Postprint: Radio Variability Analysis of the Flat-Spectrum Radio Quasar B3 0307+380 at 15 GHz

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Abstract

Long-term monitoring data from the Owens Valley Radio Observatory (OVRO) show that the 15 GHz radio light curve of the flat-spectrum radio quasar B3 0307+380 exhibits multiple outburst processes. Based on a double exponential function, 12 outburst processes were fitted, obtaining the variability amplitude and rising and falling timescales for each outburst process, and further estimating the brightness temperature and variability Doppler factor . The Doppler factor ranges from , with an average value of . This result indicates that the radio emission from this source exhibits obvious beaming effects, supporting the mainstream relativistic jet model. Using the Lomb-Scargle periodogram (LSP) method and weighted wavelet Z-transform (WWZ) method, we investigated whether B3 0307+380 exhibits periodic variability, and found a period of approximately 244 days with relatively high confidence ( ), and briefly discussed possible reasons for the existence of the period.

Full Text

Analysis of 15 GHz Radio Variability of Flat-spectrum Radio Quasar B3 0307+380

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Abstract

Long-term monitoring data from the Owens Valley Radio Observatory (OVRO) reveal that the flat-spectrum radio quasar B3 0307+380 exhibits multiple flares in its 15 GHz radio light curve. Using a double exponential function, we have fitted twelve flares and derived the variability amplitude, rise and decay timescales for each event, from which we estimated the brightness temperature (T_b) and variability Doppler factor (δ_V). The Doppler factor ranges from 12.9 ± 0.58 to 38.3 ± 3.45, with an average value of 18.14 ± 1.76. This result indicates that the radio emission from this source is strongly beamed, supporting the widely accepted relativistic jet model. Employing the Lomb-Scargle periodogram (LSP) method and the weighted wavelet analysis (WWZ) method, we investigated whether B3 0307+380 exhibits periodic variability and found a period of approximately 244 ± 11 days with high confidence ($> 99\%$). We briefly discuss possible explanations for this periodicity.

Keywords: Blazar; Brightness temperature; Doppler factor; Period

1. Introduction

Blazars are a class of active galactic nuclei (AGN) with jets oriented nearly parallel to the line of sight, characterized by broadband electromagnetic emission, high luminosity, high polarization, and apparent superluminal motion [1]. They comprise two subclasses: flat-spectrum radio quasars (FSRQs) and BL Lacertae objects, distinguished primarily by the presence or absence of broad emission lines in their spectra [1].

It is widely believed that blazars exhibit variability across various timescales (ranging from minutes to years) in almost the entire electromagnetic spectrum, with a minority showing periodic variability phenomena [2-5]. Variability studies have consistently proven to be one of the most effective approaches for exploring the internal radiation processes and physical mechanisms of blazars. Due to the small angle between the blazar jet and the line of sight ($\theta < 10^\circ$), the observed radiation is significantly enhanced by the Doppler effect [1][6]. The Doppler factor (δ) can be defined in terms of two intrinsic parameters: the bulk flow velocity in the jet (β) and the viewing angle (θ). However, since both quantities are not directly observable, developing alternative methods to estimate the Doppler factor becomes necessary. Among various approaches, estimating the Doppler factor (δ_V) through radio variability is relatively straightforward and has been widely applied [7-10].

B3 0307+380 (J2000: RA = 03h 07m 47.70s, Dec = +38° 02' 48.3") is an FSRQ detected in gamma-ray emission [11] at a redshift of $z = 0.816$. In this work, we utilize long-term monitoring data at 15 GHz from the Owens Valley Radio Observatory (OVRO) [12] (spanning approximately 11.4 years from January 8, 2008 to May 25, 2019) to investigate the radio variability of B3 0307+380, estimate its radio brightness temperature and variability Doppler factor, and examine whether periodic variability exists. We adopt the cosmological parameters $H_0 = 73$ km s^{-1}Mpc^{-1}, $\Omega_{\rm matter} = 0.27$, and $\Omega_{\rm vacuum} = 0.73$.

The 15 GHz long-term photometric data for B3 0307+380 were obtained from the OVRO website (http://www.astro.caltech.edu/ovroblazars/). After removing a few bad data points, the final dataset comprises 664 points covering a Modified Julian Date (MJD) range of approximately 54473-58628. Figure 1 [Figure 1: see original paper] presents the light curve, with MJD on the horizontal axis and 15 GHz flux density (in Jy) and errors on the vertical axis (most errors are too small to be discerned in the plot).

2. Doppler Factor Estimation

Based on the scale limited by variability timescales, reference [13] provides the formula for calculating the brightness temperature of blazars:

$$T_b = 1.05 \times 10^{10} \frac{\Delta F}{Jy} \left(\frac{t}{day}\right)^{-1} \left(\frac{\lambda}{cm}\right)^{2} \left(\frac{D_L}{Mpc}\right)^{2} \quad \mathrm{K}$$

where T_b is the brightness temperature, ΔF is the flux variation (variability amplitude) in Jy, t is the variability timescale in days, λ is the observed wavelength in cm, and D_L is the luminosity distance in Mpc.

