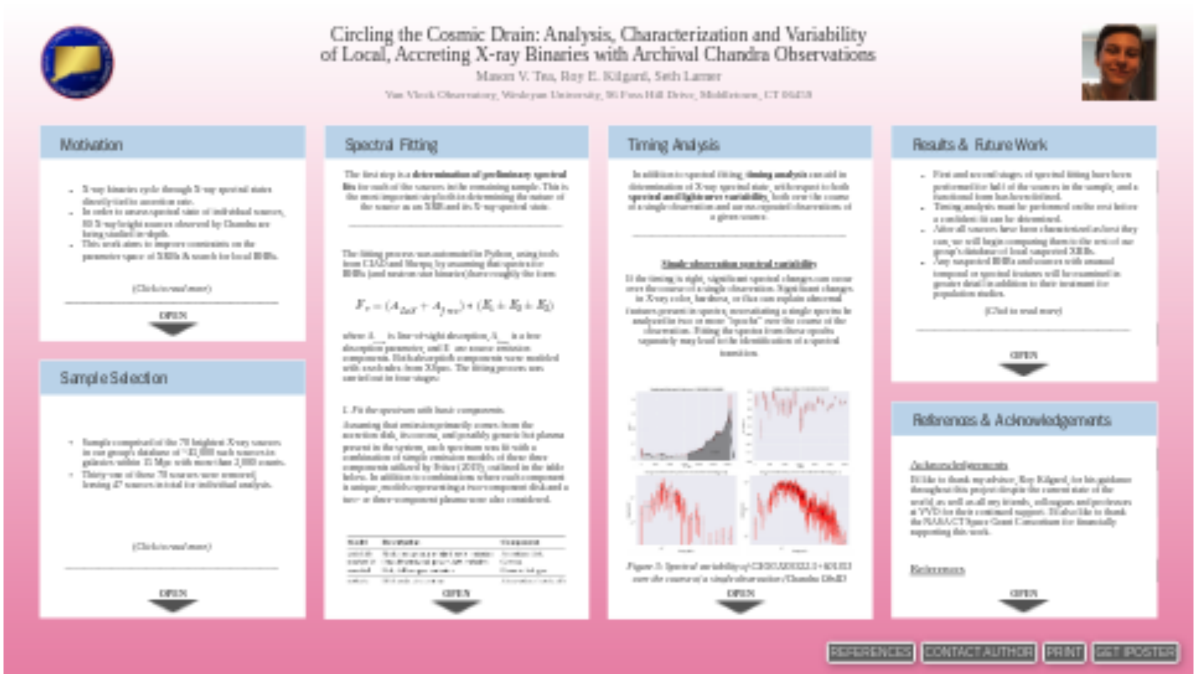
Circling the Cosmic Drain: Analysis, Characterization and Variability of Local, Accreting X-ray Binaries with Archival Chandra Observations



Mason V. Tea, Roy E. Kilgard, Seth Larner

Van Vleck Observatory, Wesleyan University, 96 Foss Hill Drive, Middletown, CT 06459

PRESENTED AT:

AAS 237

237TH MEETING OF THE AMERICAN ASTRONOMICAL SOCIETY
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MOTIVATION

- X-ray binaries cycle through X-ray spectral states directly tied to accretion rate.
- In order to assess spectral state of individual sources, 80 X-ray bright sources observed by Chandra are being studied in-depth.
- This work aims to improve constraints on the parameter space of XRBs & search for local BHBs.

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X-ray binaries (XRBs) are known to cycle through distinct X-ray spectral states, directly tied to their accretion activity (Remillard & McClintock, 2005).

Observing a full cycle would allow for a **determination of the nature of the compact object** as either a black hole or a neutron star, and detailed analysis of its spectral features and variability presents an opportunity to **determine X-ray spectral state.**

Because the time required for detailed analysis of such sources is prohibitively long for large samples, my work focuses on a sample of **roughly 80 Chandra observations of the brightest extragalactic X-ray sources within 15 Mpc** from our group's database.

In its current stage, this work seeks to make **confident determinations of X-ray spectral state** for the entire sample, giving special attention to suspected **black hole binaries (BHBs)** and sources presenting unusual spectral and/or temporal characteristics.

A detailed analysis and characterization of both spectral and temporal features of any XRBs found in this sample has the potential to **inform tighter constraints on the parameter space of the local XRB population**, which is the final goal of this project.

