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 analysis results from Lomb-Scargle spectrograms and Hilbert-Huang transform (HHT) for the 4 Hz quasi-periodic oscillations (QPO) around the black hole X-ray binary XTE J1550-564. HHT is a time-frequency method especially for analyzing non-stationary and non-linear data, so it is suitable for revealing the nature of the quasi periodicity. Comparing with these two time-frequency analysis methods, Hilbert spectra show better resolution and demonstrate that the QPO is composed of a series of intermittent signals appearing occasionally. We conclude that the intermittent feature of the QPO rules out the interpretations of the continual frequency modulation.

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

1. Introduction

The quasi-periodic oscillations (QPOs) have been detected in many accreting black hole systems. The QPOs are named by their broad peaks (see Fig. 1) in the Fourier power spectra made from their X-ray light curves. Such broad peak could be caused by a periodic oscillation with finite coherence time, a frequency-changing oscillation or multiple oscillations. Time-frequency analysis methods, like spectrogram, wavelet analysis and Hilbert-Huang transform (HHT), are able to reveal the nature of QPOs around black holes. Remillard et al. (2002) found a 4 Hz QPO in the black hole X-ray binary XTE J1550-564 during its 1998-1999 outburst. Lachowicz and Done (2010) utilized wavelet and matching pursuit algorithm, which is a wavelet-based time-frequency method, to analyze the 4 Hz QPO, and found the QPO is 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 analyzing of this 4 Hz QPO in XTE J1550-564.

2. Observation

We extracted the RXTE/PCA light curve observed on September 29, 1998 (MJD 51085) with 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 this light curve with the Lorentzian components and found its 4.1 Hz QPO (see Fig. 1).

3. Results

3.1. The Lomb-Scargle spectrogram

For the feasibility test of time-frequency analysis methods for the QPO, we first applied Lomb-Scargle spectrogram (i.e., dynamic power spectrum). Spectrogram is a time-frequency distribution produced by dividing a light curve into small segments and transforming these segments into a sequence of Fourier spectra or Lomb-Scargle periodograms along the time axis. The 4 Hz QPO signal can be detected (see Fig. 2) but the resolution is insufficient for further analysis.
3.2. Hilbert-Huang transform

Huang et al. (1998) developed a time-frequency method, Hilbert-Huang transform (HHT), to decompose a signal into basis components defined by the signal itself and transform these components into instantaneous frequencies as functions of time. Because HHT provides an algorithm for analyzing non-stationary and non-linear data, it could be suitable for revealing the nature of the quasi periodicity. We therefore employed HHT to study the detailed time-frequency variation of this QPO.

The algorithm of HHT involves two steps (Wu and Huang, 2009):

1. Decomposing a signal into intrinsic mode functions (IMFs) by ensemble empirical mode decomposition (EEMD) method.
2. Producing the instantaneous frequencies and amplitudes of IMFs through Hilbert transform.

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

4. Discussion and Future Works

We have applied Lomb-Scargle spectrogram and HHT to study the 4 Hz QPO of XTE J1550-564. The two time-frequency analysis methods have consistent results but the spectra from HHT have better resolution. The spectrograms show that the QPO is composed of a series of intermittent signals between 3 Hz and 5 Hz with lifetime less than a few seconds. If this QPO were caused by accreting materials spiraling inwards, signals with monotonically increasing frequency would appear in the spectrograms. However, we found that the broad peaks are more likely caused by multiple, frequency-changing oscillations with finite coherence time. Therefore, we conclude that the intermittent feature of the QPO rules out the interpretations of the continual frequency modulation and favors the model of turbulent accretion flow (Lachowicz & Done, 2010). Further analyzing on the light curves of the source with HHT and then actually determining for the distribution of the lifetimes will be the future works.

References

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