Tracking X-ray Spectral Modulations of a 6-Hz Type-B Quasi-periodic Oscillation in GX 339-4 using Hilbert-Huang Transform

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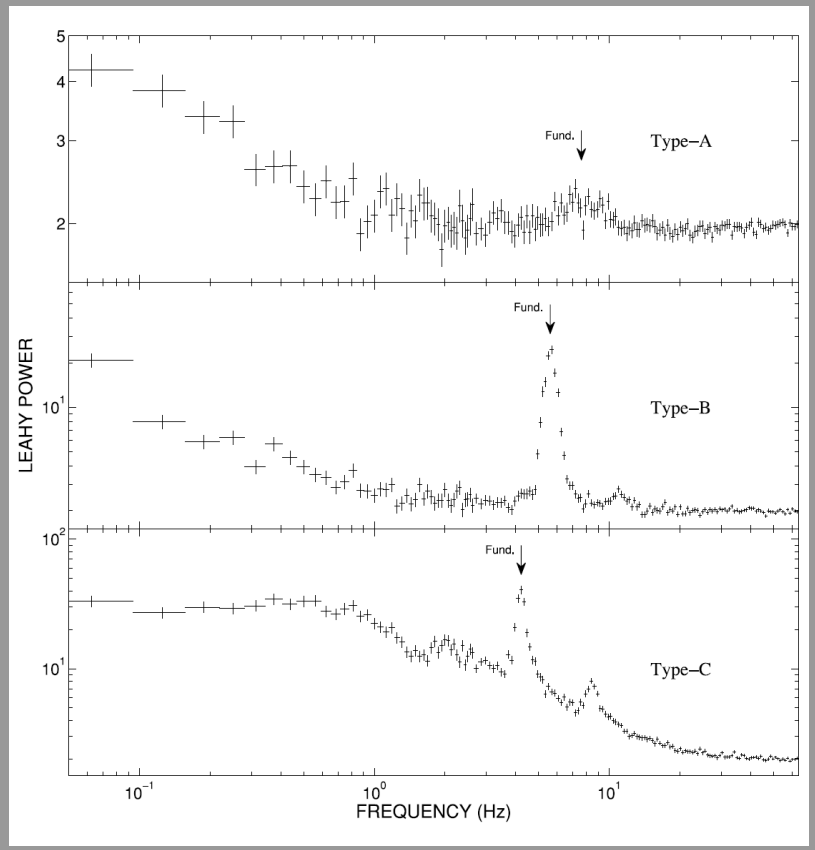
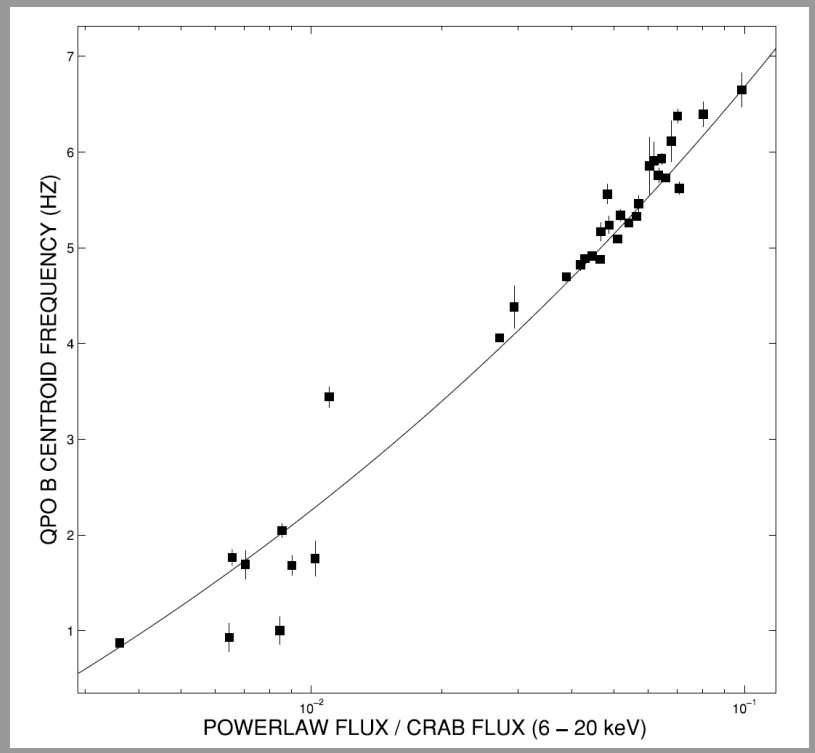
Shining from the heart of darkness: black hole accretion and jets
@Kathmandu, Nepal

