Medium- and Long-Term Optical Variability of the Flat-Spectrum Radio Quasar 3C 454.3 (Postprint)

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Abstract

Blazars exhibit pronounced and dramatic large-amplitude variability, and investigations of variability on medium to long timescales are crucial for revealing the variability characteristics and underlying mechanisms of these sources. By analyzing raw variability data for the flat-spectrum radio quasar 3C 454.3 in the optical B, V, R and infrared J, K bands from June 2008 to July 2017, and employing the power spectrum method, we investigate the medium to long-term periodic variability properties of 3C 454.3. Our study reveals a primary variability period of 1.25 years, with the 4.57-year period representing a superposition of the 1.25-year cycle. The variability of 3C 454.3 across optical, infrared, and radio bands exhibits certain correlations. The results demonstrate that the infrared luminosity of 3C 454.3 is brighter than that in the optical bands, and the infrared variability is more intense than in the optical bands.

Full Text

Study on the Medium and Long-Term Photometric Variability Characteristics of the Flat-Spectrum Radio Quasar 3C 454.3

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Abstract

Blazars exhibit pronounced and dramatic large-amplitude photometric variability, and investigations of variability on medium and long timescales play a crucial role in revealing the characteristics and underlying mechanisms of these variations. By analyzing original photometric data for the flat-spectrum radio quasar 3C 454.3 from June 2008 to July 2017 in the optical B, V, R and infrared J, K bands, we have studied its medium and long-term periodic variability characteristics using power spectrum analysis. Our research identifies a primary variability period of 1.25 years, with the 4.57-year period representing a superposition of the 1.25-year cycle. The optical, infrared, and radio band variations of 3C 454.3 show certain correlations. The results demonstrate that the infrared luminosity of 3C 454.3 is brighter than that in the optical bands, with infrared variability being more intense than optical variability.

Keywords: flat-spectrum radio quasars, 3C 454.3, long-term variability, power spectrum method

1 Introduction

3C 454.3 (redshift z = 0.859) is a low-luminosity, low-redshift flat-spectrum radio quasar that exhibits clear and dramatic photometric variability. This object has attracted considerable attention from multiple research groups, with a long history of optical observations and extensive observational and theoretical studies. Previous research indicates that 3C 454.3 shows a "redder-when-brighter" trend in the optical bands. The source displays strong variability in gamma-ray, optical, and infrared bands, with its intense infrared variations being associated with gamma-ray emission. The light curves of 3C 454.3 reveal long-term periodic variability, with some blazars even exhibiting periodicities exceeding ten years. Long-term observational data are essential for studying variability periods and radiation models. Power spectrum analysis is commonly employed to discuss periodicity in astronomical variability. Zhang et al. previously used this method to analyze B, V, R, and I band data for the BL Lac object S5 0716+714, identifying a long-term variability period of 1.1 years. Li et al. applied both the Jurkevich method and power spectrum analysis to study radio band periodicities of (1.57 ± 0.12) yr and (6.15 ± 0.50) yr at 22 GHz and 37 GHz in 3C 454.3. Variability studies are crucial for revealing the characteristics and mechanisms of blazar emission.

2 Long-Term Light Curves of 3C 454.3

We obtained nearly ten years of historical photometric data for 3C 454.3 in optical and infrared bands from the SMARTS database, covering June 2008 to July 2017. The dataset includes optical B, V, R and infrared J, K bands, comprising 891, 855, 878, 861, and 752 observations respectively, for a total of 4,237 data points. If observations were possible daily, the actual coverage rates would be 26.81%, 25.72%, 26.41%, 25.90%, and 22.62% of the theoretically observable nights for the B, V, R, J, and K bands respectively, averaging 25.49%. Few celestial objects have such densely sampled multi-band observations. Using a daily sampling unit, the sampling frequency is approximately 0.25 times per day. According to the Nyquist sampling theorem, the sampling period must be less than half the minimum signal period, and the sampling frequency should exceed twice the maximum signal frequency, yielding a Nyquist frequency of approximately 0.125 times per day. This indicates that the observational data are suitable for calculating variability periods longer than 8 days, consistent with the Nyquist sampling theorem.

