

**THE FIRST COHERENT CENSUS OF OPTICAL VARIABILITY IN X-RAY
BINARIES WITH GEMINI**

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Bachelor of Science, George Mason University, 2023

A thesis submitted
in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in

PHYSICS

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LETHBRIDGE, ALBERTA, CANADA

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Dedication

To beloved family, to dearest friends, and to all the amazing people I've met along the way.

Abstract

X-ray binary systems (XRBs) consist of a compact object, such as a black hole or neutron star, that accretes matter from its companion star, ejecting a portion of the accreted matter into relativistic jets. It has been shown that time-domain observations, measuring how observed emission changes over time, can be used to address key open questions in compact object research. In particular, pairing time-domain methods with multi-wavelength observations probing different regions within an XRB, can provide further insight into the accretion and jet launching mechanisms of these systems. To this end, the Gemini Optical FAST timing of X-Ray Binaries (*GOFAST-XRB*) project is a Gemini Large and Long Program that aims to track matter as it propagates from inflow (probed by X-ray light) to outflow (probed by optical light), and characterize how this depends on the nature of different compact objects. This program uses observations in the optical and X-ray wavelengths from Gemini's *Alopeke* and *Zorro* instruments and several X-ray telescopes, such as the Neutron star Interior Composition Explorer (NICER), Hard X-ray Modulation Telescope (HXMT), and Einstein Probe (EP). In this thesis, I develop the foundational optical data processing pipeline for the *GOFAST-XRB* program. This pipeline extracts the intensity of the sampled XRBs on rapid sub-second timescales (known as lightcurves) from the raw Gemini telescope data, and quantifies how these measurements vary over different timescales. My work represents a novel use for the Gemini *Alopeke* and *Zorro* instruments, directly enabling a new observation and data analysis mode; rapid time-series observations. In the future, my pipeline can be incorporated in the Gemini observatory software packages and made available for use by the broader astronomical community.

Acknowledgments

I would like to thank my supervisor, Dr. Alexandra Tetarenko, and my colleagues in the LUX research group for all their guidance and support throughout my studies and for giving me such a memorable and enjoyable time in Lethbridge. I would like to thank my family and friends for always supporting me no matter what and for being there every step of the way, no matter the distance that separates us.

I acknowledge that the University of Lethbridge is located on Blackfoot Confederacy traditional territory. As a visitor to this land, I deeply appreciate and honor the Blackfoot people, who have known and cared for this land since time immemorial. Their traditional knowledge has deepened my understanding and appreciation of the land, the Blackfoot people, and their story. They have inspired me to be more knowledgeable and conscientious of the land and the First Nations, Inuit, and Metis that inhabit and care for it, a practice that I will continue into the future.

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List of Abbreviations

BH Black Hole

BH XRB Black Hole X-ray Binary

CCD Charge Coupled Device

EP Einstein Probe

FB Flaring Branch

FBO Flaring Branch Oscillation

FITS Flexible Image Transport System

FOV Field of View

FWHM Full Width Half Maximum

GOFAST-XRB Gemini Optical FAST Timing of X-ray Binaries

GTI Good Time Interval

HB Horizontal Branch

HBO Horizontal Branch Oscillation

HID Hardness Intensity Diagram

HFQPO High Frequency Quasi-Periodic Oscillation

HMXB High Mass X-ray Binary

HRCam High Resolution Telescope

HXMT Hard X-ray Modulation Telescope

LFQPO Low Frequency Quasi-Periodic Oscillation

LMXB Low Mass X-ray Binary

MAXI Monitor of All sky X-ray Image

NB Normal Branch

NB Normal Branch Oscillation

NICER Neutron star Interior Composition Explorer

NS Neutron Star

NS XRB Neutron Star X-ray Binary

PanSTARRS Panoramic Survey Telescope & Rapid Response System

PDS Power Density Spectrum

QPO Quasi Periodic Oscillation

rms Root Mean Square

RXTE Rossi X-ray Timing Explorer

SOAR Southern Astrophysical Research Telescope

VLT Very Large Telescope

WCS World Coordinate System

XRB X-ray Binary

Chapter 1

Introduction

1.1 A Brief History of Stellar Remnants: Black Holes, Neutron Stars, and White Dwarfs

Black holes and neutron stars are among the strangest objects in the universe, and as such, they can serve as laboratories for the physics of the extreme, hosting environments that can not be replicated on Earth. The beginnings of what are today known as black holes trace back to 1784 when John Michell first suggested that there could be objects with a high enough mass that light could not escape their gravitational field [1]. In 1915, Albert Einstein formulated his theory of General Relativity, describing how mass can bend space, the origin of gravity, and how interactions between massive objects can generate gravitational waves that ripple through spacetime [1]. Karl Schwarzschild furthered this line of thinking, conceptualizing the singularity, a point-like object with infinite mass [1]. Such an object would generate a gravitational field so strong that not even light can escape its pull.

The abstract idea of such an extreme object as a singularity became much more concrete through the study of the most common and familiar objects in the universe; stars. Comprised primarily of hydrogen, stars are powered by nuclear fusion in their cores and produce an immense amount of energy in the form of emitted radiation. The mass of a star determines its evolutionary path and its lifetime, with more massive stars being short-lived compared to less massive stars (such as the Sun). A star's mass also determines what type of object it will leave behind once its lifespan is over; stellar remnants include white dwarfs,

neutron stars, and black holes [1]. In 1931, Subrahmanyan Chandrasekhar proposed a limit, now known as the Chandrasekhar limit, to the mass of a stable white dwarf above which it collapses further under its own weight into a neutron star or black hole [1]. Sir Roger Penrose determined a numerical value for the Chandrasekhar limit in 1965, finding that white dwarfs with masses of approximately 1.4 times that of the Sun could undergo further gravitational collapse to form a neutron star or a black hole. This in turn showed that “completely collapsed gravitational objects” could theoretically exist, as they were called until John Wheeler coined the term “black hole” in 1967 [1].

White dwarfs are the most common stellar remnant, as they represent the final evolutionary stage of stars with masses below $10 M_{\odot}$, which form over 90% of the stellar population [2]. The energy released by stars through hydrogen fusion counterbalances the gravity of the star, preventing it from collapsing. Once the star’s hydrogen stores are depleted, helium fusion begins, producing carbon and oxygen nuclei. At this point, nuclear fusion halts and without the resulting energy to counterbalance gravity the star begins to collapse under its own weight until another source of internal pressure stops the process (electron-degeneracy pressure; [2]). According to the Pauli exclusion principle, two electrons cannot occupy the same state. Therefore, if they are confined closely enough, they will exert pressure, known as electron-degeneracy pressure, as they repel each other via the Coulomb force. The result is an electron-degenerate core enveloped in hydrogen and helium, known as a white dwarf [2].

More massive stars leave behind neutron stars at the end of their lifetimes [3]. Neutron stars were first conceptualized by Baade and Zwicky in 1934, just two years after the discovery of the neutron by Chadwick [3]. Baade and Zwicky noted that a massive object made up mostly of neutrons would be strongly gravitationally bound, more so than normal stars, and that they could be formed in supernovae, large explosions that occur at the end of massive stars’ lifetimes [3]. However, since neutron stars would be too small and too faint to detect, they did not become relevant again until 1967 when Bell and Hewish discovered

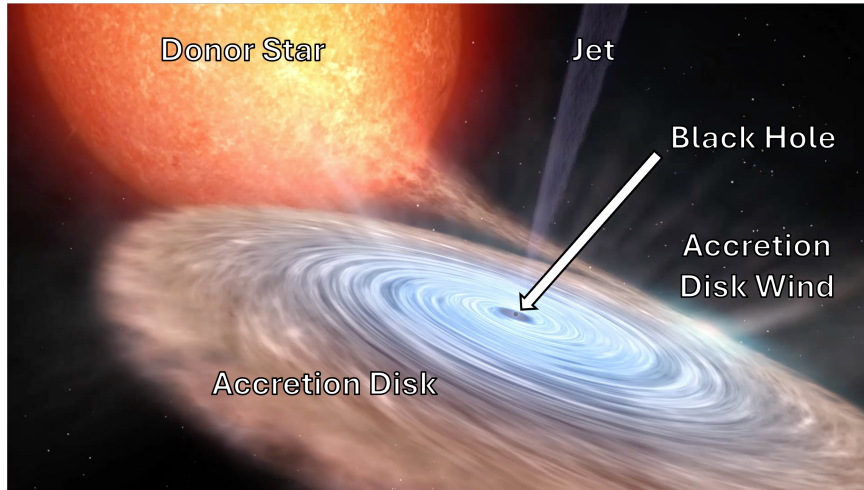


Figure 1.1: A schematic of an X-ray binary. Here a compact object (a black hole in this case) is accreting mass from the companion object (a donor star). The accreted material forms an accretion disk around the black hole, which ejects a portion of the in-falling matter as relativistic jets from its poles or as a wide-angle accretion disk wind. Adapted from [6].

the first pulsar, PSR B1919+211. Gold subsequently proposed that this pulsar, a celestial object that emitted pulses of light with an extremely precise period, could be adequately explained by a rapidly rotating neutron star with a strong magnetic field [3].

1.2 X-Ray Binary Systems

An X-ray binary system (XRB) consists of a stellar-mass compact object, such as a black hole (BH) or a neutron star (NS), and a donor star from which the compact object accretes mass, emitting X-rays in the process. The angular momentum of the system causes the accreting matter from the companion star to form a differentially rotating disk around the compact object, rather than flowing directly onto the compact object [4]. A portion of the accreting matter may be ejected from the system as relativistic plasma jets or an accretion disk wind [5]. A schematic of an XRB is shown in Figure 1.1.

1.2.1 Mass Accretion and Ejection

XRBs can be categorized not only by their compact objects, either black holes (BH XRBs) or neutron stars (NS XRBs), but also by the masses of their companion stars and

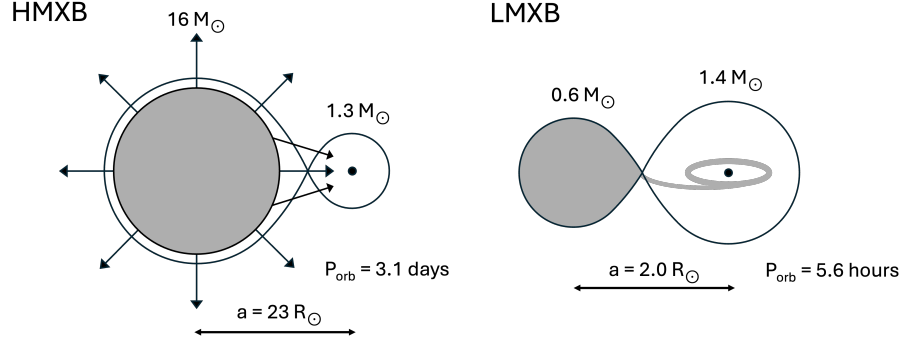


Figure 1.2: The different accretion mechanisms of HMXBs and LMXBs. Here the companion star is shown on the left and the compact object is shown on the right in both panels, while the Roche lobes are illustrated by a solid black line. *Left:* The $16 M_{\odot}$ companion star emits a stellar wind that is depicted as arrows radiating outward from the star and directed toward the $1.3 M_{\odot}$ compact object. *Right:* The $0.6 M_{\odot}$ companion star fills its Roche lobe. In this case, the overflowing matter crosses into the Roche lobe of the $1.4 M_{\odot}$ compact object where it forms an accretion disk. Adapted from schematics originally produced in [11].

their level of activity. Low mass X-ray binaries (LMXBs) are those whose companion stars have a mass typically $\lesssim 1 M_{\odot}$ [7]. On the other hand, high mass X-ray binaries (HMXBs) have companion stars whose masses are $\gtrsim 10 M_{\odot}$ [8]. LMXBs and HMXBs also differ in how they accrete matter from their donor stars. LMXBs accrete mass primarily via Roche lobe overflow, where the gravitational pull of the compact object pulls on and distorts the companion star past its Roche lobe (the limit within which matter is gravitationally bound to the star). On the other hand, high mass stars typically lose mass via a continuous outflow of matter from their surfaces, a process known as stellar wind [9]. Therefore, HMXBs will accrete mass when the compact object captures this stellar wind from its companion [10]. Figure 1.2 illustrates the different accretion mechanisms of HMXBs and LMXBs.

In both cases, a portion of the accreted matter is ejected via collimated, relativistic jets and wide-angle accretion disk winds. The collimated jets are launched due to the action of magnetic fields. In particular, prevailing theories posit that the accretion disk has a magnetic field whose vertically-extending component can accelerate matter up to ultra-relativistic speeds (near the speed of light) along the poles of the compact object, ultimately leading to a collimated jet outflow [12]. Accretion disk winds occur as the accretion rate

nears the Eddington limit, the luminosity (or power output) at which the outward pressure exerted by radiation is balanced by the inward pressure of gravity [13]. As the accretion rate approaches the Eddington limit, the radiation pressure overcomes the force of gravity and some of the accreting matter is ejected as a wide-angle wind outflow [13]. These winds are slower than the jets, but can carry significantly more mass from the accretion disk [13].

