Accretion Flows and Neutron Star Heating
in Low-Mass X-ray Binaries

by

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B.A., University of California, Berkeley (2010)

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Abstract

X-ray binaries are excellent test beds for studies of high-energy accretion flows and the properties of compact objects. Neutron star (NS) low-mass X-ray binaries (LMXBs) vary in brightness by almost 8 orders of magnitude and are hosts to diverse accretion flows, transporting varying amounts of energy and mass toward the central NS, as well as expelling significant mass from the binary. This thesis aims to shed light on the accretion flow properties across the mass and luminosity scale, with particular emphasis on constraining the matter accreted on the neutron star surface and the resulting heating, which has important implications for measurements of the NS mass and radius. We have utilized X-ray instruments with substantially different sensitivities in flux and resolving power, each suited to our focused study of the accretion flow in a particular luminosity regime.

In our study of the accretion disk wind in GX 13+1, we analyzed the Chandra High-Energy Transmission Grating spectrum of the NS binary accreting near its Eddington limit. We found multiple plasmas with different ionization states and velocities produce the observed absorption complex, in contrast to previous analyses that only found one absorption zone. The accretion disk wind expels mass from the disk at a rate comparable to the accretion onto the NS, and is consistent with a Compton-heated outflow, the driving mechanism likely behind all accretion disk winds in NS LMXBs and, possibly, all BH LXMBs. Frequent monitoring with the Swift X-Ray Telescope allowed us to observe SAX J1750.8-2900 in the relatively short-lived transition between outburst and quiescence. We found its X-ray spectrum softens towards lower luminosities, which can either be due to a radiatively-inefficient accretion flow or an increasing contribution of the boundary layer emission as the source’s flux decreases. This work contributes to the establishment of spectral softening as a common property of the accretion flow in NS LMXBs between outburst and quiescence. We also found the transition does not produce significant NS heating.

In our studies of NS LMXB quiescent emission, we utilized an XMM-Newton observation of Cen X-4 while the source was at its brightest quiescent luminosity ever recorded. We found the first evidence of multi-temperature thermal emission in a
non-pulsing quiescent NS. We have interpreted the hotter of the two thermal components as a potential hotspot on the NS surface, indicative of a magnetically channeled accretion flow and motivation for further studies into NS heating in quiescence. Finally, we present the results from a recent XMM observation of the extremely faint system SAX J1810.8-2609. We find that the thermal component is consistent with a cooling NS radiating heat from nuclear reactions activated during outburst. We also present a revised estimate of the time-averaged mass accretion rate based on a more detailed outburst history and a range of outburst properties, finding the outburst history is in agreement with the quiescent thermal luminosity and discounting assertions of enhanced cooling mechanisms in the NS of SAX J1810.8-2609.

Thesis Supervisor: Deepto Chakrabarty
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I would like to dedicate this thesis...

To my parents who have unconditionally supported and encouraged my academic endeavors. They instilled a lifelong love of learning in all of their three daughters.

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Chapter 1

Introduction

X-rays are produced by some of the hottest ($10^6-8$ K) environments in the Universe. Through X-ray observations we can study extreme astrophysical phenomena across a vast parameter space of size and density. At low densities ($n < 10^9$ cm$^{-3}$), we can probe stellar coronae and the intergalactic medium. At the other end of the density spectrum are X-ray binaries. This thesis focuses on a subset of X-ray binaries called low-mass X-ray binaries, which consist of a compact object, either a neutron star (NS) or black hole (BH), in a binary with a stellar companion less massive than the Sun. The outer layers of the companion become gravitationally unbound and the material is transferred to the compact object via an accretion disk. These binaries have multiple sources of X-rays, including the accretion disk itself and coronae that form around the central object. LMXBs with NSs have even more potential sources of X-ray emission due to the presence of the NS surface and magnetic field. A boundary layer and polar caps are the result of the accretion flow interacting with the NS surface and can produce X-rays. Even in the absence of continuous accretion, NS LMXBs are expected to produce thermal X-ray radiation as their surfaces radiate heat deposited in the NSs during intense accretion episodes.
1.1 Low-Mass X-ray Binaries

Low-mass X-ray binaries contain a NS or BH in orbit with a low-mass ($\lesssim 1 \, M_\odot$) companion. NSs and BHs are both products of the evolution of massive stars. Stars are supported by the radiation and gas pressure produced by nuclear reactions in their interiors, primarily the fusion of hydrogen into helium which releases $\sim 25 \, \text{MeV}$ per reaction. For stars with initial masses of $M \gtrsim 7 \, M_\odot$, at the end of their lifetime their core has undergone multiple stages of nuclear burning, fusing atoms into heavier and heavier elements until an iron core is formed.

The iron nucleus has one of the highest binding energies per nucleon (8.8 MeV), and no energy can be released upon subsequent fusion of iron and heavier nuclei. The battle between pressure and gravity is lost, and the star undergoes a complete collapse in a violent explosion known as a supernova (SN). Depending on the progenitor’s initial mass, the end product of the SN is either a neutron star or black hole. For massive stars with $M \sim 7 - 12 \, M_\odot$, their collapsed cores resist total collapse due to support provided by nuclear forces. The resulting object has a radius of $\sim 5 - 15 \, \text{km}$, and a typical mass of $1.4 \, M_\odot$. NSs have an upper mass limit of $\sim 3 \, M_\odot$ set by the transition where neutrons become relativistic and degeneracy pressure can no longer support the NS. More massive stellar progenitors ($M \gtrsim 12 \, M_\odot$) have collapsed cores that are too massive to be supported by neutron degeneracy pressure. The SN results in a singularity, known as a black hole. BHs produced through SN have masses in the range of 5 to tens of solar masses.

Post supernova, the hot NS remnant has a core temperature of $\sim 10^{11} \, \text{K}$; the proto-neutron star cools via neutrino emission from its interior and photon emission from its surface. After $10^5$ years, a young NS in isolation can still be detected in the soft X-rays down to luminosities of $L_X \sim 10^{32} \, \text{erg s}^{-1}$, but it will continue to cool and eventually produce insignificant radiation (see Page et al. 2004). If the compact object’s massive progenitor was originally in a binary with a low-mass companion or the compact object is captured by a low-mass star in a dense stellar environment, such as a globular cluster, the compact object can form a low-mass X-ray binary with
Figure 1-1: The NS mass-radius relationship predicted by several different theories for the NS equation-of-state. The upper left corner of \((M, R)\) values is ruled out due to the causality constraint. The lower right portion rules out \((M, R)\) values for NSs whose centrifugal force will exceed its own gravity, resulting in the break-up of the NS. PSR J1614-2230 is a NS LMXB with a white dwarf companion and is host to one of the most massive NSs known \((M = 1.97 \pm 0.04 \, M_\odot\), Demorest et al. 2010). This image was created by the LOFT proposal team\(^1\).

