Postprint: TESS Detection of Day-scale Quasi-Periodic Oscillations in the Blazar PKS 0422+004

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Abstract

Observations by the Transiting Exoplanet Survey Satellite (TESS) reveal a quasiperiodic oscillation (QPO) of approximately 7.4 days in the optical light curve of the blazar PKS 0422+004 (α = 04 24 46.8421990080, δ = +00 36 06.329375028) in Sector 32. The Lomb-Scargle Periodogram (LSP) method was employed to identify significant periods, and the Weighted Wavelet Z-transform (WWZ) method was utilized for time-frequency domain analysis to further validate the results. Finally, based on two models—the Schwarzschild black hole (a = 0) and the extreme Kerr black hole (a = 0.9982)—the mass of the central black hole of this blazar was estimated. Adopting the 7.4-day period as the primary period, the derived black hole masses are 1.11 × 10^9 M (Schwarzschild black hole) and 7.07 × 10^9 M (extreme Kerr black hole), respectively.

Full Text

Detection of Day-scale Quasi-periodic Oscillations in Blazar PKS 0422+004

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Abstract

We report the detection of a quasi-periodic oscillation (QPO) with a period of approximately 7.4 days in the optical light curve of the blazar PKS 0422+004 observed by the Transiting Exoplanet Survey Satellite (TESS) in Sector 32. Using the Lomb-Scargle Periodogram (LSP) method to search for significant periodic signals and the Weighted Wavelet Z-transform (WWZ) method for time-frequency domain analysis, we validate this periodicity. Based on both Schwarzschild black hole (a = 0) and extreme Kerr black hole (a = 0.9982) models, we estimate the mass of the central black hole in this blazar. We obtain black hole masses of 1.11×10^8 M (Schwarzschild black hole) and 7.07×10^7 M (extreme Kerr black hole), adopting the 7.4-day period as the dominant timescale.

Keywords: blazar; PKS 0422+004; LSP method; quasi-periodic oscillation

1. Introduction

Blazars are a special class of active galactic nuclei (AGN) characterized by violent activity and extreme physical processes. The phenomena and processes observed in active galaxies primarily originate from their active galactic nuclei [1]. As a subclass of AGN, blazars feature relativistic jets of charged particles oriented nearly along the observer's line of sight ($ $10°) [2,3]. They are typically divided into two categories: BL Lacertae objects (BL Lacs) and flat-spectrum radio quasars (FSRQs). FSRQs exhibit prominent emission lines in optical and ultraviolet bands [4], while BL Lacs display featureless continuous spectra or very weak emission lines [3]. Blazars are among the most variable extragalactic objects, showing large-amplitude rapid variability and relatively high polarization across radio to optical wavelengths [5], with radiation dominated by non-thermal emission [6].

Quasi-periodic oscillations (QPOs) are frequently detected in X-ray binaries [7] and occasionally observed in various blazars and other AGN subclasses, with timescales ranging from minutes to years [8]. The Transiting Exoplanet Survey Satellite (TESS), launched by NASA in 2018, is a space telescope designed primarily to search for exoplanets orbiting the brightest dwarf stars [9]. TESS is equipped with four wide-field optical CCD cameras, each with a 24° × 24° field of view, which are combined to create a 24° × 96° sector. The satellite divides the celestial sphere into 26 sectors, with 13 covering each celestial hemisphere. TESS completes observations of one sector in approximately 27 days, enabling a full-sky survey in about two years [10]. Due to TESS's rectangular field of view, certain regions appear in multiple sectors, particularly near the poles, while gaps exist near the celestial equator [11]. TESS data, including optical observations of target objects, are archived in the Mikulski Archive for Space Telescopes (MAST) and are publicly accessible [12].

2. Data and Methods

We retrieved the optical light curve data for PKS 0422+004 from the MAST Portal (https://mast.stsci.edu). This blazar, with redshift z = 0.268, has AB magnitudes of 16.65 mag and 15.94 mag in different bands. The target was observed in TESS Sector 32. The data products record time in Barycentric TESS Julian Day (BTJD), defined as Julian Day minus 2457000, corrected to the Solar System barycenter. This time format is not affected by leap seconds [10]. The Sector 32 observations span BTJD 2173–2200, meaning sources with variability periods shorter than 27 days can be detected. For clarity, we use BTJD as the time unit in our analysis.

TESS provides two types of flux data: Simple Aperture Photometry Flux (SAP_{FLUX}) and Pre-search Data-conditioned Simple Aperture Photometry Flux (PDCSAP_{FLUX}). The SAP data contain various instrumental effects as raw measurements, while PDCSAP flux partially corrects for instrumental artifacts that could affect periodic signals [15]. Since our study focuses on short-timescale periodicity, we employed PDCSAP data for analyzing this blazar's period.