1.2.2 Emission Mechanisms

Several different emission processes operate in XRB systems, which are outlined below. Figure 1.3 focuses on the X-ray wavelength portion of the emission spectrum and Figure 1.4 shows the entire emission spectrum of the BH LMXB XTE J1118+480, representing an example of how the different emission processes produce light at different wavelengths (from low energy radio light to high energy X-rays).

Thermal Accretion Disk Emission

As accreting matter is transferred from the companion star to the compact object, the gravitational potential energy of the matter is released [14]. Some of this energy is converted into rotational kinetic energy, while the rest is converted into thermal energy that is radiated from the accretion disk (mainly in the form of ultraviolet and X-rays; [14]). The resulting spectral emission profile is characterized by a multi-temperature, thermal blackbody, that is produced by the temperature gradient within the disk; $T(r) \propto r^{-3/4}$, where r represents the disc radii (see Figure 1.3; [12]). Due to the heavy dependence of blackbody emission intensity on temperature (as described by the Stefan-Boltzmann Law), the hotter, inner regions of the accretion disk dominate the thermal emission of the XRB compared to the cooler, outer regions.

Inverse Comptonized Emission

Compton scattering is a specific interaction between radiation and charged particles, usually electrons. An incident photon with a wavelength, λ , transfers energy to a charged

particle upon collision, resulting in the particle recoiling and a photon with a longer wavelength, λ' , being emitted. Inverse Compton scattering is the opposite process; a high energy, relativistic electron transfers energy to a photon, resulting in a photon with a higher energy and shorter wavelength than before [15]. Inverse Comptonization constitutes part of the X-ray emission spectra of XRBs. Around the compact object exists a cloud of hot plasma usually referred to as the corona [16]. The corona is the source of the inverse Comptonized emission, as it scatters the lower energy X-ray photons that originate from the thermal accretion disk. The resulting spectral emission profile of this inverse Compton process takes the form of a power-law across the X-ray wavelengths, typically dominating the emission at higher energies (shorter wavelengths) when compared to the thermal accretion disk emission (see Figure 1.3; [17]).

Reflected Emission

Coronal emission can be reprocessed by reflecting off of the accretion disk. The main spectral features of this reflected emission is the presence of the iron K line around 6–8 keV and the “Compton hump” above 10 keV (named for its origin from the Compton scattering of higher energy photons by relatively cooler gas in the accretion disk, see Figure 1.3; [18]).

Jet Synchrotron Emission

Magnetic fields are the main driver of relativistic jet outflows of XRBs and may be intrinsic to the compact object or arise from the accretion flow [20]. The vertical component of the magnetic field in the inner radii of the accretion disk may transfer energy and angular momentum away from the disk, resulting in jets that extend from the poles of the compact object [20]. As the relativistic ejected matter accelerates within the magnetic field of the jet, it produces synchrotron emission, which displays a power-law spectral emission profile across radio to infrared wavelengths of light (see Figure 1.4; [15]).

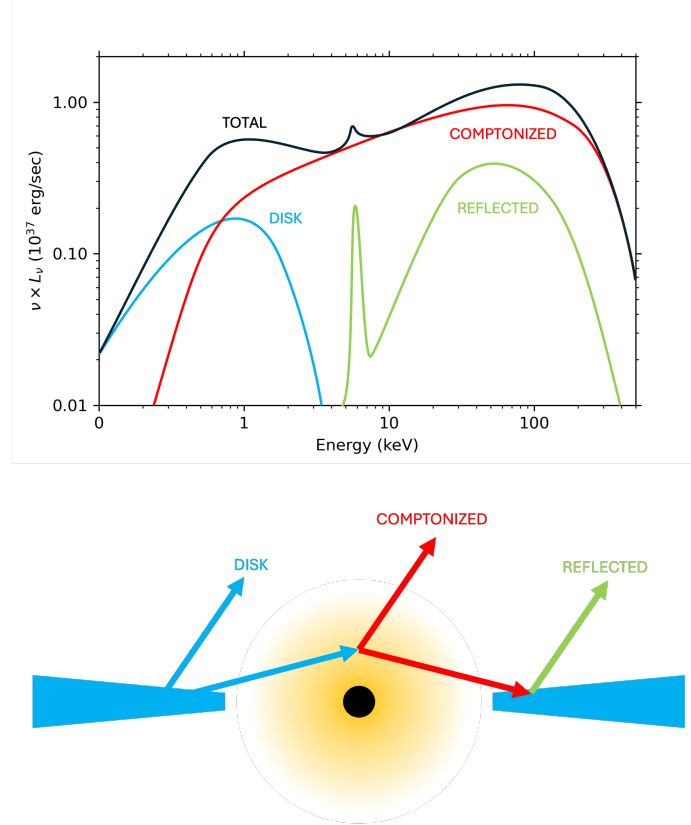


Figure 1.3: Geometric and X-ray spectral properties of a BH XRB. *Top:* A typical emission spectrum of an accreting BH XRB in the X-ray wavelengths consists of three main components: the thermal disk, non-thermal Comptonized emission, and reflected emission. *Bottom:* The accretion geometry of a BH XRB. Here all three components heavily interact with each other, where the thermal disk emission can be Comptonized via the corona, which can then reflect off of the disk to produce a reflected component in the spectrum. Adapted from [19].

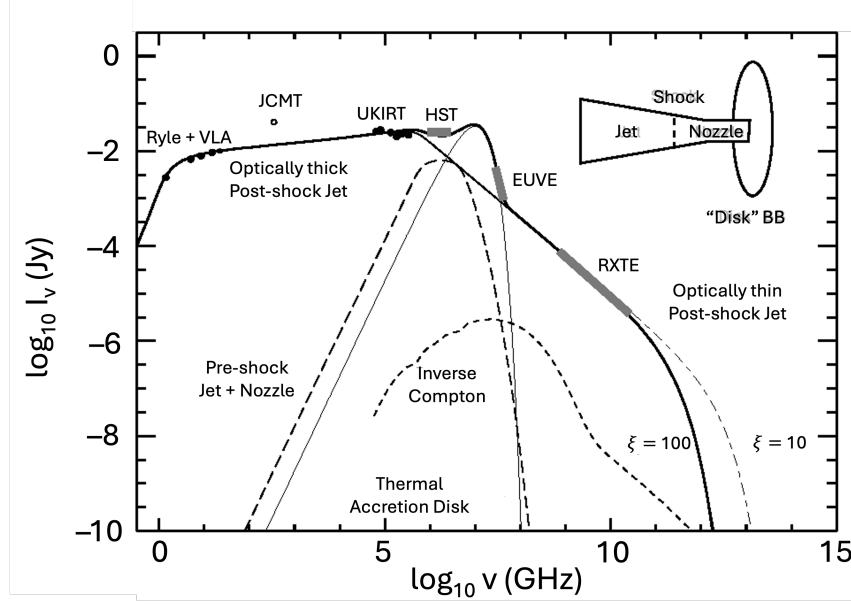


Figure 1.4: The broadband emission spectrum of the BH LMXB XTE J1118+480. The unique spectral shape seen here in radio–X-ray light is produced by a superposition of emission from many different processes originating from different regions in the XRB. Adapted from data presented in [21].

Boundary Layer and Surface Emission

While in BH XRBs the accreting matter passes through the event horizon, in NS XRBs the accreting matter can interact with the physical surface of the neutron star. This interaction can lead to several other emission processes that can produce X-ray emission.

If the neutron star is rotating more slowly than the inner edge of the accretion disk, then a boundary layer will be formed near the surface of the neutron star as the more quickly rotating accreting matter slows down and spreads over the neutron star’s surface. This component produces X-ray emission via the Comptonization of X-ray photons passing through the hot gas [22, 23].

Additionally, as matter accretes onto the neutron star surface, its motion becomes dominated by the neutron star’s magnetic field. In particular, the material follows magnetic field lines and forms accretion columns at the magnetic poles of the neutron star [24]. If the magnetic and rotation axes are misaligned, then as the neutron star rotates the X-ray emission will appear to pulsate when the accretion columns rotate in and out of view [24]. Further,

as matter accumulates on the surface of the neutron star, it can undergo a thermonuclear explosion via a runaway nuclear reaction (known as X-ray bursts). These explosions produce a large burst of X-ray emission increasing the X-ray light output of the XRB by a factor of around ten [25, 26].

1.2.3 The Outburst Cycle

As XRBs accrete material they can enter an outburst state, characterized by increased emission intensity (quantified by the power output, known as luminosity) and mass accretion rates [27]. The frequency with which an XRB undergoes outbursts categorizes it as either a transient or a persistent source (see Figure 1.5). Transient XRBs spend most of their time (periods lasting months to decades) in a quiescent state in which there is very little accretion, and thus the system appears very faint at X-ray wavelengths. While persistent XRBs can maintain an outburst state for extended periods of time, with higher mass accretion rates and brighter X-ray emission intensity, they can still exhibit accretion state changes similar to transient sources but on different (typically shorter) timescales [28]. Transient sources tend to be LMXBs [29] with long-term mass accretion rates of around $10^{-10} M_{\odot} \text{ yr}^{-1}$, quiescent X-ray luminosities around $10^{29} - 10^{33} \text{ erg s}^{-1}$, and outburst luminosities $10^{39} \text{ erg s}^{-1}$. Persistent sources are typically HMXBs with accretion rates up to $10^{-6} M_{\odot} \text{ yr}^{-1}$ and X-ray luminosities up to $10^{40} \text{ erg s}^{-1}$ [28, 30, 31].

The XRB outburst process can be explained reasonably well by the disk instability model [33]. In the quiescent state, the accretion disk is in a cool, un-ionized state. As it builds up by steadily accreting mass from the companion star, the temperature of the disk begins to rise. The opacity of the disk is highly dependent on the temperature, so as the disk warms it becomes more optically thick, absorbing radiation that ionizes the hydrogen in the disk. In turn, the viscosity of the disk increases and matter is accreted more rapidly, resulting in a heating wave that travels through the disk. This in turn triggers a rapid influx of matter onto the compact object and causing an X-ray outburst. Afterward, as the mass

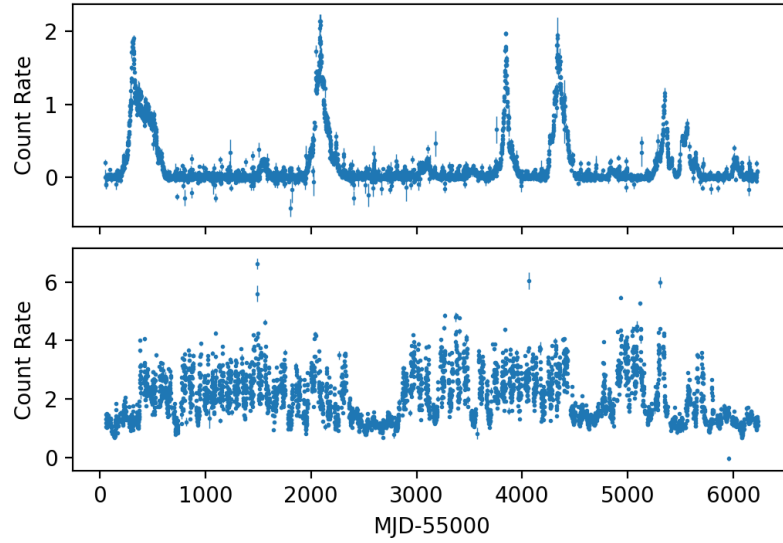


Figure 1.5: Examples of transient and persistent XRB accretion activity over long timescales. All data shown here is taken from the Monitor of All-sky X-ray Image (MAXI; [32]) telescope, where light intensity (in units of photon count rate) is plotted as a function of time (known as a lightcurves). *Top:* The lightcurve of the transient BH XRB source GX 339–4 exhibiting clear outbursts interspersed by periods of quiescence. *Bottom:* The lightcurve of the persistent BH XRB source Cygnus X–1 exhibits extended periods of increased brightness.

in the accretion disk depletes, the temperature drops and the accretion rate slows until the ionized hydrogen recombines. At this point, the same process that lead to the X-ray outburst happens in reverse and the XRB returns to a cool, un-ionized quiescent state [28].

BH XRB Outbursts

A BH XRB outburst cycle can be split up into different accretion states, which are best tracked using a hardness-intensity diagram (HID; see Figure 1.6). As a BH XRB transitions through its different accretion states, its X-ray intensity can be plotted against its hardness ratio (the ratio of X-ray detector counts in two different energy bands or wavelengths¹; [34, 35]). The outburst cycle begins from quiescence at point A in Figure 1.6, known as the Hard Comptonized State. This state is characterized by low X-ray luminosity and higher energy (hard) X-ray emission. In the Hard Comptonized State, the X-ray spectra is predominantly Comptonized emission from the corona, and may be accompanied by a weak, thermal spectrum from a truncated accretion disk [28]. The Hard Comptonized State is additionally associated with the detection of bright radio emission, indicating the presence of a collimated jet [28]. As the outburst continues, the X-ray luminosity quickly rises as the XRB transitions from points A to B in the HID, followed by a softening of the X-ray spectra from B to C (Intermediate State), at which point the XRB then enters the Soft Disk-Dominated State (D). In the Soft Disk-Dominated State, the X-ray spectra is dominated by lower energy (soft) thermal emission from the accretion disk and lacks radio emission, possibly a result of the quenching of the collimated jet [28]. Finally, as the mass in the accretion disk is depleted (D to E), the XRB transitions through another intermediate state (E to F) and returns to quiescence as the X-ray spectra harden and the X-ray luminosity decreases (F to A; [36]).

