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The re-analysis of quasi-periodic oscillation of the blazar J1359+4011

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HIGHLIGHTS

- We choose structure function method and discrete correlation function method to investigate the possible period of J1359+4011 in 15 GHz.
- We find a possible quasi-periodic oscillation of about 120–130 days.
- The instabilities in the accretion flow and global p-mode oscillations in a thick disc are possible reasons for this observed behavior.

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ABSTRACT

J1359+4011 is a flat spectral radio quasar monitored by the Owens Valley Radio Observatory 40 m radio telescope since 2008. The light curve of J1359+4011 in 15 GHz shows a possible quasi-periodic behavior by visual inspection. In order to confirm this quasi-periodic behavior, we utilize two classical methods: structure function method and discrete correlation function method, to investigate the possible time-scale of oscillation in the time series of J1359+4011. The analytical result shows a possible time-scale of oscillation of 120–130 days. The instabilities in the accretion flow could be a possible explanation for the modulation of the light curve; and global p-mode oscillations in a thick disc could be another possible reason for this behavior.

1. Introduction

Blazars are subclass of Active Galactic Necluei (AGNs), whose light curves usually show obvious characteristics of large amplitude and short timescale variability. Some blazars present the quasi-periodic behavior at radio and optical wavebands. The variability timescale is usually from several minutes, several hours to the order of years. e.g., OJ 287 had been found as a possible quasi-periodic variability of 12 years in optical band (Sillanpää et al., 1988; Fan et al., 2010) AO 0235+164 had been found as a possible quasi-periodic variability of 2.5 years (Wang, 2014) and other possible results of ∼ 5 years or ∼ 6 years (Raiteri et al., 2001; 2006), BL Lac 2200+420 had been found as a possible quasi-periodic variability of 7.2 years (Smith and Nair, 1995), 7.8 years (Hagen-Thorn et al., 1997), 0.60 and 0.88 years (Fan et al., 1998), ∼ 2 years and ∼ 8 years (Villata et al., 2004). Many possible models can explain the quasi-periodic behavior of the light curves, such as accretion disk instability (Pihajoki et al., 2013) and quasi-periodical flux variation induced by the doppler beaming effect from a precessing jet (Caproni et al., 2013).

J1359+4011 is a flat spectrum radio quasar (FSRQ) with redshift $z = 0.407$, whose gamma-ray radiation has not been detected by the Fermi Gamma-ray Space Telescope up to now. King et al. (2013) analyzed the light curve of J1359+4011 about 4.1 years in 15 GHz, and found a quasi-periodic oscillation (QPO) with a time-scale of oscillation varied between 120 days and 150 days by means of the weighted wavelet Z-transform method (King et al., 2013). It is the only source which shows a possible quasi-period behavior obviously in the Owens Valley Radio Observatory (OVRO) catalogue of over 1200 objects. In this paper, some fresh data which is from 2012.9 to 2014.5 about 1.6 years are added into the data series. In order to find much more reliable quasi-periodic results, we analyze the data series by means of two different methods: structure function (SF) method and discrete correlation function (DCF) method, which are different from the method used in King's works.

In Section 2, we show the light curve and discuss their basic properties. In Section 3, we introduce two analytical methods and their analytical results explicitly. The discussion is in Section 4 and the conclusion is in Section 5.

2. Data

The flux densities of blazar J1359+4011 in 15 GHz is observed as one of the samples of over 1800 AGNs by the 40 m telescope in the Owens Valley Radio Observatory. The total light curve is from August 2008 to May 2014 with 315 data points. The data are corrected and

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1384-1076/

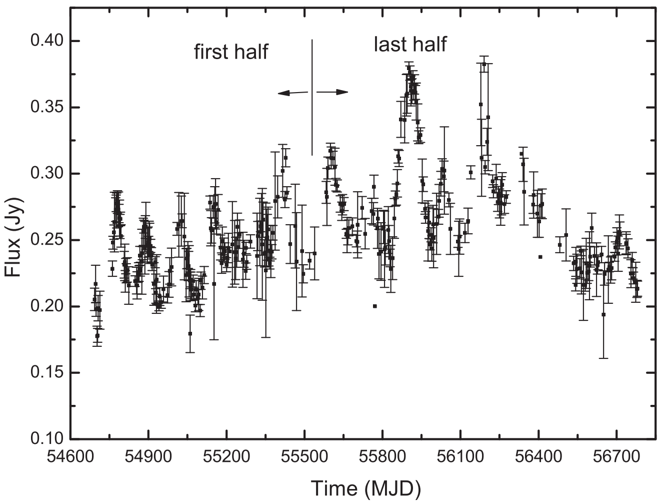

Fig. 1. The light curve of J1359+4011 in 15 GHz.

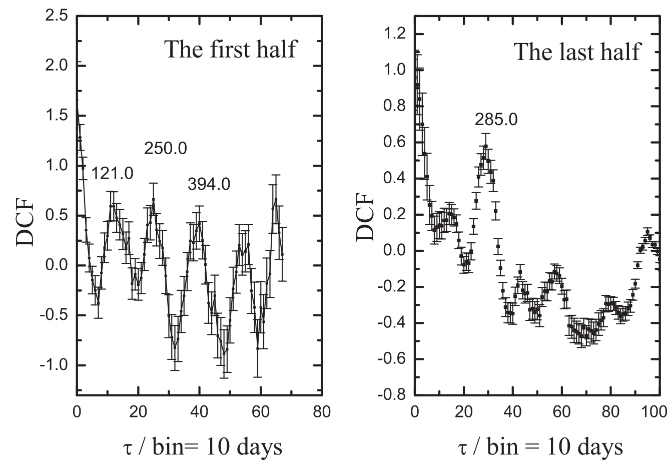

Fig. 2. The periodic analytical results by discrete correlation function method.

calibrated to form regularly updated light cure which are available on the internet[1]. The light curve of J1359+4011 about 5.7 years is presented in Fig. 1.

