Phase resolved spectrum analysis of mHz QPOs in 4U 1636-53 using Hilbert-Huang Transform

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Abstract

We present the phase-resolved spectroscopy based on Hilbert-Huang Transform (HHT) for millihertz quasi-periodic oscillations (mHz QPOs) in 4U 1636-536. This ~8mHz QPO can be detected about several thousand seconds before type-I X-rat burst. It was interpreted as marginally stable burning on neutron-star surface. We used the HHT to extract the QPOs instantaneous phases, and constructed its phase-resolved spectra for whole cycle. The spectral parameter modulations show the neutron star surface temperature is likely positively correlated with the variation of neutron star luminosity.

Introduction

4U 1636-53 is a neutron star low-mass X-ray binary exhibiting Type-I X-ray burst occasionally. Type-I X-ray burst is caused by unstable thermonuclear reaction of accreted fuel on the neutron-star surface. Millihertz quasi-periodic oscillations (mHz QPOs) can sometimes be detected several thousand seconds prior to a type-I burst in ~5% of X-ray bursters. The mHz QPOs may interpreted as marginally stable nuclear burning (Heger et al. 2007), but it needs more observation evidences to support it. Lyu (Lyu et al. 2015) detected ~8mHz QPO from four XMM-Newton observations in 4U 1636-53. In this research, we use Hilbert-Huang Transform (HHT) to analyze those four observations. HHT is a powerful tool to allow us to obtain instantaneous frequency, amplitude and phase for non-stationary periodicity phenomena, such as QPO. With well-defined phase, the oscillation profile of ~8mHz QPO for 4U 1636-53 can be precisely revealed. Furthermore, we processed the phase-resolved spectral analysis to obtain the spectral parameter variations for the whole cycle. The analysis result and preliminary interpretation for this ~8mHz QPO are presented in this poster.

Observation and Hilbert-Huang Transform Analysis

The data used in this study were collected by the European Photon Imaging Camera (EPIC-PN) of XMM-Newton in the timing mode with photon energy between 0.8 to 11 keV. For timing analysis, we binned the events into 1.3333 s resolution light curves which is beneficial for HHT analysis. The dynamic power spectrum for the ~8 mHz QPO of an XMM-Newton observation is shown as Figure 2. Its variable periodic can be clear seen. Huang et al. (1998) developed HHT to analyze non-linear and non-stationary signal. HHT can decompose a signal into oscillatory components called intrinsic mode functions (IMFs). The ~8mHz oscillation is concentrated on 6th IMF (see Figure 3) whose corresponding instantaneous phases, frequencies and amplitudes through Hilbert transfer are shown as Figure 4. The oscillation profile, shown as Figure 5, was made by folding the light curve according to the phase obtained by Hilbert transfer of 6th IMF.

Phase-resolved Spectral Analysis

Using the phase defined by HHT, we divided the whole cycle into 20 bins and extracted individual energy spectrum of them. These spectra were fitted with the spectral model:

$$PHABS\times(BBODY + DISKBB + NTHCOMP)$$

where PHABS is photoelectric absorption, BBODY is blackbody from neutron-star surface, DISKBB is multi-color disk blackbody, NTHCOMP is inverse Compton scattering process in the corona. Because the mHz QPO is considered as metastable nuclear burning on neutron star surface, the only parameters in BBODY were set to be variable amount different phase bins and the parameters of other components were tied with the optimal values evaluated from detected spectra of whole cycle. Figure 6 illustrates modulations of spectral parameter, showing that the neutron-star surface temperature is probably positively correlated with the variation of neutron-star luminosity (see Figure 6).

Summary

We have utilized HHT to characterize the HHT-based timing properties, extracted the 4U 1636-53 ~8 mHz QPOs' instantaneous phase, and then constructed its modulation profile and phase-resolved spectra. In addition to revealing the more precise modulation profile, we resolved the spectral parameters for the whole QPO cycle, which was unachievable in previous studies with traditional analysis methods. The spectral modulation shows that the neutron-star temperature positively correlates with the neutron-star luminosity. This may be explained by that nuclear burning on neutron-star surface is marginally stable due to competition between the burning and cooling process (Galloway et al. 2017). In addition to 4U 1636-53, mHz QPOs have been seen in other four neutron star low-mass X-ray binaries. More studies on mHz QPO in 4U 1636-53 as well as the other four sources are in processing.

