Variability of X-ray Sources in Nearby Galaxies

by

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Chapter 1

Introduction

X-ray sources include a variety of different objects, from supernova remnants to active galactic nuclei and X-ray binaries. An X-ray binary is a type of binary star system where the primary star is a compact object such as a black hole or neutron star. The compact object is accreting material from the other star, called the secondary or donor. X-ray binaries can be separated into three classes, depending on the mass of the donor star: High Mass X-ray Binaries (HMXBs), Low Mass X-ray Binaries (LMXBs) or Intermediate Mass X-ray Binaries (IMXBs). In this chapter, we focus on the first two classes. HMXBs and LMXBs can both have either a neutron star or black hole as the primary. X-ray binaries are some of the brightest sources in the universe, making it possible to observe individual sources in galaxies at large distances, and allows us to compare them to our own population of X-ray binaries. They also allow us to study more complicated stellar evolution and accretion physics.

In this thesis, I will discuss variability properties of X-ray binaries from a sample of nearby galaxies observed with the Chandra X-ray Observatory.
Chapter 1 provides an overview of X-ray binaries, including ultraluminous X-ray sources. Chapter 2 outlines the methods used for this study. Chapter 3 highlights some broad results as well as individual X-ray binaries. Chapter 4 provides a discussion of the work and future work.

1.1 X-Ray Binaries

1.1.1 X-ray Emission

The emission of X-rays occurs in and around the compact object’s accretion disk. Material is provided for the accretion either via Roche Lobe overflow or by stellar winds. The material has excess angular momentum and can’t accrete directly onto the compact object, instead forming a disk around it with the material in Keplerian orbits. Viscous interactions in the disk cause material to lose angular momentum and move inwards, getting hotter as it gets closer to the inner part of the disk. The innermost stable circular orbit (ISCO) occurs at around $3 R_s$ ($R_s = \frac{2GM}{c^2}$) for a Schwarzschild black hole (Shakura & Sunyaev 1973) (McClintock & Remillard 2006). The temperature in the hottest parts of the disk are high enough to emit X-rays. The disk is geometrically thin but optically thick. X-ray emission can also arise from a non-thermal corona, or from synchroton emission from jets.
1.1.2 HMXBs

In HMXBs, the secondary star has a mass $\geq 10\,M_{\odot}$—like O stars or B-emission (Be) stars. Massive stars have stellar winds that eject material that can be accreted by the compact object. Mass loss by winds can reach $\sim 10^{-6}\,M_{\odot}\,yr^{-1}$ (Tauris & van den Heuvel 2006).

Stars stay on the main sequence for $\sim 10^{10}\left(\frac{M}{M_{\odot}}\right)^{-2.5}$, so more massive stars have shorter lifetimes. HMXBs reside in spiral galaxies, where there are young stars from recent star formation. In the Milky Way, HMXBs are in the galactic plane. HMXBs are good tracers of recent star formation. The luminosity and the number of HMXBs in a galaxy is related to the star formation rate (SFR). The luminosity for the HMXBs in a galaxy combined is given by (Mineo et al. 2012) for the energy range 0.5 - 8 keV

$$L_{\text{XRB}} \text{ (ergs s}^{-1}) = 2.61 \times 10^{39} \text{ SFR (}M_{\odot}\,\text{yr}^{-1})$$

And the number of bright HMXBs ($L_x > 10^{38}$ ergs s$^{-1}$) is given by

$$N_{\text{XRB}} = 3.22 \times \text{SFR (}M_{\odot}\,\text{yr}^{-1})$$

Knowing how many HMXBs there are with respect to the SFR can tell us the fraction of objects that had an active accretion phase in a binary (Mineo et al. 2012).
1.1.3 LMXBs

For LMXBs, the secondary is a low mass star ( \( M \leq 1.5 \, M_\odot \) ) such as a red giant. Since the secondary star is not massive enough to have stellar winds, accretion occurs via Roche Lobe overflow. As the star expands, it reaches its Roche limit – the radius at which material is still gravitationally bound to the star – and material is free to be accreted by the compact object. Accretion rates are around \( 10^{-10} \) to \( 10^{-8} \, M_\odot \, \text{yr}^{-1} \) (Tauris & van den Heuvel 2006).

Elliptical galaxies contain only LMXBs, as there is no active star formation to give rise to high mass stars. LMXBs also reside in spiral galaxies. In our galaxy, LMXBs are located in the bulge and globular clusters.

Unlike HMXBs, the number of LMXBs is not proportional to the SFR, but rather it’s proportional to the total stellar mass in the galaxy. The number of LMXBs with \( L_x > 10^{37} \, \text{ergs s}^{-1} \) is \( \sim 143 \) sources per \( 10^{11} \, M_\odot \). The combined luminosity of LMXBs ( \( L_x > 10^{37} \, \text{ergs s}^{-1} \) ) is \( \sim 8 \times 10^{39} \, \text{ergs s}^{-1} \) per \( 10^{11} \, M_\odot \) (Gilfanov et al. 2004).

1.2 Black Hole Spectral States

Black hole X-ray binaries (BHB) appear to have five different spectral states, with varying intensity and dominated by either thermal or non-thermal emission. The five states are: 1) Quiescent state, 2) Low/Hard (LH), 3) Intermediate 4) High/Soft (HS) and 5) Very High (VH) (McClintock & Remillard 2006).
Quiescent State

The quiescent state of a BHB has faint emission that can be fit as a power law. Since this is the faintest state, the companion star is more easily observed and a dynamical mass estimate of the back hole can be obtained using radial velocity. A mass estimate of the primary would serve to distinguish a black hole from a neutron star; however, sources in other galaxies that are in this state are outside the detection limits of Chandra.

