Time series decomposition using dynamic factor model: application to black hole X-ray light curves with NICER

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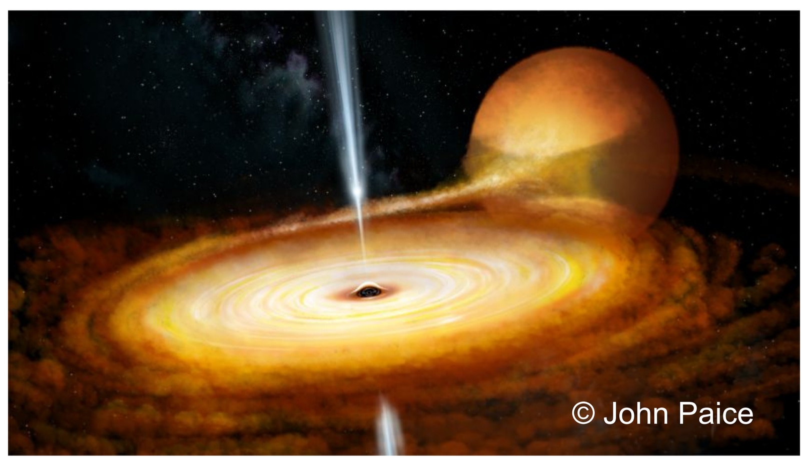
We introduce a new approach to decompose observed light curves into component variabilities using the result of the energy spectrum analysis. The target object is a black hole binary (BHB), which is thought to consist of several components (accretion disk, corona, reflection, etc.). Neutron star Interior Composition Explorer (NICER) observation of the BHB nova MAXI J1820+070 in 2018 gives a well-suited dataset. We apply the dynamic factor model, which is a time series version of the factor analysis, to this data and success fully decompose the observed light curves into the component variabilities.

1. Background

A black hole binary (BHB) is a binary system that consists of a black hole and secondary star similar to the Sun. BHB is known to have some spatial structures like standard disk (red), corona (blue), jet(blue), and so on. There are mainly two states; the soft state and the hard states. The geometry of the soft state is well-understood, but the geometry of the hard state is still a topic of ongoing debate. Comprehending the geometry of BHBs is crucial for advancing our understanding of their evolution and overall theory. Advanced statistical methods can be used to assess geometric quantities, which can lead to a better understanding of BHBs.



2. Instrument and Data

We utilize data from the BHB nova MAXI J1820+070, which experienced an outburst on March 11, 2018. This dataset was obtained through the Neutron star Interior Composition Explorer (NICER), a mission focused on X-ray timing spectroscopy with high time resolution and a large effective area. This allows us to perform both spectral and time series analysis using the same dataset. MAXI J1820+070 exhibited four sequential outbursts. For the development of statistical model, we focus on the data obtained immediately after the first outburst.

3. Method

Our data analysis is based on the dynamic factor model (DFM), which is formulated in the state space framework. The DFM enables the representation of data with a reduced number of latent series $\boldsymbol{x}_t$, which can be equal to or fewer than the number of observed series $\boldsymbol{y}_t$. They are connected with a weight matrix $\boldsymbol{A}$. In our study, we use the scaled flux in the fitted energy spectrum. In this way, we decompose the variabilities of the components estimated by the energy spectrum fitting. We assume that the transition of the latent states follow the vector autoregressive (VAR) model, which provides analytical tools such as power and cross spectra.

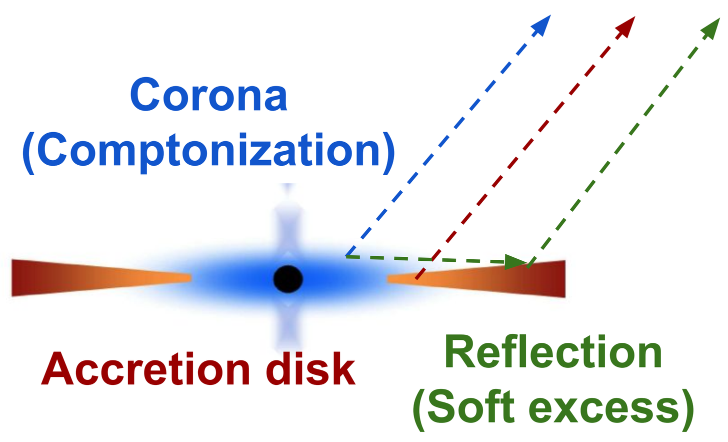
$$\boldsymbol{y}_t = \boldsymbol{A}\boldsymbol{x}_t + \boldsymbol{v},\ \boldsymbol{v} \sim \mathcal{N}(0, \boldsymbol{V}) \quad \textbf{: Observation equation}$$