The companion. These systems emit considerable radiation as the NS and material accreted onto the NS are heated to temperatures \(\sim 10^6\) K, which correspond to X-ray wavelengths. The low-mass companions are not associated with significant X-ray emission, as they are low-mass stars, either on the main sequence or newly evolved red giants, but may also be stellar remnants themselves, known as white dwarfs.

### 1.1.1 The NS Equation of State

LMXBs are the product of many astrophysical phenomena and provide opportunities to study accretion physics, binary interactions, the NS spin evolution, and stellar evolution. Additionally, a whole field is focused on measurements of the NS mass and radius. Because the NS mass-radius relation depends only on the ultra-dense matter equation of state (EOS) a precise measurement of a NS’s mass and radius (to within

\(^{1}\text{http://sci.esa.int/loft/} \)
10%) can place strict constraints on the EOS, see Figure 1-1. As NSs are the densest objects in the Universe and their core densities \( \rho \gtrsim 10^{15} \text{ g cm}^{-3} \) cannot be created in terrestrial labs, the NS mass-radius relation may be the only way to understand matter at such high densities (see Glendenning [2000], Lattimer and Prakash [2001], Baldo and Burgio [2012] for a review).

The dense matter EOS is relatively well-understood at densities \( \rho \lesssim 10^{15} \text{ g cm}^{-3} \); nuclear physics experiments measuring nuclear masses, the neutron skin thicknesses (i.e. the layer of neutrons surrounding heavy nuclei) and heavy-ion collisions have been useful in constraining the low-density EOS, but at higher densities the EOS is largely unknown. Loose constraints on the EOS have been made through causality restrictions (the speed of sound within the NS must be less than the speed of light), hydrodynamical stability (the NS must be stable against gravitational collapse), and the current best estimates of the NS mass range. The most massive NS observed has a \( M \sim 2 \, M_\odot \), while the minimum NS mass is believed to be \( \sim 0.8 \, M_\odot \) based on our understanding the supernova progenitor mass requirements (see Özel et al. 2012 for a review of NS birth masses).

Figure 1-2 provides a look into the NS interior. Once the ultra-dense matter EOS has been identified, we will finally know what form of matter exists deep within the NS core. Through dynamical and timing measurements of pulsars in binaries that take advantage of general relativistic effects sensitive to the NS mass, several dozen NS masses have been precisely measured (see Thorsett and Chakrabarty [1999] for an overview). Precise measurements of the NS radius, however, have proven difficult. In Sections 1.3 and 1.4.1.1, we will explore two methods for mass-radius measurements unique to NSs in LMXBs.

### 1.1.2 Roche-lobe Overflow

Not all binaries with a low-mass and a high-mass star will form a LMXB. The binary must survive the initial SN of the massive star that produces the NS or BH, and the orbital separation must be significantly reduced (by a factor of \( \sim 100 \)) in order for

\(^2\)https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_about.html
mass transfer to occur. In LMXBs, the compact object accretes from its companion via Roche-Lobe overflow.

The condition for Roche-lobe overflow requires a look at the gravitational potential of a binary with two masses, $M_1$ and $M_2$, separated by distance $a$. To determine the force on and the subsequent motion of a nearby test mass, $m$, it is best to use the corotating coordinates shown in Figure 1-3. The gravitational potential per unit mass due to $M_1$ and $M_2$ is given by

$$\Phi = -G \left( \frac{M_1}{s_1} + \frac{M_2}{s_2} \right) - \frac{1}{2} \omega^2 r^2,$$

where $r_1$ and $r_2$ are the respective distances of $M_1$ and $M_2$ from the center-of-mass located at the origin and $\omega$ is the orbital angular frequency (i.e. $\omega = \frac{2\pi}{P}$ where $P$ is the orbital period). The derivative of the potential ($d\Phi/dx$) is the force on the test mass. Points where $d\Phi/dx = 0$, i.e. where the net force on the test particle is zero, are known as Lagrange points. Contours of equipotential surface (i.e. $\Phi$ has the same
Figure 1-3: The origin in this coordinate system is the center of mass (COM) between two objects $M_1$ and $M_2$, themselves separated by a distance $r_1 + r_2 = a$. A test mass, $m$, is located at distance $R$. We can use this coordinate system to map out the effective gravitational potential.

Figure 1-4: The contours in this plot are equipotential surfaces which are points with the same gravitational potential, $\Phi$, value. The two objects in this binary have a mass ratio $q = M_2/M_1 = 0.4$. The $L_1$, $L_2$, and $L_3$ Lagrange points are unstable equilibrium points; if a test particle is displaced from $L_1$, for example, it will accelerate away from $L_1$ in the direction of displacement.
value) are plotted in Figure 1-4. The inner Lagrange point, \( L_1 \), is a unique point in the binary. Matter at \( L_1 \) is bound to the binary system, but is not specifically bound to either \( M_1 \) or \( M_2 \). The distance from the primary NS, with mass \( M_1 \), is given by:

\[
\ell_1 = a \left[ 0.500 - 0.227 \log_{10} \left( \frac{M_2}{M_1} \right) \right].
\] (1.2)

In LMXBs, the secondary companion’s stellar envelope extends beyond, or overflows, its Roche Lobe, the equipotential surface surrounding the star. Once the stellar material passes through the \( L_1 \) point, it becomes bound to the compact object and moves towards the NS.

Photoimaging and spectroscopic optical studies of LMXBs can reveal the nature of the companion, including its mass and spectral type. LMXBs are just one subclass of X-ray binaries; high-mass X-ray binaries (HMXBs) contain a NS or BH in a binary system with a high-mass companion (\( > 10M_\odot \)). Most of these systems do not undergo mass-transfer via Roche-lobe overflow. Rather, the compact objects are wind-fed via the companion’s powerful stellar wind. Despite the commonality of a compact object and stellar companion, these objects have significantly different spectral and timing properties compared to LMXBs. They are relatively short-lived systems (\( \sim 10^{5-7} \) years) due to the short lifetime of the massive companion and as a result, the NSs’ magnetic fields have not evolved significantly from their nascent values. Thus, their magnetic fields remain high (\( B \sim 10^{12} \) G) and the magnetic field channels accretion flow onto the NS; most of the NSs in HMXBs are detected as accretion-powered pulsars. We will not discuss HMXBs in further detail as this thesis only contains detailed studies NS LMXBs. We will now simply refer to NS LMXBs as LMXBs and will specify ‘BH LMXBs’ if the discussion turns to properties of LMXBs with BHs.

### 1.1.3 Accretion Physics

The stellar material passing through the inner Lagrange point, \( L_1 \), possesses both energy and angular momentum, which prevents it from falling radially onto the NS. The material orbits the central object, forming a ring of material known as an accre-
tion disk in the plane determined by the binary's orbital angular momentum. The material in the accretion disk loses energy and angular momentum via viscous torques and turbulence. The energy released via accretion is equal to the change in the potential energy from a particle located at infinity brought to the neutron star's surface. Accretion is an extremely efficient process; it releases more energy per unit mass than nuclear fusion, $\eta_{\text{acc}} \sim 0.2$ vs $\eta_{\text{nuc}} \sim 0.007$, where $\Delta E = \eta mc^2$.