Low/Hard State

The LH state is a low intensity, high energy state. Hard refers to higher energy X-rays, the low intensity is due to a lower accretion rate. During the LH state, the BHB has lower mass-accretion rates and the spectrum looks like a power law with $\Gamma \sim 1.7$. For a power law with slope $\alpha$, $\Gamma = \alpha + 1$. During the LH and Quiescent states, emission is non-thermal. During these low accretion state, the geometrically thin disk is truncated outside of the ISCO.

High/Soft State

The HS state is a high intensity, lower photon energy (soft) state. The emission during this state is thermal and the disk extends down to the ISCO. Emission in this state peaks in the Chandra energy band, making it the easiest state to distinguish in binaries.
Figure 1.1: Accretion rate during the five different spectral states in BHBs. Accretion rate goes from low in the quiescent state to high in the very high state. Taken from (McClintock & Remillard 2006)
Transitional State

Sources that are in transition between the LH and the HS states have a spectrum that is variable. This is a state that is difficult to define in parameter space without variability.

1.3 QPOs

BHB show quasi-periodic oscillations (QPOs) in power density spectra (PDS). QPOs appear on periodograms as narrow peaks and their frequency is related to Keplerian orbits in the accretion disk (Franchini et al. 2016)(Pasham et al. 2014). QPOs range from low frequencies mHz - 30Hz (LFQPOs) to higher frequencies 100-450 Hz (HFQPOs).

LFQPOs can be divided into three types depending on the shape and strength of the peak: type-A (weak and broad peak), type-B (strong and narrow peak) and type-C (strong, narrow and variable) (Belloni & Motta 2016). Type-C QPOs are particularly useful since they can be found during any of the spectral states. The left side of figure 1.2 shows examples of the 3 types for black hole LMXBs.

Ultraluminous X-ray sources (ULX) (section 1.5) also exhibit QPOs. One interesting source is the ULX M82 X-1, a possible intermediate mass black hole with mass estimates ranging from 200-800 $M_\odot$. (Pasham et al. 2014) further constrained the mass of the IMBH using QPOs in a 3:2 ratio. They found two QPOs in the frequencies $\sim 3.32$ Hz and $\sim 5.07$ Hz. For stellar mass black holes, the frequency of HFQPOs in a 3:2 ratio scales inversely with mass. They extrapolated
this relationship to an intermediate mass black hole and obtained a mass estimate of $428 \pm 105 \, M_\odot$.

M74 X-1 is another ULX with evidence of QPOs. M74-X1 has luminosities ranging from $5 \times 10^{38}$ to $1.2 \times 10^{40}$ ergs s$^{-1}$. The source is extremely variable in timescales of kiloseconds and exhibits strong flaring. (Krauss et al. 2005) found, for a single observation, very low frequency peaks in a PDS. Period folding of three different observations for the source revealed several broad peaks. M74 X-1 is likely a HMXB.

Some QPOs appear only in neutron star LMXBs but not in black hole LMXBs. One case is a QPO occurring in mHz frequencies, possibly arising from nuclear
burning of hydrogen on the neutron star’s surface (Motta et al. 2017).

1.4 Differences between BH and NS Binaries

The X-ray properties of binaries arise from an accretion disk that is similar in both black holes and neutron stars with small magnetic fields. This causes some neutron stars to exhibit the same characteristics typically used to identify black holes in binaries (McClintock & Remillard 2006).

A way to distinguish between a black hole and a neutron star comes from the lack of surface of the black hole. Due to the lack of a physical surface, material can’t reach the surface of the black hole and produce type I bursts. Type I bursts are common in neutron stars and occur when hydrogen hits the surface of the neutron star and is converted to helium. As helium accumulates on the surface, it eventually leads to a burst visible in X-rays.

Neutron stars in low mass binaries show pulsations powered by accretion. The neutron star gains angular momentum as material accretes, this causes the star to spin up. As the star spins up, its magnetic poles start to align with its spin poles and the accretion onto them produces pulsations that are weak. A star that is spinning down instead produces strong pulses (Boutloukos et al. 2011). Black holes can’t maintain a magnetic field and therefore don’t show periodic pulsations (McClintock & Remillard 2006).
1.5 Ultraluminous X-ray Sources

Ultraluminous X-ray sources (ULX) are bright sources that reside outside of the galactic nucleus and have luminosities that exceed the Eddington Limit for a 10 $M_\odot$ star. The Eddington Limit is the maximum luminosity a star of a given mass can have before radiation pressure exceeds gravity and material gets blown away. For a mass $M$, the limit is given by

$$L_{\text{Edd}} \approx 1.38 \times 10^{38} \frac{M}{M_\odot} \text{ ergs s}^{-1}$$

ULX have a range of luminosities from $10^{40}$ to $10^{42}$ ergs s$^{-1}$. To obtain such high luminosities, a stellar mass black hole would have to accrete at a super-Eddington rate, or have beaming effects. Another option is that some ULX might be intermediate mass black holes ($>100$ $M_\odot$). Or, as is the case for M82 X-2 (section 1.5.2), the compact object might be a pulsating neutron star. The mechanisms by which M82 X-2 and other ULX pulsars produce such high luminosities is not known. The existence of ULX with a relatively low mass compact object (neutron star) tells us that X-ray luminosity alone can’t be used to estimate the mass of the compact object.

