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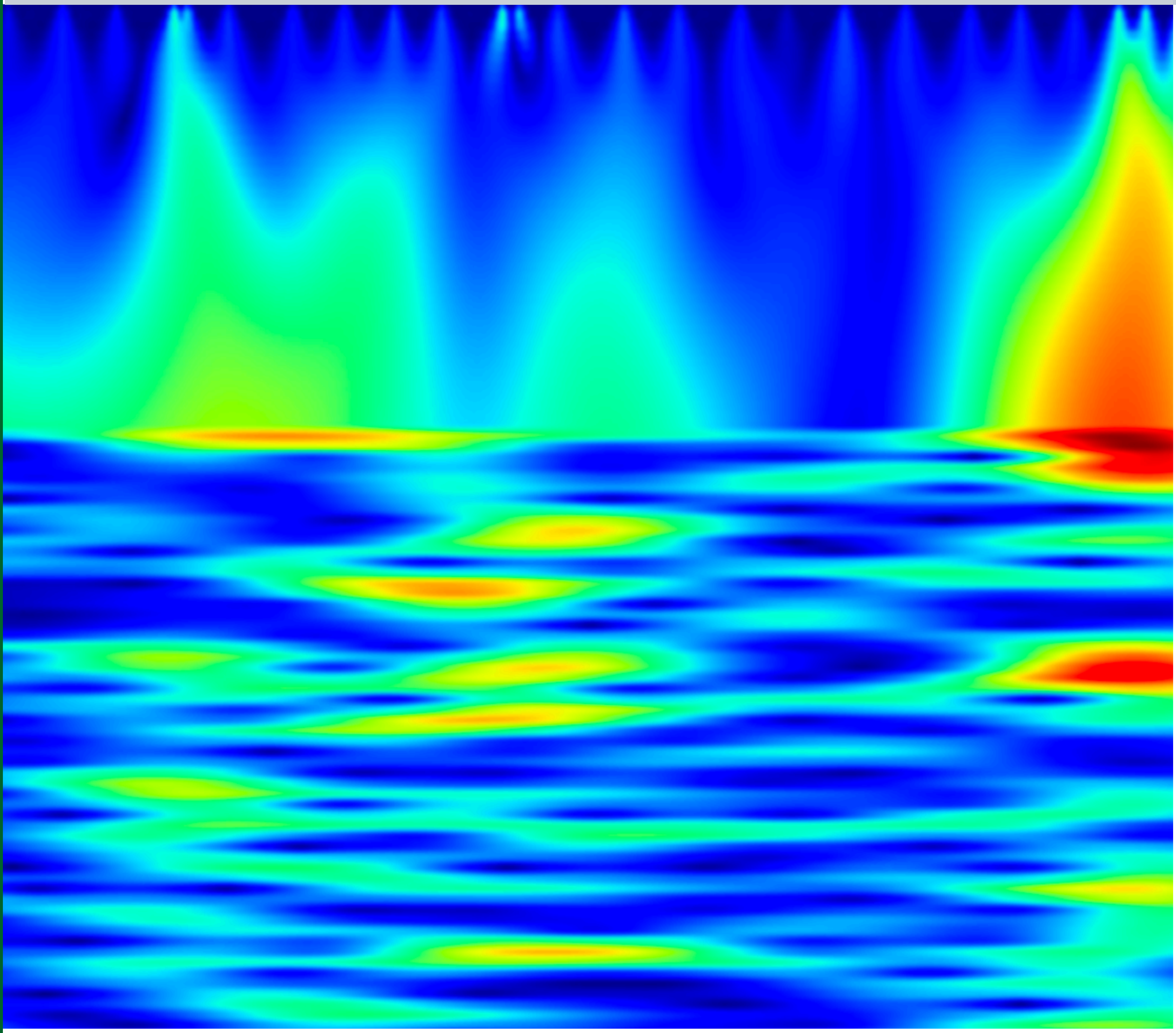

Department of Physics, Prithvi Narayan Campus, Pokhara
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Cover: Wavelet time–frequency representation for the NEAR condition. The figure shows stronger low-frequency activity over time, suggesting greater mental effort and engagement when surrounding stimuli are close to the target. (Figure 3(a), Himalayan Physics 12, 1-14, (2025))

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Himalayan Physics

Detection of quasiperiodic oscillation in x-ray light curve of blazar OJ 287 using SWIFT/XRT

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Abstract: Blazar OJ 287, a unique BL Lac object, exhibits rich variability across multiple wavelengths. This study investigates the possible presence of Quasiperiodic Oscillation (QPO) in the X-ray regime using archival data from the SWIFT/XRT telescope. The dataset comprises light curve observations from 2005 to 2022. By applying Power Spectral Density (PSD), phase folding, and epoch folding methods, we identify a consistent QPO at approximately 1.59 hours. To validate the significance of this detection against red noise, we performed statistical tests, including false alarm probability calculations and Monte Carlo simulations based on red noise models. The PSD spectrum shows a broad power-law decline consistent with red noise, but multiple distinct peaks in the high-frequency range ($10^{-4} - 10^{-3}$)Hz exceed the 99.7% confidence level derived from 1,000 red noise simulations. These results confirm that the detected QPO features are unlikely to be due solely to stochastic variability. This strengthens the case for a genuine QPO signal, suggesting coherent physical processes, such as accretion disk instabilities or jet modulation near the central supermassive black hole. The detection provides valuable insight into the emission mechanisms of blazars and supports the presence of periodic activity in the inner regions of OJ 287.