¹The hardness ratio can be thought of as the colour of the system; just as the visible light colours from red to blue have increasing energies, so to do X-rays, from soft to hard.

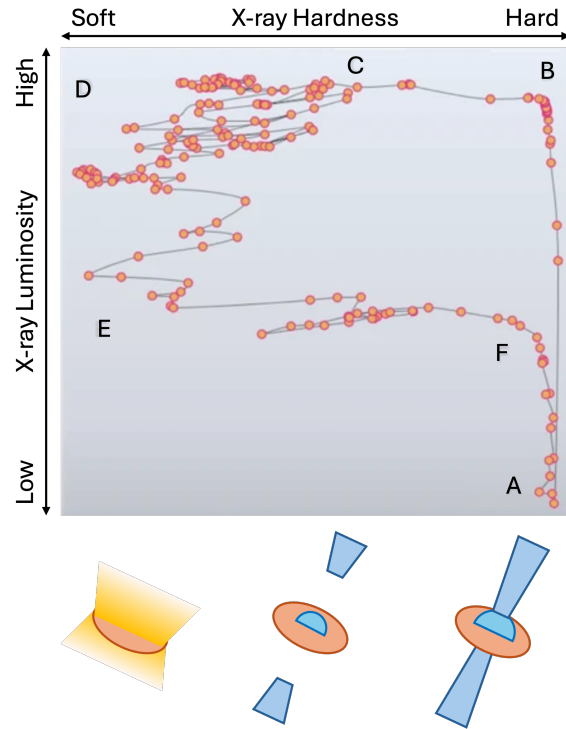


Figure 1.6: An example hardness-intensity diagram (HID) of a BH XRB. Here data is shown for an outburst of the BH XRB GX 339–4. The horizontal axis represents the X-ray hardness and the vertical axis represents the X-ray luminosity (or emitted power). Along the bottom, schematics of the accretion geometries of the different states are shown: the Soft Disk-Dominated State (*left*), the Intermediate State (*center*), and the Hard Comptonized State (*right*). Adapted from [35].

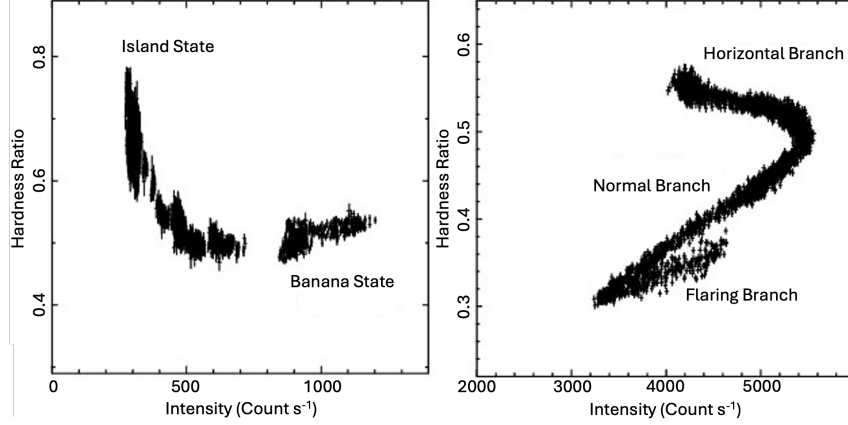


Figure 1.7: Example hardness-intensity diagrams (HIDs) for atoll and Z-track NS XRB sources. *Left:* The atoll source 4U 0614+091 exhibiting distinct banana and island states. *Right:* The Z-track source GX 340+0 showing its horizontal, normal, and flaring branches. Note that the axes in this figure are flipped when compared to Figure 1.6 for BH XRBs. The data shown here is based on observations from the Rossi X-ray Timing Explorer (RXTE) presented in [37].

NS XRB Outbursts

NS XRBs also show outburst evolution similar to BH XRBs, and can be categorized as atoll sources or Z-track sources. Lower luminosity LMXBs tend to be atoll sources, defined by their two different states. These atoll states are the banana state (hardness is relatively constant for a wide range of X-ray luminosities) and the island state (the spectrum hardens at lower luminosities; [37]). On the other hand, Z-track sources exhibit three distinct branches in their HIDs: the horizontal (HB), normal (NB), and flaring branches (FB). Figure 1.7 displays the HIDs for two NS XRBs, 4U 0614+091 and GX 340+0, showing the clear differences in the HIDs for the two types. Furthermore, atoll sources exhibit X-ray bursts, while Z-track sources generally do not, instead experiencing strong flares that constitute the flaring branch [37].

1.3 Time-Domain Properties

As an XRB cycles through different stages of an outburst, its X-ray spectrum changes along with the X-ray hardness. For example, X-ray spectra of the different X-ray spectral

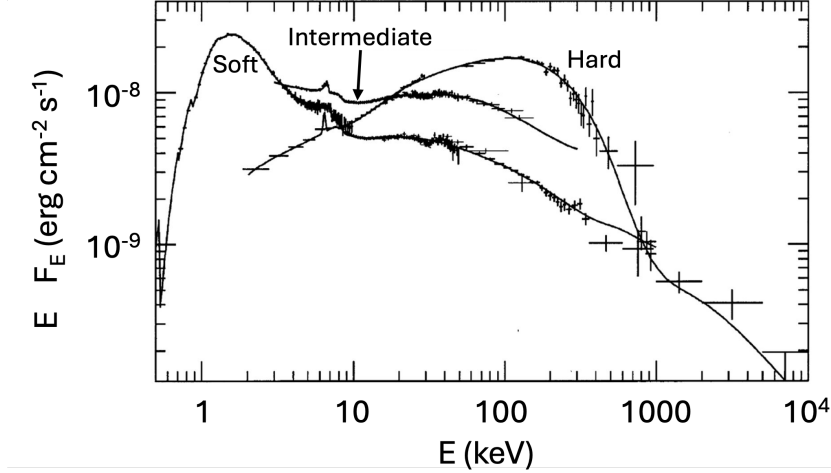


Figure 1.8: The X-ray (and gamma-ray) emission spectra of BH XRB Cygnus X-1 in different accretion states. The horizontal axis corresponds to the energy of the emitted light, while the vertical axis corresponds to the emitted light intensity. The Soft Disk-Dominated State, Intermediate State, and Hard Comptonized State exhibit distinct differences in their emission spectra, reflecting different emission processes dominating the light output (i.e., thermal emission in the Soft Disk-Dominated State vs Comptonized emission in the Hard Comptonized State). Adapted from [39].

states of a representative BH XRB are shown in Figure 1.8. In the Hard Comptonized State, X-ray emission is characterized by a power-law shape X-ray spectrum at higher energies, with a photon index ² of $\Gamma \sim 1.6 - 2.1$ [36]. Conversely, when the XRB enters the Soft Disk-Dominated State, its X-ray spectrum becomes dominated by a blackbody-like shape at lower energies and a weaker, steeper power-law shape at higher energies [36]. As described above, this spectral shape evolution is driven by the changing accretion geometry and emission processes throughout outburst. In particular, the blackbody-like component arises from the thermal emission generated by an optically thick (or opaque) accretion disk, and the power-law emission arises from non-thermal Comptonized emission generated by the corona component.

Other wavelengths of light also present changing emission properties throughout an outburst. While the accretion flow is dominated by X-ray emission [27], different regions

²The photon index, Γ , describes the power-law dependence of the X-ray spectrum on the wavelength produced by the inverse Compton emission process. More precisely, the photon number density, $N(E)$, is proportional to the energy of the emitted photons, E , according to, $N(E) \propto E^{-\Gamma}$ [38].

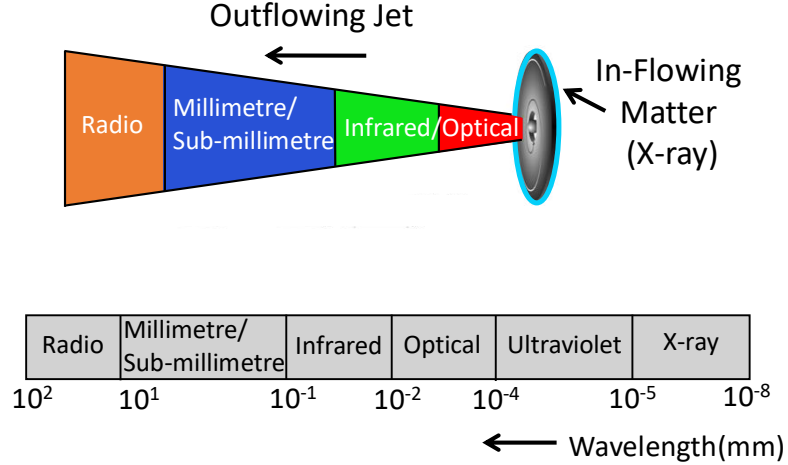


Figure 1.9: A schematic of the different emission regions of an XRB. In the outflowing jet, the wavelength (energy) of emitted light increases (decreases) as the distance between the emitting region and the central compact object increases. Image Credit: A. Tetarenko.

within the XRB can emit at different wavelengths. Notably, the relativistic jets that are ejected from the XRB emit radio, infrared, and optical emission [40], with shorter wavelengths (higher energies) probing closer to the compact object (see Figure 1.9; [41]). In the Hard Comptonized State, the jet emission shows a flat emission spectrum extending from radio through infrared wavelengths (with spectral index, $\alpha \sim 0$, where light intensity $\propto \nu^\alpha$ and ν is electromagnetic frequency³; [36]). As the XRB transitions from the Hard Comptonized State to the Soft Disk-Dominated State, bright radio flares may occur, signifying the launch of discrete jet plasma blobs, which display a steep ($\alpha < 0$) spectrum. This is then followed by the disappearance of the radio emission altogether, signifying a quenching of the jet [36, 42].

1.3.1 Rapid Timescale Correlated Variability

While the emission spectra of XRBs can vary from state to state, the emission within each state can itself vary on shorter timescales as well (known as variability). As such, time-domain studies of XRBs can provide valuable information on the accretion, ejection,

³Electromagnetic frequency (ν) is related to wavelength (λ) of light, $c = \nu\lambda$, where c is the speed of light. Note that the spectral index, α , is related to X-ray photon index, $\alpha = \Gamma - 1$.

and emission mechanisms of these systems. Time-domain observations are also particularly powerful since XRBs have angular sizes in the sky that are too small for current imaging capabilities to probe. Thus, studying the variations in XRB emission intensity over time allows for a new avenue of investigation. Recent studies [43, 44, 45] have developed techniques to generate time-series observations (known as lightcurves) with current instrumentation that is capable of characterizing the radio, infrared, optical, and X-ray light variability of XRBs. Notably, these multi-wavelength time-domain studies have found optical and infrared variability on timescales ~ 0.1 seconds, radio jet variability on timescales on the order of 10^1 seconds, and strong correlations between variability among different wavelengths of light. For example, [44, 45] have found correlated variability in the infrared and X-ray wavelengths of the transient BH XRB GX 339–4 (where the infrared signal lags behind the X-ray by 100 ms), and [28] found similar correlated emission at longer wavelengths (lags of minutes between the radio and infrared signals) in the BH XRB MAXI J1820+070. As different wavelengths of light probe different emission regions in the XRB (Figure 1.9), these correlations are indicative that variability in the jet is causally connected (and possibly driven by) variability in accretion flow.

1.3.2 The Fourier Domain

Short-term variability in XRB emission can also be studied using Fourier transforms, that convert XRB lightcurves to power density spectrum (PDS). These tools characterize variability amplitude across a range of different timescales, and can be used to extract interesting physics. For example, [43] found clear breaks in the Fourier PDS of multi-wavelength emission lightcurves at specific timescales in the BH XRB MAXI J1820+070, allowing for estimation of the size scale of the emission regions. Further, PDSs of X-ray (and sometimes infrared/optical) lightcurves often reveal sharp peaked features known as quasi-periodic oscillations (QPOs; see Figure 1.10), which indicate characteristic timescales at which there is a process repeatedly generating strong variation in the emission. As such,

QPO signals can directly probe the dynamics and the geometry of accreting matter under extreme gravitational conditions, which current imaging capabilities are not able to capture directly [46].

Quasi-Periodic Oscillations (QPOs)

QPOs can be characterized by three parameters; their central frequency, their quality factor Q (the ratio of the central frequency to the Full Width at Half Maximum [FWHM] of the peak), and their fractional root mean square (rms) amplitude (measure of the relative intensity of the QPO with respect to the total mean intensity; [47]). These signals can be generally classified into two categories based on their central frequencies; low frequency QPOs (LFQPOs) ranging from $10^{-3} - 10^1$ Hz or high frequency QPOs (HFQPOs) ranging from $10^1 - 10^2$ Hz [47].

In BH XRBs, LFQPOs can be further classified into three types [48]. Type A QPOs can be found in the Soft Disk-Dominated State and Intermediate State, are characterized by a weak, broad peak, and possibly tied to Compton emission [49]. Type B QPOs are usually detected during the Intermediate State, and have a frequency around 4–6 Hz [47]. Type C QPOs are the most common among LFQPOs with frequencies ranging from $10^{-3} - 10^1$ Hz, and are most commonly found in the Hard Comptonized State [47].