ULX show similar properties to the spectra of BHB, which have variable X-ray emission. ULX have been observed in the HS and the LH state. The first ULX to show states similar to those of BHB was ESO 243-49 HLX-1 (Webb et al. 2014) – a possible intermediate mass black hole. HLX refers to hyperluminous x-ray source. It has luminosities ranging from $1.9 \times 10^{40}$ to $1.3 \times 10^{41}$. The LH state for HLX-1 has accompanying radio flares.
1.5.1 ULX Accretion

Sub-Eddington emission for ULX requires black hole masses of at least $100 \, M_{\odot}$. For a black hole of that mass to be in a binary system, the progenitor mass would be much greater than $100 \, M_{\odot}$. Since stars of such high mass are less common, binaries in which the primary is a neutron star or stellar mass black hole are more likely (King et al. 2001). Stars with masses greater than $120 \, M_{\odot}$ are less common since the star’s radiation pressure is high enough to blow itself apart.

Intermediate mass black holes (IMBH), are thought to be the missing link between stellar mass black holes and the supermassive black holes found at the center of galaxies. ULX could be a way to find IMBH. As discussed earlier in the chapter, M82 X-1 is an IMBH candidate with a black hole mass estimate of $\sim 428 \, M_{\odot}$ (Pasham et al. 2014).

The Eddington limit assumes emission is isotropic. If emission is not spherical and instead has a preferred direction, that could lead to an overestimate of the total luminosity. A beaming factor $b$ is defined by (King et al. 2001) as $b = \frac{\Omega}{4\pi}$, where $\Omega$ is the solid angle of the emission. Therefore the beaming factor has values below 1. The beaming factor can turn an observed luminosity $L_{\text{sph}}$ (assumed to be spherical) into a smaller luminosity $L$ and allow for masses below those of IMBH.

$$L = b L_{\text{sph}}$$

A beaming factor of 0.01-0.1 leads to black hole masses similar to those for binaries in the galaxy (King et al. 2001). Mild beaming can’t account for all cases of super-Eddington luminosities and more extreme beaming is not favored.
Eddington luminosities are possible in a thin accretion disk due to the photon-bubble instability (Begelman 2002). Photon-bubble is a type of runaway instability. In regions smaller than the gas scale-height, areas with low density and high radiation pressure lose material at a faster rate than higher density areas. This makes the already low density area decrease in density, and therefore easier to be blown away by radiation pressure. The instability leads to an inhomogeneous disk and allows radiation to leave the disk at high rates. The radiation can exceed the Eddington limit without changing the geometry of the disk (Begelman 2002).

1.5.2 M82 X-2

M82 X-2 is the second brightest ULX in that galaxy. Observations using NuSTAR revealed that M82 X-2 is an accreting neutron star, rather than a black hole. The observations show a pulse with a period of 1.37 seconds, caused by the rotation of the magnetic field of a neutron star. The spin is changing at a rate of $-2 \times 10^{-10}$ s s$^{-1}$ (spin down). There is also a secondary period of 2.53 days, due to the orbit of the star in the binary system, which is almost circular. The source can reach a luminosity of $L_x = 1.8 \times 10^{40}$ ergs s$^{-1}$ (Bachetti et al. 2014), which exceeds the Eddington limit for a neutron star by a factor of $\sim 90$.

The change in spin and pulsations coming from a binary system all point to the source of the high luminosity to be a neutron star. This means that an unknown fraction of ULX could be accreting neutron stars that have been identified as something else.

Matter from a Keplerian accretion disk falls onto the neutron star following the path of its magnetic field. The strength of the magnetic field can then be im-
important to achieve such high luminosities. With high enough magnetic fields \((\mathbf{B} \sim 4 \times 10^{13} \text{ G})\), opacity effects allow for higher luminosities (Bachetti et al. 2014)(Karino & Miller 2016). The range of magnetic fields could be from \(10^{11} \text{ G}\) up to magnetar level magnetic fields (\(\mathbf{B} \sim 10^{15}\)).

Due to the high luminosity it is unclear how the pulsar is powered. Bachetti et al. 2014 suggested Roche limit overflow from the primary as a possible accreting mechanism. Other possible mechanisms include spherical or disk winds.

Assuming that accretion occurs at a corotation radius, the strength of the magnetic field required for a particular \(L_x\) can be given by

\[
B_{\text{NS}} = 4.46 \times 10^{13} \zeta^{\frac{1}{2}} \left( \frac{M_{\text{NS}}}{1.4\, M_\odot} \right)^{5/6} \left( \frac{R_{\text{NS}}}{10^6 \, \text{cm}} \right)^{-3} \left( \frac{\dot{M}}{2 \times 10^{20} \, \text{g s}^{-1}} \right)^{1/2} \left( \frac{P_S}{1.37 \, \text{s}} \right)^{5/6}
\]

Where \(\zeta\) is the ratio between \(v_{\text{accretion}}\) and \(v_{\text{free-fall}}\) and the rate of mass accretion for this system is close to \(3.1 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}\) (Karino & Miller 2016). Typical values for the radius and mass of the neutron star give a magnetic field just high enough where electron opacity is reduced to allow for higher luminosities.