[Figure 1: see original paper] shows the ten-year light curves of 3C 454.3 in the B, V, R, J, and K bands. Between June 2008 and July 2017, the source exhibited mean magnitudes of 16.108 mag, 15.537 mag, 15.122 mag, 13.419 mag, and 11.594 mag in the B, V, R, J, and K bands respectively. The maximum magnitudes were 17.337, 16.756, 16.585, 15.092, and 15.017; the minimum magnitudes were 13.964, 13.448, 12.97, 11.012, and 9.188; and the magnitude variations (Δmag) were 3.373, 3.308, 3.615, 4.08, and 5.829. All bands show variability amplitudes of at least 3 magnitudes, as summarized in .

The average observational error is approximately 0.02 mag, with the mean magnitude variation range being $\Delta\text{mag} = 4.041$ mag across the light curves, resulting in a signal-to-noise ratio of S = 0.5%. Due to this low signal-to-noise ratio, we have not considered the impact of observational errors in our light curve and periodicity analyses.

The light curves reveal that the optical and infrared luminosity of 3C 454.3 varied dramatically over the ten-year period. Using the central wavelengths of the B, V, R, J, and K bands, we investigated their relationship with the corresponding maximum, minimum, mean, and differential magnitudes. [Figure 2: see original paper] demonstrates that longer wavelengths in the B, V, R, J, and K bands correspond to lower maximum, minimum, and mean magnitudes, while showing larger magnitude differences (variability amplitudes). Lower magnitudes indicate brighter luminosities, suggesting that the infrared bands are generally brighter than the optical bands. The light curves in [Figure 1: see original paper] also show that the variability trends across the B, V, R, J, and K bands are nearly identical.

3 Photometric Variability Properties of 3C 454.3

We employ power spectrum analysis to investigate the periodicity of 3C 454.3.

3.1 Power Spectrum Analysis Method

In power spectrum analysis, for a stationary random signal x(t) with autocovariance function x( ), the power spectral density function is defined as the Fourier transform of ( ), i.e., Sx ( ) =   x( ) e i , with the inverse Fourier transform being given by the definition of the autocovariance function x( ) = , ( ) − -, (−) − -. Since Sx( ) represents the power contributed by the signal between and + , Sx( ) represents the distribution of power relative to frequency and is thus called the power spectral density function.

For a stationary time series *Xn+, if its covariance sequence x(k), k = 0, 1, 2,*

⋯*satisfies x( ), the auto-power spectral density of* Xn+ is defined as x( ) = ( ) e i , where Δt is the data sampling interval. The autocovariance sequence x( ) is defined as x( ) = −1. The power spectral density function can also be obtained directly from the discrete Fourier transform of the digital sequence ( ) using ( ) = ( ) X( ) 2. Due to the periodicity of the discrete Fourier transform of digital sequences, ( ) is also periodic, and is therefore called the periodogram estimate of the digital sequence.

It can be proven [11] that for a random signal = e i 0 + , where is a stationary normal sequence with power density ( ) continuous at 0, the periodogram ( ) of must reach its maximum at some frequency near 0 on the interval ,− , -, and when N is large, ( ) = , = 0, 0, 0. In equation (10), 0 is the intrinsic frequency of signal . When N is large, ( ) forms a prominent peak near 0, with smaller power spectral density values at other frequencies. This characteristic allows identification of periodic components in the signal. When the signal contains more than one periodic component, multiple maxima appear in ( ). To distinguish genuine periods, the amplitudes of periodic components corresponding to each frequency must be determined using least squares fitting based on the frequencies at which the periodogram maxima occur.

The sampling data from SMARTS are not uniformly sampled time series. When calculating the photometric periods of 3C 454.3 using the power spectrum method, we performed interpolation using the average of adjacent data points to fill gaps in the light curve data.

The above describes the fundamental principles of period measurement using power spectrum analysis. The theoretical reliability of this method for studying long-term variability in blazars is discussed in reference [9].

3.2 Results

Power spectrum analysis yields the power spectrum diagrams for 3C 454.3 in the B, V, R, J, and K bands, each displaying two primary frequency peaks.

In the B band power spectrum, periods of 454.5 and 1666.7 days are identified, corresponding to 1.25 and 4.57 years respectively. The full width at half maximum (FWHM) is 0.00035 for the peak frequency at 0.00060 (1/day) and 0.00030 for the peak frequency at 0.00220 (1/day), as shown in [Figure 3: see original paper].

The V band power spectrum similarly shows periods of 454.5 and 1666.7 days (1.25 and 4.57 years). The FWHM values are 0.00038 for the peak at 0.00060 (1/day) and 0.00032 for the peak at 0.00220 (1/day), as illustrated in [Figure 4: see original paper].