One can calculate the temperature profile of the disk and find that the characteristic disk temperature depends on the mass of the NS, its radius and the accretion rate of the material through the accretion disk onto the NS, $T \propto (M_{\text{NS}} \dot{M}/R_{\text{NS}}^3)^{\frac{1}{4}}$. For a NS ($M = 1.4 \, M_\odot$, $R = 10 \, \text{km}$) accreting at a rate of $10^{17} \, \text{g s}^{-1}$, this corresponds to a disk temperature of $10^7$ Kelvin ($\sim 900$ eV), which corresponds to $\lambda \sim 15 \, \text{Å}$, X-ray wavelengths. One can also calculate the temperature of a thermalized blackbody at a comparable luminosity with the same size of a NS has a temperature in the $10^6-8$ K range, which shows these objects emit primarily at X-ray wavelengths. Half of the energy produced via accretion, $L_{\text{acc}}$, is released in the accretion disk while the other half is released in the immediate vicinity of the NS as the matter reaches the NS surface.

$$L_{\text{acc}} = G \frac{M \dot{M}}{R} \tag{1.3}$$

The maximal mass transfer rate from the low-mass companion to the NS is set by the binary parameters (masses, radii, and orbital separation). The maximal accretion rate onto the compact object, however, is limited by the NS's mass and the composition of the accreted material. The accretion energy released through photons exerts outward force on the infalling material, primarily through Thomson scattering of electrons. The Eddington luminosity corresponds to the accretion rate when radiative pressure produced by the accretion luminosity exceeds the inward gravitational attraction of the infalling material, preventing further matter from being accreted:

$$L_{\text{Edd}} = \frac{8\pi GMm_p c}{(1 + X)\sigma_T} \tag{1.4}$$
where $\sigma_T$ is the Thomson cross-section ($6.7 \times 10^{-25}$ cm$^{-2}$) and $X$ is the hydrogen mass fraction. For a NS, the Eddington luminosity is $\sim 2 \times 10^{38}$ erg s$^{-1}$. Equating the Eddington luminosity to the accretion luminosity (Eqn. 1.3) we can estimate the corresponding Eddington mass accretion rate:

$$M_{\text{Edd}} = 1.8 \times 10^{-8} \left( \frac{R}{10 \text{km}} \right) \left( \frac{1 + X}{1.7} \right)^{-1} M_\odot \text{ yr}^{-1}. \quad (1.5)$$

NS LMXBs spend most of their lifetimes accreting at rates nowhere near their Eddington luminosities or even at a significant fraction of the Eddington limit ($1 - 10\% \Rightarrow 10^{36-37}$ erg s$^{-1}$). Most LMXBs are transients, where the accretion rate onto the NS varies by 8 orders of magnitude (see Liu et al. 2007). These systems exhibit periods of intense accretion known as outburst with characteristic luminosities $L_X = 10^{36-38}$ erg s$^{-1}$. Outbursts typically last weeks to months or even years in the case of persistent accretors and recurrence timescales are on the order of $1 - 50$ years (see e.g. White and van Paradijs [1996] for a review). Most transients spend the majority of their duty cycle in periods of low or negligible accretion onto the NS ($\dot{M} < 10^{-15} M_\odot \text{ yr}^{-1}$) known as quiescence. Quiescent states generally last years but may also extend for several decades. As the accretion rate onto the NS varies significantly between outburst and quiescence so do the X-ray spectra. Outburst spectra are dominated by emission from the inner accretion disk, hot coronae, and a boundary layer. While quiescent spectra do not show direct evidence of the accretion flow, the observed emission is indicative of ongoing accretion and also display thermal emission from the accretion-heated NS surface.

### 1.2 Accretion Disk Instability Model

The mechanism likely behind the luminosity changes in transient LMXBs, including BH and NS systems as well as white dwarf cataclysmic variables (CVs), is known as the disk instability model (DIM) [Osaki, 1974, Hoshi, 1979, Cannizzo et al., 1988, van Paradijs, 1996]. It is a result of the high-temperature dependence of hydrogen ionization and recombination, resulting in an accretion disk that is unstable in the
5000 – 1000 K temperature range (depending on the radial distance from the center). The accretion disk alternates between ‘hot’ and ‘cold’ states where hydrogen is either fully ionized or neutral; the transition is captured in a S-curve diagram, shown in Figure 1-5. In the ‘cold’ state of quiescence, hydrogen is neutral and the disk opacity and viscosity are low. The inward drift of material is slow and mass accumulates in the outer disk; the accretion disk’s surface density, defined as \( \Sigma \) with units g cm\(^{-2}\), increases. The accretion disk is heated as more matter accumulates. Eventually, the surface density reaches the critical value, \( \Sigma_{\text{max}} \), where the disk is hot enough such that hydrogen starts to become ionized. The transition to a fully ionized disk is rapid. The disk’s viscosity suddenly increases, triggering a sudden flux of material through the accretion disk towards the central NS. The onset of outburst is correlated with the accretion disk transition. Eventually, all of the hydrogen is ionized and the disk reaches a temperature and surface density on the ‘hot’ equilibrium branch \( \gtrsim 7500 \text{ K} \). The light curve for a transient NS LMXB is shown in Figure 1-6; the outbursts are the spikes in the RXTE ASM count rate. In outburst, the X-ray flux is about about a million times greater than in quiescence.

Of course, the quiescence-outburst cycle is not so simple in reality. To match the observed quiescent flux levels, the outburst durations and recurrence times, additional factors including disk self-irradiation, disk truncation, and the thin disk transition to a radiatively-inefficient accretion flow must be taken into consideration or invoked.

1.3 NS LXMBs in Outburst

Soft X-rays from accreting compact objects in X-ray binaries were first discovered with the launch of rockets equipped with Geiger counters [Giacconi et al., 1962]. Over the following 50 years, X-ray telescopes have evolved to reach extraordinary flux sensitivities as well as angular and energy resolution. While in outburst, NS LMXBs evolve between states with different luminosities and spectral and timing properties. Atoll sources follow a hysteresis path in the variability-luminosity space similar to BH transients, as shown in Figure 1-7. They begin outburst in spectrally
Figure 1-5: The surface density vs effective temperature relation for a thin, hydrogen disk. Points corresponding to $dT/d\Sigma < 0$ are unstable. Once $\Sigma_{\text{max}}$ is reached, the disk rapidly becomes ionized, the viscosity increases and material moves quickly through the disk. The image is taken from Lasota [2016].