Keywords: Quasi-periodicity • Light curves • Active galactic nuclei • BL lac objects • Epoch folding

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I. Introduction

Blazars are among the most extreme and variable subclasses of active galactic nuclei (AGNs), characterized by relativistic jets oriented nearly along our line of sight, which results in pronounced Doppler boosting effects. This orientation not only enhances the observed luminosity but also contributes to rapid and high-amplitude variability across the electromagnetic spectrum, from radio to gamma-ray energies. AGNs as a whole present a wide range of observational appearances classified based on properties such as radio loudness, spectral line widths (broad or narrow), and viewing angles. Fig. 1 illustrates a unification model that helps categorize these diverse AGN types, suggesting that many of them are intrinsically

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similar but appear different due to orientation effects. Within this framework, blazars represent the class of AGNs viewed nearly face-on, where the jet is closely aligned with our line of sight. A blazar's emissions are typically dominated by non-thermal processes originating from the relativistic jets, and their variability characteristics provide crucial insights into the physical mechanisms near supermassive black holes (SMBHs). Among these enigmatic sources, OJ 287 stands out as an archetype due to its unique long-term optical behavior and its suspected binary SMBH system, making it a valuable laboratory for studying jet-disk interactions, accretion physics, and relativistic astrophysics.

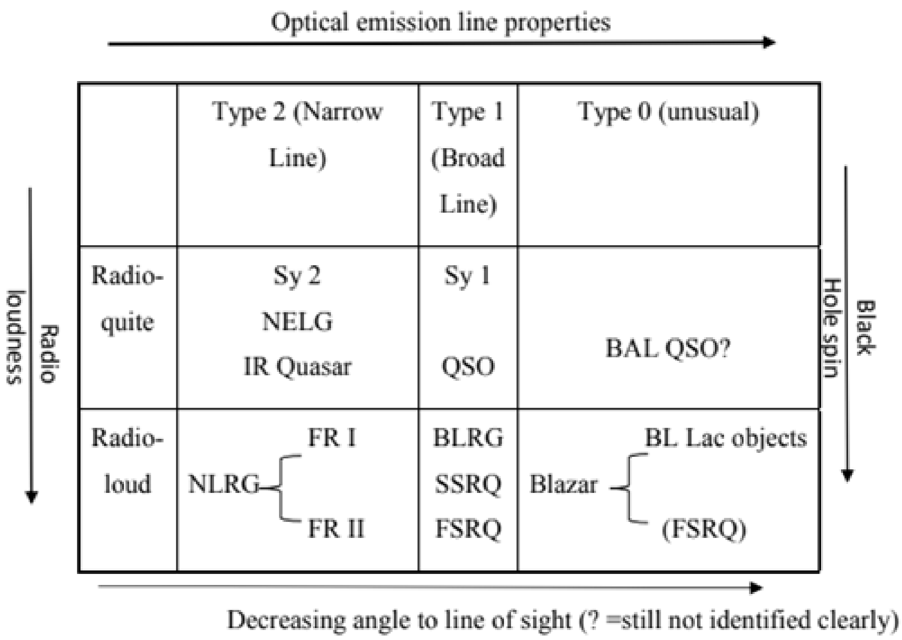

Figure 1. Classification of AGN based on radio loudness and optical emission line properties [1]

OJ 287 is a well-known blazar situated at a redshift of approximately z = 0.306. For over a century, it has exhibited recurrent optical outbursts at intervals of roughly 11 to 12 years. A systematic study of these events revealed a characteristic double-peaked structure in the outburst profiles, laying the foundation for the development of the binary supermassive black hole (SMBH) model proposed to explain the system's unique variability. In this model, a secondary black hole repeatedly plunges through the accretion disk of a more massive primary black hole, causing the observed double-peaked flares. A more refined version of the model, incorporating general relativistic effects to predict outburst timings precisely, has been highly successful in reproducing OJ 287's distinctive light curve, making it a crucial testbed for general relativity [2]. This behavior led to the proposal of a binary black hole model in which a secondary SMBH periodically perturbs the accretion disk of the primary, causing predictable impacts and resultant bursts of emission. This model has gained traction over time and has been refined to incorporate general relativistic effects such as precession and gravitational radiation losses [3].

Despite significant advances in our understanding of OJ 287 in the optical domain, its high-energy behavior, particularly in the X-ray regime remains less explored. X-ray studies are crucial because they probe the innermost regions of the jet and the accretion disk, where interactions between magnetic fields, relativistic particles, and radiation processes are most intense. Past studies have hinted at the presence of quasi-periodic oscillations (QPOs) in blazars across various wavelengths, including radio, optical, and gamma-ray bands [1, 4]. QPOs in AGNs are often associated with periodic processes near the SMBH, such as orbiting hotspots in the accretion disk, jet instabilities, or binary black hole interactions. However, detecting such signals in blazars is notoriously challenging due to the dominance of red noise, irregular sampling, and short observational baselines [5].

The X-ray variability of OJ 287, specifically, has not yet been firmly linked to any periodic process, partly due to data limitations and methodological challenges. The present study aims to address this gap by analysing long-term X-ray observations of OJ 287, obtained from the Swift/XRT (X-Ray Telescope) instrument, spanning the period from 2005 to 2022. Swift/XRT provides continuous and well-calibrated X-ray monitoring, enabling robust time-series analysis of variable sources, such as blazars. Swift mission launch and orbital characteristics are shown in Table 1. In this work, we employ multiple period-searching techniques, including Light Curve, Epoch Folding, and Power Spectral Density (PSD) analysis. These tools are particularly effective in handling unevenly sampled astronomical data. They are designed to distinguish genuine periodic signals from stochastic red noise, which is prevalent in the light curves of AGNs [6, 7].

Our preliminary findings suggest the presence of a consistent QPO with a period of approximately 1.594 hrs., detected through multiple independent methods. Such a QPO, if confirmed, would support the hypothesis that periodic structures and processes exist even in the highly turbulent environments of blazar jets. Furthermore, it would offer critical observational evidence to strengthen models involving precessing jets or binary SMBH systems in OJ 287. The identification of X-ray QPOs in a source already known for its optical periodicity would significantly advance our understanding of the coupling between jet dynamics and central black hole activity [8].