For a magnetic field of this strength, accretion via spherical winds from an OB-type primary can be excluded. However, Roche overflow is a viable option for stars between 5 and 11 \(M_\odot\) (Karino & Miller 2016). The masses have to be lower than the initial mass of the now neutron star, and low enough that a circular orbit is still stable. M82 X-2 exhibits properties similar to that of HMXBs with a Be star as the primary, so disk accretion is also possible.
Chapter 2

Methods

2.1 Data

We used publicly available data taken by the Advanced CCD Imaging Spectrometer (ACIS) instrument on the Chandra X-ray Observatory. Galaxies were selected by their distance from the Milky Way, with a cut-off distance of 15 Mpc. An exception was made for the Large and Small Magellanic clouds, which were not included in the sample. In those two galaxies, it is possible to detect X-ray sources with luminosities not possible to observe in other galaxies.

The data set used for this thesis was compiled and used for Simon Wright’s honor thesis (Wright 2017). While the initial sample of observations was the same for both theses, data were managed separately, except for a subsample of sources described in this section. In particular, we did not investigate whether any of the source in the larger sample are background sources.
Data Extraction

Chandra Source Catalog

For observations already in the Chandra Source Catalog (CSC), Simon provided me with a list of all galaxies observed by Chandra within 15 Mpc. For this dataset, I simply downloaded all available data for each observation. This dataset contains 175 different observations and \(\sim 3000\) individual sources. We will refer to this sample as the CSC sample.

Wavdetect

We also added additional sources to our sample from observations not found in the CSC. Simon used the CIAO data analysis system tool wavdetect. For an observation, wavdetect identifies potential point sources and provides region files and count information for the source. Any sources detected by wavdetect within 10 degrees of the Large Magellanic Cloud were ignored, as well as any source with less than 50 counts. This dataset contains \(\sim 400\) observations with \(\sim 9000\) individual sources. We will refer to this sample as the wavdetect sample.

Ray-tracing

The necessary region files for lightcurve extraction were produced by the ray-tracing tools SAOTrace and MARX. For an individual source, given its position in the sky, SAOTrace models the path each photon takes inside the Chandra telescope. The second tool MARX models the ACIS detector and creates a simulated source at the same position as the detected source. This allows us to fit the point spread function (PSF) of the exact position of the detected source on ACIS. A separate script produced region files based on the PSF. Background regions were
also created, with twice the size of the source region.

\textit{subsample}

A smaller sample of sources was used for some analyses (section 3.1-3.2). This smaller sample of $\sim 6500$ sources, contains only the sources within $D_{25}$ of a galaxy. $D_{25}$ is an elliptical contour, containing 25 magnitudes/arcsec$^2$ of a galaxy. The purpose of this is to get rid of any background sources such as Active Galactic Nuclei (AGN). We will refer to this sample as the subsample.

\section*{Testing for Variability}

To find potentially interesting sources, we tested for variability using the CIAO tool \texttt{glvary}. \texttt{glvary} implements the Gregory-Loredo (G-L) algorithm (section 2.2) and returns a variability index for each source. Variability index has a value ranging from 0 to 10 (table 2.1). \texttt{glvary} also produces a lightcurve that is “probability-weighed”. This lightcurve was not used for any analysis.

For timing analysis, we require at least 100 counts per source; however, fewer counts are allowed to simply detect variability. We ran \texttt{glvary} on all 12000 sources in our sample. Of those sources, 1113 had a variability index $\geq 3$.

For further analyses, from the 1113 sources, we selected those that are at least considered variable (Var. index $\geq 5$) and with at least 100 counts. That left us with 140 sources from the CSC sample, and $\sim 600$ sources from the wavdetect sample.
Table 2.1: Var. Index Diagnostics

<table>
<thead>
<tr>
<th>Var.Index</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Definitely not variable</td>
</tr>
<tr>
<td>1</td>
<td>Considered not variable</td>
</tr>
<tr>
<td>2</td>
<td>Probably not variable</td>
</tr>
<tr>
<td>3</td>
<td>May be variable</td>
</tr>
<tr>
<td>4</td>
<td>Likely to be variable</td>
</tr>
<tr>
<td>5</td>
<td>Considered variable</td>
</tr>
<tr>
<td>≥ 6</td>
<td>Definitely variable</td>
</tr>
</tbody>
</table>

Lightcurve Extraction

Background-subtracted lightcurves for the sources were created using the CIAO tool dmextract. The lightcurves were binned by time using a specified binlength based on the source and background counts and area.

\[
\text{binlength} = \frac{\text{counts per bin}}{\text{total net counts}} \times \text{exposure}
\]

\[
\text{total net counts} = \text{total source counts} - \frac{\text{source area}}{\text{bkg area}} \times \text{bkg counts}
\]

For each source, a lightcurve was produced for the following energy bands 300-8000 eV, 300-1000 eV, 1000-2000 eV, and 2000-8000 eV. The energy bands were based on the ACIS energy bands where Chandra is most sensitive.

Dither

Chandra dithers during each observation. The dithering occurs in a Lissajous pattern spanning 16” and adds some exposure in gaps between CCDs. It also helps prevent pile-up. Pile-ups occur when more than one photon hits the detector in the same place at the same time and two separate events are recorded as a single
event with higher energy. For ACIS, the period for dithering is 1000s for Y and 707s for Z.