Figure 1-6: An $RXTE$ ASM light curve of NS LMXB 4U 1608-52 from October 1995 to March 2012. Major outbursts in 1998, 2002 and 2010 are indicated. The source spends most of its time in the faint state of quiescence. The image is taken from Lei et al. [2014].
Figure 1-7: A cartoon generalization of luminosity-variability phase space occupied by NS LMXBs in outburst. NS LMXBs can be classified either as atoll or Z sources. The atoll sources in outburst evolve along the path marked by the thin grey line encircling the ‘A’ label, while Z sources occupy the region in the upper left corner. Soft states for both atoll and Z sources are typically radio quiet, while the strong radio emission in the hard spectral states is associated with jet synchrotron radiation. The image is taken from Muñoz-Darias et al. [2014].

hard, variable states, increasing in luminosity until they transition to the bright soft state; eventually their luminosity decreases and they enter a low, hard state before returning to quiescence. Z sources, in the top left corner, are much brighter (accreting at $> 0.5 \frac{L_X}{L_{Edd}}$ throughout outburst), exhibit less variability and have much softer spectra. Strong radio emission has also been detected in the hard states, which indicates highly-collimated outflows, known as jets, are active, while the soft spectral states are associated with outflows known as accretion disk winds (Ponti et al. 2014; see Fender and Muñoz-Darias 2016 and Russell et al. 2011, Ponti et al. 2012 for overviews of jets and winds in BH LMXBs).

Figure 1-8 is a cartoon depicting a NS LMXB in outburst. The accretion disk extends close to the NS surface, and the luminosity is dominated by the bright inner disk as well as boundary layer emission, where the accretion flow meets the NS surface. Outflows drive mass from the binary system through energetic jets or a wind launched
Figure 1-8: An artist's rendition of a LMXB, which traces the flow of material from the low-mass companion to the central compact object. In outburst, the X-ray luminosity is dominated by emission from the inner accretion disk and the volume immediately surrounding the compact object which may contain a corona or a boundary layer. Image credit - Robert Hynes.

from the outer accretion disk. The stream-impact point is where the accretion flow of the companion meets the accretion disk. In high-inclination systems, this point can obscure the accretion disk, creating periodic dips in the light curve [White and Swank, 1982].

Gaining an accurate picture of the NS LMXB outburst states is critical to understanding the objects at significantly lower accretion rates. In particular, accreting NS exhibit several characteristic outburst phenomenon that help identify the LMXB compact object as a NS, as well as offering methods to measure the NS properties, including the spin, magnetic field, mass and radius.

Across a wide range of accretion rates, nuclear burning of accreted material on the NS surface is unstable [Hansen and van Horn, 1975, Bildsten, 1998, Strohmayer and Bildsten, 2006]. Runaway helium burning on the NS surface of weakly magnetic stars \((B < 10^{10} \text{ G})\) produces bright X-ray flashes, known as type I X-ray bursts. During the brief
bursts (lasting 10s of seconds), the X-ray luminosity increases by over 2 orders of magnitude (see Lewin et al. [1993] and Galloway et al. [2008] for a review). As this type of burst depends on the existence of a physical surface, detection of a type I X-ray burst from a transient LMXB is evidence that the system is host to a NS, as opposed to a BH.

In a subset of X-ray bursts, the outward force of the radiation produced by the nuclear burning exceeds the local Eddington limit. The outer layers of the NS expand while the flux remains near the critical Eddington value; these events are known as photospheric radius-expansion (PRE) bursts. To first order, the peak burst flux is related to the NS mass and radius as well as the distance to the object, so type I X-ray bursts are potentially useful phenomenon to constrain all 3 parameters [van Paradijs, 1979, Paczynski, 1983, Kato, 1983]. In reality, the burst characteristics also depend on the composition of the accreting material, the NS core temperature and the presence of burning ashes from recent bursts amongst other accretion parameters, which requires more extensive modeling and correction factors in order to obtain accurate mass-radius constraints. Figure 1-9 compares the flux and blackbody radius and temperature evolution in a PRE and non-PRE bursts.

1.4 NS LMXBs in Quiescence

Studies of LMXB quiescent behavior has only been made accessible with the relatively recent launch of X-ray telescopes with significant soft X-ray sensitivity (< 5 keV) and low backgrounds, including Roentgensatellit (ROSAT, 1990), Advanced Satellite for Cosmology and Astrophysics (ASCA, 1993), Chandra (1999) and XMM (1999). With the first detection of quiescent NS LMXBs at luminosities \(10^{31-32}\) erg s\(^{-1}\), it was unknown whether one was detecting emission from the NS surface, an accretion flow surrounding the compact object, or even the low-mass stellar companion [Rutledge et al., 1999, Lasota, 2000].

Chandra and XMM have particularly advanced the study of quiescent LMXBs. It has been revealed that most quiescent NS LMXBs exhibit a combination of thermal
Figure 1-9: The panels on the left are for a PRE burst in NS LMXB 4U 1636+536 [Galloway et al., 2006]. The blackbody radius increases as the outer layers of the NS expand rapidly. The non-PRE burst (on the right) does not exhibit the double-peaked temperature profile or the blackbody radius expansion.

and nonthermal radiation (see Figure 1-10) with the relative contributions varying significantly from source to source. Some quiescent LMXBs have purely thermal spectra [Heinke et al., 2003], while others are entirely nonthermal [Campana et al., 2002, Heinke et al., 2009]. The thermal emission is commonly interpreted as direct emission from the NS surface.

1.4.1 NS Surface Emission

During outburst, matter is accreted onto the NS, compressing the upper layers of the NS interior, stimulating density-sensitive pycnonuclear reactions and electron capture in the NS crust; the reactions release \( Q_{\text{nucl}} = 1.5 - 2 \) MeV of heat per accreted baryon [Haensel and Zdunik, 1990a, 2008]. This process is known as deep crustal heating (DCH). As long as some fraction of the deposited heat (on the order of 0.01 to 1) is not radiated via neutrino cooling but rather heats the NS interior, these reactions can maintain a core temperature of \( T_C \sim (5 - 10) \times 10^6 \) K [Brown et al., 1998]. Even after accretion stops, the NS surface will thermally radiate at a luminosity proportional
Figure 1-10: Quiescent NS LMXB spectra typically exhibit thermal and nonthermal components, each contributing ~ 50% to the total flux. Above is the 0.5 – 10 keV luminosity versus the fractional contribution of the powerlaw component to the total flux. The powerlaw flux fraction tends to increase below luminosities of $10^{32}$ erg s$^{-1}$. SAX J1808.4-3658 has an entirely nonthermal spectrum, while some globular cluster sources (plotted as black circles) have nonthermal flux fractions < 10%. The image is taken from Jonker et al. [2004a].
the time-averaged outburst mass accretion rate, $\langle \dot{M} \rangle$. This radiation has been proposed as the origin of the thermal emission in quiescent LMXBs, $L_{\text{NS,q}}$:

$$L_{\text{NS,q}} \sim 9 \times 10^{32} \frac{Q_{\text{nucl}}}{1.5 \text{ MeV}} \times \frac{\langle \dot{M} \rangle}{10^{-11} \text{M}_\odot \text{yr}^{-1}} \text{erg s}^{-1},$$

where $10^{-11} \text{M}_\odot \text{yr}^{-1}$ is a typical time-averaged accretion rate of a transient NS LMXB [Rutledge et al., 2002].