Table 1. Key mission parameters for the satellite launched in November 2004 [7]

Mission Parameter	Value
Launch Date	November 2004
Launch Vehicle	Delta 7320
Orbit	Low Earth, 600 km altitude
Total Mass	1270 kg
Total Power	1650 W
Mission Life	2yr
Orbital Lifetime	5yr

In this paper, we present the methodology, results, and implications of our analysis in detail. We begin by discussing the nature of QPOs and the motivation for studying them in the context of blazars.

We then describe the Swift/XRT data used, followed by the analytical techniques employed [9]. The results section highlights the detection and statistical significance of the 1.594 hrs. periodicity, and the discussion explores plausible physical interpretations. Our findings contribute to the growing body of literature on blazar variability and provide a foundation for future studies leveraging multi-wavelength and higher-cadence observations of OJ 287 and similar sources.

II. Materials and Methods

Setting up the software

The Swift X-ray Telescope (XRT) was used to analyze the X-ray emission from OJ 287 in the energy range of 0.3–10 keV [10]. For this study, we used the Swift-specific tools provided in the HEASoft software package (v6.30), maintained by the NASA High Energy Astrophysics Science Archive Research Center (HEASARC). The characteristics of the XRT are summarized in Table 2. Observations were taken in both Windowed Timing (WT) and Photon Counting (PC) readout modes. To process the data, we also installed the Swift/XRT Calibration Database (CALDB v1.0.2) locally on our Ubuntu 20.04 dual-boot system. The calibration files were essential for calibrating and cleaning the event data using the xrtpipeline. Similarly, the mode and alignment of the detector instrument are shown in Table 3. The general FTOOLS and XANADU suites were installed automatically with HEASoft. For timing analysis, we specifically used XRONOS v6.0 from the XANADU package. Additionally, SAOImage DS9 (v8.3) was used to define source and background regions and to assist in handling pile-up corrections.

Table 2. Technical specifications and operational characteristics of the XRT instrument [10]

Parameter	Specification
Telescope	3.5 m Wolter I, 12 shells
Detector	EPIC CCD-22
Detector Format	600×600 pixels
Pixel Size	40 m 40 m
Readout Mode	Image (IM) Mode, Photodiode (PD) Mode, Windowed Timing (WT) Mode, Photon Counting (PC) Mode
Pixel Scale	2.36 arcsec/pixel
PSF	18 arcsec HPD @ 1.5 keV 22 arcsec HPD @ 8.1 keV
Field of View	23.6 × 23.6 arcminutes
Position Accuracy	3 arcseconds
Time Resolution	0.14 ms, 1.8 ms, or 2.5s
Energy Range	0.2 - 10 keV
Energy Resolution	140 eV @ 5.9 keV (at launch)
Effective Area	125 @ 1.5 keV 20 @ 8.1 keV
Sensitivity	2 erg in seconds
Operation	Autonomous

Swift data

We retrieved Swift-XRT observational data for OJ 287 from the Swift-XRT Master Catalogue, focusing on observation IDs (ObsIDs) with exposure times of at least one kilosecond. The selected dataset spans a period of approximately 17 years, from January 3, 2005 (MJD 53430.03889) to September 4, 2022 (MJD 59678.13488). A total of 428 unique ObsIDs were collected, comprising 83 observed exclusively in Windowed Timing (WT) mode, 391 observed exclusively in Photon Counting (PC) mode, and 8 ObsIDs triggered in both modes. Some data were not available in the SWIFTMASTR database during monitoring by the X-ray telescope. Being highly variable and non-thermal, it can exhibit very high X-ray fluxes during flares. Therefore, for blazar OJ 287, we would strongly prefer the Windowed Timing (WT) mode during periods of high X-ray flux or flaring activity. The cumulative exposure time for this dataset is 1215.88 kiloseconds, representing the most extensive Swift-XRT observation campaign of OJ 287 analyzed to date.

Table 3. Summary of operational modes and performance characteristics of the XRT [7]

Mode	Image Capability	Spectral Capability	Time Resolution	On-Board Event Reconstruction	Flux Level Mode Switch
PU & LR	No	Yes	0.14 ms	No, done on ground	0.6–60 Crab
WT	1D	Yes	1.7 ms	No, done on ground	1–600 mCrab
PC	2D	Yes	2.5 s	No	$<$ 1mCrab
IM	2D	No	0.1 s (short) 2.5 s (long)	Not applicable	$>$ 140 mCrab (short) $<$ 5.6 mCrab (long)

Data extraction

The Level 1 FITS files, including event lists, raw images, and associated headers, were processed using the xrtpipeline task available in HEASoft (v6.30) along with CALDB (v1.0.2) calibration files. This pipeline converts the Level 0 telemetry data into Level 1 products, which are then refined into calibrated Level 2 files. Specifically, raw event data undergoes event list processing, while raw images are corrected for bias and bad pixels. These steps produce calibrated event lists and images, respectively. The event lists are then screened for data quality, and images undergo coordinate transformation to align with sky coordinates. The resulting Level 2 FITS files contain cleaned, scientifically usable data. Further processing yields Level 3 files, which comprise high-level science products, such as spectra, light curves, or exposure maps.

This multi-step reduction process is summarized in Fig 2, which outlines the hierarchical structure of Swift-XRT data processing from Level 0 telemetry to Level 3 science-ready products. The source position analyzed in this study corresponds to the well-known blazar OJ 287, located at RA = 133.703645 and DEC = 20.108511 (J2000 coordinates).