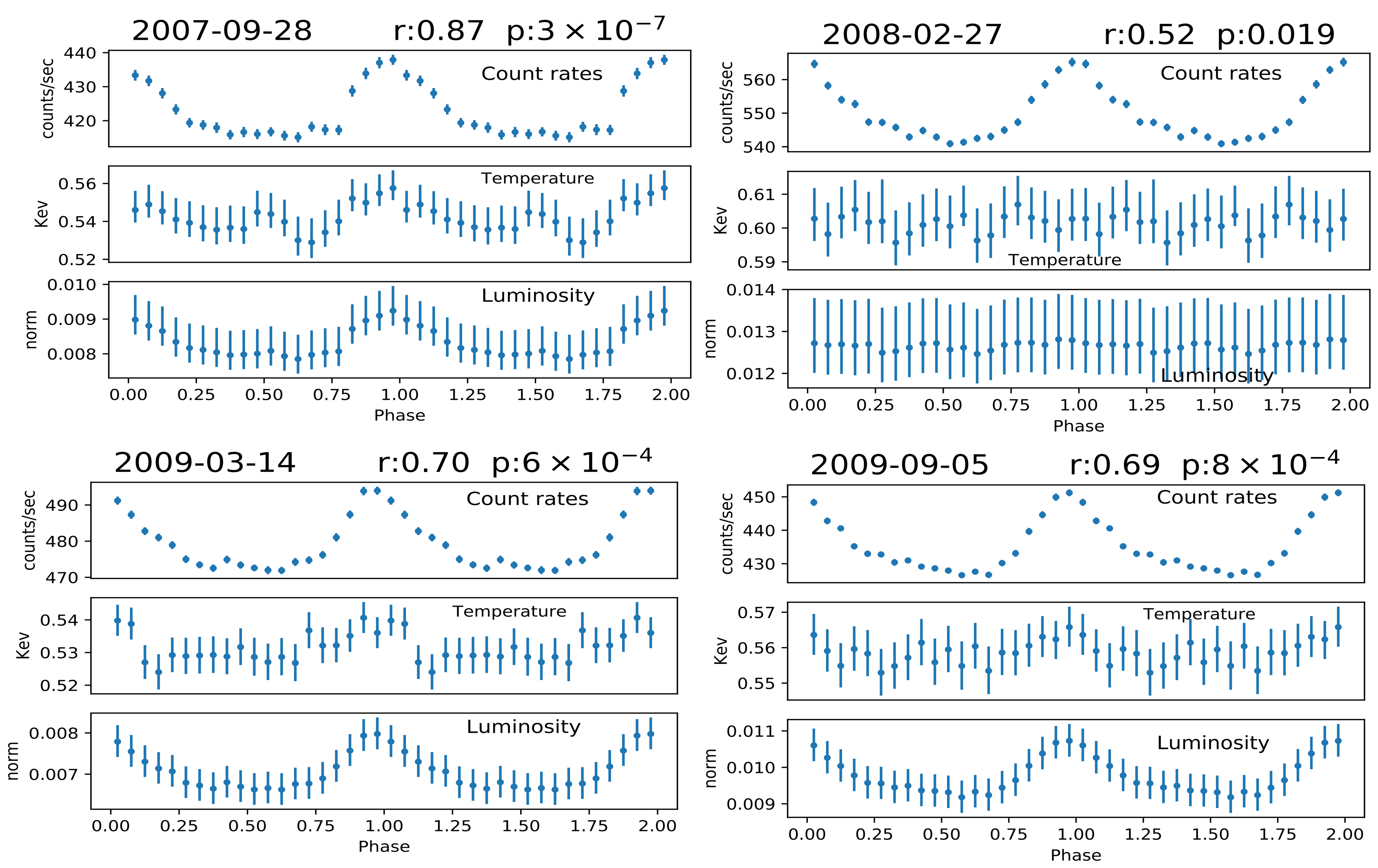

Figure 6. Spectral modulations of NS surface temperature and luminosity.