In Z-track NS XRBs, LFQPOs are classified according to where the XRB is along its Z-track at the time the QPO is detected; the so called flaring branch, normal branch, and horizontal branch oscillations (FBO, NBO, and HBOs). These NS QPOs are analogous to type A, B, and C QPOs of BH XRBs. Z-sources also exhibit HFQPOs with frequencies even higher than those of BH XRBs (known as kHz QPOs). LFQPOs present in atoll sources can be called HBO-like or FBO-like according to their similarities to their Z-source counterparts [50]. Figure 1.10 shows the similarities between BH XRB and Z-source LFQPOs.

While the origin of QPOs is still an open question, Type B and C QPOs likely arise from

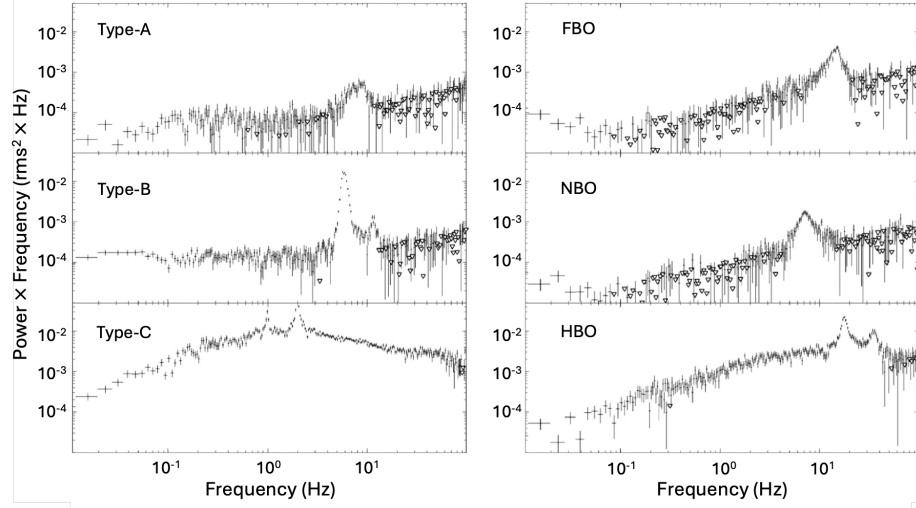


Figure 1.10: Examples of quasi-periodic oscillation (QPO) signals in XRBs. *Left*: Power density spectrum exhibiting type A, B, and C QPOs of the BH XRBs XTE J1859+226 (*top*) and GX 339–4 (*center and bottom*). *Right*: Power density spectrum exhibiting FBOs, NBOs, and HBOs, the NSXRB analogues of BH LFQPOs, of the NS XRBs GX17+2 (*top and center*) and Cyg X–2 (*bottom*). Adapted from [50].

the geometric properties of the system. Type C QPOs require an azimuthally asymmetric geometry, pointing toward precession of the accretion flow as the cause of these QPOs [50]. Since these LFQPOs are much stronger in the Comptonized emission compared to the disk emission, it is likely that it is the corona component that is undergoing precession. In NS XRBs, kHz QPOs are likely explained by the oscillations of the accretion disk with variable density, known as the Rayleigh-Taylor effect [51].

1.4 The Gemini Optical FAST Timing of X-Ray Binaries Program

Despite the successes of previous XRB multi-wavelength timing studies, there are still some pitfalls:

- Past studies were one-off observations (failing to capture variability across accretion states in an outburst).
- Limited access to optical instruments capable of the high-speed imaging needed for fast-timing studies.

- Longer and shorter wavelengths were sampled separately (making it difficult to draw connections between the accretion flow and different regions of the jet).
- BH XRBs were the primary targets (with NS XRBs relatively neglected in terms of these timing studies).

To remedy these shortcomings, the Gemini Large and Long program, Gemini Optical FAST timing of X-ray Binaries (*GOFAST-XRB*), was launched. The primary goal of this program is to track the variations in the accreting material propagating from disk to jet in XRBs. To accomplish this task, the program provides dense, optical wavelength time-series data of five target XRBs over a three year period (2024 to 2027) using Gemini’s *Alopeke* and *Zorro* instruments. Combining these optical data with X-ray time-domain observations of these XRBs will then reveal more information on the relationship between inflow and outflow. Further, instead of one-off observations, the program provides repeated, high-cadence optical coverage over several years of the target XRBs, allowing for more cohesive observations across different accretion states. By addressing past shortcomings in XRB timing studies, *GOFAST-XRB* acts as an anchor point for future multi-wavelength timing studies of XRBs.

1.4.1 Target XRBs

The *GOFAST-XRB* program targets four NS XRBs and one BH XRB, allowing for sampling of two types of compact objects.

Cygnus X-2

Cygnus X-2 is a well-studied Z-track LMXB [52], first discovered in the X-rays in 1966 [53]. The system contains a NS with an estimated mass of $\approx 1.71 \pm 0.21 M_{\odot}$ [54] and a bright companion with a mass $\approx 0.5 M_{\odot}$ [55]. Cygnus X-2 has an inclination (angle with respect to the line of sight) of $i \approx 62.5^{\circ} \pm 4^{\circ}$ and a distance of $d = 7.2 \pm 1.1$ kpc [56]. Of the six Z-track XRBs in the Galaxy, Cygnus X-2 is one of two that exhibits thermonuclear

X-ray bursts [57]. Cygnus X-2 additionally serves as the archetype and namesake of a subclass of NS LMXBs, “Cyg-like”, where the flaring branch in the HID lies at lower intensities, forming a backward “C” shape [58]. X-ray QPOs have been found at 500 and 860 Hz using the Rossi X-Ray Timing Explorer (RXTE) in Cygnus X-2 [59].

Scorpius X-1

Scorpius X-1 is a Z-track LMXB [52] that is the archetype of a subclass of NS LMXBs, “Sco-like”. As opposed to “Cyg-like” XRBs, the flaring branch of the HID lies at higher intensities [58]. Scorpius X-1 was discovered in 1962 [60], and is the brightest extrasolar X-ray source in the sky. This source lies at a distance of 2.33 kpc [61], making it the closest Z-track source in the Galaxy [62]. Scorpius X-1 has an inclination of about 22° , with the NS and companion star masses of approximately $1.5 \pm 0.1 M_\odot$ and $0.4 M_\odot$, respectively [63]. Scorpius X-1 exhibits QPOs in the X-ray wavelengths [61]. These X-ray QPOs correlate with motion along the Z-track in the HID. Specifically, along the normal branch, there were strong QPOs of about 6 Hz, and during transitions to and from the flaring branch, there were weaker QPOs reaching up to 15 Hz. X-ray and optical emission of Scorpius X-1 have been studied with time-domain observations on longer timescales of tens of seconds to minutes. With X-ray (from *Copernicus* and *SAS-3*, the Small Astronomy Satellite 3) and optical (from La Silla Observatory) observations, [64] have found that the X-ray and optical emission of Scorpius X-1 are highly correlated (where the optical lags behind the X-ray on timescales of 10 s). This correlated optical and X-ray emission has been attributed to the reprocessing of the X-ray emission to optical emission in the outer accretion disk.

Aquila X-1

Aquila X-1 is a transient NS LMXB, first discovered in 1973 [65], and known to undergo $\sim$ annual outbursts [66, 67]. The system is an atoll source [68], that is known to show thermonuclear X-ray bursts [26]. It is located at a distance of 6 ± 2 kpc, with an inclination $36^\circ < i < 47^\circ$ [66], and a measured neutron star mass of roughly $1.5 M_\odot$ [69]. Aquila X-1

has displayed two kHz X-ray QPOs at around 800 Hz and 1100 Hz [70].

4U 1608–52

4U 1608–52 is a transient, atoll LMXB [71] that was discovered in the early 1970s using the two *Vela-5* satellites [72]. The system is approximately 3.1–3.7 kpc away [73], and its NS has a mass of about $1.74 \pm 0.14 M_{\odot}$ [74]. 4U 1608–52 is known to undergo thermonuclear X-ray bursts [75], and goes into outburst on a period ranging from every 80 days to every few years [76]. X-ray LFQPOs as well as kHz X-ray QPOs have been detected in this system [77].

GX 339–4

GX 339–4 is a transient BH XRB that was discovered in 1972 by the MIT X-ray detector on the Orbiting Solar Observatory 7 satellite [78], and is the most extensively studied transient BH XRB in the Galaxy [79]. In 43 years after it was discovered, it has gone into outburst 20 times, and has exhibited the full array of spectral states [80], making it a prime target for the *GOFAST-XRB* program. The mass of the BH is estimated to be between 2.3 and 9.5 $M_{\odot}$ [81], and the system is estimated to lie at a distance of 8.4 ± 0.9 kpc [82]. Strong type A, B, and C X-ray QPOs have been frequently observed in GX 339–4 during its outbursts [83]. Using simultaneous infrared and X-ray observations from the Very Large Telescope (VLT) in Chile and RXTE respectively, [45] have found that the infrared emission is highly correlated with the X-ray (where the infrared lags behind the X-ray emission by approximately 0.1 s). This correlated infrared and X-ray emission has been attributed to the coupling between the accretion flow and jet.

1.5 Chapter Summary

XRBs are binary systems of a compact object, such as a neutron star or a black hole, that accretes mass from its companion star, forming a rotating accretion disk and ejecting a portion of the accreting mass as a relativistic jet. These systems can serve as laboratories

for the behavior of matter in extreme environments, but since they are too small in the sky to observe directly, time-domain observations can become a powerful tool. The *GOFAST-XRB* program aims to use dense, time-domain observations from the Gemini Observatory’s ‘*Alopeke* and *Zorro*’ instruments to track the propagation of variations from inflow to outflow in XRBs, and ultimately allow for a better understanding of the physics of matter in extreme conditions. The target XRBs that were chosen for this program cover a wide range of different properties in the Galactic XRB population, enhancing the scientific output of the *GOFAST-XRB* program.

The following chapters of this thesis will cover the methodology of the data processing pipeline that I have developed for *GOFAST-XRB*, the preliminary results that the pipeline has produced (focusing on two NS and BH case study sources), and finally discuss the current limitations of the pipeline, as well as the next steps that can be taken to improve the pipeline and obtain higher quality results.

Chapter 2

Methodology

2.1 Observational Instruments and Data

The data analyzed in this thesis of the target XRBs are taken by the Gemini Observatory using its ‘*Alopeke* and *Zorro* instruments. These instruments are located at the Gemini North and Gemini South telescopes in Hawaii and Chile, respectively. The two are identical instruments with dual-channel speckle imaging capabilities [84]. Initially built to perform speckle interferometry with the goal of high angular resolution optical light astronomy, these instruments have the ability to make images on rapid timescales, allowing for high precision time-domain astronomy as well [84]. Speckle interferometry works by using short exposure times that effectively “freeze” the atmosphere in place, removing atmospheric fluctuations that can distort images [85]. However, when these instruments operate in their “wide-field” mode, they offer a field of view of approximately 1 arcminute, and can function as conventional imaging instruments in two optical wavelengths (known as filters) simultaneously [84].

The raw data from ‘*Alopeke* and *Zorro* observations are made available on the Gemini Observatory Archive⁴. These observations are provided in the form of a series of 30 s long cubes, consisting of 1000 frames of 30 ms exposures. These data are in the Flexible Image Transport System (FITS) file format. A summary of the observations taken for the *GOFAST-XRB* program (as of 1 May 2026) is provided in Table 2.1, with the central wavelengths for each optical filter that was used listed in Table 2.2.

⁴The Gemini Observatory Archive is available at <https://archive.gemini.edu/searchform>.

Table 2.1: A summary of the *GOFAST-XRB* optical observations of the target XRBs taken by the Gemini Observatory’s ‘*Alopeke* and *Zorro*’ instruments.

Target	Compact Object	Observation Date (UTC)	Total Exposure Time (hrs)	Instrument	Optical Filters
Cyg X-2	NS	Aug 15, 2024	3.33	‘Alopeke	Red-z, Blue-g
		25 Sep 2024	3.03	‘Alopeke	Red-z, Blue-g
		26 Sep 2024	3.33	‘Alopeke	Red-z, Blue-g
		30 Sep 2025	3.14	‘Alopeke	Red-z, Blue-g
		4 Apr 2026	1.13	‘Alopeke	Red-z, Blue-g
Sco X-1	NS	12 Feb 2025	0.98	‘Alopeke	Red-i, Blue466
		13 Feb 2025	0.98	‘Alopeke	Red-i, Blue466
		14 Feb 2025	0.98	‘Alopeke	Red-i, Blue466
		15 Jun 2025	3.14	‘Alopeke	Red-z, Blue-g
		3 Jul 2025	3.16	Zorro	Red-z, Blue-g
		5 Feb 2026	0.82	Zorro	Red-z, Blue-g
		30 Apr 2026	3.15	Zorro	Red-i, Blue-g
		1 May 2026	3.16	Zorro	Red-i, Blue-g
		20 Sep 2024	0.17	Zorro	Red-z, Blue-g
		21 Sep 2024	3.33	Zorro	Red-z, Blue-g
Aql X-1	NS	6 Aug 2025	3.15	‘Alopeke	Red-z, Blue-g
		10 Aug 2025	3.16	‘Alopeke	Red-z, Blue-g
		11 Mar 2025	3.14	Zorro	Red-z, Blue-g
		13 Mar 2025	3.15	Zorro	Red-z, Blue-r
4U 1608-52	NS	15 Mar 2025	2.70	Zorro	Red-z, Blue-r
		10 May 2025	3.18	Zorro	Red-z, Blue-g
		11 May 2025	3.15	Zorro	Red-z, Blue-r
		12 Sep 2025	3.14	Zorro	Red-z, Blue-g
GX 339-4	BH	6 Oct 2025	3.21	Zorro	Red-z, Blue-g
		10 Oct 2025	2.57	Zorro	Red-z, Blue-g

Table 2.2: Central wavelengths for each filter used in the Gemini observations [84].

