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CHARACTERIZING THE TIME-FREQUENCY PROPERTIES OF THE 4 Hz QUASI-PERIODIC OSCILLATION AROUND THE BLACK HOLE X-ray BINARY XTE J1550-564

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ABSTRACT

We present the results from analysis of the Hilbert-Huang transform (HHT) for the 4 Hz quasi-periodic oscillations (QPO) around the black hole X-ray binary XTE J1550-564. The resultant Hilbert spectra demonstrate that the QPO is composed of a series of intermittent signals appearing occasionally. From the analysis of the HHT, we further found the distribution of the lifetimes for the intermittent oscillations and the distribution for the time intervals with no significant signal (the break time). The mean lifetime is 1.45 s and 90% of the oscillation segments have lifetimes less than 3.1 s whereas the mean break time is 0.42 s and 90% of break times are less than 0.73 s. We conclude that the intermittent feature of the QPO could be explained by the Lense-Thirring precession model and rules out interpretations of continual frequency modulation.

Key words: accretion, accretion disks – X-rays: binaries – X-rays:individual (XTE J1550-564)

1. INTRODUCTION

Low-frequency quasi-periodic oscillations (QPOs) with frequencies ranging from 0.1 Hz to 10 Hz have been detected in many accreting black hole systems. They are named for the broad peaks (see Figure 1) in the Fourier power spectra made from their X-ray light curves. Such broad peaks imply that there are unstable frequency oscillations which could be caused by a periodic oscillation with finite coherence time, a frequency-changing oscillation or multiple oscillations. Time-frequency analysis methods, like spectrograms, wavelet analysis and the Hilbert-Huang transform (HHT), are able to reveal the nature of QPOs around black holes. Remillard et al. (2002) discovered a 4 Hz QPO in the black hole X-ray binary XTE J1550-564 during its 1998-1999 outburst from a RXTE/PCA observation. Lachowicz & Done (2010) utilized wavelet and matching pursuit algorithma to analyze the 4 Hz QPO, and found that the QPO was composed of a series of discrete oscillations. Despite the success of wavelet analysis, the details of the QPO signal may be distorted by pre-selected basis functions. We therefore employ HHT for further analysis of the 4 Hz QPO in XTE J1550-564.

2. OBSERVATIONS

We extracted the RXTE/PCA light curve observed on September 29, 1998 (MJD 51085) with a bin size of 0.01 sec. Following the standard procedure of finding QPO features [Rao et al. (2010)], we fitted the average power spectrum of the same observation with Lorentzian components and found its 4.1 Hz QPO (see Figure 1).

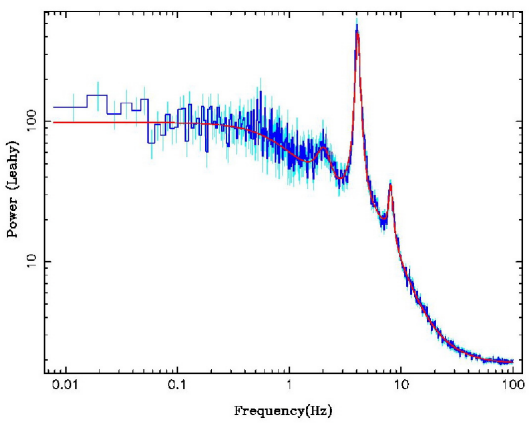

Figure 1. The Fourier power spectrum of the 4 Hz QPO in the black hole X-ray binary XTE J1550-564 with the best fit of the multi-Lorentzian model.

3. RESULTS

3.1. Hilbert-Huang Transform Analysis

Huang et al. (1998) developed a time-frequency method, the Hilbert-Huang transform (HHT), to decompose a signal into basis components defined by the signal itself, and to transform these components into instantaneous frequencies as functions of time. We

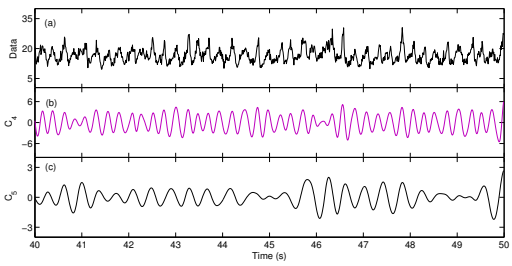

Figure 2. A typical light curve and the corresponding IMFs (C4, C5). (a) Original light curve. (b) Fourth component, C4, which corresponds to the 4 Hz oscillation. (c) Fifth component, C5, which corresponds to the QPO sub-harmonic. Units of y-axis are k counts s^{-1}.