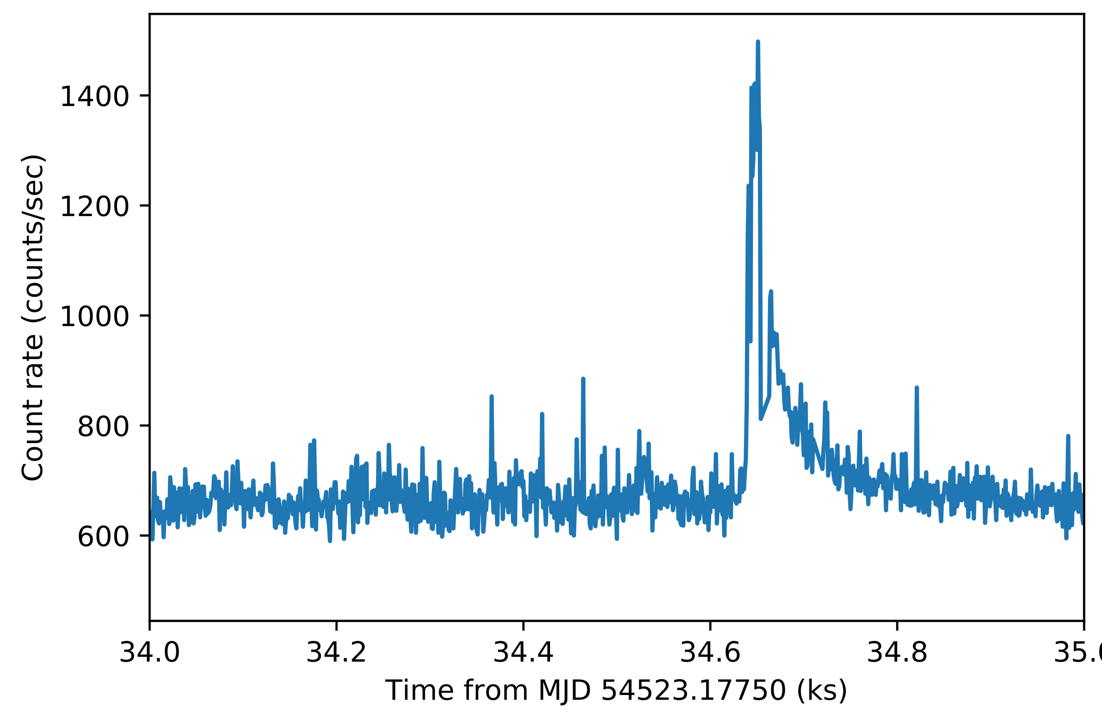

Figure 1. 4U 1636-53's Type-I X-ray burst in 2008. The mHz QPOs have been found in this observation before Type-I X-ray burst.