Filter	Central Wavelength (nm)
Red-z	947
Red-i	765
Blue-r	620
Blue-g	479
Blue466	466

2.2 Data Processing Pipeline

Since *Alopeke* and *Zorro* were not originally designed to provide high time resolution optical images of XRBs, a new pipeline must be built to process the data of these instruments for the purposes of the *GOFAST-XRB* program. The development of this pipeline is the main goal of this thesis. A flow chart describing the main steps of my pipeline is shown in Figure 2.1, with the steps described in detail in the following sections. These steps were tested, cross-checked, and validated on simulated images. In these simulated images, I injected a known ground truth variability pattern for an isolated stellar-like source over a series of frames to make sure each pipeline step performed as intended and could recover the known pattern.

The data pipeline⁵ I designed primarily makes use of functions present in the `photutils`⁶ and `stingray`⁷ Python packages to construct optical lightcurves in both filters of the target XRBs and compute their PDS.

- `photutils` is a Python library designed to perform photometry of astronomical sources [86]. Photometry is a process by which light emission intensity can be extracted from regions in an image (apertures), and thus can be used to construct lightcurves, which measure the brightness of a source as it varies over time. This tool is a coordinated package of the broader `astropy` Python package, which provides core functionality

⁵The source code for the pipeline is available at <https://github.com/ejelo/gofast-xrb>

⁶The `photutils` documentation is available at <https://photutils.readthedocs.io/en/stable/index.html>.

⁷The `stingray` documentation is available at <https://docs.stingray.science/en/stable/index.html>.

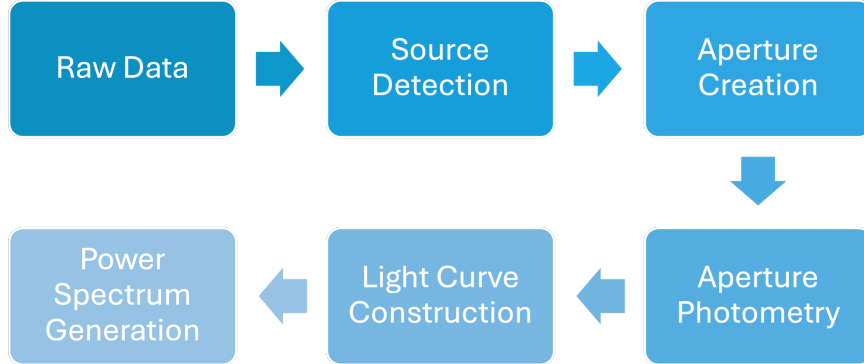


Figure 2.1: A flow chart summarizing the main steps of my ‘*Alopeke* and *Zorro*’ optical time-series data processing pipeline. Starting from raw data, sources in the field of view are identified and apertures are created to encompass all of their emission in the images. The process of photometry is then performed to extract the total intensity of the light in each aperture. This process is used sequentially on all of the data frames to construct a lightcurve. The emission variability in this lightcurve can then be analyzed by generating its PDS.

and commonly used tools for astronomical research [87]. `photutils` provides the functions necessary to perform aperture photometry on a set of observations, such as source detection, background subtraction, and aperture creation.

- `stingray` is a Python library designed to perform time-series analysis of astronomical data, supporting a variety of common Fourier analysis techniques [88, 89]. Given intensity measurements and their corresponding timestamps, `stingray` constructs a `Lightcurve` object which can be analyzed using the package’s built-in Fourier analysis methods. This includes generating its PDS to quantify on which timescales the emission in the lightcurve strongly varies.

2.2.1 Source Detection and Aperture Creation

A reference image is first created for each night of observations by averaging the first 30 s data cube of raw data in the set, yielding a time-averaged image of the entire 30 s exposure. The `detect_sources` method from the `photutils.segmentation` library is then applied to this reference image to identify any sources of emission in the field of view that fall above a certain brightness threshold. `detect_sources` first requires initial processing of the reference image, namely background subtraction and convolution with a Gaussian kernel. To this end, `photutils` provides the `Background2D` class to estimate the background noise of an image. I can use this tool to separate the image into subregions, and then estimate the background in each subregion to create a low-resolution background image. In each subregion, the `sigma_clipped_stats` are calculated (pixels above a certain intensity level, corresponding to sources, are masked and the statistics are recalculated), and then the background noise level is estimated, in this case with the `MedianBackground` class. The low-resolution background image is then median filtered to suppress spurious pixels that can cause local over or underestimations. The final background image can then be interpolated using `scipy.ndimage.zoom` and finally subtracted from the reference image to produce a background subtracted image for source detection [86].

To facilitate source detection, the background subtracted reference image is convolved using a Gaussian kernel to amplify sources and suppress noise. The `detect_sources` function can then be used on the convolved, background subtracted image with a specified intensity threshold and a n_{pixels} threshold (the number of connected pixels that must exist for a source in the image to be detected). This produces a `SegmentationImage` that identifies the detected sources using different positive integer values and non-sources using zero. In the case where two sources are in close proximity to each other in the reference image, the corresponding segmentation image might identify them as a single source. To distinguish the two sources, deblending is required using the `deblend_sources` function. The deblended segmentation image can then be passed onto the `SourceCatalog` class, cataloging

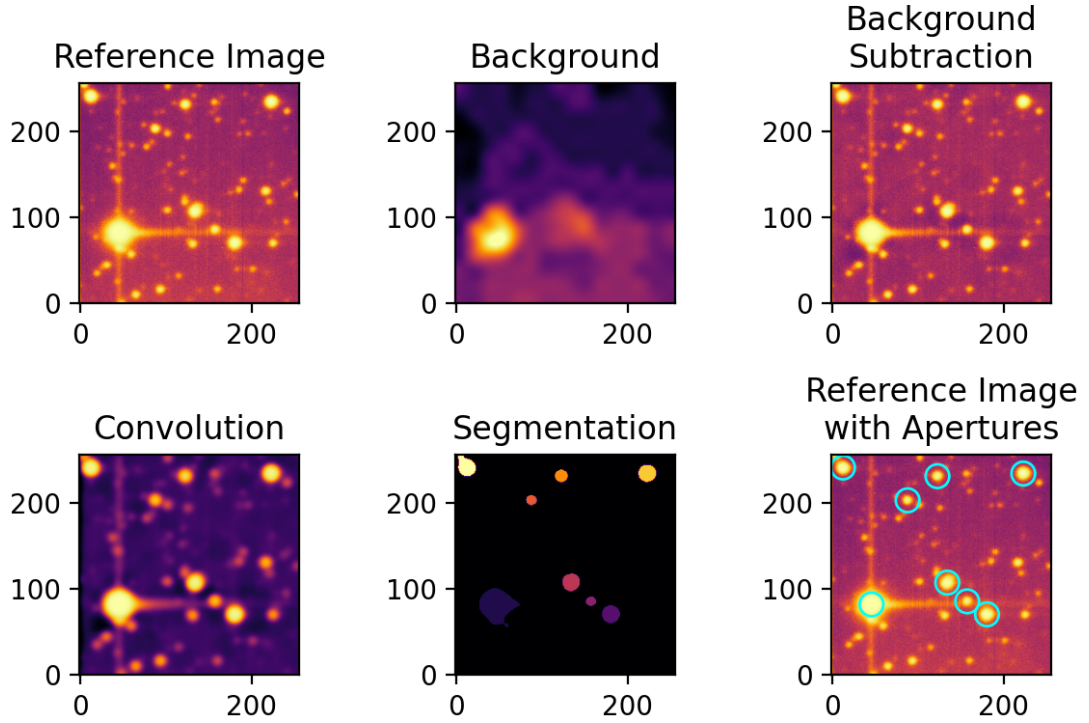


Figure 2.2: The process of source detection and aperture creation starting from the reference image (*top left*) for the 12 September 2025 observation of GX 339–4 in the blue filter. The background (*top center*) is estimated using `Background2D` then subtracted to yield the background subtracted reference image (*top right*), which is then convolved with a Gaussian kernel (*bottom left*) to produce a segmentation image (*bottom center*). The segmentation image is used to create apertures, which identifies sources above a certain brightness threshold in the field of view (*bottom right*).

all the sources that were detected in the image.

Circular apertures around the detected sources can then be easily created using the `make_circular_apertures` method of the `SourceCatalog`, using the centroids of each segment as the aperture position, along with a specified radius [86]. A $1''$ radius was chosen, with its corresponding pixel conversion found using the plate scale information stored in the raw data header of the data cubes. An example of the aperture creation process, involving background subtraction, convolution, and segmentation, is shown in Figure 2.2.

2.2.2 Aperature Photometry

To check that the previous process has correctly identified the target XRB and a nearby comparison star in the raw data images, I make use of a finding chart. These finding charts map out the sources in the field of view using large scale astronomical surveys (e.g., PanSTARRS; [90, 91]), which are then compared to our raw data images with the apertures plotted on top of the reference image. Once verified, the corresponding apertures are recorded and used to process the raw data cube files of a particular night of observations. The reference images in the red and blue filters for each XRB, with apertures shown, as well as their finding charts are given in Figure 2.3.

For each raw data cube present in a night of observations, the time-averaged exposure is calculated and a median `Background2D` image is extracted using the same method described previously. I assume that the telescope pointing is stable throughout a 30 s exposure (i.e., the length of one data cube), but correct for any change in image dimension or shift in field of view relative to the reference image in each sequential cube making up the night of observations. To do this, I make use of the image registration tool in the `astroalign.register` function from the `astroalign` Python package and image scaling tool in the `skimage.transform.rescale` function from the `Scikit-image` package.

Once the scaling and translation transformations are found, the pipeline begins iterating through each frame of all the raw data cubes. Each frame is further checked as the data cube is iterated through, discarding frames that are blank, saturated, or otherwise unusable. The predefined apertures are then applied to the frame to extract the instantaneous intensity of the target and comparison star, along with their associated errors using the `sep.sum_circle` function from `sep` (a source extraction and photometry Python library).

2.2.3 Lightcurve Construction

The intensities, errors, and their associated timestamps measured in the previous step ultimately make up the lightcurves for both the target XRB and the comparison star in a

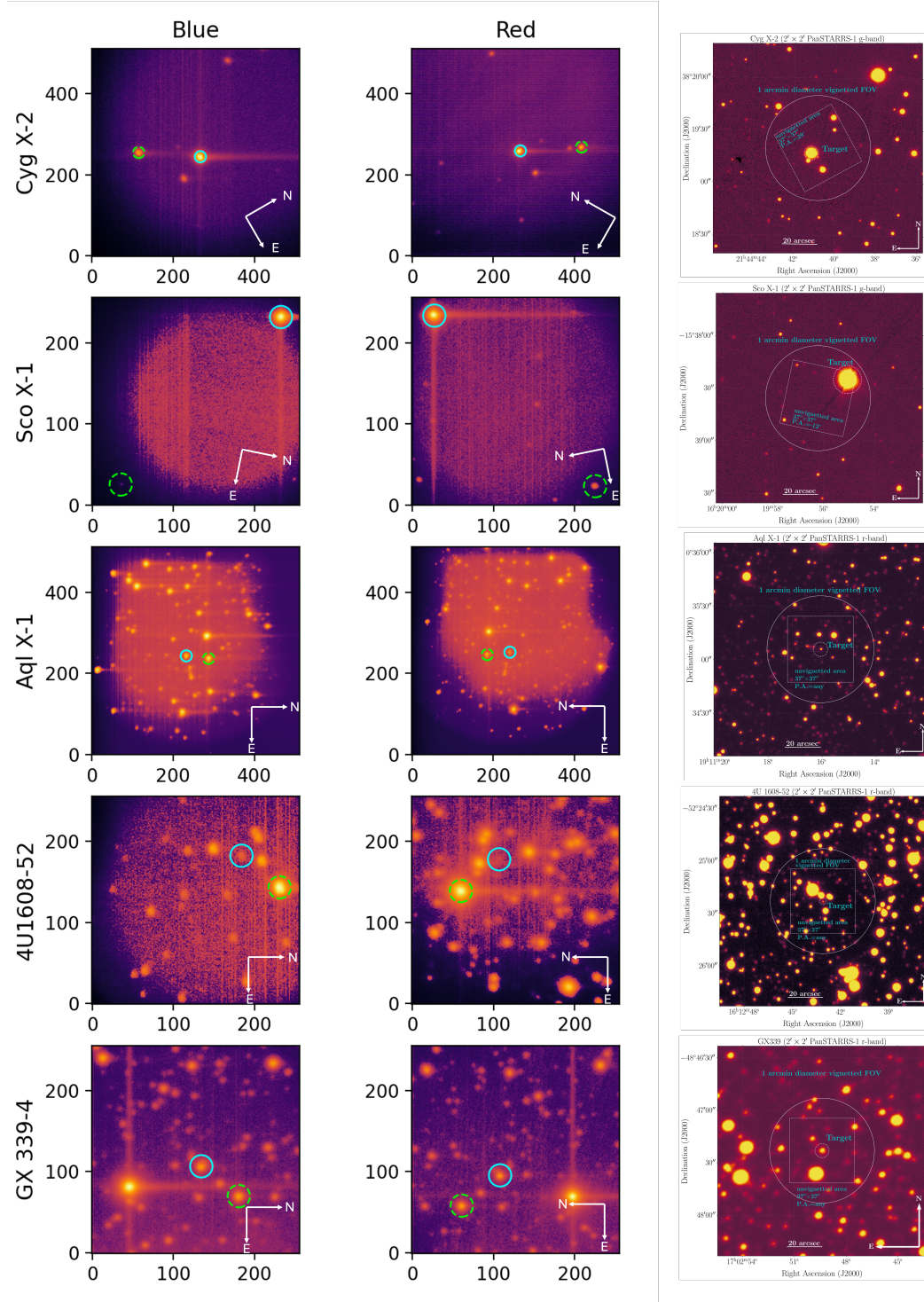


Figure 2.3: Reference images of the fields for each observed XRB. Shown here is the blue (*left*) and red (*center*) filters, alongside finding charts created from PanSTARRS–1 data (*right*). The target XRB and comparison stars are identified by a solid cyan and a neon green dashed circle, respectively. The fields of view are rotated with respect to the finding charts with the rotated directional axes shown in each reference image.