October 18, 2016

Quasi-periodic Oscillations (QPOs) in GX 339-4



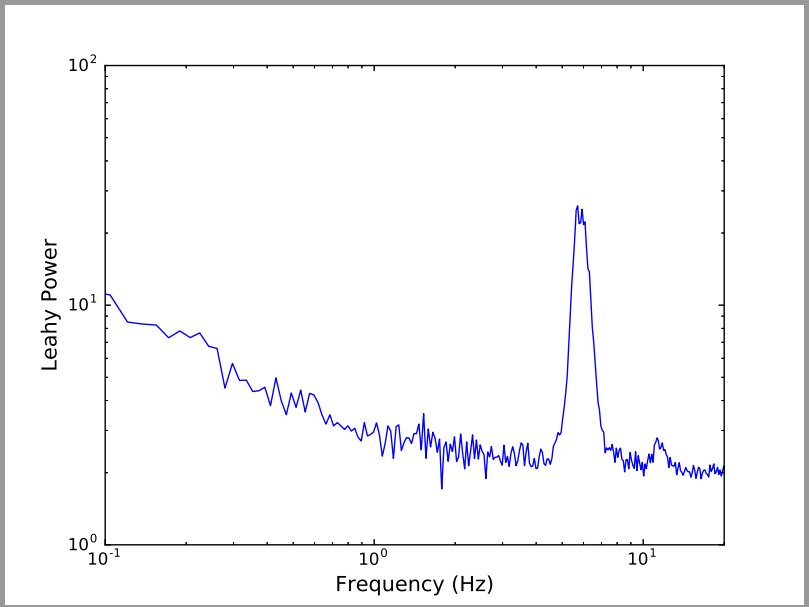
(Motta et al. 2011)



(Motta et al. 2011)