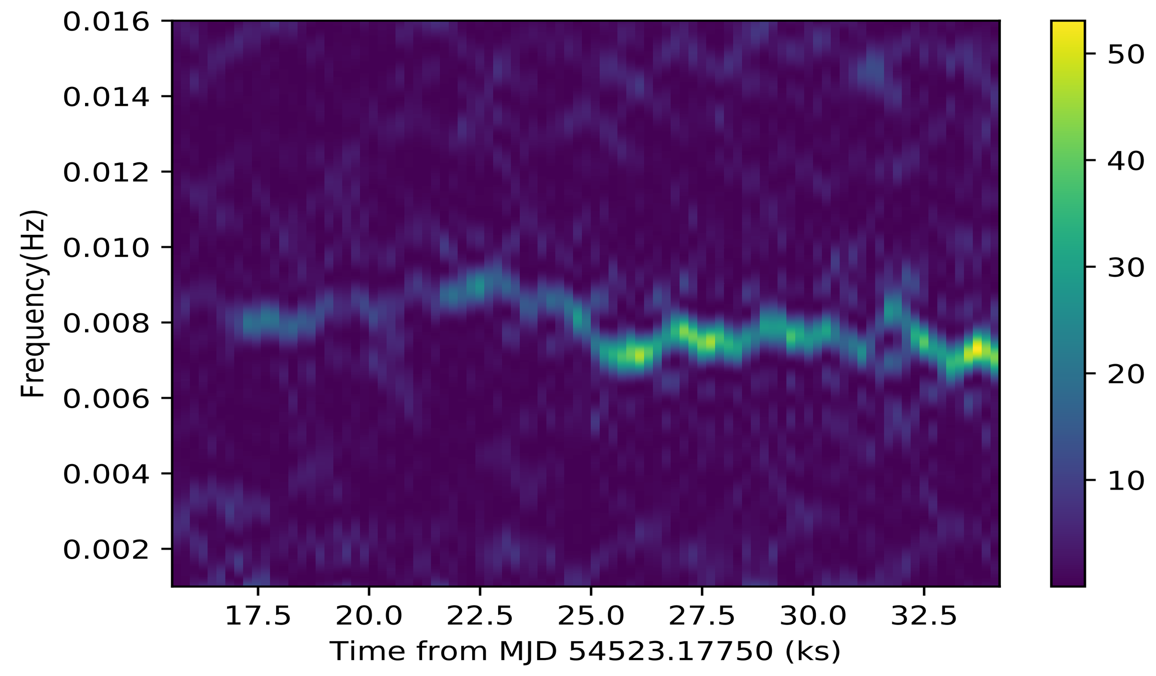

Figure 2. The Lomb-Scargle spectrum of ~8mHz QPOs from 4U1636-536 in 2008.

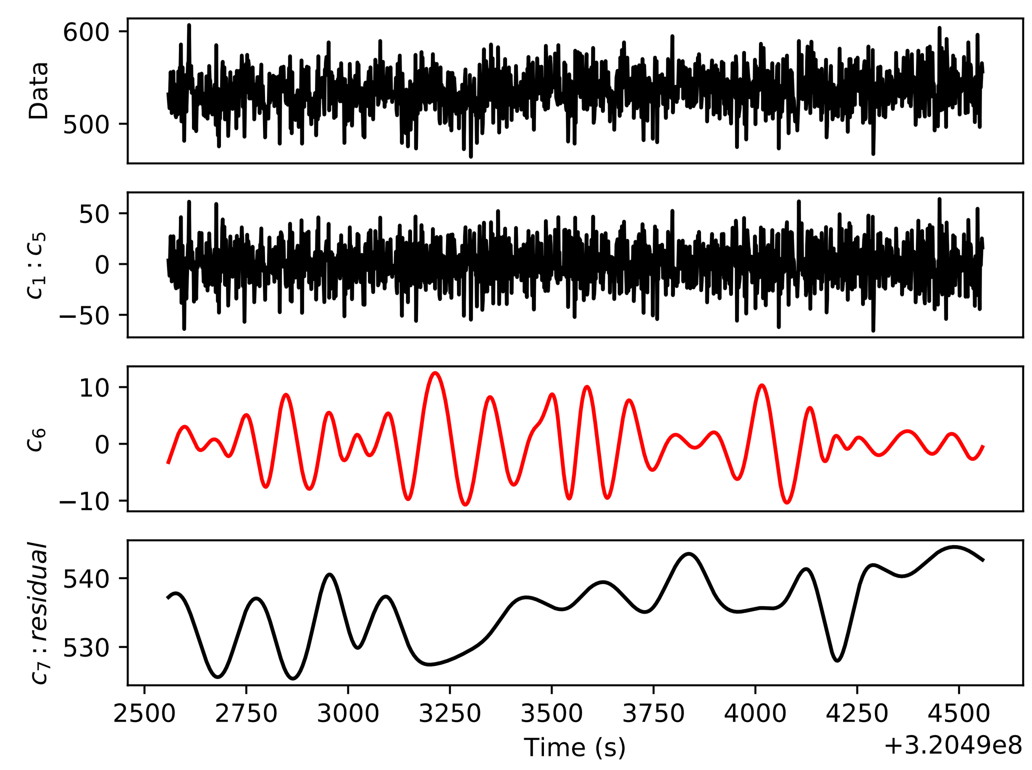

Figure 3.
(a) Original light curve.
(b) The high frequency noise.
(c) The sixth IMF which corresponds to 8 mHz QPOs.
(d) The low frequency noise.