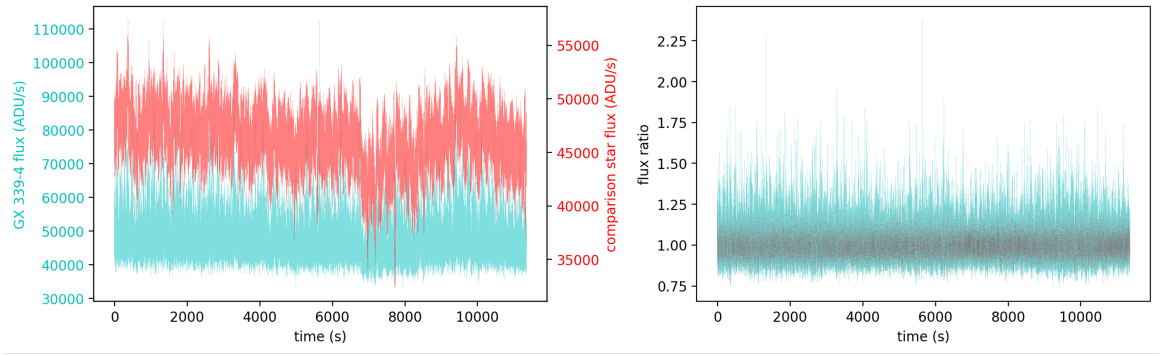


Figure 2.4: Example lightcurves output from the pipeline. (*Left*) The red filter lightcurves for GX 339–4 (cyan) and a comparison star (red) produced from the 12 Sep 2025 observation. (*Right*) The ratio of the two lightcurves in the *left* panel. The large scale artificial variations induced by the atmosphere have been clearly removed in the ratio lightcurve.

particular filter. To account for the multiplicative effects of atmospheric variations on the measured intensity, the ratio is taken by dividing the target by the comparison star intensity for each frame. As a result of using a single model 2D background for the duration of the 30 s exposure of a particular raw data file, the background is sometimes overestimated, resulting in intensity values that are negative, close to zero, or zero. To remedy this without losing any information, the lightcurves can be median matched, shifting one lightcurve upward so that its median matches the other. Examples of the individual target and comparison lightcurves, as well as their ratio, are shown in in Figure 2.4.

2.2.4 Power Spectrum Generation

Once the ratio lightcurve is constructed for the set of observations, a PDS can be generated using the `stingray` package. This begins with finding the good time intervals (GTIs) of the lightcurve, the periods of time during which there are measurements, to reduce the effects of data gaps. The GTIs typically consist of the 30 s exposures, given the small time gaps between each data cube. Once the GTIs are defined, a `Lightcurve` object can be constructed using the aperture intensities, errors, timestamps, and GTIs to be used with further Fourier analysis functions from the `stingray` library. With `stingray`, an `AveragedPowerspectrum` can be generated, which calculates the PDS for each segment of

the lightcurve (as defined by the GTIs), and then averages all the resulting PDSs together [92]. The resulting PDS can then be inspected to identify timescales of significant XRB variability in the optical filters sampled. For instance, any peaks that can be found in the PDS may correspond to a QPO signal. An example of an `AveragedPowerspectrum` is shown in Figure 2.5.

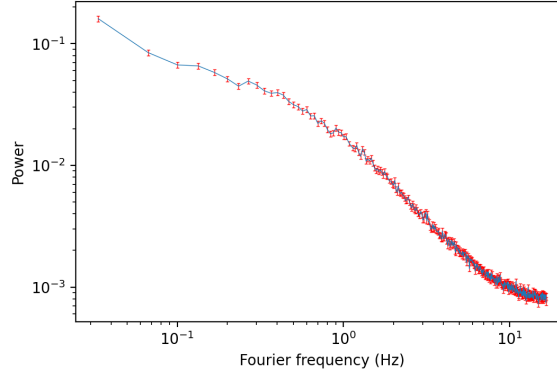


Figure 2.5: Example averaged power spectrum (PDS) of the red filter lightcurve of GX 339–4 produced from the 12 Sep 2025 observation. No QPOs are visible, despite there being significant variations on timescales down to the scale of hundreds of milliseconds.

2.3 Chapter Summary

Since Gemini’s *Alopeke* and *Zorro* instruments were not initially designed to observe XRBs on rapid timescales, a new pipeline was required to analyze their data for the purposes of the *GOFAST-XRB* program. The pipeline I designed primarily makes use of functions present in the `photutils` and `stingray` Python packages to perform aperture photometry on the Gemini observations and build lightcurves that measure the brightness of our target XRBs as they vary with time. My pipeline also provides diagnostic tools to quantify any variability detected in these lightcurves, and then analyze this variability using Fourier techniques. The following chapter will showcase the preliminary results of the pipeline, focusing on two case study XRBs, Cygnus X–2 (NS XRB) and GX 339–4 (BH XRB).

Chapter 3

Results

Using the data processing pipeline outlined in Chapter 2, the lightcurves and PDS for each target XRB were generated for both the red and blue optical filter observations taken with the *GOFAST-XRB* program so far up to May 2026. Cygnus X-2 and GX 339-4 were selected as representative NS and BH XRB case studies for the pipeline output to display in this thesis, as their observations led to clean, consistent results. I also briefly discuss the remaining targets, highlighting the areas where the pipeline failed to produce reasonable results and needs to be improved.

3.1 Cygnus X-2

Figure 3.1 displays the pipeline output for the 25 Sep 2024 observation of Cygnus X-2. The lightcurves for this observation are generally well-behaved, with only a few errant dips. From the PDS, the variability amplitude clearly drops after 10^{-1} Hz before leveling out to a baseline white noise level starting at around 10^0 Hz. The blue filter also appears to have a higher white noise level when compared to the red filter.

To search for any variability evolution between accretion states sampled by our observations so far, I processed all four nights of observations of Cygnus X-2 with the pipeline. To estimate an average variability amplitude for each night of observations for comparison purposes, the pipeline also calculates the fractional rms. This statistic represents the square root of the integral of the PDS [92], where a higher fractional rms can indicate a higher degree of variability. To identify the accretion state of the target for each observation, I

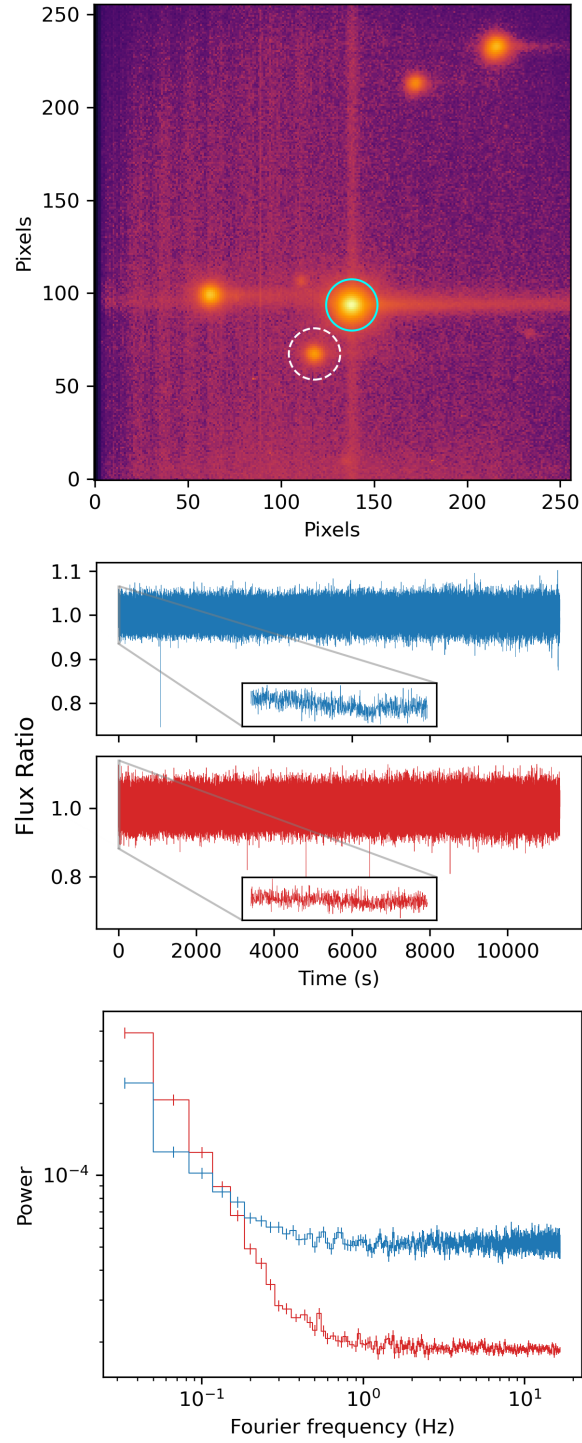


Figure 3.1: (*Top*) Reference image of Cygnus X-2 from the 25 Sep 2024 observation with the XRB (solid cyan) and a check star (dashed white) identified. (*Center*) The blue (*top*) and red (*bottom*) optical lightcurves for this observation, with corresponding insets displaying the lightcurves of a single 30 s data interval. (*Bottom*) The averaged PDS in the blue and red filters generated from the lightcurves in the *center* panel.

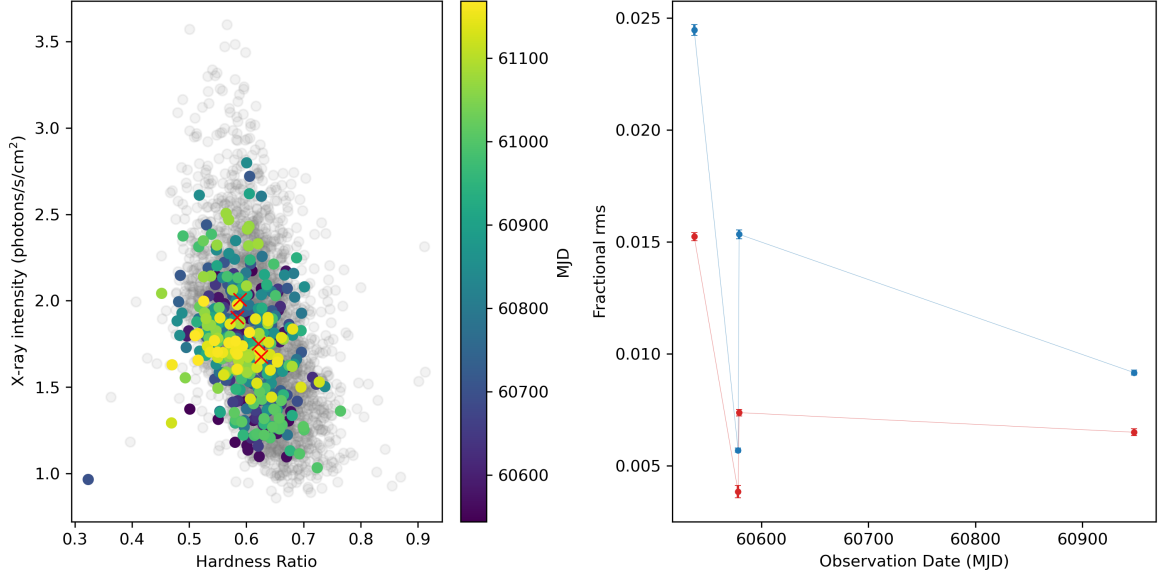


Figure 3.2: (*Left*) HID of Cygnus X–2 using X-ray data from MAXI, where the X-ray intensity is taken in the 2–20 keV energy band and the hardness ratio is defined as the ratio of the 10–20 keV and 2–4 keV energy bands. The MAXI observations covering the time period over which the Gemini observations of Cygnus X–2 were taken are shown in colour, with older historical data shown in gray [93]. The points marked with a red X coincide with the Gemini observations for Cygnus X–2. (*Right*) Measurements of average variability amplitude (fractional rms) extracted from the PDS for each observation night.

generate the HID of Cygnus X–2 using 1-day binned MAXI X-ray data (see Figure 3.2). Overall, our observations of Cygnus X–2 so far sample a range of X-ray hardness, showing preliminary evidence of changes in the variability amplitude as the hardness evolves.

