Abstract

A black hole binary (BHB) is a binary system consisting of a black hole and a non-degenerate star. The black holes came into existence with Cygnus X-1 in the 1970s, when two pioneers of X-ray astronomy, Minoru Oda and Ricardo Giacconi, boldly speculated that the rapid X-ray flux variability distinctively seen from this source could only be attributable to a black hole. Since then, many features of BHBs have been identified, such as spectral changes and transient behaviors, but the rapid variability from milliseconds to seconds remains one of the most distinctive features of BHBs. The origin of the rapid variability is still unknown, but it is believed to carry information about the accretion and ejection processes and the strong gravitational field in the vicinity of a black hole.

X-ray observations of BHBs record the energy and arrival time of individual X-ray photons from BHBs. Spectral and light curve analyses have been performed, but they were done independently from each other. On the one hand, traditional spectral analysis was performed for time-sliced spectra ignoring the correlation among them in time. On the other hand, traditional light curve analysis was performed without considering the changing contributions of spectral components in time. We need to develop a method for the joint spectral and timing analysis.

The statistical modeling approach provides the answer. If we denote the observed count in a time bin $n \in \{1, \cdots, N\}$ and an energy bin $m \in \{1, \cdots, M\}$ as c_{nm}, we regard c_{nm} as a realization of the probability variable C_{nm}. The goal is then to estimate the joint probability distribution of $p(C_{11}, \cdots, C_{NM})$. In this manner, timing and spectral information can be modeled jointly. This approach also has advantages including noise as a model component and using latent variables to describe the changes in the system behind observed values.

The statistical modeling approach sounds straightforward and suitable for the analysis of BHB data but has been scarcely used. Several reasons hampered the application to real data, including data quality, modeling techniques, computational resources, and physical models to interpret joint probability. However, recent advances in all of them are clearing these obstacles. It is high time to start using statistical modeling as the norm of X-ray spectral and timing analysis. In this thesis, we demonstrate that this is possible and even crucial in deriving new insights from BHBs by applying the method to the actual data of a BHB.

We use the data of MAXI J1820+070 observed with The Neutron star Interior Composition ExploreR (NICER). MAXI J1820+070 is a transient BHB discovered in 2018. The source exhibited many spectral and timing features common among BHBs in both the hard and soft states. The low interstellar extinction and the proximity made the

source extremely bright in flux reaching ∼4 Crab. NICER is the X-ray observing instrument onboard the International Space Station. The unprecedented collecting area and a large dynamic range of NICER and the brightness of the source resulted in an extreme count rate of $\mathcal{O}(10^4\ \mathrm{s}^{-1})$, which is rich enough to apply statistical modeling. We focus on a 50 s length of data during the hard state near the flux peak of the BHB.

We applied classical time series modeling to the X-ray light curves constructed at 0.5–2.0, 2.0–5.0, and 5.0–10 keV. We first used the autoregressive (AR) model for each light curve, and a reasonable fit was obtained. Because noise is included in the AR model, the univariate description functions (e.g., correlation function and power spectrum) are less noisy than those made by the traditional analysis using the raw data. Next, we used the vector autoregression (VAR) model. Because the mixture among the multi-band light curves is included, the fitting improved from the AR model. This implies the importance of the spectral mixture for the observed light curves.

We therefore proceeded with the linear Gaussian state-space modeling to the multi-band X-ray light curves in five energy bands. The observed light curves are treated as observation variables, whereas the intensity changes of the physical spectral components (Comptionized, disk blackbody, and soft excess components) were treated as latent variables. The system equation was described by the VAR model and the observation equation was described by a linear matrix. In this manner, we included both the spectral mixture and the correlation in time in a single model. As a result, we could derive the multivariate description functions (e.g., cross-covariance, cross spectra, and coherence) among the spectral components, not among the multi-band light curves. This is the advantage of using the latent variable in a model.

We produced the spectrally-decomposed power spectra and derived the break frequencies of the Comptionized, disk blackbody, and soft excess components. We also produced the spectrally-decomposed cross spectra to derive the time lags among them. From these results, we found that the three components affect each other in the causality order of the disk blackbody, Comptonized, and soft excess emission. The different break frequencies in the three components, the time lag between these components, and the mutual power contribution all point to the geometry of the truncated accretion disk.

This work is one of the first successful applications of the state-space modeling approach to BHB data analysis. We demonstrated the possibility and utility of the joint spectral and timing analysis by applying it to the actual data and obtaining new insights into BHBs. We consider that this should be one of the standard approaches to analyzing the data to come in the near future with advanced observing technologies.