Dithering may introduce a periodic signature to the source lightcurve. The CIAO tool \texttt{dither\_region} provides the fractional area covered by the detector over the time of the observation. Sources where the fractional area covered dropped by more than 10 percent were flagged.

\section*{2.2 G-L Algorithm}

\textbf{Description}

For a signal, the G-L method compares models with constant rate to periodic models using Bayes’s theorem (Gregory & Loredo 1992) and gives the probability that flux during the observation is not constant. The result doesn’t depend on the number of periods tested but rather on the range of periods used. It also prefers simpler models for the period.

The \texttt{glvary} implementation of the G-L algorithm is a robust test for variability (Rots 2006) – even for time series with gaps in the data – and is insensitive to the shape of a lightcurve. \texttt{glvary} takes into account the fractional change in area covered during observations and makes note of sources with variability timescales that are related to the dither period. Since the test requires a significant deviation from a constant count rate, it is still appropriate for sources with a low count rate.
2.3 Periodograms

For each source that had a variability index $\geq 5$ we created Lomb-Scargle (L-S) periodograms to attempt to find the timescale of variability, and possibly QPOs. We produced periodograms for each of the three energy bands combined (broadband), as well as individually (soft, medium, hard).

The purpose of the L-S periodogram is to identify potential periods for irregular time series by determining the power of each period. We used the python implementation of the L-S algorithm from gatspy/AstroML (Vanderplas 2015).

Timescale Sensitivity

A lower and upper bound to what periods we are sensitive to can be placed by the nature of the observing process. The lower bound on the periods we can detect is given by the Nyquist rate – two times the Nyquist frequency, the highest sampling rate the signal can have. The frame time for ACIS is $\sim 3.2$ seconds, so we could detect periods as low as $\sim 6.4$ seconds. The upper bound to our sensitivity is the exposure time of the observation. In our sample, all observations were at least 5 kiloseconds long, but this number varies.

Frequency grid

The frequency grid for periods to be probed was determined uniformly accross all sources. While we somewhat arbitrarily decided on an upper limit of 15000 seconds, there are not many Chandra observations with exposure times long enough
that would allow for a period of variability much greater than 15000 seconds. The minimum period probed was set equal to the binning time of the lightcurve, though we are only sensitive to at least twice that. Each frequency grid contained 10000 frequencies.

**Fast vs General Lomb-Scargle**

Gatpsy offers three different implementations of the L-S algorithm, we used two of them depending on the number of bins for each lightcurve: LombScargle and LombScargleFast. LombScargleFast is only appropriate for lightcurves with more than 50 points. The number of operations goes as $O[N\log N]$ for N data points for the Fast algorithm, and it goes as $O[N^2]$ for LombScargle.

**Determining Significance**

We used lomb_scargle_bootstrap, also from the python module AstroML, to determine the significance level for the power of the signal. We determined three significance levels for confidence of 90%, 80% and 70%. Attempts to calculate higher significance did not give good results. While 90% confidence is not a statistically significant result ($\sim 1.64 \sigma$), it’s suggestive of a characteristic timescale of variability.

### 2.4 Sample Bias

Our sample is a volume-limited sample, as we selected all sources in galaxies within 15 Mpc that were observed by Chandra. While our sample is not biased
towards luminosity, it is not completely unbiased. This is due to the smaller number of observations done by Chandra and the exclusion of observations with lower photon count in some cases.

For an estimate of the completeness of our sample, we compared the list of galaxies observed by Chandra to the Updated Nearby Galaxies Catalog (UNGC). The UNGC includes galaxies within 11 Mpc, but in spite of not covering the entire volume of our sample, it was selected over other catalogs such as the NASA/IPAC Extragalactic Database (NED) since it provides more consistent distance indicators and galaxy morphologies.

In that volume, Chandra has observed only a small fraction of dwarf and irregular galaxies, so only spiral and elliptical galaxies were included in the comparison. The list was also reduced to include only observations with exposure time $\geq 5$ kiloseconds, as exposures shorter than make it difficult to resolve point sources other than AGN. We find that within that distance and exposure time, Chandra has only observed $\sim 20\%$ of spirals and $\sim 35\%$ of ellipticals. While our sample is not complete, it covers a large enough fraction of galaxies for our purposes.
Chapter 3

Results

In this chapter, we present results based on the large sample of X-ray binaries and their variability, as well as interpretations of few individual sources of interest.

3.1 Variability and Galaxy Morphology

Figure 3.1 shows a histogram for the number of sources in spirals, ellipticals or other galaxy types that have a certain variability index. While we have variability information for 1113 sources, only the sources included in the subsample (section 2.1) were used for this. We also excluded any sources that are known supernova remnants. This left us with data for 286 sources with variability index in the range 3 to 10, and their respective galaxies.

Figure 3.2 shows the histogram normalized, including only galaxies classified as ellipticals and spirals. Here we see that at very high variability index (Var. Index = 9 or 10), the fraction of sources is greater for spirals than for ellipticals. As
discussed in section 1.1.2, we find HMXBs only in spiral galaxies, while LMXB reside in both ellipticals and spirals. Since spiral galaxies have both HMXB and LMXB, we would expect the LMXBs in spirals to appear in the overlapping region (dark yellow) in figure 3.2. Conversely, we would also expect the excess of highly variable sources in spirals to be mostly HMXBs. HMXBs are typically transient on longer timescales, but we may be seeing very large variability in short-timescales for some of them.