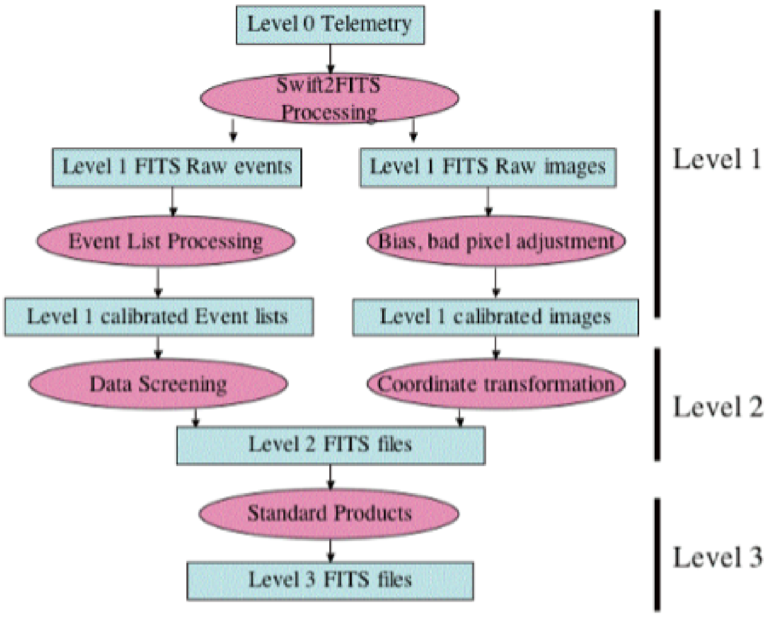

Figure 2. Flow diagram illustrating the various stages of Swift data processing [7].

Pileup

A pile-up occurs when multiple photons strike the detector within a single readout cycle, resulting in artificially high-energy events. In the case of Swift/XRT, pile-up becomes a concern in different modes at specific count rate thresholds: it is significant above 100 counts per second in Windowed Timing (WT) mode [11], and above 0.5 counts per second in Photon Counting (PC) mode. To identify and mitigate the effects of pile-up, spectra were initially extracted using a full circular region and then re-extracted after excluding the point spread function (PSF) core. For the two ObsIDs affected by pile-up in WT mode, an annular extraction region was employed with an inner radius of 1 pixel and an outer radius of 20 pixels to avoid the distorted core. In the case of 1 PC mode ObsIDs, where the count rates ranged from 3.59 to 8.98 counts per second, the data were excluded entirely due to severe spectral distortion caused by pile-up.

Background reduction

Background counts were removed using Poisson statistics. We defined both source and background regions using DS9 (v8.3) and included them in the pipeline command. For non-pile-up data, a 20-pixel circle was used for both source and background. One observation (00093249014) was discarded due to very low counts (0.199 c/s), resulting in a “dot” image. Three other ObsIDs lacked sufficient exposure time for binning.

Data processing

We processed the Swift-XRT data by first defining the source and background regions using the DS9 software. For observations without pile-up, we used a circular region with a 20-pixel radius for both the source and background. For pile-up-affected data, we followed the method described in subsection 2.4. The source and background region files were saved for each observation ID.

After setting the regions, we generated high-level data products, including spectra, light curves, and images, from the cleaned event files. We used the attitude file and housekeeping file from the downloaded data during this process. The analysis also produced ancillary response files (ARFs), which include corrections for point spread function (PSF) losses and CCD defects.

Finally, we used the FV software to extract the binned light curve data into text files, which were used for further analysis with Python. After all corrections, such as PSF correction, background subtraction, and pile-up handling, our data were ready for scientific analysis of OJ 287.

Light curve

For this study, the light curve of the blazar OJ 287 was analyzed using observational data from MJD 53539.0 (approximately 2005) to MJD 59678.13488 (approximately 2022) covering approximately 17 years, as shown in Fig 3. The analysis was performed using the LCURVE tool, applied to a single time series in the 0.3–10 keV energy range. A bin time of 300 seconds was used to smooth the data over consistent intervals. To ensure the full-time span was represented in a single plot, the number of new bins per interval was set to the maximum, allowing the complete light curve to be displayed in one PGPLOT window.

Power spectral density analysis

The Power Spectral Density (PSD) of the time series was computed to analyze the distribution of power across frequencies. The PSD was obtained using the Fast Fourier Transform (FFT) of the uniformly binned light curve data. For a discrete time, series $(x(t_j))$, where j=1, 2.... n the Fourier transform is given by:

$$X(f) = X\left(t_j\right) e^{-i 2\pi f t_j} \tag{1}$$

The power at each frequency is then calculated as the square of the modulus of the Fourier coefficients:

$$Power(f) = \left|X\left(f\right)\right|^2 \tag{2}$$

To normalize the result and obtain the PSD, the power is divided by the frequency bin width Δf :

$$\text{PSD}(f) = \frac{|X(f)|^2}{\Delta(f)} \tag{3}$$

This normalization ensures that the units of the PSD are in power per unit frequency (rms^2/Hz). Furthermore, for a stationary random process with autocorrelation function r[k], the PSD is also related via the Discrete-Time Fourier Transform (DTFT):

$$S(f) = \sum_{s=-\infty}^{\infty} r[k] e^{-i2\pi fk} \tag{4}$$

This relationship forms the theoretical basis for the spectral analysis of stochastic time series. All PSD computations were performed using these formulations [12].

Epoch folding and periodicity testing

Epoch folding is a time-domain technique used in time-series analysis, particularly effective for detecting periodic signals in observational data. Unlike traditional frequency-domain methods, epoch folding can identify signals of arbitrary shape and is less sensitive to irregular sampling or data gaps. It also avoids common frequency-domain issues, such as aliasing and red noise contamination.

