NSYSU

physics 書報討論 Weekly Seminar

Learning and Predicting the Nonlinear Variability of X-ray Binaries with the Koopman Operator

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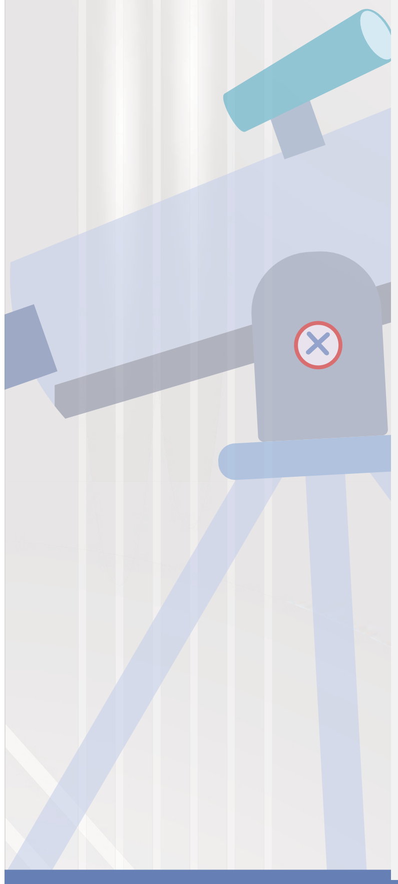
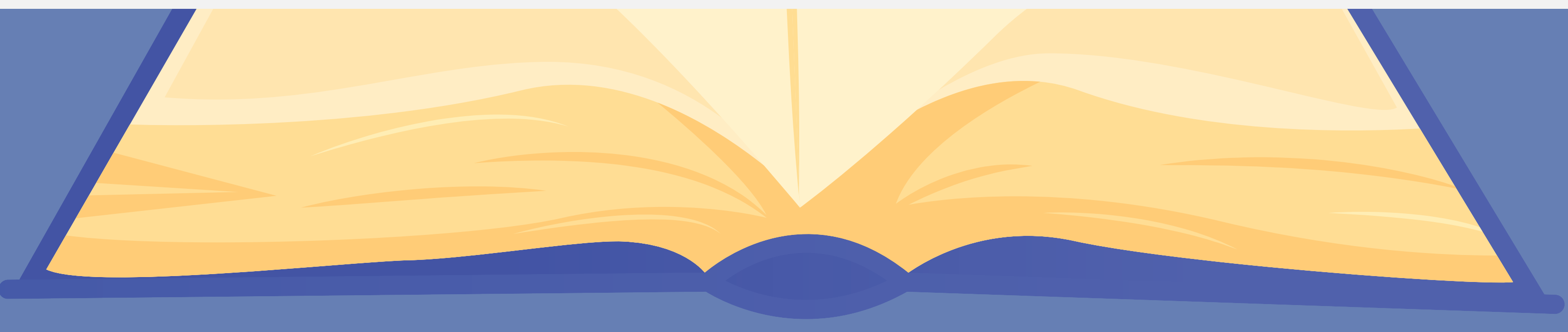
X-ray variability in compact object binaries probes the nonlinear dynamics of corona–jet interactions and accretion disk instabilities. Standard timing techniques, while effective at characterizing periodic and quasi-periodic variability, do not capture the underlying nonlinear dynamics or predict their evolution. We introduce Koopman operator theory and its data-driven approximation, extended dynamic mode decomposition (EDMD), to astrophysical light curves for the first time. In this framework, the Koopman operator $\mathcal{K}$ represents nonlinear evolution as an infinite-dimensional linear operator whose eigendecomposition decomposes complex systems into independently varying, linearly evolving modes. We show that Koopman eigenvalues map onto quasi-periodic oscillation (QPO) frequencies and that process noise induces damping that broadens QPO spectral widths, enabling physical interpretations of the corresponding eigenmodes. We further demonstrate that Koopman eigenfunctions can predictively partition state space into distinct flux regimes, often preceding state transitions by days to weeks, and that direct flux forecasts can be generated by iteratively applying $\mathcal{K}$. Applying this method to RXTE ASM and MAXI data of 4U 1705–44, a well-studied X-ray binary, we forecast X-ray flux weeks in advance using eigenfunction-based partitions and direct flux predictions. The key benefits of this framework are its generalizability to linear and nonlinear astrophysical systems, interpretability through mode decompositions, and predictability through evolving captured dynamics, establishing Koopman operator theory as a new frontier of astrophysical timing analysis.





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