Figure 1 shows that the 15 GHz light curve of B3 0307+380 exhibits multiple flares. We selected twelve complete flares containing both rise and decay phases and fitted them using the double exponential function formula from reference [14]:

$$F(t) = F_0 + c\left[\exp\left(-\frac{t_0 - t}{t_r}\right) + \exp\left(-\frac{t - t_0}{t_d}\right)\right]^{-1}$$

where F_0 represents the baseline flux, t_0 is the time corresponding to the flare peak, t_r and t_d are the exponential rise and decay timescales respectively, and c measures the flare amplitude.

We performed nonlinear least-squares fitting using the LMFIT package in Python, specifically calling the `leastsq()` function (see https://lmfit.github.io/lmfit-py/ for details). The fundamental principle is to minimize the sum of squared residuals (SSR) between observed flux values $F_i(t)$ and model-predicted flux values $f_i(t)$:

$$SSR = \sum_{i=1}^{N} [F_i(t) - f_i(t)]^2$$

where N is the number of observational points. The Levenberg-Marquardt (LM) algorithm is a numerical method for solving nonlinear models that is commonly applied to least-squares curve fitting [15], and the `leastsq()` function we employed is based on this algorithm.

The fitting details and parameters for the twelve flares are presented in Figure 2 [Figure 2: see original paper] and Table 1 . The first column gives the flare number; the second column shows the MJD range; the third column lists the number of observational points N; the fourth column provides the reduced minimum SSR ($\hat{\beta} = SSR_{\min}/(N-5)$); and columns 5 through 9 present the five fitted parameters with their errors. Using the fitted parameters c or F_0, along with equation (1), we calculated the brightness temperature T_b for each rise or decay phase. Comparing equation (1) with equation (2) in reference [7], we emphasize that when calculating T_b for each rise or decay phase, the ΔF value should be taken as half of the fitted parameter c.

It is generally accepted that the brightness temperature of jet components in blazars cannot exceed the inverse Compton limit temperature $T_{\rm IC} = 10^{11.5}$ K [16] or the equipartition brightness temperature $T_{\rm eq} = 10^{10}$ K [17]. Our calculated brightness temperatures T_b exceed $T_{\rm IC}$ or $T_{\rm eq}$ by several orders of magnitude, indicating significant Doppler boosting effects. Following reference [8], we adopt $T_{\rm eq}$ as the intrinsic brightness temperature and further estimate the corresponding variability Doppler factor using:

$$\delta_V = \left(\frac{T_b}{T_{\rm eq}}\right)^{1/3}$$

Figure 3 [Figure 3: see original paper] shows the distribution of the Doppler factor δ_V. The values range from 12.9 ± 0.58 to 38.3 ± 3.45, with a median of approximately 18.14 ± 1.76.

3. Periodicity Analysis

Historical literature has continuously reported periodic variability in blazars [18][19]. Studies of periodic variability in blazars are crucial for understanding the physical mechanisms of internal radiation and the geometric properties of emission regions. Commonly used periodic analysis methods in astronomy include the Lomb-Scargle periodogram (LSP) method [20][21] and the weighted wavelet analysis (WWZ) method [22]. We have also employed these two methods to explore whether periodic variability exists in the 15 GHz light curve of B3 0307+380, with the results presented in Figure 4 [Figure 4: see original paper].

The left panel of Figure 4 shows the LSP analysis results, where we provide 95%, 99%, and 99.7% confidence curves based on the red noise Monte Carlo method from reference [23]. The results reveal a period of approximately 244 ± 11 days with $> 99\%$ confidence, along with another period of approximately 465 ± 40 days at $> 99\%$ confidence, which is roughly twice the former. The right panel presents the weighted wavelet analysis results, which also roughly show a period of about 250 days that is basically persistent, particularly during the middle portion of the observation period.

4. Summary and Discussion

The primary characteristics of blazar light curves are large-amplitude, rapid variability across multiple wavebands accompanied by high polarization. The beaming effect of relativistic jets is generally considered responsible for these extreme observational features. The long-term monitoring data from OVRO show that the flat-spectrum radio quasar B3 0307+380 exhibits multiple flares in its 15 GHz radio light curve. We fitted twelve flares using a double exponential function and derived the distribution of variability Doppler factors, which range from 12.9 ± 0.58 to 38.3 ± 3.45 with an average of 18.14 ± 1.76. This demonstrates that the radio emission from B3 0307+380 experiences significant Doppler boosting, supporting the widely accepted relativistic jet model.

Periodic variability in blazars may be related to relativistic motion of emission regions along helical trajectories within the jet [24]. Specifically, helical motion causes periodic changes in the viewing angle, leading to corresponding variations in the Doppler factor and thus modulating the Doppler-boosted radiation flux. Figure 5 [Figure 5: see original paper] shows the variation of the Doppler factor across the twelve flares. The MJD value for each point adopts the fitting parameter t_0 and its error, while δ_V takes the average of the Doppler factors during the rise and decay phases and their errors. The figure reveals that the Doppler factor indeed exhibits certain oscillations over time. We speculate that the radio periodic variability of B3 0307+380 may be associated with a helical jet model. It should be noted that the confidence level of the $ $244-day radio period is only $> 2\sigma$, which requires further confirmation. Additionally, regarding the interpretation of the period, the helical jet model is merely one possible explanation, and many other mechanisms deserve consideration [18][25].

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