Postprint: Correlation and Quasi-Periodic Analysis of Light Curves of Blazars CGRaBS J0929+5013 and J2146-1525

Authors: Chen Junping, horsepower, Gong Yunlu, Zhihui Chen, Yang Xing, Chang Xin, Li Yong, Yi Tingfeng

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Abstract

We employed the Lomb-Scargle periodogram method and the Weighted Wavelet Z-transform method to analyze approximately 12 years of observational data for the blazars CGRaBS J0929+5013 and J2146-1525 at 15 GHz radio and gamma-ray bands. Our analysis indicates that both blazars may exhibit quasi-periodic oscillation signals in the radio band, with quasi-periods of 1435 days (3.93 years) and 1321 days (3.62 years), respectively, and confidence levels $>3\sigma$ (99.7%). In contrast, the gamma-ray band shows weaker periodicity in flux variations. Based on the helical jet model in supermassive binary black hole systems, we estimated the primary black hole masses of CGRaBS J0929+5013 and J2146-1525 to be 4.3\$$\times10^{9} and 2.7\times$\$10ˆ9 solar masses, respectively. To investigate the origin of flux variability in the radio and gamma-ray bands, we calculated the correlation between these bands for both blazars using the discrete correlation function, and found no significant correlation. This suggests that the radiation in these bands may originate from different regions.

Full Text

Preamble

Correlation and Quasi-Periodic Oscillation Analysis of Light Variation in Blazars CGRaBS J0929+5013 and J2146-1525

Chen Junping[1],[2], Ma Li[1], Gong Yunlu[1], Chen Zhihui[1], Yang Xing[2],[3], Chang Xin[1], Li Yong[1], Yi Tingfeng[1],[2]

[1]School of Physics and Electronic Information, Yunnan Normal University, Kunming 650500, China
[2]Guangxi Key Laboratory for Relativistic Astrophysics, Nanning 530004, China

[3]School of Physical Science and Engineering Technology, Guangxi University, Nanning 530004, China

Abstract: We analyzed approximately 12 years of observational data at 15 GHz radio and gamma-ray bands for the blazars CGRaBS J0929+5013 and J2146-1525 using the Lomb-Scargle periodogram (LSP) and weighted wavelet Z-transform (WWZ) methods. Our analysis indicates that both objects may exhibit quasi-periodic oscillation signals in the radio band, with periods of 1435 days (3.93 years) and 1321 days (3.62 years) respectively, each exceeding the 3σ confidence level (99.7%). The gamma-ray band shows weaker periodicity. Based on the spiral jet model in supermassive binary black hole systems, we estimate the primary black hole masses of CGRaBS J0929+5013 and J2146-1525 to be approximately 4.3$×10^{9}$ M and 2.7$×10^{9}$ M , respectively. To investigate the origin of variability in the radio and gamma-ray bands, we calculated the cross-correlation between these bands for both sources using the discrete correlation function. No significant correlation was found, suggesting that the radiation in these bands likely originates from different regions.

Keywords: blazar; CGRaBS J0929+5013; CGRaBS J2146-1525; LSP method; WWZ method

1. Data Analysis

We collected approximately 12 years of data at 15 GHz radio and 0.1–200 GeV gamma-ray bands for J0929+5013 (J0929.3+5014) and J2146-1525 (J2146.4-1528) from the Owens Valley Radio Observatory (OVRO) 40m telescope (https://sites.astro.caltech.edu/ovroblazars/) and the Fermi Gamma-ray Space Telescope (Fermi-LAT, https://fermi.gsfc.nasa.gov/ssc/data/access/lat/10yr_{catalog}/ap_{lcs}.php). The OVRO 40m telescope is equipped with an off-axis dual-beam Dicke-switched system to reduce variable atmospheric emission and features a cooled receiver with 3 GHz bandwidth centered at 15 GHz. Each radio source is monitored approximately twice per week. The gamma-ray data were obtained using aperture photometry (with a 1° radius and maximum zenith angle of 105°), thus gamma-ray background photons were not removed. However, the background photon flux remains relatively stable and its impact on our variability analysis is negligible. We processed the gamma-ray data for J0929+5013 and J2146-1525 using the Fermi toolkit to obtain 7-day, 10-day, and 30-day binned data. Since the LSP and weighted wavelet Z-transform methods yielded essentially identical results for all binning schemes, we selected the 30-day binned data for our analysis.