Figure 3.1: Galaxy Morphology vs Variability Index. ‘Other’ refers to galaxies that are classified as anything other than spiral or elliptical.
3.2 Variability and Color

Here, we explore whether the color properties of the variable sources in the subsample differ from the subsample properties as a whole. For each source, the photon counts were split into the three bands previously defined: soft (S), medium (M), and hard (H). From this we obtained a hardness ratio. Hardness ratio (HR) is typically defined as $HR = \frac{A-B}{A+B}$, where A stands for high energy counts and B
stands for low energy counts. For Chandra, two hardness ratios are defined by (Wright 2017):

\[
\text{soft color} = \frac{M - S}{S + M}, \quad \text{hard color} = \frac{H - M}{M + H}
\]

A plot of soft color vs hard color (a color-color diagram) can help characterize our sources, as different populations of X-ray sources fall on different parts of the diagram (Figure 3.3).

Figure 3.4a. shows a color-color diagram for all of the sources from the subsample, with the variable sources (variability index \( \geq 6 \)) highlighted in green. From this we can see two things:

1- For the whole subsample, we see a break between the color of HMXBs and LMXBs (See (Wright 2017) figure 4.9). The break disappears for the variable sources, implying that – for short-timescales – variability is independent of the mass of the donor.

2- We see sources with variability in the region where thermal supernova remnants fall. Thermal supernovas are leftover from core collapse supernovae and are typically found in regions of star formation (Prestwich et al. 2003).
Figure 3.3: Classification scheme for different populations of X-ray sources. Hard-
ness ratios defined as soft color = $\frac{M-S}{S+M+H}$, hard color = $\frac{H-M}{S+M+H}$ (Prestwich et al. 2003)
Figure 3.4: Soft Color vs Hard Color.

(a) Color-Color diagram with variable sources highlighted in green.

(b) Color-Color diagram for sources with $L_x > 10^{38}$ ergs s$^{-1}$. Variable sources highlighted in green.
Figure 3.4b shows the same color-color diagram with only the sources that have $L_x > 1 \times 10^{38} \text{ ergs s}^{-1}$, close to the Eddington limit for $1 \ M_\odot$. The Eddington limit for a $1.44 \ M_\odot$ neutron star (minimum mass for a neutron star) is $\sim 1.80 \times 10^{38} \text{ ergs s}^{-1}$. Placing the lower limit on luminosity should leave us with only the brightest neutron stars or ultraluminous pulsars. The majority of the sources left should be binaries with a black hole primary.

We still see many variable sources in the HMXB region of the diagram. If these are black hole HMXB then they would be in either the very high state, since the luminosity is high, or in a transitional/hard disk state, since they are in a ‘hard’ region. In our galaxy, the X-ray binaries with a black hole primary are all LMXB, except for Cygnus X-1. Since we see mostly the black hole HMXBs in our subsample, the population of X-ray binaries in our own galaxy may be different than those in other galaxies.

We also still see some sources in the thermal supernova remnant region. This is of interest since supernova remnants are not variable on short-timescales. These sources will be flagged for future follow up.

### 3.3 Individual Sources

We visually inspected the lightcurves and periodograms for the 140 variable sources from the CSC sample to try to find interesting behavior. Here, we discuss 8 of those sources, their variability timescale, type of binary, possible nature of the compact object, and galaxy properties. For each source, we found its position in the color-color diagram shown in figure 3.4a. From that we categorized the source as either a HMXB or LMXB if appropriate. We estimated the source’s X-ray
luminosity ($L_x$) using a variety of methods.

Our goal is to have a systematic, automated way of examining a large number of sources. The process of choosing these 8 sources was not systematic, but we see that by just visually selecting a small number of sources we are able to characterize some of the behaviors, and show the capabilities of this type of study.

4736 source 4

Figure 3.5 shows a periodogram and lightcurve for the source in the energy range 300 - 8000 eV. In figure 3.5a we see three different peaks above the 90% significance line at periods: 4784 s, 7002 s, and 9590 s. In the medium energy band (not shown), the peak near 4800s is still prominent, while the other two peaks still appear with reduced power.

Using a power law with $\Gamma = 1.5$ to fit the source’s spectrum, we find $L_x \sim 10^{38}$ ergs s$^{-1}$. The colors of the source place it in the LMXB region of the color-color diagram.

The variability timescale and the source’s high luminosity could suggest that the primary in the LMXB is a black hole in the transitional/intermediate state.

The galaxy associated with the source is M101. This is a spiral galaxy (SAB(rs)cd) at a distance of $\sim 7$ Mpc.
Figure 3.5: Obs Id = 4736, Source 4, Var. Index = 9. a) Periodogram for the source lightcurve in the energy range 300 -8000 eV. Y-axis shows power, X-axis is period. Dashed lines show significance levels of 90%, 80% and 70% b) Lightcurve for the source is shown in black, error bars in red. Binning time of 315 seconds.
2454 source 1

Figure 3.6 shows a periodogram and lightcurve for the source in the energy range 300 - 8000 eV. In figure 3.6a we see a broad peak above the 90 % significance line at 2035 s. The peak is visible in all 3 energy bands, but is only above 90 % significant in the hard band. There is another sharp peak around 220 seconds probably due to the sampling of the lightcurve, which has a binning time of 212 seconds.

