analyze these non-uniform data without requiring interpolation, though the resulting power spectra may contain spurious peaks.

To further evaluate the reliability of peaks in the power spectrum results, we simulate numerous light curves and calculate their power spectra using the LSP method. By sampling these simulated results, we estimate confidence levels for each band, enabling assessment of peak reliability and yielding more accurate quasi-periodicities. Notably, our analysis reveals only a single period without other interfering signals. We refer to this approach of simulating extensive light curves as the Monte Carlo simulation method. To verify the reliability and feasibility of our Monte Carlo results, we apply the WWZ method to data from all five bands for long-period analysis, obtaining consistent results. Using the standard deviation formula from Zhang et al., we calculate confidence levels for each band, confirming the reliability of our derived quasi-period. This study marks the first application of WWZ and Monte Carlo simulation methods to discrete optical (B, V, R) and infrared (J, K) band data of blazar 3C 454.3 for period analysis, establishing a novel approach for investigating long-period variability in blazars. Both methods effectively extract quasi-periods from non-stationary signals, significantly improving computational precision.

Through these combined approaches, we identify a consistent quasi-periodic light variation of approximately 454 days across all five bands. From this long-period study, we derive the central black hole mass and radiation region radius of 3C 454.3, providing important parameters for physical models of active galactic nuclei (AGN).

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1 Observational Data and Research Methods

Figure 1 [Figure 1: see original paper] presents the light curves of blazar 3C 454.3 in optical B, R, V bands and infrared J, K bands from the SMARTS database and literature [5], with Julian Date on the horizontal axis and magnitude on the vertical axis. The red, orange, and blue lines represent optical B, V, and R band light curves, respectively, while the purple and black lines represent infrared J and K band light curves.

Using the magnitude-to-flux conversion relation, we transform the magnitude values for all five bands into flux values according to the following formula [14]:

$$F = 3.64 \times 10^{-2.5m} \text{ Jy}$$

where F is the flux in each band (in Jy) and m is the corresponding magnitude.

1.1 Long-Period Analysis of Light Curves

After obtaining magnitude data from the SMARTS database and literature [5], we convert them to flux values using the above relation. We then employ Monte Carlo simulation and the Weighted Wavelet Z-Transform (WWZ) to calculate periods and confidence levels for each band. Specifically, after extracting flux data from the light curves shown in Figure 1, we use the LSP method to assess the feasibility and accuracy of confidence level evaluation. Subsequently, we apply WWZ to calculate variability periods for the corresponding bands and determine confidence levels using the standard deviation formula.

1.2 Lomb-Scargle Periodogram (LSP) Method for Long-Period Analysis

Detecting periodic signals hidden in noise represents a crucial objective in astronomical time series analysis. The LSP method performs phase correction on periodograms of non-uniformly sampled time series, mitigating false periods introduced by irregular sampling intervals. Unlike many other techniques, LSP does not require uniformly spaced data or interpolation, thereby reducing artificial interference. Consequently, LSP is particularly effective for identifying quasi-periodic oscillations concealed in noise.

Consider a time series $x(t_j)$, where $j = 1, 2, 3, \dots, N$. The LSP power spectrum $P_x(\omega)$ is given by:

$$P_x(\omega) = \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_{j=1}^{N}(x_j - \bar{x})\cos\omega(t_j - \tau)\right]^2}{\sum_{j=1}^{N}\cos^2\omega(t_j - \tau)} + \frac{\left[\sum_{j=1}^{N}(x_j - \bar{x})\sin\omega(t_j - \tau)\right]^2}{\sum_{j=1}^{N}\sin^2\omega(t_j - \tau)}\right\}$$

where $\bar{x}$ is the mean of the time series, N is the number of data points, and τ is the time-phase correction term:

$$\tau = \frac{1}{2\omega}\tan^{-1}\left(\frac{\sum_{j=1}^{N}\sin 2\omega t_j}{\sum_{j=1}^{N}\cos 2\omega t_j}\right)$$

The light curves in Figure 1 represent non-uniform time series, making detection of true hidden periods challenging. While the LSP equation can analyze power spectra of real data, spurious peaks may appear, complicating identification of genuine periods. Therefore, confidence level assessment of power spectrum peaks becomes essential.