$$\boldsymbol{x}_{t+1} = \boldsymbol{B}\boldsymbol{x}_t + \boldsymbol{w},\ \boldsymbol{w} \sim \mathcal{N}(0, \boldsymbol{W}) \quad \textbf{: State equation}$$

4. Analysis

Spectral Fitting

We use the NICER data ranging from 0.5-10.0 keV. Phenomenological model fitting was performed with *XSpec*. We fitted with the dominant Comptonization, the accretion disk, and reflected (referred to as the soft excess) components, which are commonly accepted to be exist in BHB.



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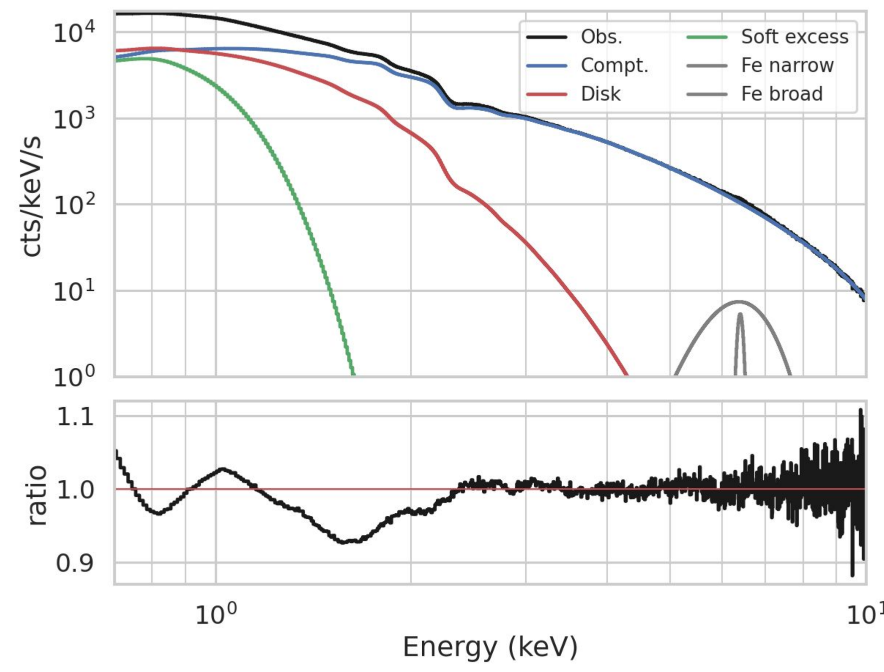
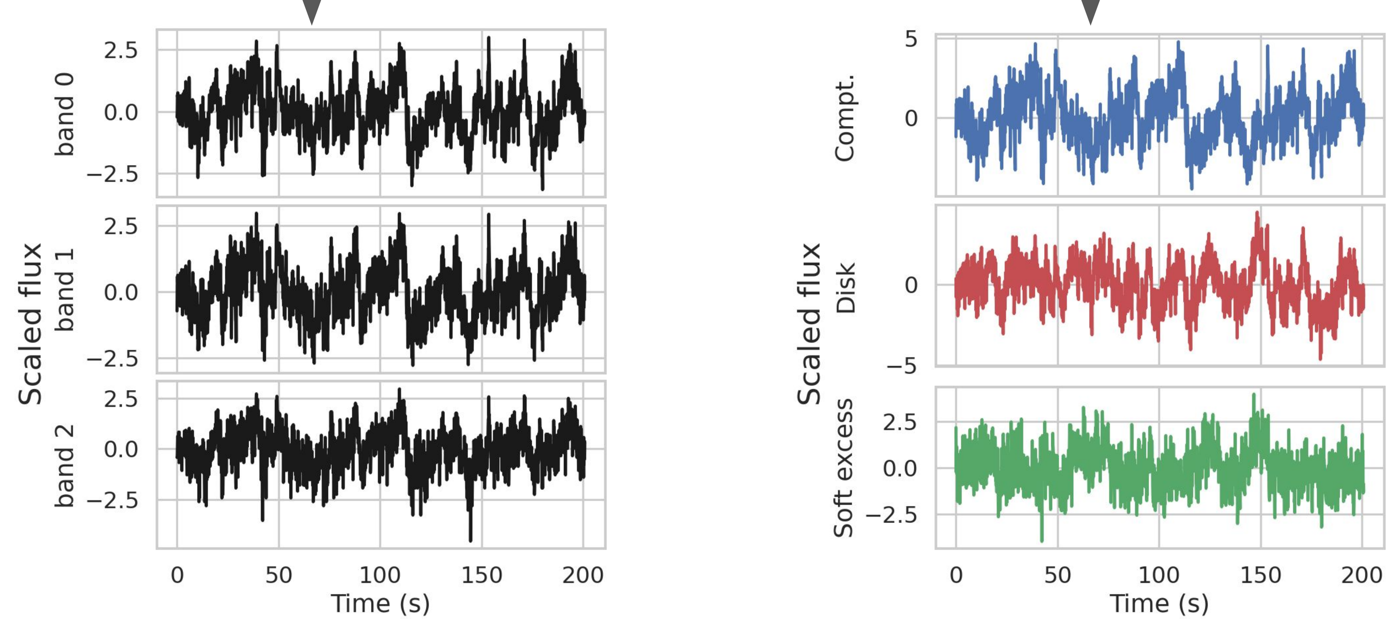