In this method, the observed light curve is folded over a range of trial periods and divided into MMM phase bins. For each trial period, the variability across phase bins is evaluated using a chi-squared statistic defined as:

$$\chi^2 = \sum_{j=1}^{M} \frac{(x_j - \bar{x})^2}{\sigma_j^2} \tag{5}$$

where:

- x_j is the mean count (or flux) in the j^{th} phase bin,
- $\bar{x}$ is the overall mean across all phase bins,
- σ_j is the standard deviation of the j^{th} bin,
- MMM is the total number of phase bins.

In the absence of a periodic signal, or when the data represent Gaussian noise, the χ^2 statistic follows a chi-squared distribution with a mean close to MMM. However, if a periodic signal is present in the data, the χ^2 value at the corresponding trial period will show a significant peak, indicating the most likely periodicity. This peak typically represents the intrinsic period of the source under observation [13].

Similarly, for timing analysis, the trial period range is typically set between 1.0 and 2.0 hours with a step size of 0.001 hours to ensure adequate resolution. The number of phase bins (M) is usually chosen as 16 to balance phase resolution and counting statistics. The peak χ^2 value is calculated based on these parameters to identify the most significant periodicity. The standard deviation σ_i for each phase bin j is computed as the square root of the counts in that bin, $\sigma_i = \sqrt{n_j}$, assuming Poisson statistics.

Phase-folded light curve

Phase folding is a technique used to analyze periodic signals in time-series data by folding the light curve over a given trial period. This method converts observation times into phase values using:

$$\varphi_j = (\frac{t_j - t_0}{P}) \tag{6}$$

where t_j is the observation time, t_0 is the reference time (epoch), and P is the trial period. The resulting phase values (typically from 0 to 1) are used to bin and plot the data, producing a phase-folded light curve. If the correct period is chosen, the folded curve reveals a clear and repetitive pattern. If not, the plot appears scattered, and the process is repeated with different periods. In this study, we generated phase-folded light curves for the blazar OJ 287 using the efold task from the XRONOS package in HEASOFT FTOOLS [14].

Statistical validation

To assess the statistical significance of quasi-periodic oscillations (QPOs) in the power spectral density (PSD), we followed the procedure outlined in Vaughan [8]. The observed PSD was derived from our light curve data and down-sampled to reduce computational load. We then fitted a power-law model to the PSD in log–log space, representing the expected red noise background. To generate confidence thresholds, we performed 1,000 Monte Carlo simulations of red noise using a chi-squared distribution with two degrees of freedom, scaled by the fitted power-law. From these simulations, we calculated the 95% and 99.7% confidence levels (corresponding to 2σ and 3σ, respectively). These thresholds were then overplotted onto the observed PSD to visually and quantitatively identify statistically significant peaks that may indicate the presence of QPOs.

III. Results and Discussion

Light curve

The analyzed light curve of the blazar OJ 287, spanning from MJD 53539.0 (approximately 2005) to MJD 59678.13488(approximately 2022), reveals a distinct periodic modulation in its counts (Fig. 3). A prominent peak in this modulation is observed around 2016 (MJD 57442). The average count rate during this period is found to be 0.27220 ± 0.0011 counts per second, with a standard deviation of 0.20004 counts per second. The minimum and maximum count rates recorded are -0.22897 counts per second and 1.7314 counts per second, respectively. The maximum positive count rate of 1.7314 counts per second directly corresponds to the brightest observed state of the blazar, indicating a period of high photon detection from the source. Conversely, the minimum count rate of -0.22897 counts per second represents the faintest observed state. This negative value is a statistical outcome of the background subtraction process; it does not imply "negative emission" but rather signifies that the estimated background noise, when subtracted from the measured signal in the source region, statistically exceeded the actual source emission. Consequently, this indicates that OJ 287's signal was at or below the instrument's detection limit during this period.

These findings of periodic variability and significant flaring activity are consistent with existing literature on OJ 287. A notable flare observed in late 2015, near the identified peak, has been discussed in the context of the binary black hole model for OJ 287 [15]. Long-term investigations of the source's jet kinematics and multi-wavelength behavior over similar timeframes also support the presence of such variability [16, 17].

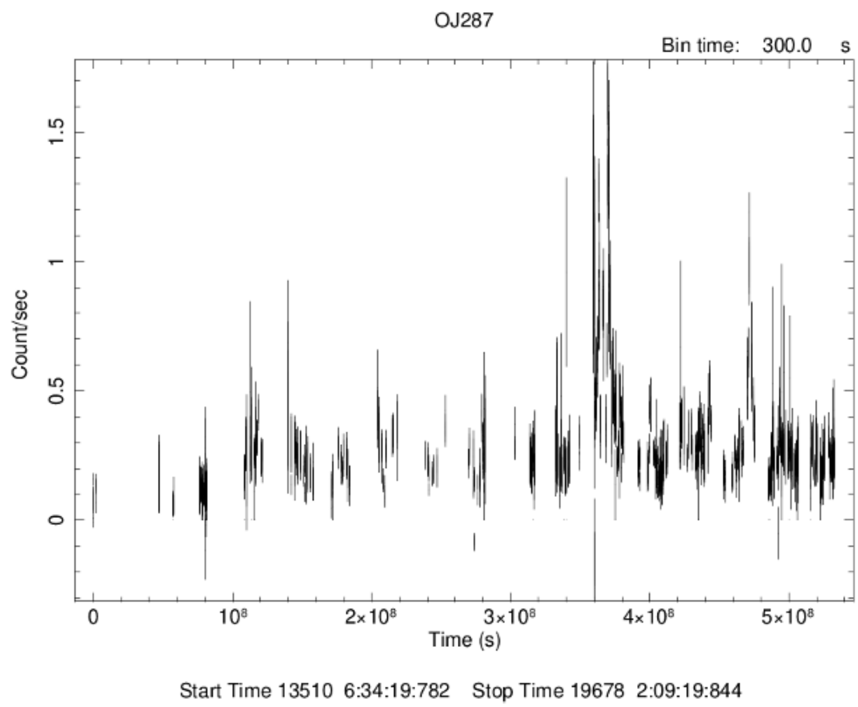

Figure 3. Long-term X-ray light curve of the source spanning 17 years (2005–2022), showing significant flux variability, including multiple outbursts and indications of possible periodic behavior. This extended temporal coverage is essential for detecting long-term trends and investigating quasi-periodic oscillations.