SAMPLE SELECTION

- Sample comprised of the 78 brightest X-ray sources in our group's database of ~45,000 such sources in galaxies within 15 Mpc with more than 2,000 counts.
- Thirty-one of these 78 sources were removed, leaving 47 sources in total for individual analysis.

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Our group's database is comprised of ~45,000 X-ray sources in galaxies within 15 Mpc (excluding the Milky Way, Andromeda, and their satellites), observed by the Chandra X-ray Observatory from its launch to May of 2016.

My sample is the product of imposing a **lower limit of 2,000 counts** on all observations in this database, representing **78 unique sources** (~0.66% of the total sources in the database). With appropriate binning, this ensures spectra which allow differentiation between physical models when fit.

After a literature search and visual inspection of each of their spectra and lightcurves, **31 of these 78 sources were removed**:

- Ten were far too noisy for significance
- Six were confirmed as non-XRBs in the literature
- Six more were found to be in galaxies much more distant than 15 Mpc that made their way into the database
- Two were nuclear sources, residing within 2 arcsec of the galactic center
- One was determined to be a background AGN

The final sample contains **47 sources in total** which have received, or will receive, a detailed spectral and temporal analysis.

SPECTRAL FITTING

The first step is a **determination of preliminary spectral fits** for each of the sources in the remaining sample. This is the most important step both in determining the nature of the source as an XRB and its X-ray spectral state.

The fitting process was automated in Python, using tools from CIAO and Sherpa, by assuming that spectra for BHBs (and neutron star binaries) have roughly the form

$$F_\nu = (A_{LoS} + A_{free}) * (E_1 \pm E_2 \pm E_3)$$

where A_{LoS} is line-of-sight absorption, A_{free} is a free absorption parameter, and E_n are source emission components. Both absorption components were modeled with `xstbabs` from XSpec. The fitting process was carried out in four stages:

1. Fit the spectrum with basic components.

Assuming that emission primarily comes from the accretion disk, its corona, and possibly generic hot plasma present in the system, each spectrum was fit with a combination of simple emission models of these three components utilized by Fritze (2019), outlined in the table below. In addition to combinations where each component is unique, models representing a two-component disk and a two- or three-component plasma were also considered.

Model	Description	Component
xsdiskbb	Multi-temperature blackbody emission	Accretion disk
powlaw1d	One-dimensional power-law emission	Corona
xsmekal	Hot, diffuse gas emission	Generic hot gas
xstbabs	ISM grain absorption	Absorption (catch-all)

Figure 1: "Base" models used as components in models for determining functional form of spectral fits.

2. Examine fits, choose the 1-2 most reasonable.

Once each of the ~10 models are fit to the spectrum, only those with a chi-square value of less than 1.3 are considered. Every model is then evaluated individually on the following criteria:

- Reasonable fit parameters and bounds
- Significant contribution of each component to the overall fit
- Visual goodness of fit
- Fit statistic

Considering these variables, I selected the best (and often second best) fits for each source by hand, defining a basic functional form for the spectrum.

3. Add complexity to emission components & test.

With a basic functional form defined, an F-test can be run between this "base" model and variations of it in which the constituent emission components were swapped for more complex models representing the same features. If a more complex model wins over the base, F-testing is continued against it in place of the base model. The additional emission components I chose to test are outlined in the table below.

Model	Description	Component
xsdiskpn	Multi-temperature blackbody emission	Accretion disk
xsapec	Collisionally-ionized plasma / diffuse gas emission	Accretion disk
xscompbb	Comptonized blackbody emission	Corona

Figure 2: More complex component models used in second round of spectral model determination. These models replace those in Fig. 1 in order to possibly fit finer details not picked up by the "base" models alone.

4. Repeat Stage 2 and determine final fit.

Once Stage 3 has been performed on each of the fits chosen in Stage 2, the results are examined in the same fashion as Stage 3, and a final spectral fit is determined.

TIMING ANALYSIS

In addition to spectral fitting, **timing analysis** can aid in determination of X-ray spectral state, with respect to both **spectral and lightcurve variability**, both over the course of a single observation and across repeated observations of a given source.

