Analysis and Sonification of the Heartbeat State in the Black Hole Binary GRS 1915+105

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The goal of this research report has been to analyze and present X-ray data from the black hole binary system GRS 1915+105 in a unique and innovative way. Using data taken from the Rossi X-ray Timing Explorer (RXTE), we created time series visualizations and recurrence plots to examine the behavior of GRS 1915+105 in the heartbeat state. To present this data in a more engaging fashion, we sonified both the time series visualization and the recurrence plot.

The goal of this research report is to present and analyze X-ray data from the black hole binary system GRS 1915+105 in a novel and accessible way. GRS 1915+105 is a bright X-ray binary star system at a distance of 8.4 kiloparsecs (kpc) away, (1) consisting of a 12 solar-mass black hole (2) and a main sequence companion star. As the black hole accrues matter from the companion, an "accretion disk" forms from hot plasma that emits strongly at X-ray wavelengths. The Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) is a satellite X-ray detector that observed GRS 1915+105 continuously throughout its mission (3).

To investigate the system's underlying dynamics, we employ sonification, the process of converting data into sound, to the recurrence plot of the X-ray data from RXTE. A recurrence plot (4) is a matrix-based visual tool used to study when a dynamical system returns to a previous state. It is constructed by plotting the times at which two states in phase space are sufficiently close (where dark points are close distances, and pale features are not). The resulting patterns can reveal underlying dynamics such as periodicity or chaos (5,6). This provides an alternate way to interact with data and has the potential to reveal features or patterns that may otherwise be visually obscure.

Our sonification methods and subsequent analysis were primarily focused on the "heartbeat" (HB) state (7) of GRS 1915+105, shown in Figure 1, which is a variability state characterized by quasi-periodic oscillations in its X-ray emissions. These oscillations reflect instabilities in the accretion disk and are among the most dynamic and studied behaviors in black hole binaries (8), making it a suitable test-case for developing a robust sonification approach for all other RXTE observations of this source.

To probe the dynamics of the RP (see Figure 1), we employed sonification. Using the Strauss Python package (9), we developed a method for sonifying the RP. The Strauss workflow, depicted in Figure 2, proceeds in stages: first, numerical data is passed to the Sources class, which maps numerical values to sound parameters such as pitch and volume. Next, the Score class applies 'musical constraints' on the sound produced (e.g., the range of musical notes to sample). Finally, the Generator class produces the audio output, which is rendered using the Channels class.

RPs are symmetric along the main diagonal and many of the physically meaningful aspects of a dynamical system show up in the diagonal features of RPs (10). Therefore, we began our sonification process by extracting parallel diagonals, aligning them so that they all began on the same anti-diagonal starting line. Treating each diagonal as we would a time series, we

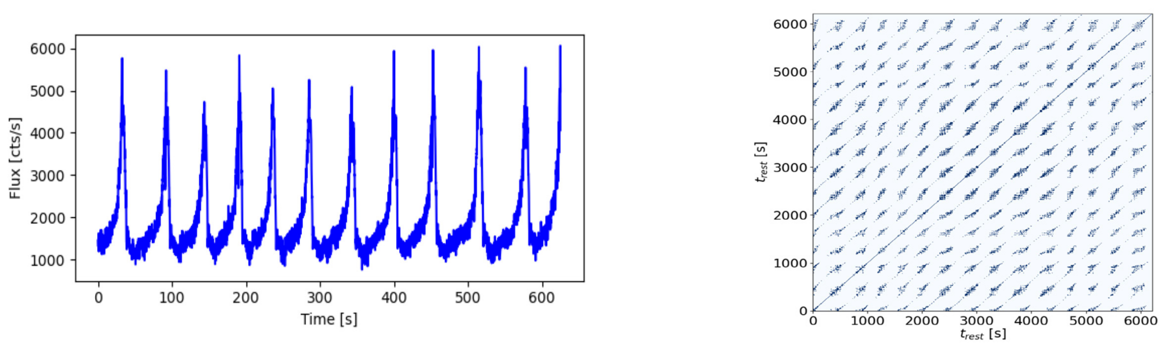

Figure 1: ***A time series and recurrence plot of GRS 1915+105 in the HB state.*** Left: *A time series of GRS 1915+105 over a time interval of 13 minutes (RXTE PCA obsid: 20402-01-31-02). These structured, quasi-periodic oscillations are a key feature of the HB state of GRS 1915+105.* Right: *The RP of the time series. The clusters of dots that loosely form diagonal lines parallel to the RP's main diagonal are cornerstone features of periodic and quasi-periodic systems. They indicate stretches of time where the system evolves in a similar way to how it evolved earlier.*

overlaid each extracted diagonal in a plot (see Figure 2). We then used Spectralization, a subclass in the Generator class, to convert this image to sound. Spectralization takes a frequency spectrum as an input and converts it to sound using an Inverse Fast Fourier Transformation (IFFT). In our case, the IFFT is applied to each column of pixels along the anti-diagonal of the RP (or column in the

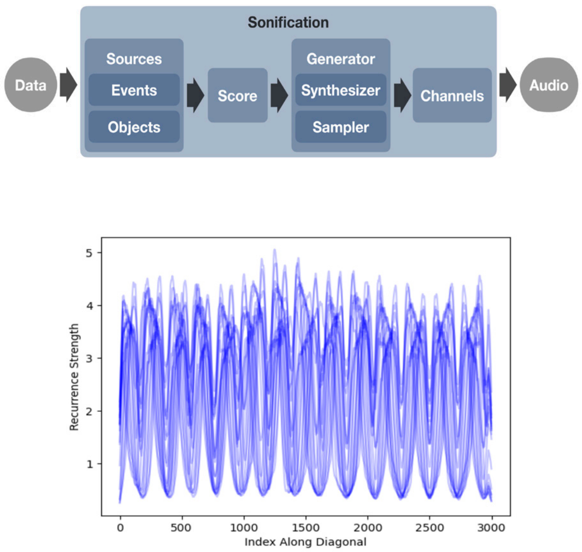

Figure 2: Workflow of the Strauss package and extracted diagonals. Top: *The workflow of the Strauss sonification procedure.* Bottom: *The image sonified by Spectralization in which all diagonals extracted from the RP are overlaid revealing the persistent periodic nature of the source. The sonification can be found as a video in the supplemental materials.*

overlaid diagonals figure) to produce a superposition of pitches at each timestep. The full sonification, composed from all columns, offers an auditory rendering of the RP's underlying structure. This essentially enables us to hear the recurrent dynamics of the HB state.

The HB state is one of many states exhibited by this highly variable source. Our method will be applied to the other states in GRS 1915+105 to compare their complex dynamics through sound. Analyzing the quantitative aspects of the RP is the next step in understanding the nature of the HB state. This could entail evaluating the frequency of state repetition or examining the diagonals' length and spacing. These methods can assist in revealing the underlying nature of the HB state, whether it is chaotic, regular, or steady, and how these features are manifested in sound.

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