3.2 GX 339–4

Figure 3.3 displays the pipeline output for the 12 Sep 2025 observation of GX 339–4. Similar to Cygnus X–2, the lightcurves produced by the pipeline for this GX 339–4 observation are also well-behaved, having little to no extreme outlying values. However, the averaged PDS for GX 339–4 exhibits noticeable differences from those of Cygnus X–2. GX 339–4 exhibits higher variability levels, even down to 10^1 Hz, corresponding to variations on the timescale of hundreds of milliseconds. The fractional rms of GX 339–4, seen in Figure 3.4, in general is also much higher than Cygnus X–2, indicating that it is more variable than Cygnus X–2 overall. Our observations of GX339–4 only sample a

very narrow range of X-ray hardness, and were taken at the end of an outburst (close to quiescence), so we can not draw any conclusions yet on variability evolution in this source with the current observations in hand.

3.3 Other Targets: Scorpius X-1, Aquila X-1, and 4U1608-52

Scorpius X-1

Figure 3.5 displays the pipeline output for the 13 Feb 2025 observation of Scorpius X-1. While the lightcurves for this observation appear generally well-behaved, the PDS in the blue filter shows a broad hump feature between 10^0 and 10^1 Hz. This odd feature does not appear in the red filter, which displays a white noise spectrum at these frequencies. The blue filter PDS feature is present in all of the observations of Scorpius X-1 taken so far. The origin of this odd feature may be related to the fact that Scorpius X-1 is very bright and can saturate optical images (this is discussed in Chapter 4).

Aquila X-1

Figure 3.6 displays the pipeline output for the 20 Sep 2024 observation of Aquila X-1. The lightcurves for this observation are not well-behaved, exhibiting extreme dips and spikes in both filters. This odd behaviour results in PDSs that appear flat with Fourier frequency, with many broad peaked features superimposed on top. These effects are present in both filters and across all of the observations (except for 6 Aug 2025) of Aquila X-1 taken so far. The origin of these feature may be related to incorrect background subtraction (this is discussed in Chapter 4).

4U 1608-52

Figure 3.7 displays the pipeline output for the 11 Mar 2025 observation of 4U 1608-52. The lightcurves for this observation are generally well-behaved, displaying very few extreme values. The PDS for both filters show a flat shape, in contrast to those seen in Cygnus X-2 and GX 339-4. This likely indicates that there are no significant variations

detected on any timescales sampled in this source. This behaviour is seen across all of our observations of 4U 1608–52 taken so far.

3.4 Chapter Summary

The preliminary results produced from my pipeline show clear differences in the optical variability properties of the sampled target XRBs. For the two case study XRBs, Cygnus X–2 and GX 339–4, we see that GX 339–4 is more variable over a broader range of timescales when compared to Cygnus X–2. These differences may be driven by the different compact objects (a NS and BH) powering these systems. However, while Cygnus X–2 and GX 339–4 show clearly detectable optical variability, 4U 1608–52 (NS) displayed little to no variability at all. This indicates that additional properties beyond the nature of the compact object must govern optical variability properties. While the pipeline performed well for Cygnus X–2, GX 339–4, and 4U 1608–52, it has trouble producing reliable results with the data from Scorpius X–1 and Aquila X–1. The final chapter will discuss the current shortcomings of the pipeline as well as the next steps that should be taken to ameliorate these pitfalls and produce higher quality results.

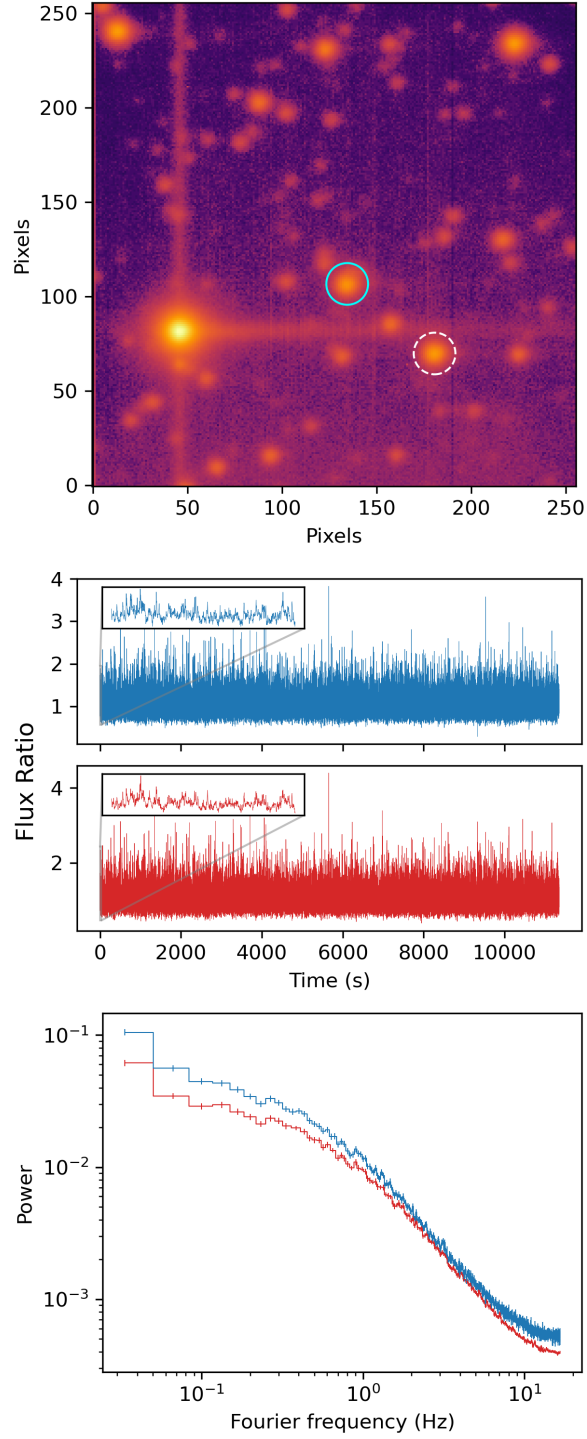


Figure 3.3: (*Top*) Reference image of GX 339-4 from the 12 Sep 2025 observation with the XRB (solid cyan) and a check star (dashed white) identified. (*Center*) The blue (*top*) and red (*bottom*) optical lightcurves for this observation, with corresponding insets displaying the lightcurves of a single 30 s data interval. (*Bottom*) The averaged PDS in the blue and red filters generated from the lightcurves in the *center* panel.

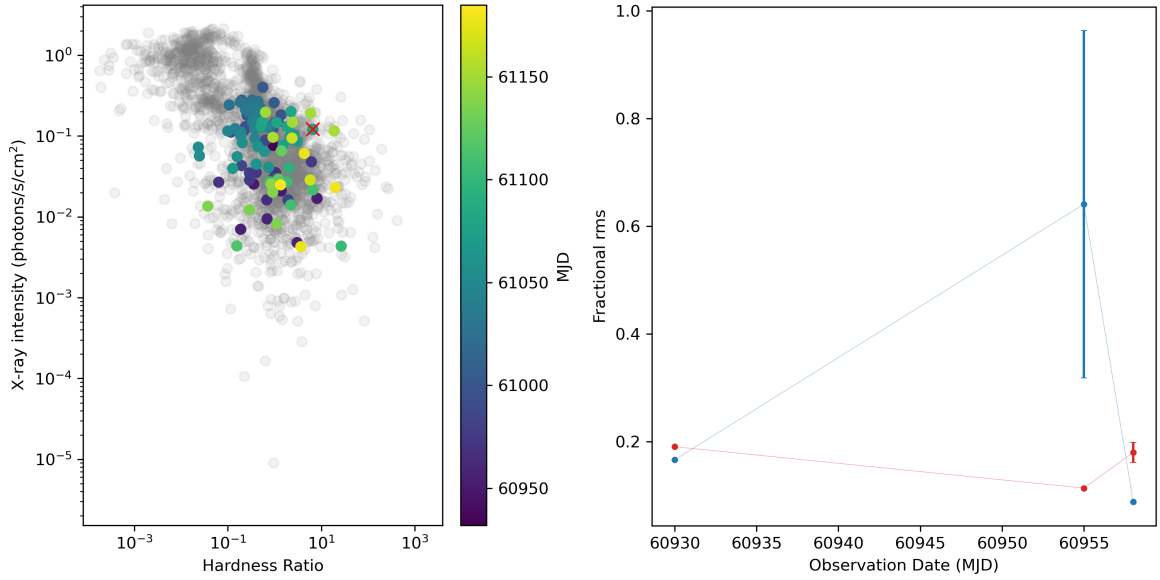


Figure 3.4: (*Left*) HID of GX 339–4 using X-ray data from MAXI, where the X-ray intensity is taken in the 2–20 keV energy band and the hardness ratio is defined as the ratio of the 10–20 keV and 2–4 keV energy bands. The MAXI observations covering the time period over which the Gemini observations of GX 339–4 were taken are shown in colour, with older historical data shown in gray [93]. The points marked with a red X coincide with the Gemini observations for GX 339–4. (*Right*) Measurements of average variability amplitude (fractional rms) extracted from the PDS for each observation night.

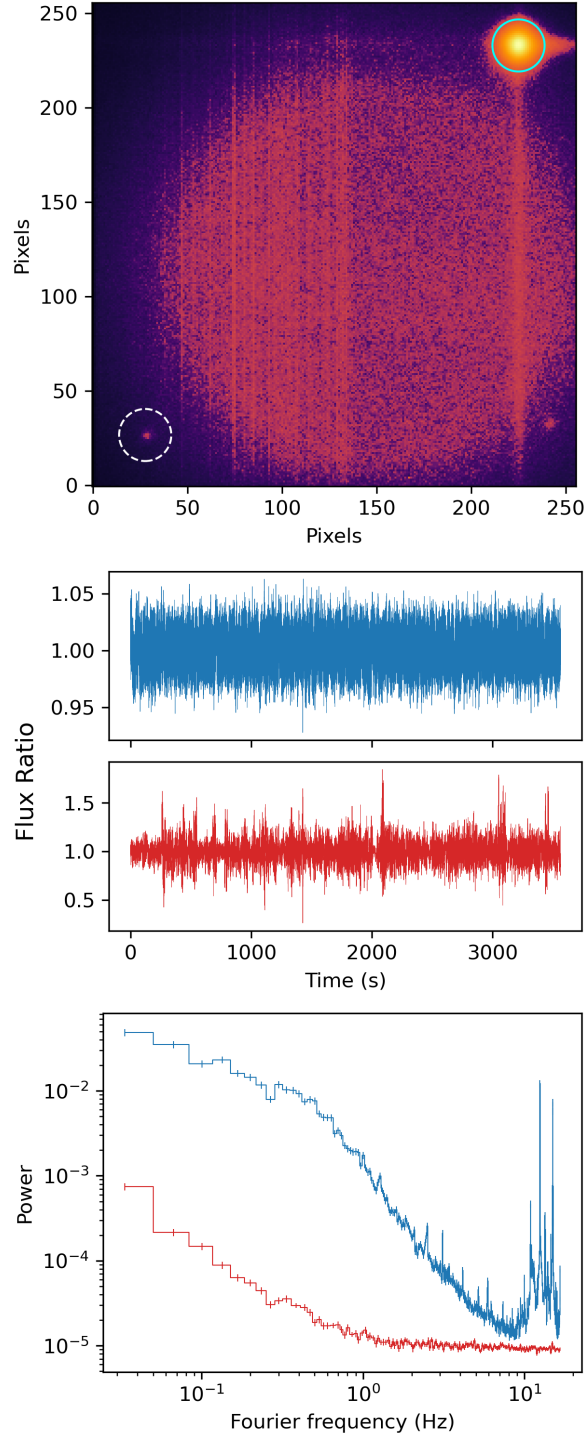


Figure 3.5: (*Top*) Reference image of Scorpius X-1 from the 13 Feb 2025 observation with the XRB (solid cyan) and a check star (dashed white) identified. (*Center*) The blue (*top*) and red (*bottom*) optical lightcurves for this observation, with corresponding insets displaying the lightcurves of a single 30 s data interval. (*Bottom*) The averaged PDS in the blue and red filters generated from the lightcurves in the *center* panel.