Phase-resolved Spectroscopy

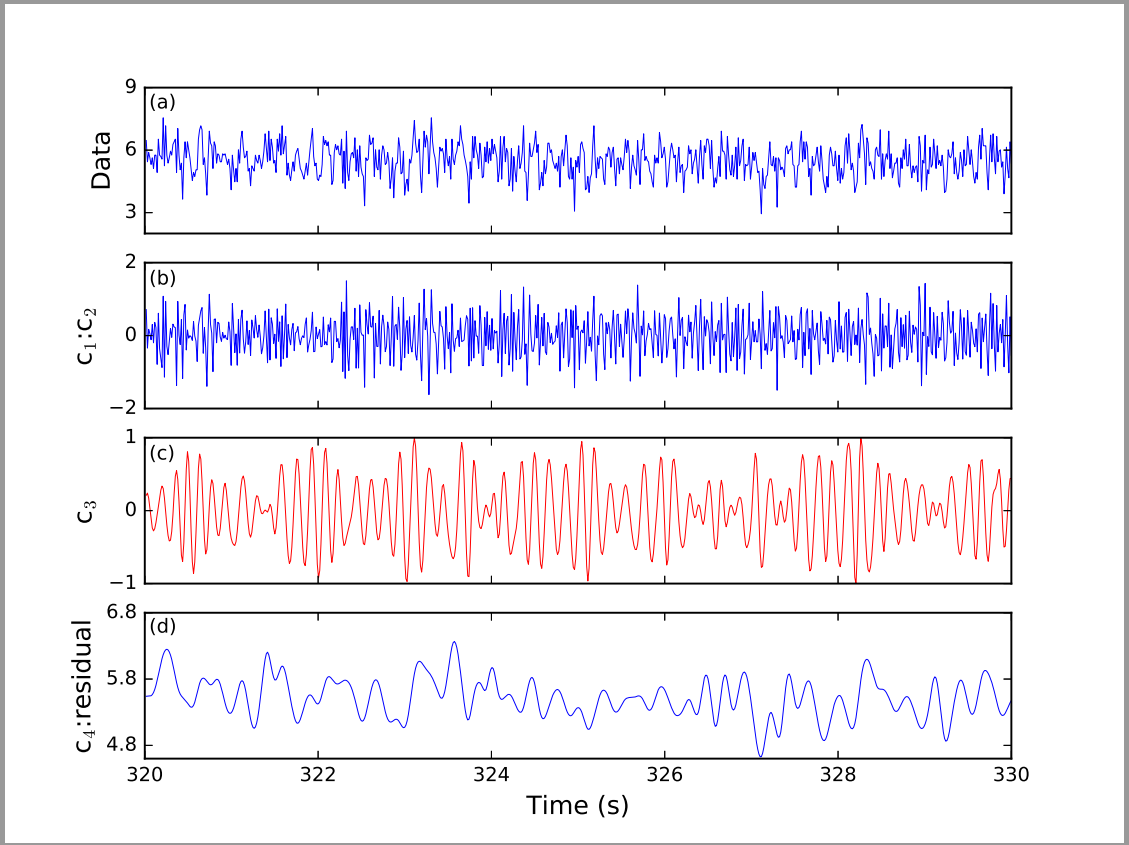
6-Hz type-B QPO in GX 339-4



- Phase
- Phase segments
- Phase-resolved spectra

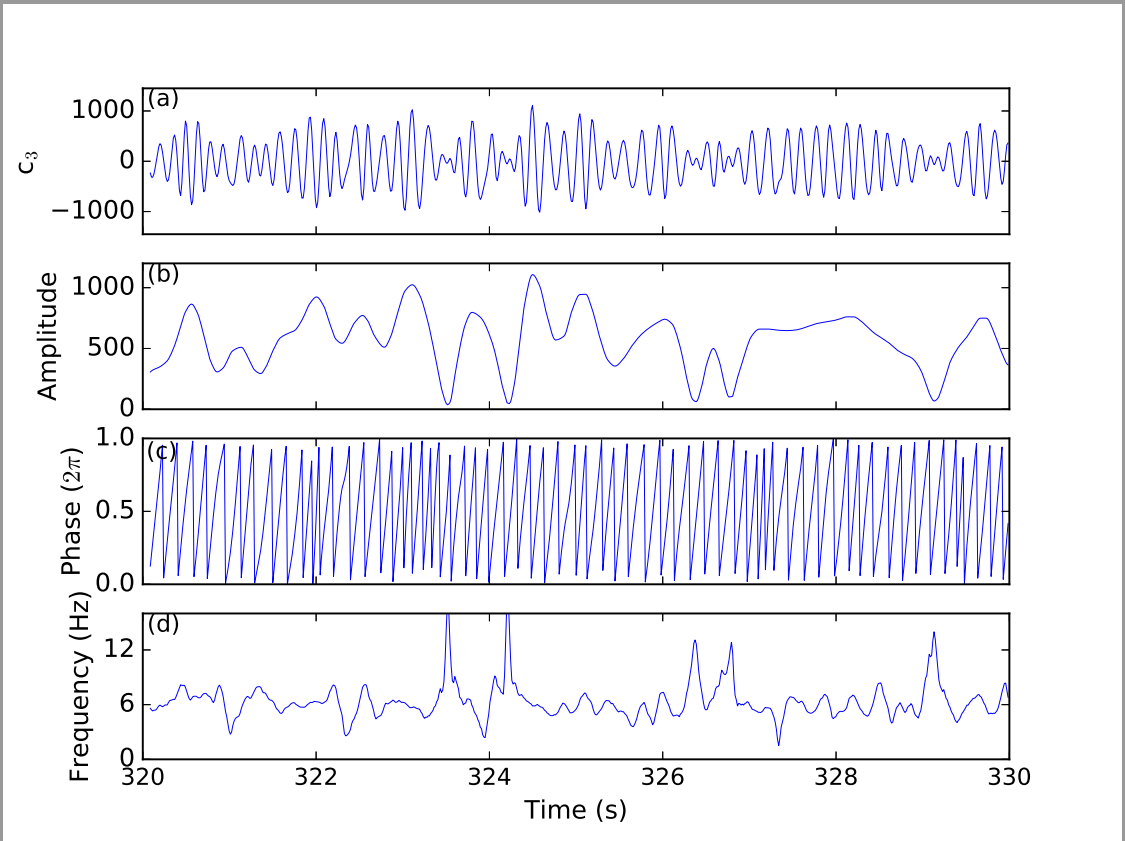
First Step of Hilbert-Huang Transform (HHT)

- Huang et al. (1998); non-stationary and non-linear signals
- First step of HHT: Empirical mode decomposition (EMD)
- Intrinsic mode functions (IMFs)