Single-observation spectral variability

If the timing is right, significant spectral changes can occur over the course of a single observation. Significant changes in X-ray color, hardness, or flux can explain abnormal features present in spectra, necessitating a single spectra be analyzed in two or more "epochs" over the course of the observation. Fitting the spectra from these epochs separately may lead to the identification of a spectral transition.

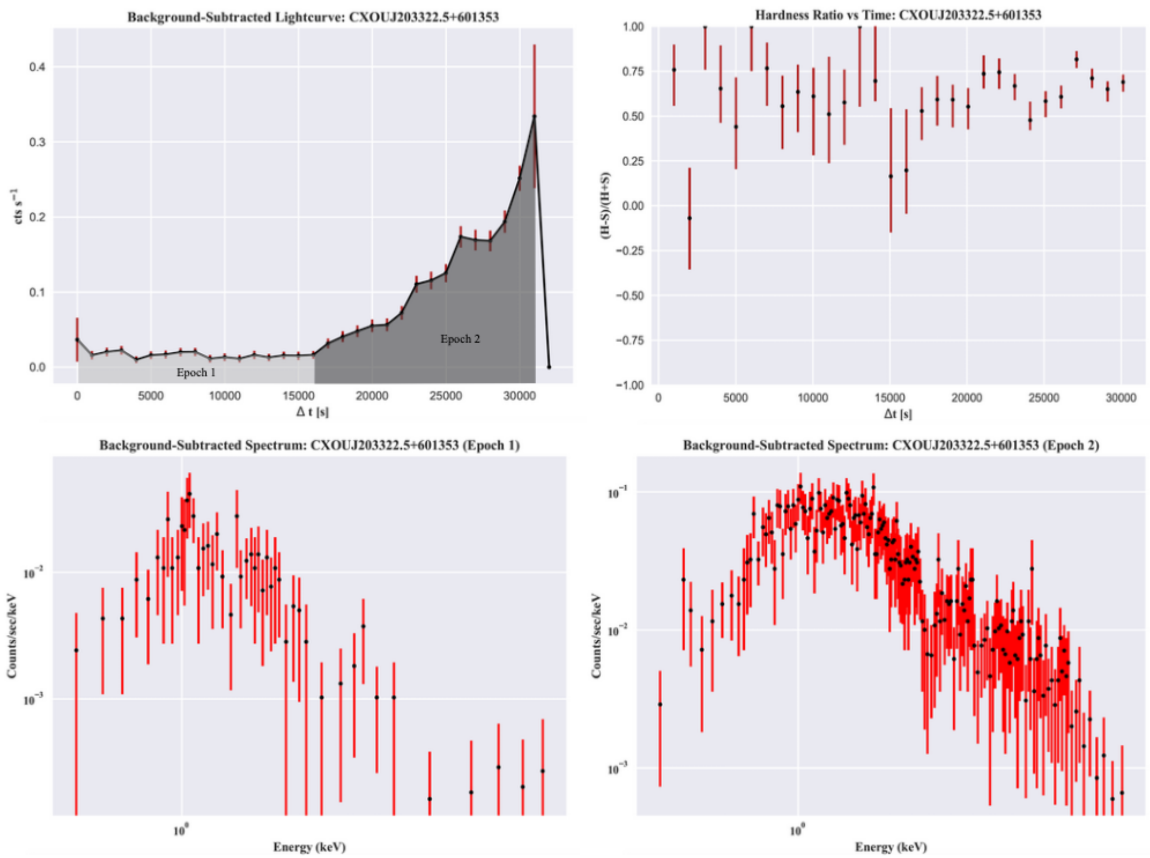

*Figure 3: Spectral variability of CXOUJ203322.5+601353 over the course of a single observation (*Chandra *ObsID 4631). Noticing the steady increase in count rate shown in the light curve, the observation was divided into two epochs, before and after the brightening event at roughly 15ks. Plotting the spectra in these two epochs separately, we can see that the shape of the spectrum changes significantly with the increase in count rate, suggesting that this may signify an accretion event in the binary. Further analysis is necessary for this object, and is forthcoming.*

Single-observation Q/POs

Varying frequencies of quasiperiodic oscillations (QPOs) in the lightcurves of XRBs are correlated with different X-ray spectral states of BHBs, and examining QPO light curves can provide information about the high-energy physics of a dynamic accretion disk, as they are hypothesized to be caused by disk instability and transitionary states. QPOs are also associated with specific

X-ray spectral states, and can lend confidence to a definition from spectral fitting.