In addition to cooling via photon emission from the surface, NSs cool significantly via neutrino emission. "Fast" cooling via the direct Urca process has a high density threshold ($\rho > 10^{15} \text{ g cm}^{-3}$) that may only be reached in the inner NS core. Additionally, this cooling mechanism requires a significant proton fraction which depends heavily on the NS EOS (see Shapiro and Teukolsky 1986, Yakovlev and Pethick 2004). The direct Urca cooling reactions are as follows:

$$n \rightarrow p + l + \bar{\nu}_l, \quad p + l \rightarrow n + \nu_l$$

where $n$ is a neutron, $p$ is a proton, $l$ is a lepton and $\nu_l$, $\bar{\nu}_l$ neutrinos and antineutrinos. "Slow" cooling processes include the modified Urca and nucleon-nucleon bremsstrahlung, which are believed to be the dominant cooling mechanisms in NSs [Pethick, 1992]. The modified Urca reaction is given by:

$$n + N \rightarrow N + p + l + \bar{\nu}_l, \quad p + N + l \rightarrow n + N + \nu_l,$$

where $N$ is either a proton or nucleon. A particular cooling model for NSs depends on the relative contributions of the neutron emission processes (fast versus slow), which in turn will depend on the assumed NS composition and structure. Cooling models with larger contributions due to "fast" cooling will have shorter cooling timescales and result in colder NSs.

Figure 1-11 shows the expected quiescent NS luminosity for heating via DCH and cooling via different models. Overall, there is good agreement between observations and the heating/cooling predictions, which supports the interpretation that the quiescent thermal luminosity is associated with DCH and cooling occurs through "slow"
Figure 1-11: The NS thermal luminosity, $L_{\text{NS}}$, in quiescence versus its time-averaged mass accretion rate for over a dozen NS LMXBs. Standard cooling models, indicated by the dotted cooling curve, only includes "slow" neutrino emission processes [Pethick, 1992]. Some NSs in LMXBs, such as 1H 1905+000, have luminosities so low that can only be explained if significant cooling via "fast" neutrino emission processes are active in the NS interior. This image is taken from Heinke et al. [2010].

Some NS appear too cool given estimates of their outburst history, which means that either the accretion rate has been overestimated or enhanced (i.e. "fast") cooling processes are active in some NS interiors.

### 1.4.1.1 Quiescent Spectral Modeling

NS quiescent thermal emission is a product of its outburst history and the heating and cooling mechanisms, which depend heavily on the NS composition and EOS. The thermal emission in quiescent NS LMXB was first modeled with a blackbody, but this yielded high temperatures and small blackbody radii ($< 1$ km) leading to the emission being interpreted as accretion hotspots on the NS surface. While a NS surface is expected to radiate like a blackbody, the emission is processed by a thin hydrogen atmosphere (scale height, $H \sim 1$ cm), shifting and distorting the emergent
Figure 1-12: NS atmosphere models for non-magnetic NSs with effective temperatures in the 4 – 270 eV range. The pure hydrogen NS atmosphere model is given by the dotted-dashed line, while the dashed and solid lines are spectra for NS atmospheres with helium and iron atmospheres. The blackbody spectrum at the same effective temperature is indicated with the dotted line. This image is taken from Zavlin et al. [1996].

NS atmosphere spectral models include variable surface gravity, an opacity due to free-free absorption and Thomson scattering, and general relativistic effects such as self-irradiation [Heinke et al., 2006, Zavlin et al., 1996]. Figure 1-12 compares model spectra for NS with different compositions versus a blackbody model at the same effective temperature. The most notable effect is that the NS atmosphere models produce much broader spectra, shifted towards higher temperatures. An important consequence of the atmospheric modeling is that the spectra are dependent on the NS mass and radius, which opens the door to make mass and radius measurements with quiescent LMXB observations.

NS quiescent spectral modeling has been incredibly successful at producing mass and radius constraints, with error bounds approaching 10% for NSs of LMXBs located in globular clusters [Guillot et al., 2011, Guillot et al., 2013]. Observations of the same NS LMXB in outburst and in quiescence can lead to two independent measurements of the NS mass and radius, via PRE burst and quiescent spectral modeling. An example of this technique is shown in Figure 1-13, which shows mass and radius constraints for the NS in Aql X-1. While NS atmosphere models have worked well
Figure 1-13: Mass-radius contours obtained from modeling the cooling tail of PRE bursts in NS LMXB Aql X-1 (plotted in black) and quiescent spectral modeling (plotted in red). Different EOS theories are indicated by the solid green and black curves. This image is taken from Li et al. [2017].

to model the soft X-rays in quiescent NS LMXBs, the mechanism that heats the NS (i.e. DCH) cannot explain the significant nonthermal radiation also seen in quiescent LMXB spectra (see Campana et al. 2002, Heinke et al. 2009). The thermal emission has also been found to be variable on short (100s of seconds) and long (year) timescales [Cackett et al., 2010, Bernardini et al., 2013]. DCH only allows for variability in the thermal emission between outbursts and not on short timescales. Both of these shortcomings have raised doubts as to whether a NS heated via DCH is the only source of thermal quiescent emission in NS LXMBs.

1.5 X-ray Instruments

The work featured in this thesis has made use of a number of X-ray telescopes. In this section, we present an overview of several X-ray telescopes, detailing their advantages, such as energy resolution or effective area.

Most of the X-ray telescopes launched in the past 20 years use grazing incidence
mirrors to focus the X-rays onto a focal plane. The X-rays are incident at a low angle (several tens of arcseconds to several degrees) from the plane of the mirror; the mirrors are then organized in concentric shells forming a Wolter telescope design. The X-ray detectors often make use of charge-coupled devices (CCDs), which are primarily made of silicon. An incident X-ray photon is absorbed in the silicon, resulting in the ejection of a number of electrons proportional to the absorbed photon energy. The normal advantages associated with CCDs apply to X-ray detectors, including their high-quantum efficiency and linear response. The disadvantages are tied to their relatively low time-resolution. Long read-out times (>ms) exclude most CCD observations from being used in timing analyses of LMXBs, which require sub-millisecond time resolution. Additionally, CCDs are subject to pile-up, which is when two or more photons are incident at the same time and are read as a single event with an energy equal to the sum of the two incident photons’ energies; this has the effect of reducing the observed flux and distorting the spectral energy distribution. Fortunately, pile-up can be reduced by observing a target off-axis or reducing the read-out time by limiting the number of CCDs illuminated during the observation. Additionally, spectral models have been developed that allow the observer to quantify the level of pile-up in an already completed observation and ameliorate the pile-up distortions on the continuum model parameters.