Dynamic Factor Model Inference

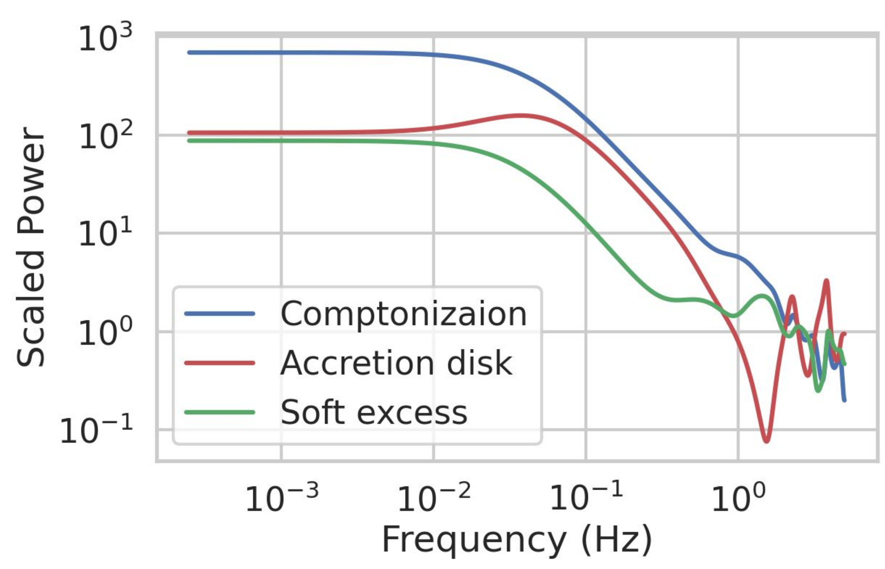
The photons are divided into three bands (0.5-2.0, 2.0-5.0, and 5.0-10.0 keV) to create light curve with 0.1 s time bins. Based on the energy spectrum result, the number of latent series is assumed to be three and we set the weight matrix $\boldsymbol{A}$ to have a triangular shape. The estimated component curves exhibit different variabilities. As anticipated, the dominant variability in all observed curves is attributed to the Comptonization factor.

$$\begin{bmatrix} y_{1,t} \\ y_{2,t} \\ y_{3,t} \end{bmatrix} = \begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} \\ a_{2,1} & a_{2,2} & 0 \\ a_{3,1} & 0 & 0 \end{bmatrix} \begin{bmatrix} x_{1,t} \\ x_{2,t} \\ x_{3,t} \end{bmatrix}$$



Spectral Properties

Here, we introduce one of the most distinctive spectral results, the power spectra computed from the VAR model. All of the power spectra exhibit a broken power-law shape, but they have different power indices. The power index of -2 for the accretion disk component is particularly noteworthy because it has not been previously measured without contamination from other components.



Poster

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