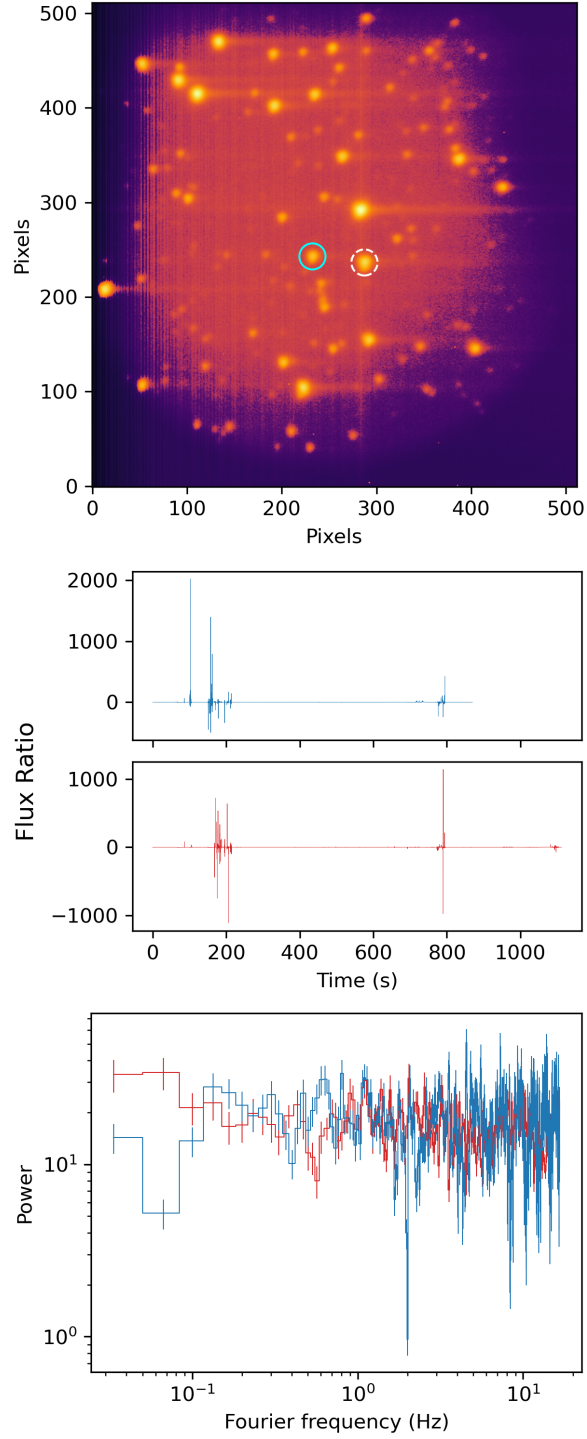


Figure 3.6: (*Top*) Reference image of Aquila X-1 from the 20 Sep 2024 observation with the XRB (solid cyan) and a check star (dashed white) identified. (*Center*) The blue (*top*) and red (*bottom*) optical lightcurves for this observation, with corresponding insets displaying the lightcurves of a single 30 s data interval. (*Bottom*) The averaged PDS in the blue and red filters generated from the lightcurves in the *center* panel.

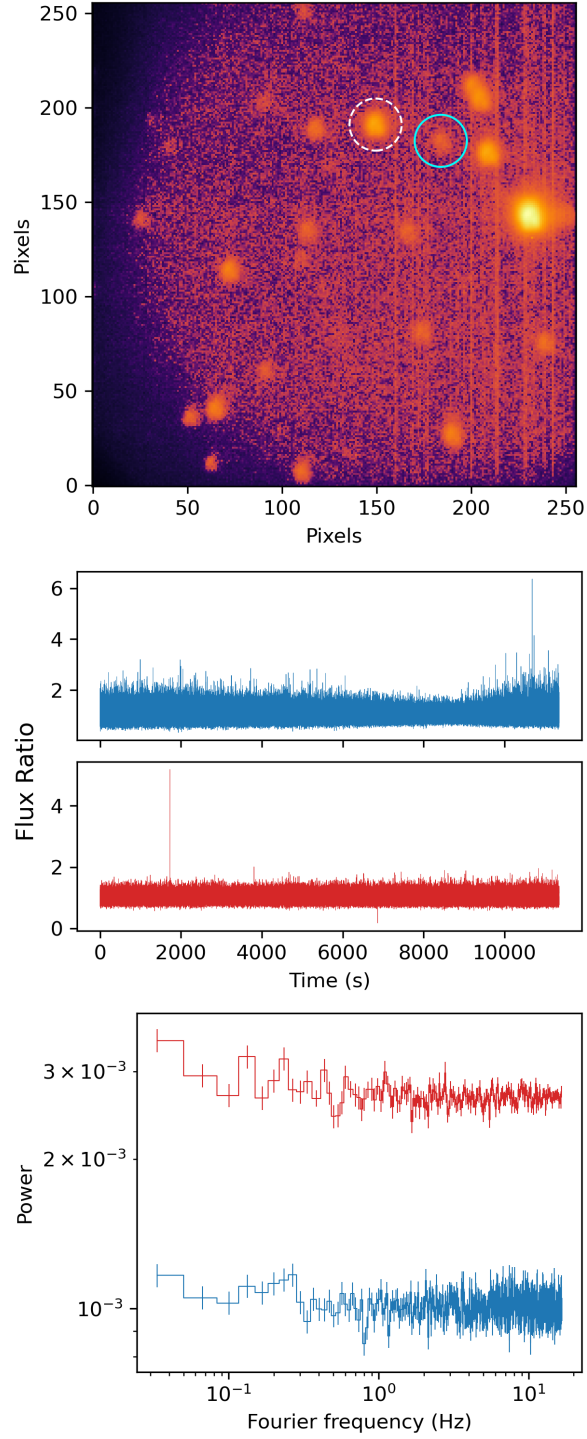


Figure 3.7: (*Top*) Reference image of 4U 1608–52 from the 11 Mar 2025 observation with the XRB (solid cyan) and a check star (dashed white) identified. (*Center*) The blue (*top*) and red (*bottom*) optical lightcurves for this observation, with corresponding insets displaying the lightcurves of a single 30 s data interval. (*Bottom*) The averaged PDS in the blue and red filters generated from the lightcurves in the *center* panel.

Chapter 4

Discussion and Conclusion

While the pipeline in its current iteration functions on a fundamental level, able to extract intensities from a set of observations to build lightcurves and compute their PDS, there are still some pitfalls that must be addressed in order to produce consistent results suitable for scientific inference and publication.

4.1 World Coordinate System Inaccuracies

A major obstacle in the development of the pipeline was overcoming the challenges posed by inaccurate World Coordinate System (WCS) information in the raw data file headers. The WCS defines the exact position in the sky that a particular image covers. This information is encoded in two key values provided in the raw data header information; the telescope sky pointing position (right ascension and declination) and the plate scale (the correspondence between a pixel in the image and its angular size in the sky). Ideally, the WCS can be used to automatically create an aperture of a particular radius around a target with a known right ascension and declination. However, this information is not correct in the raw data files. Figure 4.1 shows two apertures drawn on a reference image for GX 339–4; one created from the information in the raw data headers (red) and one drawn manually based on a finding chart (cyan). The two apertures do not match. As a result of this inaccuracy, the pipeline uses image registration techniques to ensure that subsequent apertures could be accurately drawn atop the target XRB and comparison star, relative to the reference image of the observation night (from which the apertures for that night were initialized).

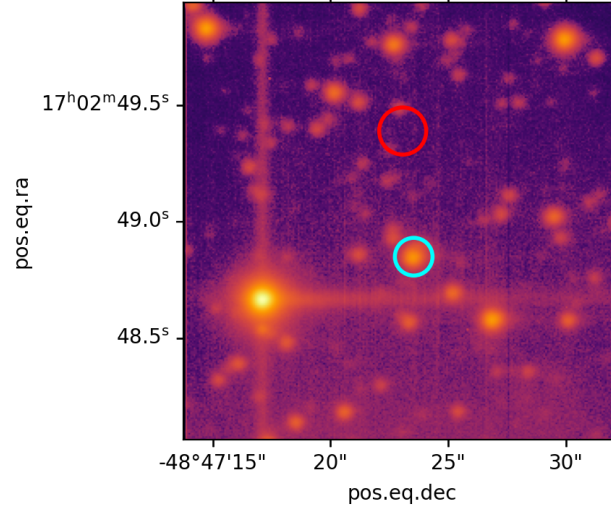


Figure 4.1: A reference image of GX 339–4 for the 12 September 2025 observation plotted using the WCS information encoded in the raw data headers. The red aperture is the target aperture created using WCS header information, while the cyan aperture is the user-defined aperture that was created by the pipeline.

With accurate WCS information, such techniques would not have been necessary, allowing for more streamlined aperture creation using sky coordinates directly.

4.2 Drifting Field of View

Another issue encountered in the pipeline development was a drifting field of view between image frames in the raw data files. There is only one header for a particular raw data file, so any positional information defined in the header applies to every frame in the corresponding 30 s exposure data cube. Therefore, if the field of view shifts in position during the 30 s exposure of a data cube, then any aperture drawn will be off target. The same image registration techniques used to correct the WCS inaccuracies were able to handle this effect in the pipeline.

4.3 Background Subtraction

The background subtraction methods used in the pipeline estimate the background emission level of an image and subtract it so that the intensity measured within an aperture more accurately reflects the target emission level. The `photutils` package methods take globally background subtracted data as inputs. This is opposed to local background subtraction, where instead an annular aperture is drawn around the target to better estimate the background closer to the target. This local method is only possible in situations where there are no other stars close to the target. While some of our target fields fall into this category (see for example Figure 4.1), making local background implausible (as an annular aperture would encompass emission from many surrounding stars), others could benefit from the option to perform a local background subtraction procedure.

Additionally, the pipeline currently creates a single background image model for every 30 s raw data cube, and not each individual 30 ms frame in the raw data cube. This method was chosen for its computational efficiency; calculating and subtracting the background per frame has proved to be computationally expensive, greatly increasing the time needed for the pipeline to process large observational data sets. However, for fainter sources, this can result in measured emission intensities that are near zero or even negative after background subtraction. In turn, this sometimes produces extreme intensity ratio values (e.g., Figure 3.6). To try and minimize the effects of dividing by near-zero values, while preserving relative computational speed, the pipeline scales the background image model per frame by a factor equal to the ratio of the median value of the frame to that of the background image model. However, this is not a complete workaround, as extreme values still occasionally occur in the lightcurves.

4.4 Complex Data Quality

The field of Scorpius X-1 presents several data challenges that the current version of the pipeline struggles to overcome. In particular, Scorpius X-1 is incredibly bright and

exists in a very sparse stellar field. As a result, Scorpius X-1 can be saturated in some frames, leading to unusable data. The outlier rejection criteria implemented in the pipeline attempts to address this issue. Further, Scorpius X-1 can drown out the emission from the comparison star, making it difficult to detect both objects in a single frame. Without a comparison star, the pipeline defaults to instead using a comparison aperture drawn in an emission free region of the image. Both of these pipeline fixes can not fully address the Scorpius X-1 issues, as evidenced by the odd PDS features in Figure 3.5.

4.5 Future Work and Conclusions

In its current state, the pipeline serves as a foundation on which further developments and improvements can be made to produce scientific results that serve the goals of the *GOFAST-XRB* program.

The first main goal of the *GOFAST-XRB* program is to produce a comprehensive census of the optical variability of XRBs in the Galaxy. The output that the pipeline currently produces is of mixed quality, with some observational data sets yielding clean lightcurves and PDSs that can be used for further investigation, while other data sets yield erratic or unexpected results that require further refinement before sound scientific inference is possible. Ultimately, key improvements that need to be made to the pipeline to consistently produce reliable data products and achieve this first goal include:

- A more robust and computationally efficient background subtraction method (to produce better behaved lightcurves without enhanced computational time).
- Working with the Gemini observatory to understand the origin of the inaccurate WCS information in the raw data headers (to allow for automatic target identification and aperture creation, eliminating the need for manual source detection and image registration).
- Implementing new methods to isolate fainter emission sources in the images (e.g.,

point spread function subtraction to recover useful information from frames affected by saturation issues in Scorpius X-1).

Despite the current shortcomings of the pipeline, interesting preliminary scientific results have been observed. For example, differences can already be seen between optical variability properties of XRBs driven by BHs vs NSs, and hints of evolution in optical variability properties of a single object with accretion state have also been observed. To further investigate these preliminary findings, the time-domain analysis portion of the pipeline also needs to be expanded. In particular, the addition of a cross-correlation analysis can provide more information by quantifying the casual relationship between the two optical filter signals, and measure any time-lag between the two signals. A function (making use of the `stingray` Python package tools) for this purpose exists in a rudimentary state within the pipeline, but remains untested.

The second main goal of the *GOFAST-XRB* program is to track how the variability signal propagates from inflow to outflow in XRBs. With lightcurve, PDS, and cross-correlation capabilities in the pipeline, the X-ray time-series observations portion of the *GOFAST-XRB* program (taken simultaneously with the Gemini optical observations) can then be incorporated into the analysis procedure. As X-ray emission probes the accretion flow and optical emission probes the jet, a comparison of PDSs and a cross-correlation between optical/X-ray time-series signals could help establish a connection between the different emission regions. Overall, this new information will provide further insight into the dynamics of XRBs and shed light on the behavior of matter in extreme, high energy and high gravity environments that are not reproducible on Earth.

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