Power spectral density

The temporal characteristics of the X-ray light curve were investigated using Power Spectrum Density (PSD) analysis. This analysis, plotting power as a function of frequency (Fig. 4), revealed a peak power of 3638 at a corresponding frequency of 1.742002×10^{-4} Hz. Further scrutiny of the light curve through PSD methods indicated a potential periodicity of 1.567 hours. However, the detection of clear QPO peaks might be hindered by the presence of various color noise components within the X-ray data. The power spectrum presented here is derived from fluxes above 0.2 keV, binned at 300-second intervals.

Binning the flux data into 300-second intervals helps to improve the signal-to-noise ratio by averaging out short-term fluctuations and reducing statistical noise. It also makes the data more manageable by decreasing the number of data points, which facilitates more precise identification of periodic signals in the power spectrum.

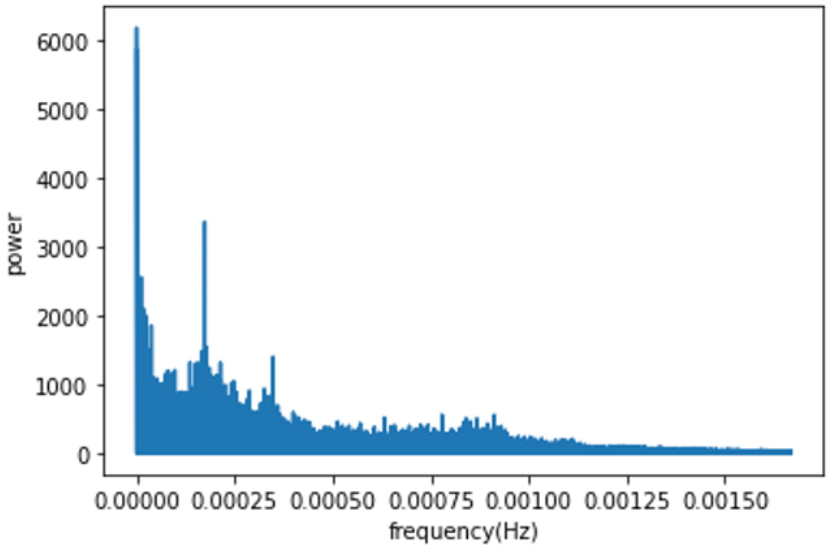

Figure 4. Power Spectral Density (PSD) of the observed light curve, illustrating the distribution of variability power across temporal frequencies. A red-noise component is evident, characterized by a power-law slope at low frequencies. The PSD was calculated using the Fast Fourier Transformation (FFT) to accommodate uneven sampling in the data.

Additionally, selecting a 300-second bin size balances temporal resolution with sensitivity to the relevant timescales of variability, allowing effective detection of quasi-periodic oscillations without losing important timing information. However, this binning can suppress fluctuations at frequencies higher than half the Nyquist frequency [18]. Moreover, gaps in the light curve pose a challenge for determining robust constraints without dedicated simulations. The observed shape of the PSD is intrinsically linked to the source's emission state, thereby providing constraints on the underlying physical processes. A comprehensive understanding of the PSD shape would require a full likelihood analysis incorporating simulated light curves to test the adequacy of a simple power-law model.

Epoch and phase folding

The epoch folding analysis, performed using the default epoch period (in days) and the period derived from the PSD (in seconds), with 19 phase bins per period and 176394 new bins per interval, yielded a refined best period of 1.594 hours for the blazar OJ 287. This confirms the presence of a quasi-periodic oscillation (QPO) signal (Fig. 5). The analysis utilized a period resolution of 300 across 35 searched values. The start and end times of the data are presented in Truncated Julian Date format.

The resulting epoch-folded light curve clearly demonstrates significant variations in source brightness as a function of phase. Given the inherent robustness of the epoch folding technique to observational irregularities, this plot further emphasizes the QPO signal detected in OJ 287.

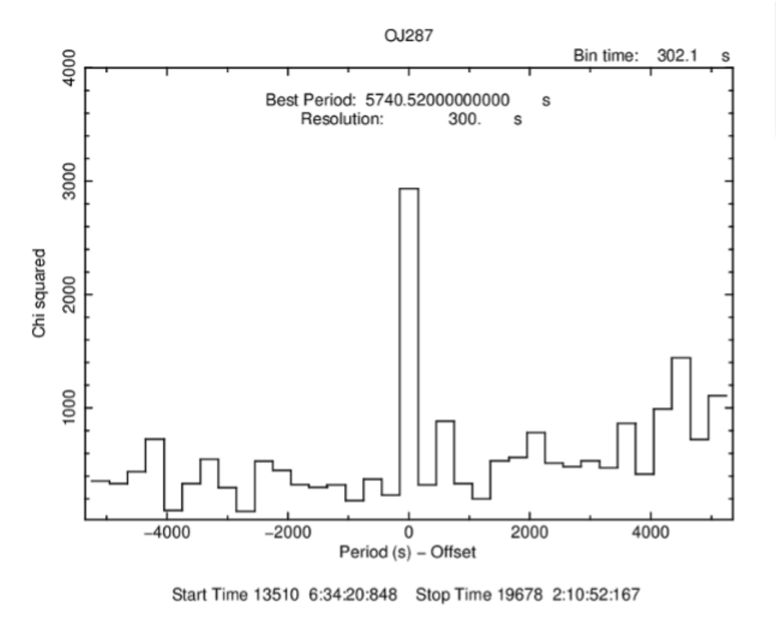

Figure 5. Epoch folding analysis of the light curve data. The curve shows the phase-folded light curve over a range of trial periods, highlighting a potential periodic modulation. The peak in the folded profile indicates a candidate period consistent with quasi-periodic oscillation (QPO) signatures observed in the power spectral density analysis.