We employed the variability index A to assess the activity level of each source, as defined in previous studies [7,10]:

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

where $f_{\max}$ and $f_{\min}$ represent the maximum and minimum flux values, respectively. The calculated variability indices are 0.55 and 0.35 for the radio band, and 0.53 and 0.46 for the gamma-ray band, for J0929+5013 and J2146-1525 respectively. Since a variability index closer to 1 indicates higher activity, these values demonstrate that both sources are relatively active in both bands. Figure 1 [Figure 1: see original paper] shows the radio and gamma-ray light curves for J0929+5013, while Figure 2 [Figure 2: see original paper] displays the corresponding light curves for J2146-1525. The horizontal axis represents Modified Julian Day (MJD), and the vertical axis shows flux density with associated errors (most errors are too small to be clearly resolved in the figures).

2. LSP Period Analysis

Studying the periodic variability of blazars is crucial for understanding the physical mechanisms of their internal radiation and the geometric properties of their emission regions. The Lomb-Scargle periodogram (LSP) method, based on Fourier transform principles, employs a sinusoidal model that can correct phase variations in periodograms of unevenly sampled time series and mitigate false periods caused by non-uniform temporal sampling within a certain range. This method is particularly effective for identifying quasi-periodic oscillations hidden within noise. The fundamental formula is given by [11]:

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

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

$$\tan(2\omega\tau) = \frac{\sum_j \sin(2\omega t_j)}{\sum_j \cos(2\omega t_j)}$$

We evaluated the confidence levels of our LSP results using Monte Carlo simulations [12]. By fitting a logarithmic power law to the LSP, we obtained power-law indices β [13] of $\beta = 0.5$ and $\beta = 0.1$ for J0929+5013 in radio and gamma-ray bands, and $\beta = 0.7$ and $\beta = 0.3$ for J2146-1525. The relatively small β values are likely due to white noise contamination; in many cases, the power-law index is approximately 1 [14].

Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper] present the Monte Carlo confidence analysis results for J0929+5013 and J2146-1525, respectively. The green curves represent the quasi-periodic frequency spectra, with peaks indicating quasi-periodic frequencies, while the black, red, and blue curves denote the 2σ (95%), 2.6σ (99%), and 3σ (99.7%) confidence levels from the Monte Carlo simulations.

In Figure 3, panels (a) and (b) show the confidence analysis results for J0929+5013 in radio and gamma-ray bands. We identify a quasi-periodic signal in the radio band with a period of 1435 days (approximately 3.93 years) at a confidence level exceeding 3σ. In the gamma-ray band, five peaks exceed the 2σ confidence level. The periods of 112, 146, and 203 days are approximately 2, 3, and 4 times the satellite precession period of 53.4 days, suggesting they are higher harmonics induced by spacecraft precession. The 192-day period corresponds to approximately half a year and is also a harmonic frequency. We consider the 311-day period as a potentially weak quasi-periodic signal in the gamma-ray band that requires further confirmation.

As shown in Figure 4 panels (a) and (b), J2146-1525 exhibits a quasi-periodic signal in the radio band with a period of 1321 days (approximately 3.62 years) at a confidence level exceeding 3σ. In the gamma-ray band, three peaks exceed the 2σ confidence level: the 108-day period is approximately twice the 53.4-day satellite precession period, while the 130-day period is approximately four times the lunar cycle of 27.3 days. We identify a 1388-day period as a weak potential quasi-periodic signal in the gamma-ray band that requires further confirmation.

3. Weighted Wavelet Z-transform Period Analysis

Wavelet analysis, evolved from Fourier transform methods, can localize signals in both time and frequency domains. Through translation and scaling operations, a mother wavelet function can be transformed into wavelet functions [15], where a and b in equation (4) represent the scaling parameter and translation parameter, respectively:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)$$

Foster defined the weighted wavelet transform (WWT), where N_{eff} is the effective number of data points, V_X is the weighted variance of the data, and V_y is the weighted variance of the model function. This approach yields high resolution at low frequencies, resulting in more effective data points at low frequencies than at high frequencies, which biases WWT values toward higher frequencies. Consequently, Foster defined the weighted wavelet Z-transform [16] based on Z-statistics:

$$Z = \frac{N_{\text{eff}} - 3}{2} \cdot \frac{V_y}{V_X - V_y}$$

Based on these principles, we developed Python programs to process the radio and gamma-ray data for J0929+5013 and J2146-1525. Figures 5 [Figure 5: see original paper] and 6 [Figure 6: see original paper] display the periodograms as functions of period, where the red, green, and blue curves represent the 2σ, 2.6σ, and 3σ confidence probability levels based on red noise, respectively, and the yellow dashed line indicates the 99.7% confidence probability level based on white noise. Quasi-periodic signals can be identified from the maxima in the weighted wavelet Z-transform diagrams.