The R band power spectrum exhibits the same periods of 454.5 and 1666.7 days (1.25 and 4.57 years), with FWHM values of 0.00035 and 0.00030 for the peak frequencies at 0.00060 (1/day) and 0.00220 (1/day) respectively, as presented in [Figure 5: see original paper].

The J band power spectrum also reveals periods of 454.5 and 1666.7 days (1.25 and 4.57 years). The FWHM values are 0.00036 for the peak at 0.00060 (1/day) and 0.00030 for the peak at 0.00220 (1/day), as shown in [Figure 6: see original paper].

In the K band power spectrum, periods of 434.8 and 1666.7 days are detected, corresponding to 1.19 and 4.57 years. The FWHM values are 0.00038 for the peak at 0.00060 (1/day) and 0.00033 for the peak at 0.00230 (1/day), as depicted in [Figure 7: see original paper].

summarizes the peak frequencies and their full width at half maximum values for each band. Our calculations demonstrate that 3C 454.3 exhibits two photometric periods in both optical and infrared bands: 1.25 years and 4.57 years.

The historical light curves in [Figure 1: see original paper] show nearly identical variation patterns across the B, V, R, J, and K bands, while [Figure 3: see original paper] through [Figure 7: see original paper] display broadly similar power spectra. This suggests that the optical and infrared luminosity variations of 3C 454.3 are fundamentally related.

As shown in [Figure 2: see original paper], longer wavelengths in the B, V, R, J, and K bands correspond to lower maximum, minimum, and mean magnitudes, while the magnitude differences (variability amplitudes) increase. Lower magnitudes indicate brighter luminosities, implying that the infrared bands are generally brighter than the optical bands. When 3C 454.3 undergoes luminosity changes, the infrared bands exhibit more dramatic variations than the optical bands. Fan et al. studied the "redder-when-brighter" trend in the optical bands of 3C 454.3 from 2006–2011, and this trend extends to the infrared J and K bands.

According to , all bands show two significant periods, with the period corresponding to frequency 0.00060 (1/day) being identical across all five bands. The 434.8-day period in the K band differs slightly from the other four bands. Calculations yield a mean period of 450.6 days across all bands, with a 95% confidence interval of [442.9, 458.3] days, or 450.6 $\pm$ 7.72 days, which can be expressed as [1.21, 1.26] years. This indicates that the 1.25-year period has a high confidence level and can be considered the primary period of 3C 454.3.

Peaks with smaller full width at half maximum values correspond to smaller errors. Therefore, the period associated with the peak frequency of 0.0022 (1/day) is more significant than that at 0.0006 (1/day). The former corresponds to a period of 1.25 years, while the latter corresponds to 4.57 years. The 1.25-year period is broadly consistent with the 1.2-year periodicity calculated by Gorshkov et al. in the radio band at 21.7 GHz, allowing us to identify the 1.25-year period as the dominant period of 3C 454.3, primarily driving its light curve variations. The presence of identical periods in optical, infrared, and radio bands suggests that the luminosity variations and periodic characteristics of 3C 454.3 are correlated across these wavelength regimes.

Our power spectrum analysis reveals periods of 1.25 years and 4.57 years. The 4.57-year period has a slightly larger FWHM and relatively greater error due to limitations in observational time coverage and data quality, suggesting possible deviation from the true period. We interpret this longer period as a superposition of the 1.25-year cycle.

Comparative analysis of the B, V, R, J, and K band variability of 3C 454.3 demonstrates that the infrared luminosity is brighter than the optical luminosity, with more intense photometric variations in the infrared bands.

We have investigated the light curves of FSRQ 3C 454.3 in the B, V, R, J, and K bands using power spectrum analysis. The results indicate that this object exhibits a primary variability period of 1.25 years in both optical and infrared bands, with the 4.57-year period representing a superposition of the 1.25-year cycle. While signal sampling has historically posed an unavoidable obstacle to medium and long-term periodicity studies, our work utilizes the latest SMARTS observations from 2008–2017 and represents the first application of power spectrum analysis to calculate periods in the optical and infrared B, V, R, J, and K bands of 3C 454.3, yielding relatively accurate results. The identical periods across optical, infrared, and radio bands suggest that the luminosity variations and periodic characteristics of 3C 454.3 are correlated across these wavelength regimes.

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