We were not able to obtain a luminosity for the source using a spectral fit, but its position on the color-color diagram falls in the range for HMXBs. The broad QPO found at $\sim 2000$ s is consistent with QPOs in other HMXBs.

The source is in the Circinus Galaxy. The galaxy is an early-type spiral galaxy (SA(s)b) with a distance of $\sim 4$ Mpc.
Figure 3.6: Obs Id = 2454, Source 1, Var. Index = 9. a) Periodogram for the source lightcurve in the energy range 300-8000 eV. Y-axis shows power, X-axis is period. Dashed lines show significance levels of 90%, 80% and 70% b) Lightcurve for the source is shown in black, error bars in red. Binning time of 212 seconds.

(a) Possible QPO at 2035 s
source 2

Figure 3.7 shows a periodogram and lightcurve for the source in the energy range 300 - 8000 eV. In figure 3.7a there is a very broad peak around 11000 seconds. Unlike the broad peak in figure 3.6a, the shape of this peak is not consistent with the shape of a QPO. A period of $\sim 3$ hours shows variability on a longer timescale.

The source has soft colors and $L_x \approx 2 \times 10^{38}$ ergs s$^{-1}$. It is likely that the binary has a black hole primary in the high/soft state.

The source is in M81. This is a spiral galaxy (SA(s)ab) at a distance of $\sim 4$ Mpc.
Figure 3.7: Obs Id = 735, Source 2, Var. Index = 7. a) Periodogram for the source lightcurve in the energy range 300 - 8000 eV. Y-axis shows power, X-axis is period. Dashed lines show significance levels of 90%, 80% and 70% b) Lightcurve for the source is shown in black, error bars in red. Binning time of 224 seconds.
**1586 source 1**

Figure 3.7 shows a periodogram and lightcurve for the source in the energy range 300 - 8000 eV. In figure 3.8a shows a broad peak that occurs at 8569 seconds. The lightcurve for this source (figure 3.8b) clearly shows a large flare in all energy bands.

Calculating the luminosity without accounting for the flare gives $L_x = 6 \times 10^{38}$ ergs $s^{-1}$, but the luminosity of flare itself is on the order of $10^{39}$ ergs $s^{-1}$. Assuming constant luminosity would lead to an overestimate and affect the possible mass of the object.

The photon count is not large enough to determine if the flare is a type I X-ray burst or a disk flare. A type I flare could mean the primary is a neutron star (section 1.4). The source falls in the LMXB part of the color-color diagram and the flaring is consistent with the behavior of LMXBs. Follow up observations would be necessary to determine the nature of the compact object.

The source is in M104, an edge-on spiral galaxy at a distance of $\sim 11$ Mpc.
Figure 3.8: Obs Id = 1586, Source 1, Var. Index = 9. a) Periodogram for the source lightcurve in the energy range 300 -8000 eV. Y-axis shows power, X-axis is period. Dashed lines show significance levels of 90%, 80%, and 70%. b) Lightcurve for the source is shown in black, error bars in red. Binning time of 431 seconds.

(a)

(b) Lightcurve shows a large flare at x seconds
2197 source 1

Figure 3.9 shows a periodogram and lightcurve for the source in the energy range 300 - 8000 eV. In figure 3.9a there is a broad peak above the 90% significance line at around 10200 seconds. There lightcurve (3.9b) shows three clear bumps separated by $\sim 10000$ seconds; the bumps are visible at medium and hard bands as well. Variability timescale of $\sim 3$ hours.

The spectrum of the source can be fit with a power law with $\Gamma \sim 2$, and gives $L_x = 1.6 \times 10^{38}$ ergs. The source falls in the LMXB part of the color-color diagram.

The source is in M63, a spiral galaxy (SA(rs)bc) $\sim 8$ Mpc away.
Figure 3.9: Obs Id = 2197, Source 1, Var. Index = 7. a) Periodogram for the source lightcurve in the energy range 300 - 8000 eV. Y-axis shows power, X-axis is period. Dashed lines show significance levels of 90%, 80% and 70%. b) Lightcurve for the source is shown in black, error bars in red. Binning time of 688 seconds.

(b) Lightcurve shows three clear bumps at 10000, 20000 and 30000 seconds.
Sources in M33

A number of the interesting sources were in the galaxy M33. It is a spiral galaxy (SA(s)cd) less than 1 Mpc away.

6376 source 2

Figure 3.10 shows a periodogram and lightcurve for the source in the energy range 300 - 8000 eV. In figure 3.10a there is a strong narrow-period around 1100. It does not appear in the other bands, but there’s another narrow peak in the soft band (not shown) around 1450 seconds. Since the peak is narrow it could be actually periodic and could be arising from disk activity.

The source falls on the HMXB part of the color-color diagram. We were unable to fit the spectrum to get a luminosity. Using the color and count rate information for the source, we estimated $L_x \sim 3 \times 10^{36}$ ergs s$^{-1}$ using the tool PIMMS. A low luminosity implies a low accretion rate.
Figure 3.10: Obs Id = 6376, Source 2, Var. Index = 8. a) Periodogram for the source lightcurve in the energy range 300-8000 eV. Y-axis shows power, X-axis is period. Dashed lines show significance levels of 90%, 80% and 70% b) Lightcurve for the source is shown in black, error bars in red. Binning time of 142 seconds.
Figure 3.11 shows a periodogram and lightcurve for the source in the energy range 300 - 8000 eV. In figure 3.11a there is a strong narrow peak at around 706 s. The peak is present in all energy bands. This is close to one of the dither periods of Chandra, but there was no change in the fractional area covered for this source during the observation.