From the light curve, we perceive a possible quasi-periodic behavior of about 100–200 days by visual inspection. King et al. (2013) ruled out the instrumental effect which is the dualbeam measurement process and modulation linked to the pointing procedure of the telescope (King et al., 2013). It means that this behavior may be caused by the intrinsic variability. We divide the data series into the first half part (from 54,695 to 55,583) and the last half part (from 55,583 to 56,780). Each part is above over 5 times the time-scale of oscillation of 100–200 days, so it is long enough to assure the accuracy of the results. We calculate the two parts separately, analyze and compare the results between them, then obtain much more reliable time-scale of oscillations.

3. The analysis of quasi-periodic behavior

In order to check out the possible quasi-periodical behavior of the J1359+4011 data series in 15 GHz. We use two different methods, which are, structure function method and discrete correlation function method to analyze the data series. The discrete correlation function method (Edelson and Krolik, 1988; Hufnagel and Bregman, 1992) is a common method to analyze the correlation between two uneven data series which has many merits comparing with the classical correlation method. e.g., it does not need interpolations and the errors have also been computed. The calculating process is as follows:

First, we calculate the value of $UDCF_{i,j}(\tau)$, with the formula:

$$UDCF_{ij}(\tau) = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{(\sigma_a^2 - e_a^2)(\sigma_b^2 - e_b^2)}}, \tag{1}$$

in which a_i and b_j are the flux in two different data series; σ_a and σ_b are the standard deviations; e_a and e_b are the measuring errors in data series. Each UDCF value corresponds to a given lag $\Delta t = t_j - t_i$ between each pair of the data series. Second, the average value in M pairs of time lag $\tau - \Delta\tau/2 \le \Delta t_{ij} < \tau + \Delta\tau/2$ is

$$DCF(\tau) = \frac{1}{M}\Sigma UDCF_{ij}(\tau), \tag{2}$$

where, M is the number of pairs in the given lag. Third, the standard deviation for the calculated DCF is:

$$\sigma_{DCF} = \frac{1}{M-1}\{\Sigma[UDCF_{ij} - DCF(\tau)]^2\}^{1/2}, \tag{3}$$

[1] http://www.astro.caltech.edu/ovroblazars/.

We set $a_i = b_j$ and analyze the data series, then obtain the results of the autocorrelation DCF. The higher the peak, the stronger the correlation. The position of autocorrelation DCF peak means the possible quasi-periodic value in the data series. Fig. 2 is the analytical result of J1359+4011 by autocorrelation DCF. The left figure is the result of first half time series, by which, the results of 113.4 days, 253.7 days and 397.8 days are found. The right figure is the analytical result of the last half time series, where a possible quasi-periodic oscillation of 285.0 days is found.

In order to check out the authenticity of quasi-periodic results which are found by the autocorrelation DCF method, we analyze the data series of J1359+4011 in 15 GHz by first order structure function method again. The SF method is a powerful and well-studied method for periodicity analysis (Simonetti et al., 1985). It is much easier to calculate and less affected by gaps in the light curves (Hughes et al., 1992). The first order structural function is usually used and defined as

$$D^{(1)}(k) = \frac{1}{N^{(1)}(k)}\sum_{i=1}^{N} w(i)w(i+k)[f(i+k) - f(i)]^2. \tag{4}$$

In above formula, $N^{(1)}(k) = \sum_{i=1}^{N} w(i)w(i+k)$, $\sigma_f^{(1)} = \frac{8\sigma_{f\delta}^2}{N^{(1)}(k)D_f^{(1)}(k)}$. $f(i)$ denotes the radiation flux of the source at a certain time, and $w(i)$ is weight factor. If the ith point has a datum, the weight factor is 1, otherwise the weight factor is 0. $\sigma_f^{(1)}$ is the deviation of the structural function, $\sigma_{f\delta}$ represents the variation of the observational errors at all data points. The minimum values of SF mean possible quasi-periodic results. The analytical result is shown in Fig. 3 with the left part of possible quasi-periods of 127.4 days, 254.1 days and 400.2 days in the first half part time series from 54,695 to 55,583, where the 254.1 days and 400.2 days may correspond to the double times and triple times value of 127.4 days; and the right part of the quasi-periodic results of 155.7 days and 285.4 days are found in the last half part time series from 55,583 to 56,780, where the 285.4 days may be the double times value of 155.7 days within the error range.

We collect all the results in Table 1. Comparing the quasi-periodic results in two different methods, we find a possible quasi-periodic result of 120–130 days in the first data series, and a possible quasi-periodic result of ∼150 days in the last data series. The last result may be influenced by the sparse time series from 56,300 to 56,500, thus the last result is a little bigger than the first one. So the real time-scale of oscillation may be between 120 days and 130 days. This result is in accordance with King's analytical result.