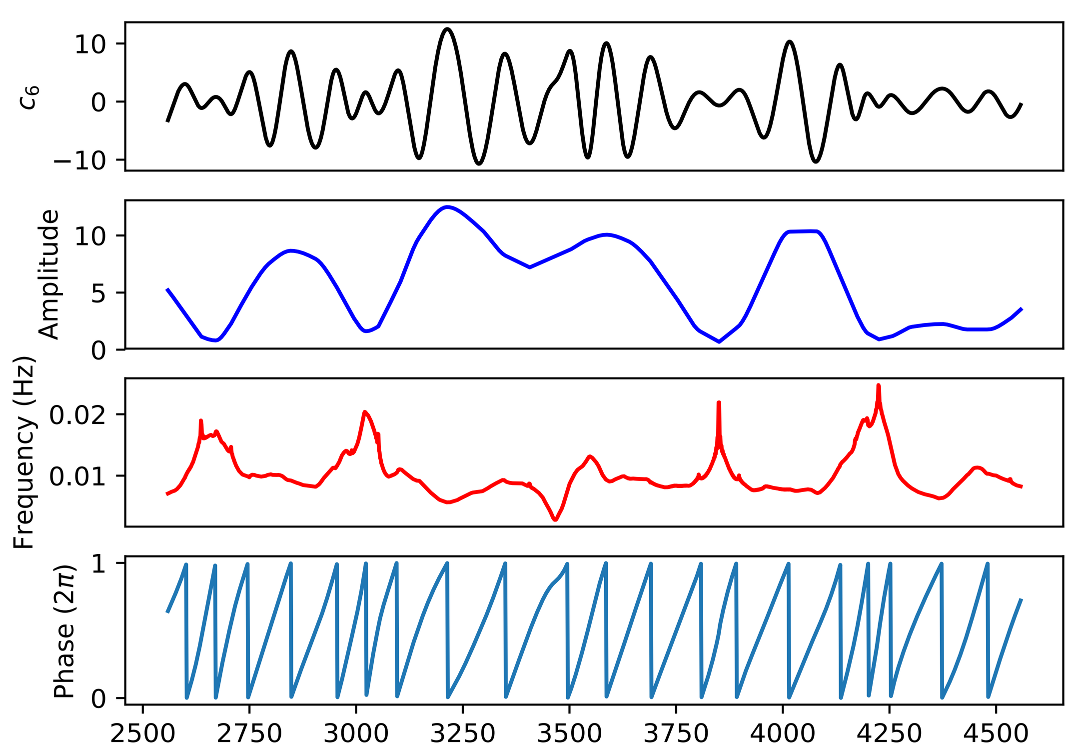

Figure 4.
(a) The sixth IMF.
(b) Instantaneous amplitude.
(c) Instantaneous frequency.
(d) Instantaneous phase.

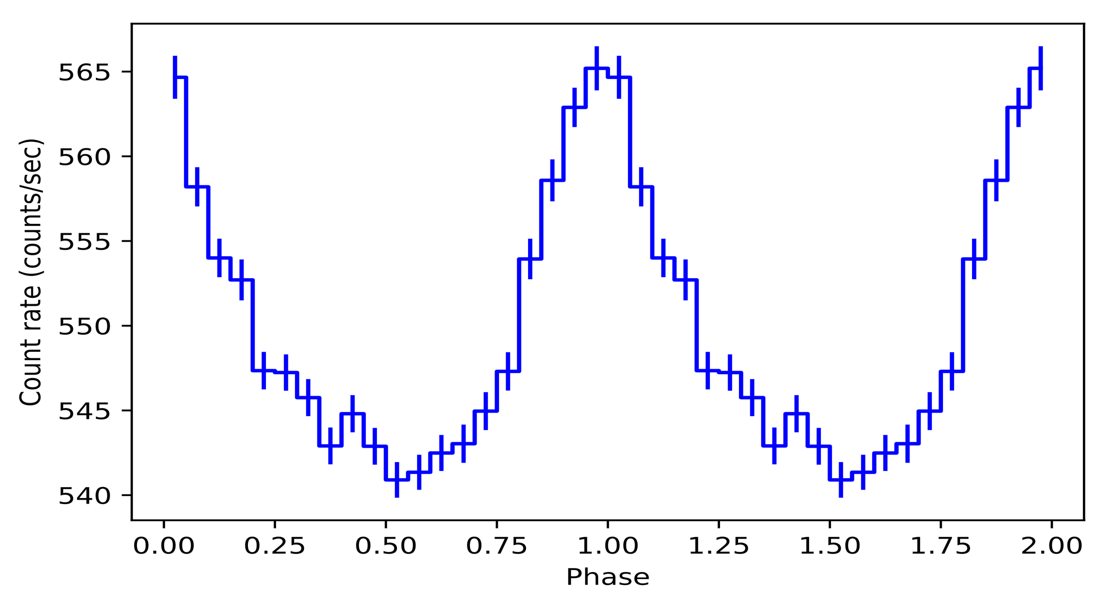

Figure 5. The oscillation profile in 2008 constructed by HHT.

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