1.3 Monte Carlo Simulation and Confidence Level Assessment

The power spectrum of AGN typically follows a red-noise power-law distribution $P(f) \propto f^{-\alpha}$. To obtain the power spectral index α, we take the logarithm of the power spectrum results and perform linear regression fitting. Figure 2 [Figure 2: see original paper] shows the logarithmic coordinates of frequency f (horizontal axis) versus power spectrum values (vertical axis), with red lines representing linear fits whose slopes correspond to the power spectral index α.

Through linear regression fitting, we obtain the power-law index α for each optical and infrared band. Based on α and the real data, we simulate 5,000 light curves, calculate their power spectra using LSP, and perform confidence sampling to derive confidence curves for each band. By combining the real data power spectrum with these confidence curves, we accurately determine periodic frequencies.

1.4 LSP Confidence Assessment Results

Figure 3 [Figure 3: see original paper] presents the Monte Carlo LSP results for optical B, R, V bands and infrared J, K bands. The vertical axis shows power spectrum values, the horizontal axis shows frequency in d^{-1}, the red curve represents the real data power spectrum, the black curve indicates 99.7% confidence level, the orange curve 99% confidence, and the purple curve 95% confidence. We identify periodic frequencies corresponding to peaks exceeding the 99.7% confidence curve, marked by black arrows.

All five bands exhibit a single prominent peak exceeding the 99.7% confidence level at the positions indicated by arrows in Figure 3. The corresponding peak frequencies, rounded to four decimal places, are all $f = 0.0022\, d^{-1}$. This yields a period of approximately 454 days in both optical and infrared bands, consistent with previous literature [5] but without introducing interfering signals.

To verify our method' s feasibility and accuracy, we apply the Weighted Wavelet Z-Transform (WWZ) to calculate periods for each band. Using the relationship between standard deviation and confidence level, we compute WWZ power spectrum confidence levels via the normal distribution standard deviation formula from previous literature.

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2 Weighted Wavelet Z-Transform (WWZ) Analysis of Long-Period Variation

Classical time-frequency analysis typically employs Fourier and wavelet transforms. However, astronomical data are often non-uniformly spaced, requiring interpolation that compromises data authenticity and may produce spurious periods. To address this, Foster [17] proposed WWZ, which more effectively handles non-uniform time series while revealing period stability.

WWZ projects time series onto three orthonormal basis functions: $\phi_1 = 1$, $\phi_2 = \cos[\omega(t_i - \tau)]$, and $\phi_3 = \sin[\omega(t_i - \tau)]$, with statistical weighting λ_i that adjusts for data non-uniformity and prevents over-dense sampling from affecting period analysis. The mother function is the Morlet wavelet [17], and WWZ is defined as:

$$Z(\omega, \tau, c) = \frac{N_{eff} - 3}{2} \cdot \frac{V_x + V_y}{V_x V_y}$$

where the numerator and denominator follow F-distributions with degrees of freedom 3 and $N_{eff} - 3$, respectively. N_{eff} is the effective number of data points, and V_x, V_y are weighted variances:

$$V_x = \frac{\sum_{i=1}^{N} \lambda_i \omega_i (x_i - \bar{x})^2}{\sum_{i=1}^{N} \lambda_i \omega_i}, \quad V_y = \frac{\sum_{i=1}^{N} \lambda_i \omega_i (y_i - \bar{y})^2}{\sum_{i=1}^{N} \lambda_i \omega_i}$$

with weight function $\lambda_i = \exp[-c\omega^2(t_i - \tau)^2]$ and effective number:

$$N_{eff} = \frac{\left[\sum_{i=1}^{N} \exp(-c\omega^2(t_i - \tau)^2)\right]^2}{\sum_{i=1}^{N} \exp(-2c\omega^2(t_i - \tau)^2)}$$

Figure 4 [Figure 4: see original paper] shows WWZ analysis results and corresponding periodic frequencies for optical B, R, V bands and infrared J, K bands.