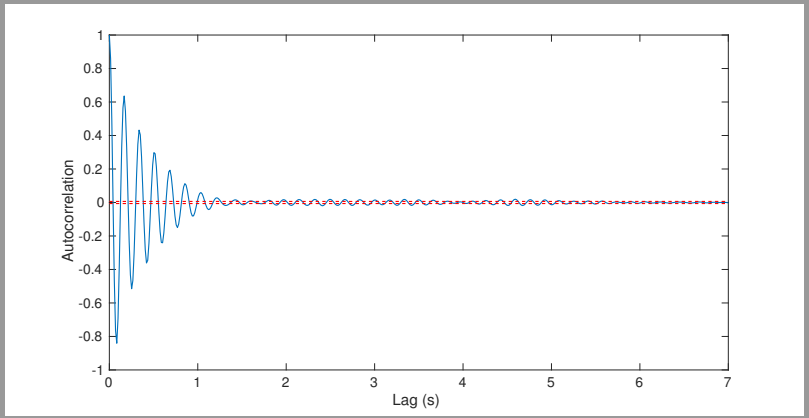
Second Step of Hilbert-Huang Transform (HHT)

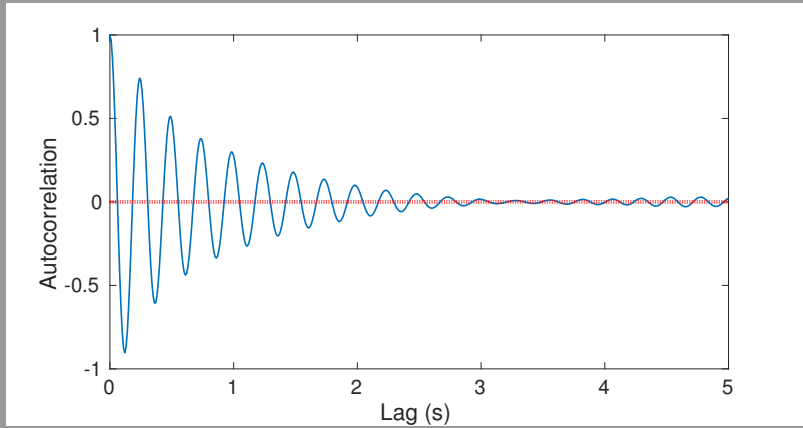
- $Y_3(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{X_3(t')}{t-t'} dt' \leftarrow$ Hilbert transform
- $X_3(t) + iY_3(t) = a_3(t) e^{i\theta_3(t)} \leftarrow$ Instantaneous amplitude & phase
- $\nu_3(t) = \frac{1}{2\pi} \frac{d\theta_3(t)}{dt} \leftarrow$ Instantaneous frequency



HHT-based Timing Properties

Autocorrelation function of the IMF c_3

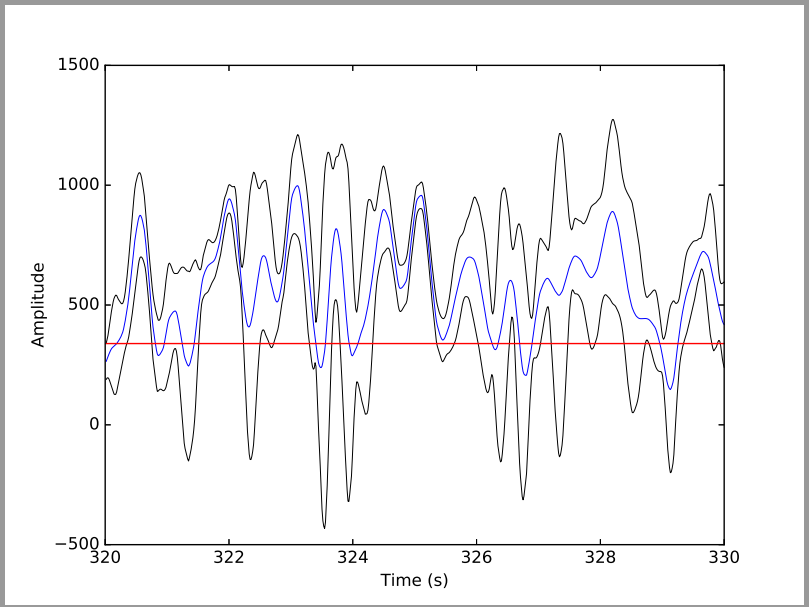




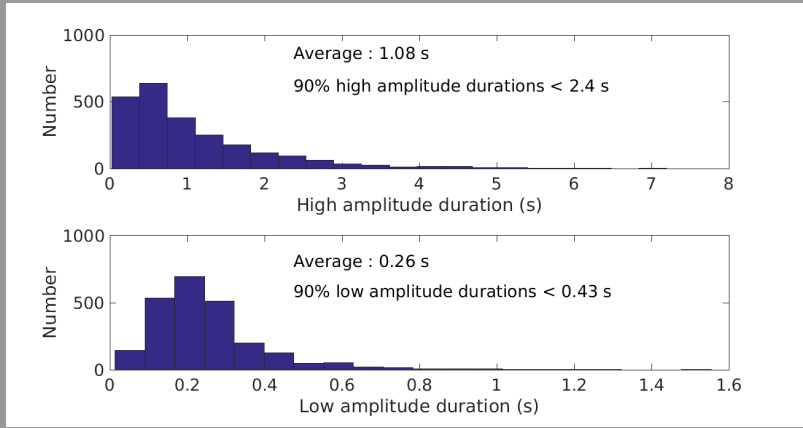
(Su et al. 2015, Intermittency of 4-Hz QPO in XTE J1550-564)

HHT-based Timing Properties (conti.)