1.5.1 Soft X-ray Telescopes

1.5.1.1 The Chandra X-ray Observatory

The Chandra X-ray Observatory [Weisskopf et al., 2002] was launched in 1999 July as NASA’s successor to the Einstein Observatory. Designed with a lifetime of 5 years, the telescope is still in operation today at high-capacity 18 years after launch. The satellite is on an elliptical high-Earth orbit with a 64-hour period, which allows for uninterrupted observations with durations as long as 48 hours.

The focal plane of the High-Resolution Mirror Assembly (HRMA) has two main X-ray detectors: the High-Resolution Camera (HRC) and the Advanced CCD Imaging
Figure 1-14: The *Chandra* ACIS CCDs have 1024 × 1024 pixel lay-out covering 8.3'' × 8.3'', which corresponds to an array size of 16.9'' × 16.9'' for ACIS-I and 8.3'' × 50.6'' for ACIS-S.

Spectrometers (ACISs). ACIS consists of two CCD arrangements, one 2 × 2 imaging array (ACIS-I) and one 1 × 6 spectroscopy array (ACIS-S), shown in Figure 1-14, and an effective area of over 600 cm² at 1.5 keV integrated over the point-spread-function (PSF). Read-out times range from 3.2 seconds down to 2.8 ms depending on the observation mode. ACIS-S is often used in conjunction with the High-Energy Transmission Gratings [Canizares et al., 2005], which include the High-Energy Gratings (HEG) and the Medium-Energy Gratings (MEG). The HEG and MEG have wavelength resolution (Δλ) of 0.0012 Å and 0.0023 Å, as well as peak wavelength sensitivities in the 1.2-15 Å and 2.5-30 Å ranges, respectively.

1.5.1.2 The X-ray Multi-Mirror Mission

The X-ray Multi-Mirror Mission (*XMM*) was launched by the European Space Agency (ESA) 1999 December. Similar to *Chandra*, it is on a highly eccentric orbit with a period of ~ 48 hours and is still operating today in 2017.

It is primarily an X-ray focusing telescope with 3 Wolter type-1 mirrors, but also
Figure 1-15: The XMM-Newton observatory system. The X-ray mirrors are on the left of the image and at the right end is the Focal Plane Assembly (FPA). The FPA includes the 2 MOS cameras and the pn camera, as well as the Reflect Grating Spectrometer (RGS) cameras. The reflection grating is located near the mirror assembly. XMM’s field of view is 30” × 30”. Image credit: ESA

has an optical/ultraviolet telescope called the Optical Monitor (OM). The European Photon Imaging Cameras (EPIC) are the main instruments, consisting of the pn camera and two MOS cameras. The pn and MOS cameras have 12 and 6 CCDs, respectively, and a combined effective area of nearly 2500 cm² at 1.5 keV. While XMM’s effective area is significantly larger than Chandra’s making it superior to observe faint objects, its poorer angular resolution (∼ 6” compared to Chandra’s subarcsecond resolution) makes it ill-equipped for some X-ray observations, such as the dense cores of globular clusters. The pn and MOS cameras have sensitivities in the 0.15 – 15 keV range with an energy resolution ∼ 75 eV (FWHM).

XMM also has the Reflection Grating Spectrometer (RGS), that can produce high-resolution low-energy spectra in the 5 – 35 Å range (∼ 0.35 – 2.5 keV). The two reflection grating arrays (RGA) are located in the mirror assembly while the RGS cameras are located in the Focal Plane Assembly (FPA); each camera consists of a linear array of 9 CCDs.
1.5.1.3 The *Swift* X-Ray Telescope

The *Swift* telescope [Gehrels et al., 2004], a part of the *Swift Gamma-Ray Burst Mission*, was launched 2004 November. It is a multi-wavelength observatory aimed at detecting gamma-ray bursts and monitoring their gamma-ray, X-ray, UV and optical afterglows. Unlike *Chandra* and *XMM*, *Swift* primarily performs continuous scans on the sky but also can be used for pointed observations. The spacecraft is on a low-Earth orbit with a period of ~96 minutes.

For studies of X-ray binaries, the Burst Alert Telescope (BAT) and X-ray Telescope (XRT) are the most relevant instruments onboard *Swift*. The BAT has a large FOV and high-energy sensitivity across the 15-150 keV range suited to detecting new bursts. Within seconds of detecting an event, the instrument calculates the burst’s position on the sky and then directs the spacecraft for further pointed observations. The XRT is an X-ray focusing telescope with a single CCD detector (600 × 600 pixels), an effective area of 100 cm$^2$ at 1.5 keV, and an energy range of 0.2 – 10 keV. It has a 23.6’ × 23.6’ FOV. As an event’s sky-position determined by the BAT can have a relatively large error, the XRT’s FOV needs to be substantially larger than *Chandra’s* or *XMM’s*. Figure 1-16 compares the γ-ray and X-ray event positions for several different satellites, including *Swift* XRT.

1.6 Organization of Thesis

This thesis contains detailed studies of four NS LMXBs, GX 13+1, SAX J1750.8-2900, Cen X-4 and SAX J1810.8-2609. We track accretion flows from the brightest outburst luminosities to the faintest quiescent levels. Our investigation begins with a persistently accreting source at $L_X \sim 0.5 \, L_{\text{Edd}}$, and then turns to a source transitioning from outburst to quiescence ($L_X = (0.1 \to 10^{-4} \, \text{Edd})$). In our studies of quiescent systems, we focus on a NS LMXB that is occasionally extremely bright, Cen X-4 with $L_X \sim 10^{-5} \, \text{Edd}$, and another, SAX J1810.8-2609, that is faint in quiescence, $L_X \sim 10^{-6} \, \text{Edd}$. 
Figure 1-16: *INTEGRAL* and *Fermi-LAT* localization of γ-ray emission, plotted in black and light purple, from a γ-ray loud eclipsing NS LMXB. The *Swift* BAT error radius is plotted in red, while the *Swift* XRT position of the X-ray emission is indicated in orange. The *Swift* XRT position agrees well with the hard X-ray detection by *NuSTAR*. The image is taken from Strader et al. [2016].

- Chapter 2: The Accretion Disk Outflow in GX 13+1. We examine the nature and role of the accretion disk wind in the NS LMXB GX 13+1, a unique source that exhibits evidence of simultaneous disk wind and jet outflows. This work was completed in collaboration with Norbert Schulz, Jeroen Homan and Joseph Neilsen.

- Chapter 3: Spectral Softening Between Outburst and Quiescence in SAX J1750.8-2900. We tracked SAX J1750.8-2900 between its outburst and quiescent states, looking for spectral trends that indicate what type of accretion flow is present. This work was performed under the guidance of Manu Linares and Jeroen Homan.