The WWZ results reveal that red regions in the left color maps correspond to peak frequencies in the right power spectrum curves. Using white noise testing with the formula $\sigma = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(\delta_i - \bar{\delta})^2}$ (valid for normal distributions), where $\delta_i = m_i - \bar{m}$ represents deviations from the mean power value and M is the number of discrete power spectrum points, we calculate standard deviations for each band. Based on the relationship between normal distribution confidence levels and standard deviation, we adopt 3σ corresponding to 99.7% confidence (blue lines in Figure 4 right panels). All bands show periodic frequencies at $f = 0.0022\, d^{-1}$, confirming the ~454-day period with >99.7% confidence, consistent with Monte Carlo LSP results.

Thus, we establish that blazar 3C 454.3 exhibits a 454-day (~1.244-year) period across optical B, R, V and infrared J, K bands.

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3 Estimation of Central Black Hole Mass and Radiation Region Radius of 3C 454.3

3.1 Central Black Hole Mass Estimation

The central black hole mass represents a parameter of great interest, as blazars harbor supermassive black holes responsible for many radiation phenomena. Long-timescale variability enables black hole mass determination. Assuming the long-period variation arises from thin accretion disk theory, we use the relation from previous literature:

$$t_{burst} = 1.37 \times 10^6 \beta^{-0.62} \mu^{-0.16} M_8^{4.52} \text{ years}$$

where β is the viscosity parameter, μ is the dimensionless accretion rate, and $M_8 = M/10^8 M_\odot$. When $\mu = 0.5$ (Eddington accretion rate), the escape velocity is lower. The thermal limit cycle time becomes $t_{cyc} = 9.0\beta^{-0.62}\mu^{-0.16}M_8^{4.52}$

years. Adopting $\beta = 0.1$ and $\mu = 0.5$, we obtain a central black hole mass of $M \approx 6.24 \times 10^8 M_\odot$ using the 1.244-year period from all five bands. This result is slightly lower than typical flat-spectrum radio quasar masses because the thin accretion disk analysis does not account for black hole spin.

3.2 Radiation Region Radius

No definitive physical model currently explains long-period blazar variability. Existing theories include binary black hole models, thin disk thermal instability [8], and helical jet models [9]. If caused by thin disk instability, the radiation region radius can be determined from the long period [8]:

$$R = 1422 \times 3.2^{10} \left(\frac{t_{cyc}}{1 \text{ Myr}} \right)^{8/3} \beta^{-2/3} M_8^{2/3} R_g$$

where R_g is the Schwarzschild radius and β is the viscosity coefficient. Using $\beta = 0.1$ and $M_8 = 6.24$ (from our derived black hole mass), we obtain a radiation region radius of $R \approx 3.68 \times 10^3 R_g$.

Table 1 presents magnitude variations for each band, showing dramatic fluctuations in both optical and infrared bands, with infrared variations being more pronounced.

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4 Conclusions

Our investigation of optical and infrared bands of blazar 3C 454.3 using LSP with Monte Carlo confidence assessment and WWZ validation reveals:

1. Both methods detect a 454-day (~1.244-year) quasi-periodic light variation in optical B, R, V and infrared J, K bands. Monte Carlo confidence assessment shows only one peak exceeding 99.7% confidence in all five bands without introducing interference. WWZ analysis confirms these results, yielding identical 454-day periods.

2. For the central supermassive black hole, combining the long-period data with literature relations yields $M \approx 6.24 \times 10^8 M_\odot$. This is slightly lower than typical flat-spectrum radio quasar masses because the thin accretion disk approach neglects black hole spin. The derived radiation region radius $R \approx 3.68 \times 10^3 R_g$ is smaller than previous literature values [10] due to our lower black hole mass estimate, making our result reasonable.

3. Based on these calculations, we predict that blazar 3C 454.3 will undergo another outburst around June 2021. We will conduct further observations using the 2.4-meter optical telescope at the Yunnan Astronomical

Observatory' s Lijiang station to verify our predictions and provide observational evidence for Monte Carlo simulation studies of blazar long-period variability.

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Note: Figure translations are in progress. See original paper for figures.