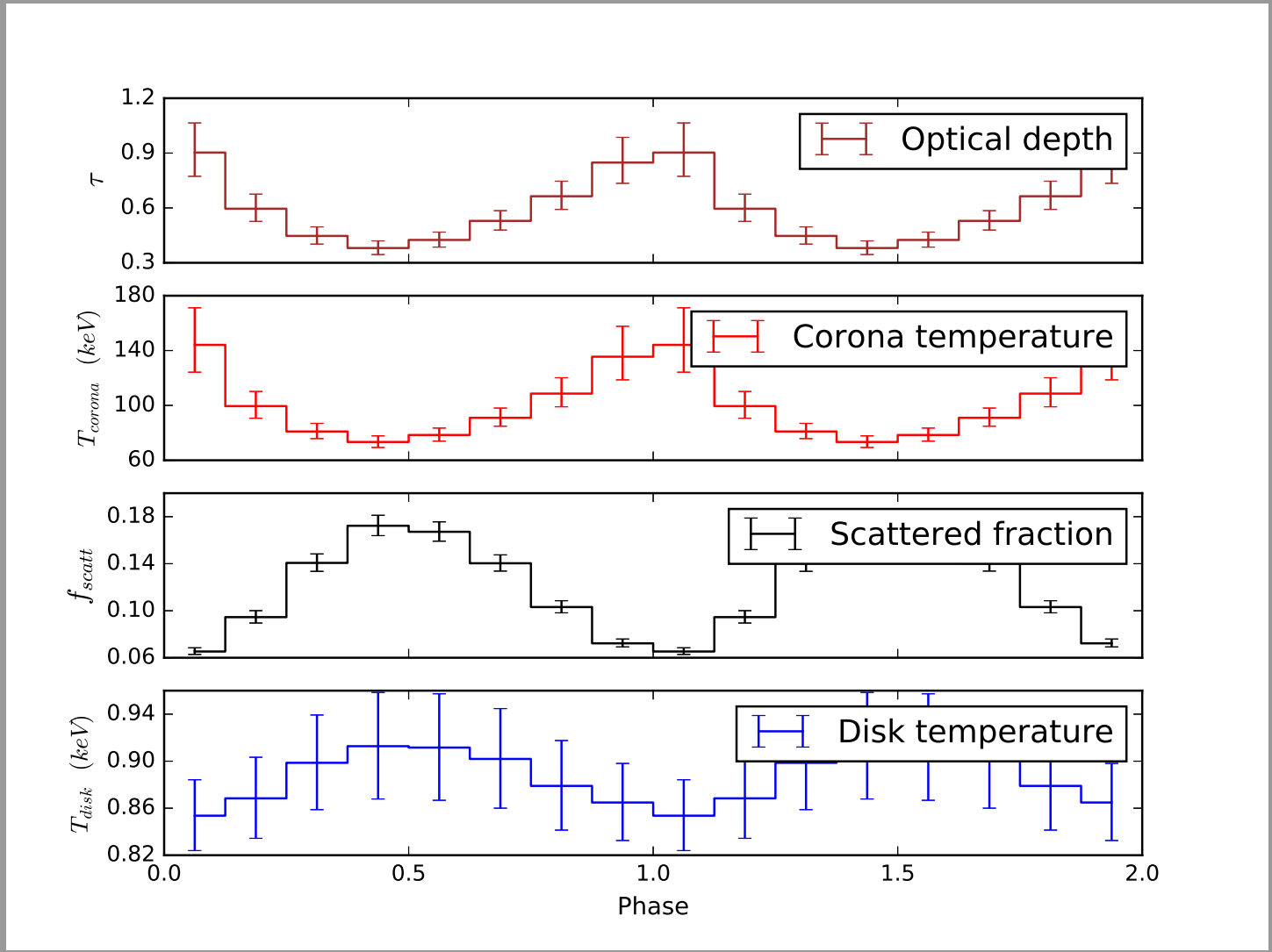
Confidence limit of the instantaneous amplitude