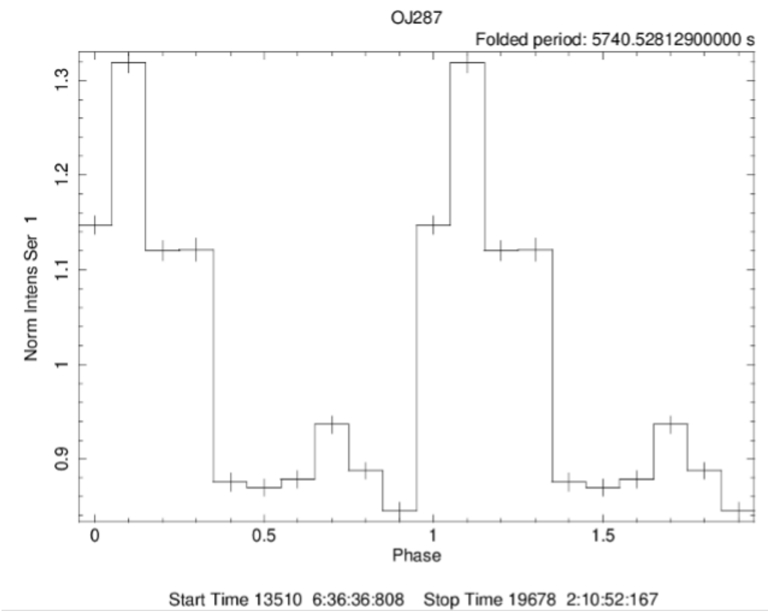

Figure 6. Phase-folded light curve using the candidate period derived from epoch folding. The data are folded over the best-fit period and binned into phase intervals to enhance the periodic signal. The resulting profile reveals a coherent modulation pattern, supporting the presence of a quasi-periodic oscillation.

The phase folded plot was generated using the default epoch period (in days) and the best period value of 1.594 hours (converted to seconds) obtained from the epoch folding analysis (Fig. 6). For this visualization, 10 phase bins per period were used, with the default value of 928312 for the number of new bins per interval. A period resolution of 300 was applied, and one interval per frame was displayed. The resulting phase-folded light curve, illustrating two complete cycles of the blazar OJ 287's emission, visually confirms the periodicity identified through the epoch-folding method. The start and end times of the data are provided in Truncated Julian Date format. This clear representation of the phase-dependent brightness variations reinforces the robustness of the detected QPO signal.

Detection and significance of quasi-periodic oscillations in the power spectrum

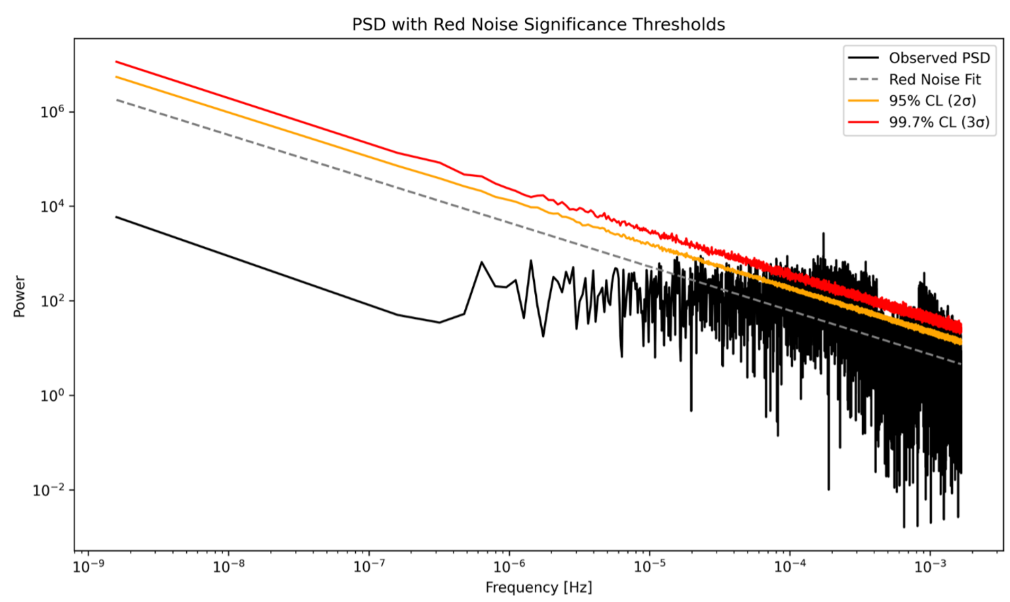

Figure 7. Power spectral density (PSD) of the observed light curve (black), overlaid with a power-law red noise fit (gray dashed line). The 95% (orange) and 99.7% (red) confidence levels were derived from 1,000 Monte Carlo simulations, assuming a χ^2 distribution with two degrees of freedom. Peaks exceeding the 99.7% threshold in the high-frequency range suggest statistically significant quasi-periodic oscillation (QPO) candidates, potentially indicating coherent processes in the accretion flow.