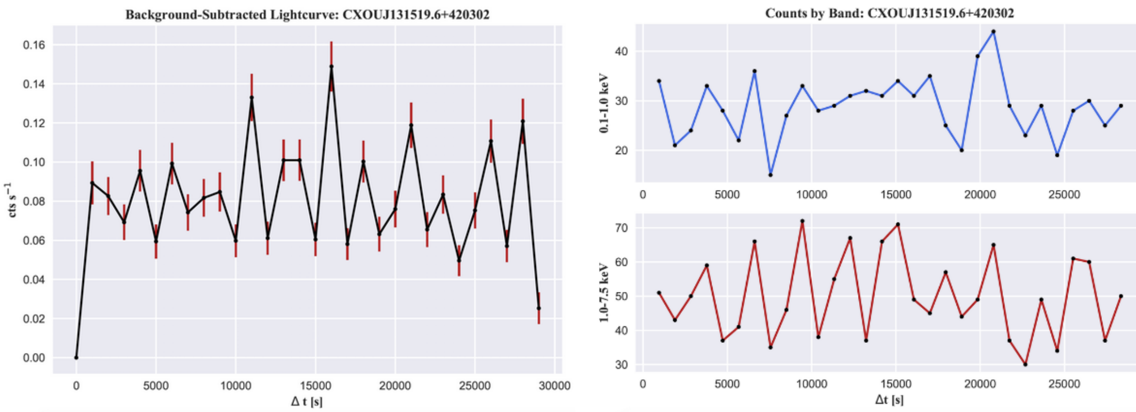

*Figure 4: Count & count rate variability of CXOUJ131519.6+420302 over the course of a single observation (*Chandra *ObsID 2197). The spectrum of this source has been fit fairly confidently with a model consisting of a single-temperature disk and a nonthermal power law component, indicative of an accreting binary. This signal could be attributed to a close-in eclipsing binary, or perhaps disk instability, among other explanations. This is speculation, however, and periodicity tests will be performed on this source as a next step.*

Multi-observation variability

Multiple observations of a single source provide an opportunity to investigate long-term changes in its spectra, possibly revealing a transition between phases of accretion in the time between observations. Once a satisfying spectral fit is defined, we can search for other observations of the source to confirm this definition or search for this long-term variability.

RESULTS & FUTURE WORK

- First and second stages of spectral fitting have been performed for half of the sources in the sample, and a functional form has been defined.
- Timing analysis must be performed on the rest before a confident fit can be determined.
- After all sources have been characterized as best they can, we will begin comparing them to the rest of our group's database of local suspected XRBs.
- Any suspected BHBs and sources with unusual temporal or spectral features will be examined in greater detail in addition to their treatment for population studies.

(*Click to read more)*

Results

Thus far, the first and second stages of the spectral fitting process have been performed on all sources in the sample, and each has had its lightcurve and X-ray color examined for variability. Functional forms for **spectral fits have been defined for 23 of the 47 sources** in the sample, the remaining 24 objects requiring **special attention for variability or more detailed analysis** before a confident determination can be made.

Future Work

Moving forward, investigations of each of the types of timing analysis aforementioned must be performed on those sources with no preliminary fits. This will be accomplished by generating **periodograms of unbinned lightcurves** to search for characteristic X-ray state frequencies and **searching for repeated observations** of sources in the *Chandra* archive which may not have appeared in the initial sample definition.

Once final models have been determined for all sources, their fit parameters, estimated luminosities and masses, X-ray colors, and frequencies of any QPOs present can be used to **classify the X-ray spectral state** of each. We can then compare these objects to those remaining in our group's database to **infer characteristics of the population of X-ray sources in the local universe.**

Of particular interest are individual sources with unusual spectro-temporal characteristics, or those which might suggest that they are **black hole binaries**, which we aim to study in-depth and **compare to the accepted parameter space for BHBs**, informing future studies.

REFERENCES & ACKNOWLEDGEMENTS

Acknowledgements

I'd like to thank my advisor, Roy Kilgard, for his guidance throughout this project despite the current state of the world, as well as all my friends, colleagues and professors at VVO for their continued support. I'd also like to thank the NASA CT Space Grant Consortium for financially supporting this work.

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