Radio QPO and Doppler Factor Analysis of the Blazar CGRaBS J0835+6835: Postprint

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Abstract

Based on observational data from the Owens Valley Radio Observatory (OVRO) 40-meter telescope, we collected data for the blazar CGRaBS J0835+6835 in the 15GHz radio band (approximately 12 years). Using the Lomb-Scargle periodogram (LSP) method and the Weight Wavelet Z-transform (WWZ) method, we detected a quasi-periodic oscillation (QPO) in CGRaBS J0835+6835 with a period of approximately 560 days. We employed the helical jet model in supermassive binary black hole systems to estimate the range of its primary black hole mass M to be approximately 3.7$×$108M ~3.5X109 M . To investigate whether this source exhibits a beaming effect, we used a double exponential function to fit six flaring episodes and found that the average value of the variability Doppler factor δ ∨ is approximately 10.76. This indicates that the radio emission from this source exhibits a significant beaming effect.

Full Text

Radio Quasi-Periodic Oscillation and Doppler Factor Analysis of Blazar CGRaBS J0835+6835

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Abstract: Based on observational data from the Owens Valley Radio Observatory (OVRO) 40-meter telescope, we collected approximately 12 years of 15 GHz radio band data for the blazar CGRaBS J0835+6835. Using both the Lomb-Scargle periodogram (LSP) method and the Weighted Wavelet Z-transform (WWZ) method, we detected a quasi-periodic oscillation (QPO) with a period of approximately 560 days. Employing a helical jet model from supermassive binary black hole systems, we estimate the mass of the primary black hole to be in the range of 3.7$×10^{8}$ M to 3.5$×10^{9}$ M . To investigate whether this source exhibits beaming effects, we fitted six flare processes with a double exponential function and found that the average variability Doppler factor δ_V is approximately 10.76, indicating significant beaming effects in the radio emission.

Keywords: Blazar; CGRaBS J0835+6835; LSP method; WWZ method

Blazars constitute a special subclass of active galactic nuclei (AGNs) and represent among the most energetic objects in the universe. Their emission originates primarily from high-energy particles in relativistic jets, and due to relativistic beaming effects, their radiation activity can be observed across gamma-ray bands. Blazars are divided into two categories: flat-spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lacs) [1]. Observational characteristics include high luminosity, high polarization, rapid variability, and non-thermal radiation [2]. The spectral energy distribution (SED) exhibits a double-peaked structure, with the low-energy peak produced by synchrotron radiation and the high-energy peak generated by inverse Compton scattering of electrons or hadronic radiation processes [3-4]. Numerous methods exist for estimating Doppler factors, among which the method using radio variability to estimate the Doppler factor (δ_V) is relatively straightforward and widely applied [5-6]. Variability studies can probe the internal radiation processes and physical mechanisms of blazars, making the investigation of astronomical variability and its potential periodicity crucial for understanding active galactic nuclei.

CGRaBS J0835+6835 (BWE 0830+6845) is a source at redshift z = 1.414 (α = 08h 35m 47.6080866785s, $\delta = +68° \ 35' \ 11.493386746''$) [7]. Romani et al. measured an R-band flux of 0.00013 mJy for this source [8], while Snellen et al. provided flux density measurements at various frequencies including 325 MHz, 609 MHz, and 5 GHz in their study of GHz-peaked spectrum source samples [9]. This paper utilizes long-term monitoring data from OVRO at 15 GHz to investigate the radio variability of CGRaBS J0835+6835 and detect potential quasi-periodic oscillations. We also employ double exponential function fitting of flare processes to test for significant beaming effects. The primary methods for analyzing QPOs in blazar light curves are the Lomb-Scargle periodogram (LSP) [10] and the Weighted Wavelet Z-transform (WWZT) [11], both of which are well-suited for handling unevenly spaced data. In this work, we apply both methods to study the periodicity of the 15 GHz radio light curve of CGRaBS J0835+6835 and evaluate the reliability and confidence of our results.

1. Light Curve

Figure 1 [Figure 1: see original paper] presents the 15 GHz radio light curve of blazar CGRaBS J0835+6835 observed with the OVRO 40-meter telescope.