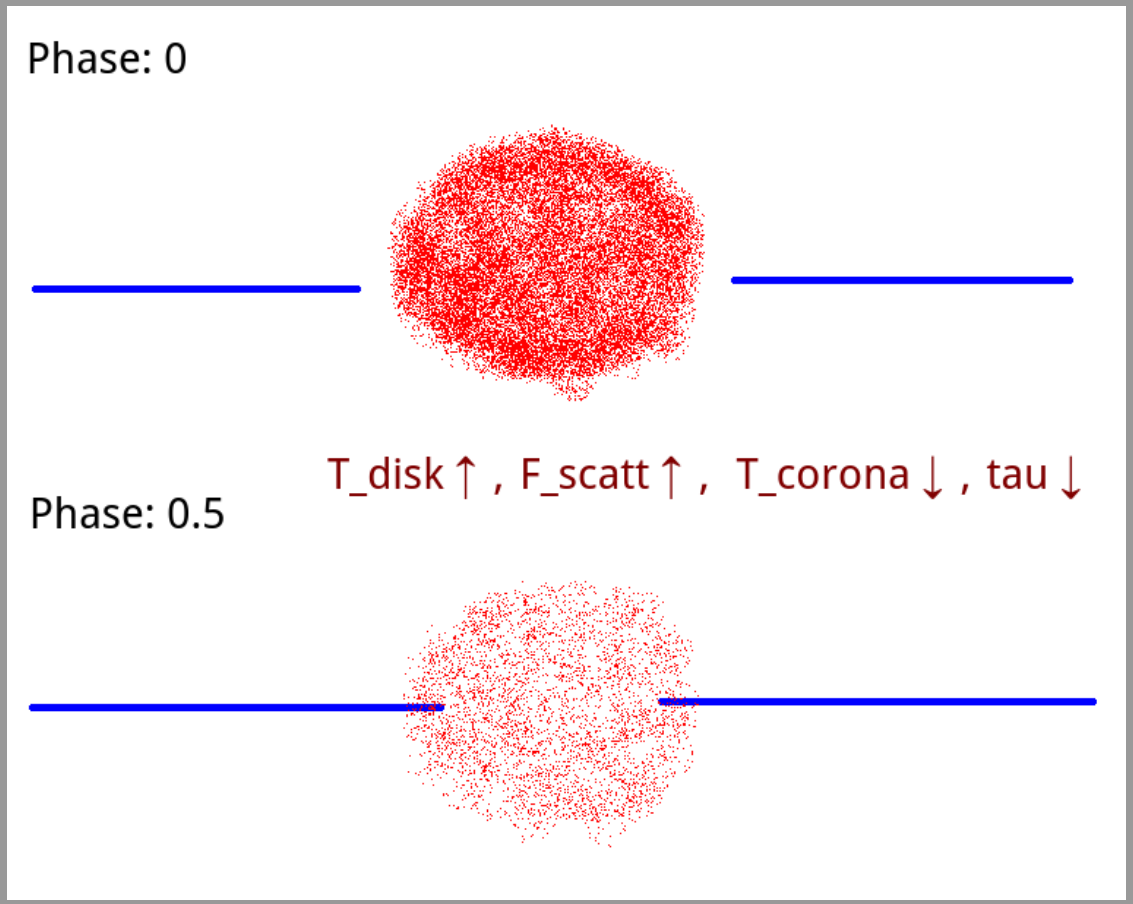
Distributions of the high amplitude (top) and low amplitude (bottom) durations



Spectral Modulations



Possible Interpretation



(Inspired by a recent simulation from Hogg & Reynolds)

Summary

Method

We utilized HHT to characterize the HHT-based timing properties, extract the QPO instantaneous phases, and then construct its phase-resolved spectra.

Results

- HHT-based timing property: the QPO is composed of a series of intermittent oscillations with ~ 1 s coherence time
- Phase-resolved spectra: significant modulations of Comptonization parameters with unignorable modulations of thermal disk components

Future Works

1	2015ApJ...815...74S Su, Yi-Hao; Chou, Yi; Hu, Chin-Ping; Yang, Ting-Chang	1.000	12/2015	A E F X R C S U	Characterizing Intermittency of 4-Hz Quasi-periodic Oscillation in XTE J1550-564 Using Hilbert-Huang Transform
2	2014ApJ...788...31H Hu, Chin-Ping; Chou, Yi; Yang, Ting-Chang; Su, Yi-Hao	1.000	06/2014	A E F X D R C S N U	Tracking the Evolution of Quasi-periodic Oscillation in RE J1034+396 Using the Hilbert-Huang Transform
3	2013ApJ...773...58H Hu, Chin-Ping; Chou, Yi; Yang, Ting-Chang; Su, Yi-Hao	1.000	08/2013	A E F X D R C S N U	Superorbital Phase-resolved Analysis of SMC X-1
4	2011ApJ...740...67H Hu, Chin-Ping; Chou, Yi; Wu, Ming-Chya; Yang, Ting-Chang; Su, Yi-Hao	1.000	10/2011	A E F X D R C S U	Time-frequency Analysis of the Superorbital Modulation of the X-Ray Binary SMC X-1 Using the Hilbert-Huang Transform