The light curve exhibits a data gap when TESS transmits observations back to Earth and ceases monitoring, resulting in non-uniform sampling. To address this, we divided each sector's light curve into segments. After processing, the light curve is shown in Fig. 1, where the x-axis represents time and the y-axis represents flux. Using Origin software's nonlinear fitting tool, we performed sinusoidal fitting on Segment 2 of the light curve, achieving a goodness-of-fit $R^2 = 0.47$. For better data visualization, we binned the data in 1-hour intervals and averaged the time and flux values within each bin.

3. Period Analysis

3.1 Lomb-Scargle Periodogram The Lomb-Scargle Periodogram (LSP) is a method for detecting periodic signals in unevenly sampled time series data by fitting sinusoidal models at each frequency [16]. For a time series with variance σ^2, the LSP power at frequency ω can be expressed as:

$$P(\omega) = (1/2\sigma^2)\ [\ (\ (X\ -\ \bar{X})\cos[\omega(t\ -\tau)])^2\ /\ \ \cos^2[\omega(t\ -\tau)] + (\ (X\ -\ \bar{X})\sin[\omega(t\ -\tau)])^2\ /\ \ \sin^2[\omega(t\ -\tau)]\ ]$$

where X are flux values, $\bar{X}$ is the mean flux, t are observation times, and τ is a phase correction term. A high power at a given frequency indicates a likely periodic signal.

Ground-based optical light curves typically suffer from uneven sampling, making it difficult to assess confidence levels for peaks in the power spectrum [17]. In contrast, TESS optical data have very uniform sampling, eliminating spurious QPOs caused by periodic sampling intervals. We used Monte Carlo simulations to establish confidence levels, assuming a red noise power-law index $\beta = 2$ for PKS 0422+004.

Fig. 2 shows the LSP power spectrum for PKS 0422+004. The black curve represents the power spectrum, while the red, blue, and green lines indicate 99.7%, 99%, and 95% confidence levels from Monte Carlo simulations, respectively. In

Segment 1, no QPO exceeds the 3σ confidence level. In Segment 2, one peak surpasses 3σ, corresponding to a period of approximately 7.4 days. We identify this as the dominant period of the source.

3.2 Weighted Wavelet Z-transform Analysis Fourier transforms provide an ideal tool for detecting periodic or quasi-periodic oscillations, but astronomical data often lack stationarity [11]. When signals exhibit short characteristic oscillation intervals, Fourier analysis may not be optimal. Wavelet analysis, evolved from Fourier transforms, can examine the temporal evolution of amplitude and phase in periodic and quasi-periodic signals [19]. By scaling and translating a mother wavelet function, we obtain wavelet functions that can analyze signals at different timescales [20].

We applied the Weighted Wavelet Z-transform (WWZ), which uses Z-statistics based on the principle that lower frequencies have more effective data points than higher frequencies. The WWZ value tends to be biased toward higher frequencies. Following this principle, we analyzed PKS 0422+004's light curve.

Fig. 3 presents the WWZ analysis results. The black curve shows the periodogram, with blue and green dashed lines representing 99% and 95% confidence levels based on red noise, respectively. In Segment 1, no peak exceeds 3σ confidence, indicating weak periodicity. In Segment 2, one peak approaches 3σ, corresponding to a period of approximately 178 hours (7.4 days), which we consider a reliable QPO detection.

4. Discussion and Conclusion

We identified a ~7.4-day QPO in both segments of PKS 0422+004's light curve. Although a substantial data gap exists between segments, analyzing the entire light curve reveals a consistent ~7.4-day periodicity, which we adopt as the source's dominant period.

To interpret this day-scale QPO, we consider three physical origins: (1) periodic pulsations in the accretion disk [23,24]; (2) jet instabilities or helical motion [25]; (3) interactions between the accretion disk and jet [26,27]. Physical processes in the accretion disk can produce optical/UV variations. Oscillations related to the disk's limit cycle may not couple with Lense-Thirring precession, while jet instabilities or helical motion could be modulated by Lense-Thirring precession [28].

The central black hole mass is a crucial physical parameter in AGN. Mainstream estimation methods include stellar/gas kinematics and reverberation mapping [29], which require spectral lines or thermal luminosity measurements. Since PKS 0422+004 lacks spectral lines and we lack its thermal luminosity, we adopt the expression from [31], assuming the period relates to the orbital timescale of spots or flares near the innermost stable circular orbit (ISCO). The black hole mass can be estimated as:

$M = (P / 1.2) \times (1 + z) \times (r/ISCO)^{3}/^{2}\ M$

where P is the period in seconds, z is redshift, and a is the spin parameter. For a Schwarzschild black hole ($a = 0$), we obtain $M = 1.11 \times 10^{8}$ M . For an extreme Kerr black hole ($a = 0.9982$), we obtain $M = 7.07 \times 10^{7}$ M .

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