After removing a few bad data points, we retained 460 data points covering a Modified Julian Date (MJD) range of approximately 54908–58871. We adopt the variability index A [12-13] to assess the activity level of the source, defined as:

$$A = \frac{f_{\max} - f_{\min}}{f_{\max} + f_{\min}}$$

where $f_{\max}$ and $f_{\min}$ represent the maximum and minimum flux densities, respectively. Larger values of A indicate more active sources. Calculations yield a radio variability index of 0.98 for CGRaBS J0835+6835, demonstrating that it is a highly active source.

In Figure 1, the blue line represents the observed light curve, while the red line shows a sinusoidal function providing a rough fit to the data.

2.1 Lomb-Scargle Periodogram Method

Detecting periodic signals hidden within noise represents a crucial objective in astronomical time series analysis. The Lomb-Scargle periodogram (LSP) method performs phase correction on periodograms of non-uniformly sampled time series and can correct for false periods introduced by uneven sampling within a certain range [10]. Consequently, the LSP method is highly effective for identifying quasi-periodic oscillations concealed in noise. Based on Fourier transform principles, the LSP method employs a sinusoidal model with the fundamental formula [14-15]:

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

where τ represents the phase correction term for time t, calculated as:

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

This formulation offers several advantages over standard discrete Fourier transforms. First, the inclusion of time terms ensures that period calculations remain invariant under time origin shifts. Second, this form makes periodogram analysis completely equivalent to least-squares fitting of sinusoidal curves to the data.

To verify the reliability of QPO detection using the LSP method, we first performed a power-law fit to the periodogram to obtain the power-law index β required for Monte Carlo confidence calculations [16]. We then developed a Python program to compute confidence levels for CGRaBS J0835+6835, with results shown in Figure 3 [Figure 3: see original paper]. The green line represents the periodogram, with peaks indicating QPO candidates. The blue, red, and black lines represent 95%, 99%, and 99.7% confidence levels from Monte Carlo simulations, respectively. Two prominent peaks appear at 562 days and 1020 days, both exceeding the 99.7% confidence threshold, confirming their reliability. Since 1020 days is approximately twice 562 days, we adopt the smallest positive period—562 days—as the QPO period for CGRaBS J0835+6835.

2.2 Weighted Wavelet Z-Transform Method

Wavelet analysis represents a powerful new analytical method that stands as another brilliant example of the perfect integration of pure and applied mathematics following Fourier analysis. Using the Morlet wavelet as the mother wavelet, the complex Morlet function is [17]:

$$\psi(t) = \pi^{-1/4} e^{i\omega_0 t} e^{-t^2/2}$$

Foster defined the Weighted Wavelet Transform (WWT) [18]:

$$WWT(\omega, \tau) = \frac{\sum_{j=1}^{N} w_j x_j \psi^*[(t_j - \tau)/s]}{\sum_{j=1}^{N} w_j}$$

where w_j represents weights and s is the scale parameter. Due to variations in wavelet shape, the effective number of data points N_{eff} at low frequencies exceeds that at high frequencies, causing WWT values to shift toward higher frequencies and introducing bias. Foster therefore defined the Weighted Wavelet Z-transform based on his Z-statistic [10]:

$$WWZ(\omega, \tau) = \frac{N_{\text{eff}} - 3}{2} \cdot \frac{|\text{WWT}(\omega, \tau)|^2}{1 - |\text{WWT}(\omega, \tau)|^2}$$

Applying equation (6) yields the QPO diagram shown in Figure 4 [Figure 4: see original paper]. The left panel displays the WWZ power distribution in the time-period plane with color scaling, while the right panel shows the time-averaged power (black curve) as a function of period. Blue dashed lines indicate 99.7%

and 95% confidence levels. The period can be determined from the maximum value in the WWZ diagram. Figure 4 reveals a clear maximum at 560 days with confidence exceeding 99.7%, confirming the reliability of this QPO detection.

3. Doppler Factor Analysis

The Doppler factor (δ) can be defined through two intrinsic parameters: the bulk flow velocity (V) and the viewing angle (θ). However, both quantities are difficult to measure directly, necessitating indirect estimation methods. Among various approaches, estimating the Doppler factor from radio variability (δ_V) is relatively simple and widely used.

We fitted six flare processes in CGRaBS J0835+6835 with a double exponential function, as illustrated in Figure 5 [Figure 5: see original paper] (MJD denotes Modified Julian Date in days). References [19-20] detail the brightness temperature formula, double exponential function, and Doppler factor estimation procedure. The double exponential function is:

$$F(t) = F_0 + \Delta F \begin{cases} \exp\left(\frac{t-t_0}{\tau_{\text{rise}}}\right) & \text{if } t < t_0 \\ \exp\left(-\frac{t-t_0}{\tau_{\text{decay}}}\right) & \text{if } t \geq t_0 \end{cases}$$

where F_0 is the baseline flux, ΔF is the flare amplitude, t_0 is the peak time, and τ_{rise} and τ_{decay} are the rise and decay timescales, respectively.