In Figure 5, panels (a) and (b) present the WWZ results for J0929+5013 in radio and gamma-ray bands. Panel (a) reveals a prominent maximum at 1435.0 days (approximately 3.93 years) in the radio band with confidence exceeding 3σ, while panel (b) shows a maximum at 306.7 days (approximately 0.84 years) in the gamma-ray band with confidence exceeding 2σ. Both bands show confidence levels exceeding 3σ based on white noise assumptions, which represents a relatively strong constraint. We conclude that J0929+5013 exhibits a reliable quasi-periodic signal of 1435.0 days in the radio band, while the 306.7-day period in the gamma-ray band requires further confirmation.

As shown in Figure 6 panels (a) and (b), J2146-1525 displays a maximum at 1320.5 days (approximately 3.61 years) in the radio band with confidence exceeding 3σ, and a maximum at 1384.8 days (approximately 3.80 years) in the gamma-ray band. Both bands exceed the 3σ confidence level based on white noise. We conclude that J2146-1525 exhibits a reliable quasi-periodic signal of 1320.5 days in the radio band, while the 1384.8-day signal in the gamma-ray band requires further confirmation.

4. Correlation Analysis

Having identified quasi-periodic signals in both bands for J0929+5013 and J2146-1525 using different methods, we investigated whether variability between the radio and gamma-ray bands is correlated for each source. We employed the discrete correlation function (DCF) method, which is well-suited for analyzing unevenly sampled astronomical observations [17]. The basic formula is:

$$UDCF_{ij} = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{\sigma_a^2 \sigma_b^2}}$$

where $\bar{a}$ and $\bar{b}$ represent the mean values of the two datasets, and σ_a and σ_b are their standard deviations. Substituting this into the DCF equation yields the correlation coefficient.

Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper] present the correlation analysis results for J0929+5013 and J2146-1525, respectively. The maximum DCF values are only 0.32 and 0.30, respectively. Since we consider correlations significant only when the coefficient falls between 0.5 and 1, we conclude that neither J0929+5013 nor J2146-1525 shows significant correlation between radio and gamma-ray bands. This suggests that the radiation in these two bands likely originates from different regions.

5. Discussion and Conclusions

Our analysis of J0929+5013 and J2146-1525 using the LSP and weighted wavelet Z-transform methods reveals that J0929+5013 exhibits a quasi-periodic optical variation of approximately 1435 days in the radio band at a confidence level exceeding 3σ, and a much weaker potential quasi-periodicity of about 309 days in the gamma-ray band at a confidence level exceeding 2σ. DCF analysis shows no significant correlation between the two bands, suggesting their radiation originates from different regions. Similarly, J2146-1525 shows a quasi-periodic signal of approximately 1321 days in the radio band at $>3\sigma$ confidence, and a weak potential quasi-periodicity of 1385 days in the gamma-ray band. The DCF analysis again indicates weak correlation between bands. Due to limited data points and insufficient temporal coverage—spanning only about four times the measured QPO timescales—we present these as two QPO candidates. Quasi-periodic oscillations are extremely rare in blazars, and longer-term observations with more data are required for confirmation.

The origin and theoretical interpretation of QPOs in blazars remain controversial. Three main explanations have been proposed: (1) the spiral jet model induced by binary black holes [18], (2) the accretion disk pulsation model for single black holes [19], and (3) the jet precession model for single black holes [20]. Based on the binary black hole spiral jet model, we estimated the masses of J0929+5013 and J2146-1525. Following Rieger's 2004 work [21], the relationship between the observed quasi-period P and the actual physical driving period P_d is given by:

$$P = \frac{P_d}{(1+z)\Gamma_b}$$

where Γ_b is the bulk Lorentz factor, approximately 7.5 [22], P is in years, and we used the reliable radio quasi-periods of 3.93 years and 3.62 years with redshifts of 0.37 and 0.70, respectively. This yields physical driving periods P_d of 161.36 years for J0929+5013 and 119.78 years for J2146-1525. Following the classification where mass ratios $R \leq 1/3$ are "major mergers" and $3 \leq R \leq 10^4$ are "minor mergers" [23], the primary black hole mass can be estimated using [24]:

$$M_{\mathrm{BH}} = \frac{c^3 P_d (1+q)}{2\pi G q}$$

where we assume a mass ratio $q = 3/2$. Substituting the parameters yields primary black hole masses of approximately $4.3 \times 10^9 M_\odot$ for J0929+5013 and $2.7 \times 10^9 M_\odot$ for J2146-1525. If we instead adopt $\Gamma_b = 15$ [25] as a parameter for minor merger SMBBH systems, the primary black hole masses become $4.0 \times 10^{10} M_\odot$ and $2.5 \times 10^{10} M_\odot$, respectively. We therefore adopt $4.3 \times 10^9 M_\odot$ and $2.7 \times 10^9 M_\odot$ as our primary mass estimates.

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