The source colors are very soft and it has an estimated $L_x \sim 3 \times 10^{37}$ ergs s$^{-1}$. Given the short timescale variability and soft colors, the source could be a cataclysmic variable. Cataclysmic variables are binary systems where the primary is an accreting white dwarf.
Figure 3.11: Obs Id = 6383, Source 1, Var. Index = 9. a) Periodogram for the source lightcurve in the energy range 300 - 8000 eV. Y-axis shows power, X-axis is period. Dashed lines show significance levels of 90%, 80% and 70% b) Lightcurve for the source is shown in black, error bars in red. Binning time of 14 seconds.
7197 source 1

Figure 3.12 shows a periodogram and lightcurve for the source in the energy range 300 - 8000 eV. In figure 3.12a there is a possible period of 705 seconds that appears in medium and hard bands as well. There is a smaller peak at 354 that only appears in 300-8000 eV. The fractional area for this source also did not change.

The source falls on the HMXB part of the color-color plot and has $L_x \sim 4 \times 10^{38}$. The high luminosity would require a very high accretion rate for a neutron star primary. The timescale of variability is also similar to that of black holes, so the source could have a black hole primary that has a low accretion rate.
Figure 3.12: Obs Id = 7197, Source 1, Var. Index = 6. a) Periodogram for the source lightcurve in the energy range 300 - 8000 eV. Y-axis shows power, X-axis is period. Dashed lines show significance levels of 90%, 80%, and 70%. b) Lightcurve for the source is shown in black, error bars in red. Binning time of 92 seconds.
Chapter 4

Discussion and Future Work

4.1 Optimizing the Study

We did not inspect the ~ 600 variable sources from the wavdetect sample. There were over 2000 periodograms for this subset of sources, for a single binning time per source. More careful studies would require probing the lightcurves for the source with different binning times, and possibly different frequency grids as well. With such a large dataset, it would become difficult to visually inspect every plot.

Our method for determining bintime (section 2.1) was chosen to try to maintain a minimum number of 15 counts in each bin. While this method worked for the majority of sources, a few of the sources had a calculated binning time that was negative and therefore not usable. Other lightcurves had binning times that were long enough to put them outside of our sensitivity. Early testing on a known ULX showed that the detection of QPOs is sensitive to the chosen bintime. Glvary may give another option for a binning time since it optimizes one for its variability.
test.

For lower counts, we could also get rid of the minimum 15 counts per bin requirement, but we would no longer be able to use any $\chi^2$ analysis and use something other than a Lomb Scargle periodogram, such as Monte Carlo power density spectral analysis.

The frequency grid that was used for the LombScargle model was also uniformly determined with 10000 frequencies, which may not be appropriate for every source. We also included frequencies as high as 1 over the binning time, though we are not sensitive to such frequencies. Starting with a period of at least twice the binning time may cut down on some computation time for a large number of sources, though most of the computing cost comes from determining significance levels.

*Dealing with Background*

An issue that arises from automating the search for periodic signals is that it may confuse changes in the background with an actual variability signal. If two different objects in the same observation have identical periodograms, if this is due to flaring in the background, an algorithm that simply flags any period peak that goes above a certain significance level would falsely select objects for further study.

*Automating other info*

It will also be necessary to implement a systematic way of determining properties for the large number of sources, as well as galaxy information. We were able to determine some things about the nature of the 8 sources individually, but this would become cumbersome for the larger sample. It would be relatively easy to automate properties resulting from the color-color diagram.
4.2 Using Chandra Archival Data

*Duty cycle*

In the Chandra Archive, there are multiple observations of the same galaxies. Each galaxy could have hundreds of X-ray sources. Finding objects in the archive that have been observed at different times and exhibit different variability could tell us something not just about the short-timescale variability but also about the changes in state of the source in longer term. This would be useful to study the duty cycle of X-ray binaries. At least for HMXBs, the number of bright sources is related to the star formation rate. Understanding the duty cycle of binaries could tell us the fraction of bright sources in the galaxy at any time and could also tell us about the star formation in the galaxy.

*Follow Up Observations*

From just the 8 individual sources that were arbitrarily selected, at least 1 of them would benefit from a follow-up observation. The source from obs id 1586 shows flaring behavior that could be indicative of a neutron star. With our luminosity estimates, the source is not bright enough to be an ULX, it could still be quite bright for a neutron star. Studying the behavior of any neutron star X-ray binary with luminosity close to the Eddington limit would help us better understand the nature of pulsar ULXs, something that is not well understood.

Closer study of other sources in the sample is likely to produce other objects in need of follow-up observations. Determining the timescale of variability and spectral states of the binaries in the sample would help define the parameters used for observations with the purpose of population synthesis.
Future X-ray telescopes currently being planned will have different sensitivities and strengths, but none of them will provide the same kind of spatial resolution as Chandra. The Lynx X-ray Surveyor mission will have high angular resolution, while the Athena X-ray observatory will have larger coverage of higher energy X-rays and high resolution spectroscopy. Studies that make use of the Chandra archival data are important as they help determine what observations to propose that make use of the unique capabilities of the Chandra observatory while it is still available.
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