Investigating the Changing Dynamics of a Black Hole Accretion Environment

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The goal of this research report has been to connect the differing physical structures of X-Ray Binaries (XRBs) to the variance in their brightness. For each selected observation of interest of GRS 1915+105, an XRB, we created a time series visualization and recurrence plot to investigate a pattern between the recurrence plots and the various spectral states: the low hard state, high soft state, and intermediate state.

The goal of this research report has been to connect the differing physical structures of the X-ray Binary, GRANAT source (GRS) 1915+105, to the variance in its brightness by using time series analysis. GRS 1915+105 is a binary star system that includes a black hole accretor and a regular star donor in close orbit to each other. The material from the donor is drawn toward the accretor forming an accretion disk, which can take various geometrical forms called "accretion states" or "spectral states," and is particularly luminous and variable at X-Ray frequencies (1). The accretion state is traditionally identified using energy spectra measurements. The most common states include the low-hard state, high-soft state, and intermediate state (transitional state), as depicted in Figure 1. What causes a change between these complex and distinct states and how each relates to its brightness variability is the object of this study.

We obtained all observations of GRS 1915+105 from the Rossi X-Ray Timing Explorer (RXTE)[1] Proportional Counter Array covering its 1997 and 2005 state transitions. The data was pulled from the High Energy Astrophysics Science Archive (HEASARC)[2] at NASA Goddard Space Flight Center, a public database for all NASA missions. We determined the accretion state for each observation using the results from (2), focusing on a subset of 120 out of the over 1000 time series with simultaneous accretion state information.

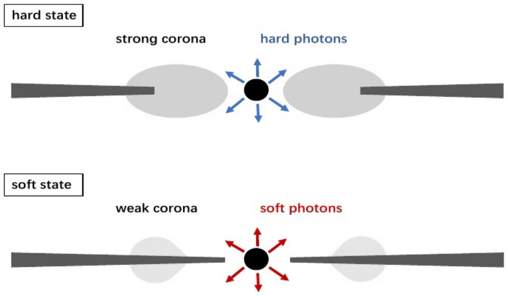

Figure 1. An edge-on view of an accreting black hole XRB in two different accretion states. (Left) The high soft state consists of a dense, thin accretion disk that approaches close to the black hole and emits lower energy ("soft") X-ray photons with a weak atmosphere (corona). This results in an energy spectrum with a peak at softer energies. (Right) The low hard state consists of a receded accretion disk and a stronger corona that emits higher energy X-ray photons. This results in a spectrum dominated by higher energies.

A recurrence plot (RP) (3) is a visualization of a square matrix, where each axis represents a point in time in a dynamical system. The entries of the RP are positive when the phase space trajectory at those two points in time are in a similar geographical spot in the phase space (and zero, otherwise). Consequently, patterns seen in the RP are unique to different dynamical systems, as shown in Figure 2 (4).

For each selected observation of interest, we created the RP using Python in the Jupyter environment. Since the RP is computed from the phase space of a system, we must transform the one-dimensional time series of brightness variations into a phase space "embedding." We use the commonly used Time Delay Method (5).

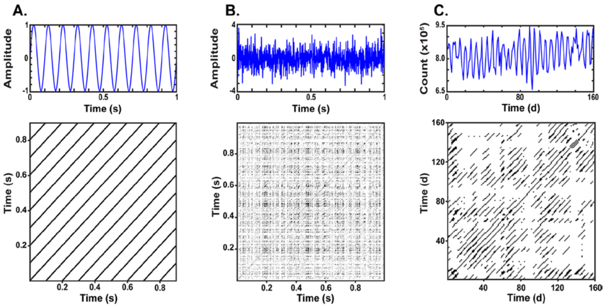

Figure 2. The time series (top row) of a periodic sine wave (A), white noise process (B), and chaotic system (C) and (bottom row) their respective visualizations as recurrence plots (7).

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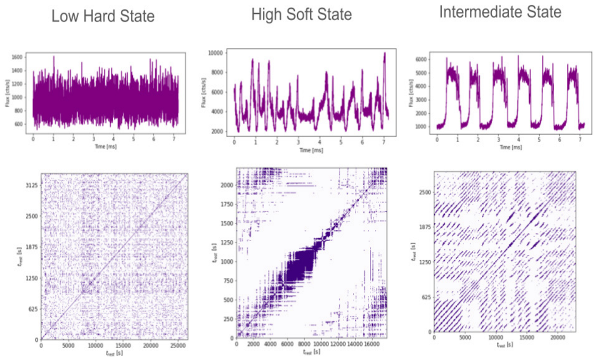
[1] https://articles.adsabs.harvard.edu/pdf/1993A%26AS...97..355B
[2] https://heasarc.gsfc.nasa.gov/docs/xte/XTE.html

This method requires one to select a time delay, τ, and a dimension, m, to reconstruct phase space vector, y(t), of a scalar time series, $x(t)$, of length, n, using the following definition: $y_i(t) = (x_i(t - \tau), x_i(t - 2\tau), \ldots, x_i(t - m\tau))$, for $i=1, 2, \ldots, n$. We determined the optimal time delay using the autocorrelation time (as recommended by (3)) and the embedding dimension via the false nearest neighbors method (FNN; 6). The FNN method estimates the optimal dimension based on minimizing the amount of "false neighbors" — points that appear to deviate significantly from each other in distance when the dimension is increased by 1. Time series missing critical data were ignored, resulting in approximately 150 RPs. A qualitative inspection of the RPs reveals a range of patterns from randomly distributed points, to large and blocky features, to individual chopped up diagonal lines, as seen in Figure 3. These features appear to be correlated with spectral state and suggest that the distinct patterns in the RP may be used to infer spectral state, in lieu of the more time-expensive and computationally-intensive energy spectra. The next steps will be to quantify the patterns in the RP (e.g., measuring line lengths and densities) and how they are statistically distinguished by spectral state to uncover any potential relationships between variability patterns and spectral state.


Low Hard State

High Soft State

Intermediate State

Figure 3. The time series (top row) of three GRS 1915+105 observations that represent each spectral state. Their respective recurrence plots are below showing stochastic, nonstationary, and chaotic visualizations (left to right).

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Samantha Spivack ('27) is a Statistics major at Villanova University with minors in Astronomy & Astrophysics and French & Francophone Studies. She worked on this project as a Spring 2024 First Year Match participant. On campus, she is involved in Alpha Phi Omega and Villanova Astronomical Society. After graduation, Spivack plans to pursue graduate studies in statistics and data science and focus on astro-statistics.

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Rebecca Phillipson is an Assistant Professor of Physics at Villanova. Dr. Phillipson earned her PhD from Drexel University in Physics in 2020. Her research interests include: the timing variability of accreting black holes and neutron stars using data from space-based X-ray and optical instruments and novel methodologies to classify and discover accreting objects from ground-based observatories. Dr. Phillipson's primary tools of study draw from nonlinear dynamics and chaos theory in combination with machine learning.