The PSD plot exhibits a broad power-law decline consistent with red noise behavior, as expected for accreting compact objects Fig. 7. The fitted red noise model (shown as a dashed gray line) provides a good approximation of the underlying variability continuum across the frequency range. The 95% (orange) and 99.7% (red) confidence level curves derived from 1,000 Monte Carlo red noise simulations are plotted above the red noise model to highlight statistically significant features. In the high-frequency region ($10^{-4} - 10^{-3}$Hz), the observed PSD (black) shows multiple distinct peaks that exceed the 99.7% confidence level. These peaks are likely not produced solely by stochastic variability. They may represent real quasi-periodic oscillations (QPOs) arising from coherent physical processes, such as disk instabilities or resonances in the accretion flow.

Importantly, no such excesses are seen in the lower frequency region (below 10^6Hz), which remains well below the simulated confidence thresholds, reinforcing that the detected peaks are not artifacts of model overfitting or noise mischaracterization. The steepness of the power-law fit (indicated by the slope of the gray line) is consistent with a red noise process. Whereas variability power increases at lower frequencies. The detection of multiple features above 3σ significance suggests the possibility of persistent or harmonically related QPOs and warrants further temporal or spectral analysis to examine their stability, coherence, and possible energy dependence. These high-confidence peaks provide evidence for characteristic timescales in the system that are distinguishable from random variability, thereby contributing key constraints for the physical modelling of the source.

Discussion

The analysis of the OJ 287 light curve from MJD 53539.0 to MJD 59678.13488 reveals significant variability, consistent with previous studies of this blazar. The observed peak in 2016 (MJD 57442), with an average count rate of 0.27220 ± 0.0011 counts per second, aligns with the notable flare reported in late 2015 [12]. This correspondence reinforces the established pattern of flaring activity in OJ 287, a characteristic often attributed to its proposed binary supermassive black hole (SMBH) system. The wide range of count rates, from -0.22897 to 1.7314 counts per second, further underscores the dramatic variability of this source. Long-term studies of OJ 287's jet kinematics and multi-wavelength behavior have also revealed similar variability patterns over comparable timeframes, supporting the findings presented here [14, 15].

The Power Spectrum Density (PSD) analysis of the X-ray light curve reveals a potential periodicity of 1.567 hours, with a prominent peak power of 3638 observed at a frequency of 1.742002×10^{-4} Hz. However, the identification of a definitive quasi-periodic oscillation (QPO) is complicated by the influence of red noise components. Moreover, the 300-second binning applied to the data may suppress higher-frequency fluctuations, and the presence of gaps in the light curve introduces additional challenges for placing robust constraints on the periodic behavior [17]. Whereas a comprehensive understanding of the PSD shape necessitates a full likelihood analysis, including simulated light curves, to rigorously test the adequacy of a simple power-law model. The observed PSD shape is intrinsically linked to the source's emission state, providing valuable constraints on the underlying physical processes.

Epoch folding analysis refines the periodicity, yielding a best period of 1.594 hours. This result confirms the presence of a quasi-periodic oscillation (QPO) signal in OJ 287. The robustness of the epoch folding technique to observational irregularities strengthens the case for this QPO detection. The phase-folded light curve, constructed using this refined period, visually demonstrates the significant source of brightness variations as a function of phase, providing compelling evidence for the QPO.

Similarly, the difference in quasi-periodicity arises primarily due to the coarser frequency resolution in the PSD and the finer period scanning capability of epoch folding [12]. Given the higher precision and phase coherence sensitivity of epoch folding, we adopt the 1.594-hour period as the final QPO period. Both measurements agree within their uncertainties, supporting the robustness of this periodicity.

The detection of a QPO in OJ 287 is particularly interesting within the framework of the binary supermassive black hole (SMBH) model. While the dominant periodicity of about 12 years is linked to the orbital motion of the SMBHs, shorter-term QPOs, such as the 1.594-hour period identified here, likely arise from smaller-scale phenomena within the system. These may include oscillations in the accretion disk, such as hot spot orbital motion near the innermost stable circular orbit (ISCO), or jet precession caused by the gravitational interaction of the binary SMBHs. The detected period is consistent with the timescales expected from disk instabilities and depends on the mass and spin of the SMBH. Additionally, since X-ray emission in blazars is often related to the jet, jet precession modulated by binary dynamics could also contribute to the observed variability. Thus, linking this QPO period to SMBH mass and orbital dynamics provides valuable constraints on the physical environment and geometry near the SMBHs, deepening our understanding of the mechanisms driving variability in OJ 287.

IV. Conclusion

The study of OJ 287's light curve reveals significant variability, with a prominent peak around 2016. X-ray light curve analysis indicates a possible periodicity of 1.567 hours, which refines to 1.594 hours, confirming the presence of a quasi-periodic oscillation (QPO). The observed variability and QPO support the hypothesis that OJ 287 is a binary system of supermassive black holes. The QPO may be related to accretion disk or jet processes within this system. However, the analysis is limited by factors such as red noise, data binning, and gaps in the data. To verify if the QPO signal is real and not just random noise, we compared our results with 1,000 computer-generated light curves based on red noise. We found that some of the peaks in the high-frequency range were stronger than what would normally be expected from noise alone. This supports the idea that the QPO is likely a valid signal. Further investigation, including a full likelihood analysis with simulated light curves, is needed. Future research should focus on detailed modelling of the accretion disk and jet dynamics, incorporating multi-wavelength observations, to enhance our understanding of the QPO and the underlying physical processes in OJ 287.

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VI. Data Availability

The data utilized in this study are publicly available from the Swift/XRT data archive maintained by NASA's High Energy Astrophysics Science Archive Research Center (HEASARC). All the observations of the blazar OJ 287 from 2005 to 2022 were retrieved using the Swift data interface: https://www.swift.ac.uk/user_objects/. The target coordinates (RA = 133.703645°, DEC = +20.108511°) were verified to match OJ 287, as listed in the TeVCat catalogue (ID OJ 286).

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