Python Wrapper for Hilbert–Huang Transform MATLAB Package

HHTpywrapper is a python interface to call Hilbert–Huang Transform (HHT) MATLAB package and plot results by Matplotlib. HHT is an empirical method to decompose a signal into basis components, called intrinsic mode functions (IMFs), based on the signal itself, and transform these components into instantaneous frequencies and amplitudes as functions of time. HHT has found many applications in different scientific and engineering fields, and it work well for signals generated by non-stationary and non-linear processes.

Requirements

- Python
- MATLAB
- Numpy
- Scipy
- Matplotlib
- pymatbridge (A simple Python => MATLAB(R) interface and a matlab magic for ipython)
- HHT MATLAB package (Please run downloadHHTpackage.py first)
- pyunpack and patool (For extracting the .zip/.rar HHT MATLAB package files)

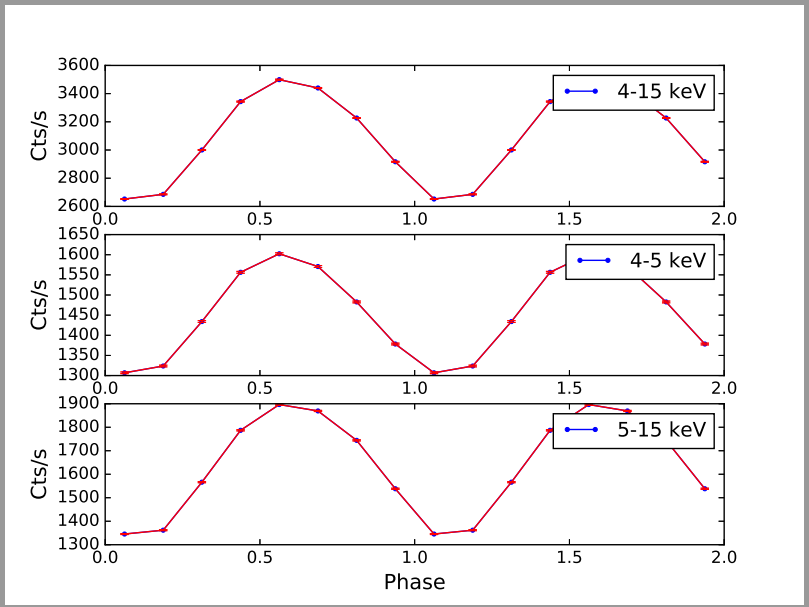
This is my project during the Astro Hack Week 2015

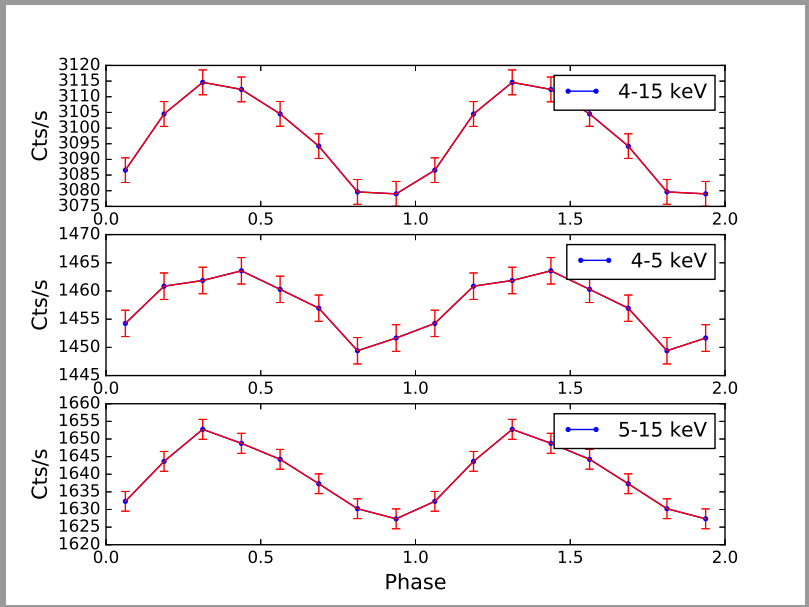
Please visit: https://github.com/HHTpy/HHTpywrapper