Using the brightness temperature formula, we estimate the radio brightness temperature of CGRaBS J0835+6835 to be in the range of 3.7×10^{13} K to 2.3×10^{14} K, exceeding the inverse Compton limit temperature or equipartition brightness temperature by several orders of magnitude and indicating significant beaming effects. The double exponential function fits to the six flares are shown in Figure 5. Following similar studies [21], we adopt the equipartition brightness temperature as the intrinsic brightness temperature to estimate the variability Doppler factor. Table 1 presents the fitting parameters for each flare: Column 1 gives the MJD range; Column 2 provides the reduced minimum residual sum of squares $\hat{\beta}$ (see reference [22] for definition); Column 3 lists the normalized chi-squared value χ^2/dof, defined as $\sum(F_i - f_i)^2/\sigma^2$/dof, where F_i is observed flux, f_i is fitted flux, σ is the standard deviation of residuals, and dof represents degrees of freedom; Column 4 shows peak MJD with errors; Column 5 gives baseline flux with errors; Column 6 lists flare amplitude with errors; Columns 7 and 8 provide rise and decay timescales with errors; Column 9 presents the Doppler factor for each flare. The δ_V values range from 8.87±0.68 to 14.45±0.23, with an average of approximately 10.76.

4. Discussion and Conclusions

Using long-term monitoring data from OVRO, we analyzed the radio light curve of CGRaBS J0835+6835 for quasi-periodic oscillations using both LSP and WWZ methods. The LSP analysis reveals QPO periods of approximately 562 days and 1020 days, both with confidence levels exceeding 3σ (99.7%). Since 1020 days is roughly twice 562 days, we identify 562 days as the fundamental QPO period. The WWZ method yields a period of approximately 560 days, also surpassing the 99.7% confidence level. The consistent results from both methods—approximately 560 days—mutually corroborate each other, leading us to conclude that the QPO period of CGRaBS J0835+6835 is about 560 days.

Additionally, we fitted six flare processes with a double exponential function, obtaining δ_V values ranging from 8.87 ± 0.68 to 14.45 ± 0.23 with a mean of approximately 10.76. These results demonstrate significant beaming effects in the radio emission of CGRaBS J0835+6835, supporting the relativistic jet model. The physical mechanisms underlying long-term variability in blazars remain an open question, with several models proposed, including supermassive binary black hole systems [23], helical jet models [24], and thin accretion disk theory [25].

Based on the 560-day QPO detected in CGRaBS J0835+6835, the underlying physical process may be helical jet motion [26]. Rieger (2004) established the relationship between the observed QPO period P and the actual physical driving period P_d as:

$$P_d \approx \frac{P}{1+z} \cdot \frac{1}{\gamma_b}$$

where the redshift $z = 1.414$ [7] and γ_b is the bulk Lorentz factor, approximately 7.5 [27]. Using this relation, we obtain a physical driving period $P_d \approx 35.75$ years. Alternatively, using $\gamma_b = 15$ as a parameter [28] yields $P_d \approx 143.00$ years. For supermassive binary black hole systems, mass ratios $R \leq 1/3$ are termed "major mergers," while $3 \leq R \leq 10^4$ are "minor mergers" [29]. Regardless of the mass ratio, the primary black hole mass can be estimated using [30]:

$$M \approx 10^8 M_\odot \left(\frac{P_d}{1\ \mathrm{yr}}\right)^{5/3}$$

where P_d is measured in years. For a "major merger" SMBBH system, we can assume a mass ratio $R = 3/2$. Substituting our parameters into equation (8) yields a primary black hole mass of $M \approx 3.7 \times 10^8 M_\odot$ for CGRaBS J0835+6835. Similarly, using $\gamma_b = 15$ as a parameter for a minor merger SMBBH system gives $M \approx 3.5 \times 10^9 M_\odot$. We therefore adopt a primary black hole mass range of $3.7 \times 10^8 M_\odot$ to $3.5 \times 10^9 M_\odot$ for CGRaBS J0835+6835.

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