- Chapter 4: Multi-temperature Thermal Quiescent Emission in Cen X-4. We examined a bright quiescent observation that shows evidence of additional spectral components in its soft X-ray spectrum. Our improved quiescent modeling may indicate that the NS magnetic field can channel the quiescent accretion flow onto the magnetic poles. This work was carried out with the guidance of my advisor, Deepto Chakrabarty.
Chapter 5: Quiescent Thermal Emission from SAX J1810.8-2609. SAX J1810.8-2609 was an interesting target as it was a member of a group of objects with faint quiescent luminosities seemingly at odds with standard heating and cooling predictions. This work was completed with assistance from Mike Nowak, Jeroen Homan, and Deepto Chakrabarty.
Chapter 2

The Accretion Disk Outflow
in GX 13+1\textsuperscript{1}

Abstract

We present the analysis of \textit{7 Chandra} HETGS observations of the persistent neutron star low-mass X-ray binary GX 13+1 on its normal and horizontal branches. Across nearly 10 years, GX 13+1 is consistently found accreting at 50-70\% Eddington, and all observations exhibit multiple narrow, blueshifted absorption features, the signature of a disk wind, despite the association of normal and horizontal branches with jet activity. A single absorber cannot account for all 7 major disk wind features, indicating multiple absorption zones are present. Two or three absorbers can produce all of the absorption features at their observed velocity shifts and widths. In a two absorber picture, one ionization zone produces the iron absorption ($\log \xi=4.1$), while a lower ionization component ($\log \xi=3.2$) generates the Ar 18, S 16, Si 14 and Mg 12 Kα lines. With three absorption zones, one highly ionized absorber ($\log \xi \approx 4.3$) produces Fe 26 absorption, while 2 other less ionized absorbers ($\log \xi < 4$) blend to produce the Fe 25, Ca 20, and lower energy lines. Assuming the most ionized absorber reflects the physical conditions closest to the neutron star, we estimate a wind launching radius of $7 \times 10^{10}$ cm for an assumed electron density of $10^{12}$ cm\textsuperscript{-3}. This is consistent with the Compton radius and consistent with a thermally driven wind. Correlating the disk outflow properties along the \textit{RXTE} color-color diagrams, we find variations in the iron absorption features are likely driven by changes in the wind column density. We also find a broad iron emission line with $\sigma=0.1$-0.3 keV that is likely associated with emission from an accretion disk corona.

\textsuperscript{1}Adapted from the paper "The Disk Wind in the Neutron Star Low-Mass X-Ray Binary GX 13+1" by Jessamyn L. Allen, Norbert S. Schulz, Jeroen Homan, Joseph Neilsen, & Deepto Chakrabarty, \textit{ApJ}, submitted.
2.1 Introduction

Warm absorbers (partially ionized gas) are common to both black hole (BH) and neutron star (NS) low-mass X-ray binaries (LMXBs), identified through the narrow absorption features imprinted on the illuminating continuum. A group of warm absorbers have only been seen in sources with high-inclinations, indicating the absorbing material is associated with the accretion disk. In all BH LMXBs and a subset of the NS binaries, the absorption features are blueshifted [Ponti et al., 2012, Díaz Trigo and Boirin, 2013, 2016, Ponti et al., 2016]; the absorbing material forms an outflow known as an accretion disk wind. When blueshifts are not present, the absorber is in a static configuration and is commonly called an accretion disk atmosphere. Warm absorbers were first observed in active galactic nuclei (AGN) in the 1970s and later in X-ray binaries with the launch of ASCA in the 1990s [Ueda et al., 1998, Kotani et al., 2000]. The high-resolution gratings onboard Chandra and XMM subsequently revealed the complexity and ubiquity of the warm absorbers in LMXBs and, in the case of accretion disk winds, showed them to be a major component of the accretion picture [Neilsen et al., 2011, Ponti et al., 2012, Ponti et al., 2014].

The warm absorbers' ionized resonance features are most often transitions in highly ionized species of iron, including the Ka line of Fe 25 and Fe 26, although some sources' spectra exhibit over 90 absorption lines from transitions in dozens of ionized species, such as the BH binary GRO J1655-40 [Miller et al., 2006, Kallman et al., 2009]. A single absorption zone can often explain the absorption features, but in a number of sources, especially those with features other than iron lines, multiple absorption zones can more accurately reproduce the complex absorption signature. In the case of accretion disk winds, outflow speeds are typically in the range 300 – 1000 km s⁻¹, although ultrafast outflows with velocities of 0.01-0.04c have been reported [Miller et al., 2015, 2016a,b]. As the absorption features are only seen in high-inclination LMXBs (60° < i < 80° constrained by the presence of dips in light curves; Frank et al. 1987) and no significant line re-emission is observed, the absorbers are believed to have an equatorial geometry with a small opening angle or possibly
a bipolar geometry with strong stratification in density and/or ionization above the accretion disk plane [Díaz Trigo and Boirin, 2013, Higginbottom and Proga, 2015].

In BH LMXBs there is a strong correlation between mass outflow and the accretion state. Accretion disk winds detected via blueshifted absorption features are found almost exclusively in soft spectral states, when the accretion disk is optically thick and the spectrum is disk-dominated [Ponti et al., 2012]. Jets, detected via strong radio emission, are active in the hard spectral states, when the inner disk is believed to be optically thin and the spectrum has significant nonthermal emission. The blueshifted, narrow absorption features are also absent in hard states of high-inclination sources, suggesting the accretion disk wind is absent. There are, however, significant exceptions to the outflow-accretion state correlation; there is strong evidence that in at least 5 luminous disk wind sources, including BH LMXB GRS 1915+105, winds and jets are simultaneous in hard spectral states [Lee et al., 2002, Homan et al., 2016].

Neutron stars may show a similar correlation between accretion state and outflow [Ponti et al., 2014], but only 30% of high-inclination NS warm absorbers exhibit definite outflows [Díaz Trigo and Boirin, 2016]. In addition, neutron star LMXB outburst tracks are more varied than BHs [Muñoz-Darias et al., 2014], and several neutron stars are included in the subset of disk wind systems with possible simultaneous jets and winds [Homan et al., 2016]. NS LMXBs are classified by their behavior as atoll or Z sources, the latter of which are brighter ($L_X > 0.5 L_{Edd}$) and less variable. In general, NSs are softer than BHs in outburst, in part due to the thermal boundary layer emission, but even NSs show significant variety in spectral softness depending on their classification, with Z sources being much softer overall than atoll sources. These issues compound to make the outflow-spectral state correlation less obvious in NS LMXBs compared to BHs.

Radiation pressure, Compton heating, and magnetic forces can all launch outflows in accretion disk systems. In NS and BH LMXBs, the warm absorber plasmas are highly ionized, leaving too few transitions in the UV and the soft X-ray for line driving to be an effective wind launching mechanism [Proga and Kallman, 2015].
In a Compton-heated outflow\(^2\), the accretion disk is strongly irradiated by the central X-ray emitting region; beyond some point in the disk, the thermal velocity exceeds the local escape velocity, generating an outflow. Several BH LMXBs, including GRO J1655-40 and GRS 1915+105 [Miller et al., 2006, 2016b], have exhibited fast and/or dense outflows. Magnetorotational instabilities or magnetocentrifugal forces can launch winds very close to the central compact object, which can account for the high wind densities and large blueshifts. There is also the possibility that different wind driving mechanisms are active at the same time but dominate in different spectral states and/or luminosities [Neilsen and Homan, 2012, Homan et al., 2016], due to a hybrid wind-driving mechanism. For the brightest disk wind sources accreting at near-Eddington rates, radiation pressure on electrons should increasingly contribute to the wind driving in addition to the dominant mechanism [Proga and Kallman, 2002, Homan et al., 2016, Done et al., 2016].