Usage

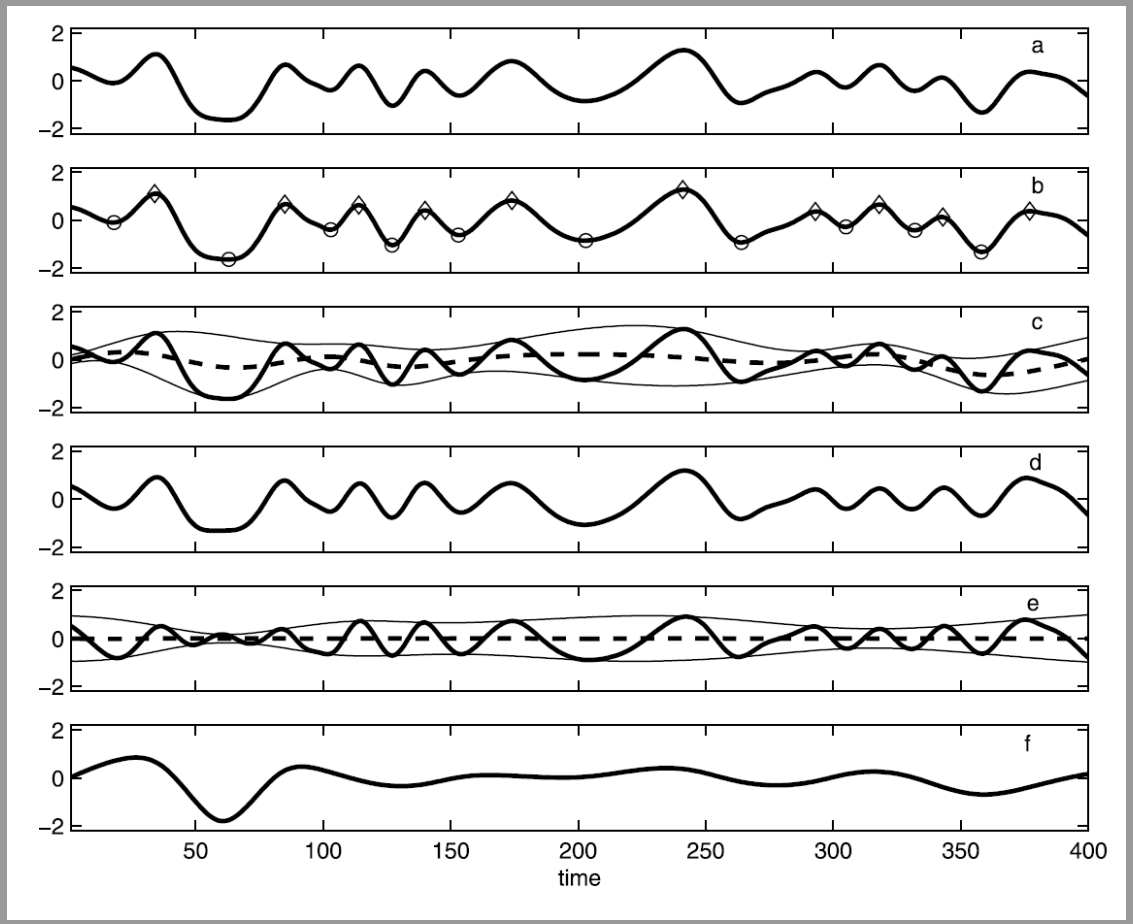
- Run downloadHHTpackage.py to download HHT MATLAB package.

Phase lag?


4-15 keV
4-5 keV
5-15 keV
Cts/s
Phase


4-15 keV
4-5 keV
5-15 keV
Cts/s
Phase

Sifting Process of Empirical Mode Decomposition



(Huang & Wu 2008)

Comparison between Analysis Methods

TABLE 1. Comparison Between Fourier, Wavelet, and HHT Analysis

	Fourier	Wavelet	HHT
Basis	a priori	a priori	a posteriori adaptive
Frequency	convolution over global domain, uncertainty	convolution over global domain, uncertainty	differentiation over local domain, certainty
Presentation	energy in frequency space	energy in time-frequency space	energy in time-frequency space
Nonlinearity	no	no	yes
Nonstationarity	no	yes	yes
Feature extraction	no	discrete, no; continuous, yes	yes
Theoretical base	complete mathematical theory	complete mathematical theory	empirical

(Huang & Wu 2008)