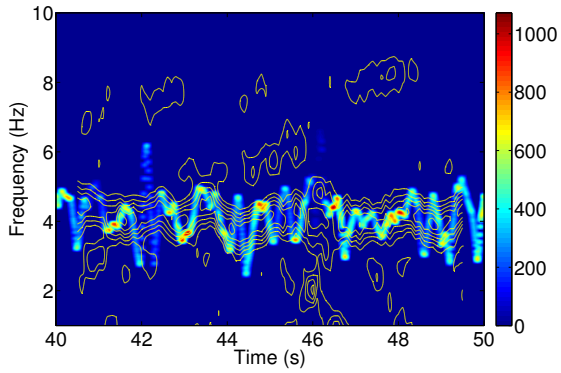

Figure 3. The resultant Hilbert spectrum of the 4Hz QPO from XTE J1550-564. The contour is the result of Lomb-Scargle spectrogram for comparison.

employed HHT to study the detailed time-frequency variation of this QPO. The algorithm of HHT involves two steps [Wu & Huang (2009)]:
(1) Decomposing the signal into intrinsic mode functions (IMFs) by the ensemble empirical mode decomposition (EEMD) method.
(2) Producing the instantaneous frequencies and amplitudes of IMFs through the Hilbert transform.

A typical example of a 10-sec light curve and two of its most significant IMF components (C4 and C5) are shown in Figure 2. Clear 4 Hz oscillations can be seen in C4 and the oscillations in C5 are likely its sub-harmonic. Figure 3 shows the resultant Hilbert spectrum for the variation of this 4 Hz QPO. It is evident that the frequency of the QPO is not only changing with time but also appearing intermittantly.

3.2. *Lifetime of the Intermittent Oscillations*

After analyzing the QPO via HHT, we demonstrated that this QPO is composed of a series of intermittent signals. Moreover, we utilized the confidence limit of the instantaneous amplitudes of IMF C4 to set a threshold for determining the lifetime of these intermittent oscillations. Figure 4 shows the confidence limit of instantaneous frequencies and amplitudes of IMF C4. The blue line and the black line are the mean and its 3-sigma confidence limits respectively. The break time intervals are defined as their mean amplitudes (blue line of the top panel of Figure 4) and are less than the average of the 3-sigma lower limit (red line) where we consider no significant signal being detected. We further found the distribution of the lifetimes for the intermittent oscillations and the distribution for the break time (see Figure 5). The mean lifetime is 1.45 s and 90% of the oscillation segments have lifetimes less than 3.1 s whereas the mean break time, the time interval without significant 4 Hz oscillation, is 0.42 s and 90% of them are less than 0.73 s.

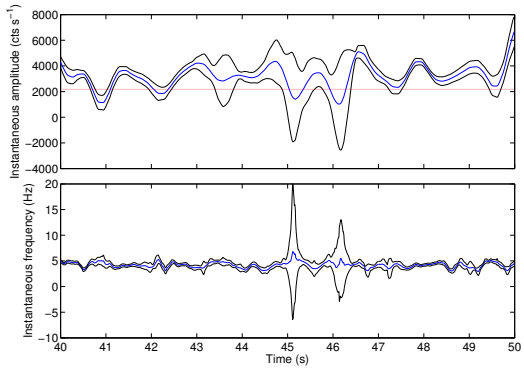

Figure 4. Confidence limit of instantaneous frequencies and amplitudes of IMF C4 which represents the 4 Hz oscillations.

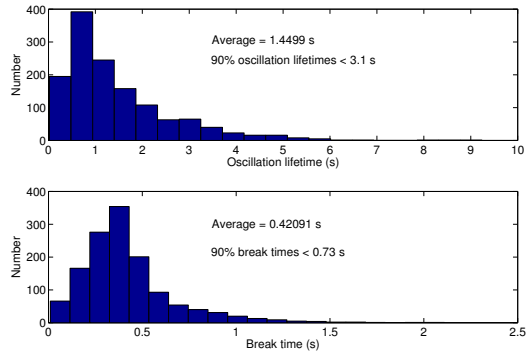

Figure 5. The distribution of the lifetimes for the intermittent oscillations and the distribution for the break time.

4. SUMMARY & DISCUSSION

We have applied HHT to study the 4 Hz QPO of XTE J1550-564. The HHT results show that the QPO is composed of a series of intermittent signals between 3 Hz and 5 Hz. We further found the distribution of the lifetimes and the break times of these intermittent oscillations. These intermittent oscillations with time scale of a few seconds indicate that the broad peaks were more likely caused by multiple, frequency-changing oscillations with finite coherence time. Therefore, we conclude that the intermittent feature of the QPO rules out interpretations of continual frequency modulation and favors the model of turbulent accretion flow [Lachowicz & Done

(2010)].

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