Determining disk wind launching mechanisms and spectral state dependence have powerful implications beyond understanding disk wind properties. While disk winds are relatively slow outflows \((v < 0.01c)\), they can carry significant mass away from the binary, comparable to the accretion rate. High mass-loss rates can create accretion disk instabilities which may produce luminosity modulations or instabilities that may drive state transitions [Begelman and McKee, 1983, Shields et al., 1986], and may also be significant enough to alter binary and spin evolution timescales [Ponti et al., 2012]. A complete picture of outflows in stellar mass compact object systems will help understand accretion on much larger mass scales, including supermassive BHs in AGN which also exhibit powerful jets and winds.

2.1.1 NS LMXB GX 13+1

The neutron star low-mass X-ray binary GX 13+1 (also known as 4U 1811-171) is a bright, persistent accretor located in the Galactic bulge. It orbits an evolved late-type K5 III star [Fleischman, 1985, Bandyopadhyay et al., 1999] and has an estimated

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\(^2\)While Compton-heated winds are often called "thermally driven" winds, we will use "Compton-heated winds", or simply "Compton winds" to be explicit about the heating mechanism.
distance of $7 \pm 1$ kpc [Bandyopadhyay et al., 1999]. Studies of infrared and X-ray light curve modulations [Corbet et al., 2010, Iaria et al., 2014] as well as X-ray dips [D’Ai et al., 2014], support a binary orbital period of 24.7 days and highly-inclined orbit ($60 - 80^\circ$) [Diaz Trigo et al., 2012].

Originally classified as an atoll source [Hasinger and van der Klis, 1989], GX 13+1 was later re-classified as a Z source due to strong secular evolution of its color-color and hardness-intensity diagrams (CDs and HID), rapid movement along its CD & HID tracks, and variability levels, all behaviors consistent with other well-established Z sources [Homan et al., 1998, Fridriksson et al., 2015].

A warm absorber in GX 13+1 was first discovered by Ueda et al. [2001], made evident by an iron Kα absorption line in GX 13+1’s ASCA spectrum. Subsequent Chandra and XMM observations revealed a more detailed picture of the ionized material’s properties via its absorption imprinted on GX 13+1’s spectrum. Analyzing a set of XMM EPIC observations, Sidoli et al. [2002] reported Kα and Kβ absorption lines of Fe 25 and Fe 26, along with a Kα Ca 20 line. Despite large velocity shifts detected in several absorption features ($-3000$ to $-5000$ km s$^{-1}$), blueshifts were not detected in all absorption lines and the errors on the outflow velocity were large ($\pm 2200$ km s$^{-1}$). A Chandra HETGS observation in 2001 of GX 13+1 revealed the Kα lines from H-like Fe, Mn, Cr, Ca, Ar, S, Si and Mg as well as He-like Fe [Ueda et al., 2004]. The absorption lines shared a common blueshift of $\approx 460$ km s$^{-1}$, corresponding to an outflow velocity of $\approx 400$ km s$^{-1}$ when corrected for proper motion. The inferred mass outflow rate of the disk wind was determined to be comparable to the accretion rate ($\approx 10^{18}$ g s$^{-1}$), indicating disk winds are a significant component of the accretion process in GX 13+1.

Ueda et al. [2004] favored a radiation-driven outflow that develops at sub-Eddington luminosities for the accretion disk wind in GX 13+1. In later XMM RGS observations of GX 13+1 Díaz Trigo et al. [2012] found strong correlations between the hard flux and the warm absorber’s properties (column density and ionization), concluding the absorber was consistent with a Compton-heated disk wind.

Madej et al. [2014] analyzed all available Chandra gratings observations of GX
Table 2.1: *Chandra* HETGS Observations

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Obs. Date</th>
<th>Mode</th>
<th>Exposure (ks)</th>
<th>Count Rate (s⁻¹)</th>
<th>RXTE Color Diagram Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2708</td>
<td>2002 Oct 8</td>
<td>TE</td>
<td>29.4</td>
<td>14.1</td>
<td>Upper NB → NB/HB vertex (^a)</td>
</tr>
<tr>
<td>11815</td>
<td>2010 July 24</td>
<td>TE</td>
<td>28.1</td>
<td>14.5</td>
<td>Mid NB → Upper NB</td>
</tr>
<tr>
<td>11816</td>
<td>2010 July 30</td>
<td>TE</td>
<td>28.1</td>
<td>14.1</td>
<td>Lower HB → Upper NB</td>
</tr>
<tr>
<td>11814</td>
<td>2010 Aug 1</td>
<td>TE</td>
<td>26.8/28.1 (^b)</td>
<td>11.8/11.6</td>
<td>NB/HB vertex → upper HB</td>
</tr>
<tr>
<td>11817</td>
<td>2010 Aug 3</td>
<td>TE</td>
<td>28.1</td>
<td>13.4</td>
<td>NB/HB vertex → NB/FB vertex</td>
</tr>
<tr>
<td>11818</td>
<td>2010 Aug 5</td>
<td>CC</td>
<td>23</td>
<td>12.9</td>
<td>Lower NB → NB/HB vertex</td>
</tr>
<tr>
<td>13197</td>
<td>2011 Feb 17</td>
<td>CC</td>
<td>10.1</td>
<td>17.9</td>
<td>...</td>
</tr>
</tbody>
</table>

\(^a\) NB=Normal Branch, HB=Horizontal Branch, FB=Flaring Branch

\(^b\) Spectra filtered/unfiltered for dip event

13+1 in an attempt to measure orbital parameters using the disk wind, but were hindered by the intrinsic variability of the source and the wind. In this paper we present a re-analysis of the same set of archived Chandra HETGS observations with the primary goal of understanding the evolution of this wind. We test several continuum models, perform a detailed absorption line fitting and utilize RXTE data to track the disk wind properties throughout the system's color-color diagram. In contrast to previous studies that assumed a single absorber, we find that the disk wind must comprise of multiple absorption zones.

### 2.2 Observations

We have analyzed all 7 Chandra High Energy Transmission Grating Spectrometer (HETGS, Canizares et al. 2005) observations of GX 13+1, for a total exposure of approximately 190 ks. The observations span 10 years, with 5 of the observations taken during a 2 week time span in July and August 2010. Observations were taken in both timed exposure (TE) and continuous clocking (CC) modes with the Advance CCD Imaging Spectrometer S-array (ACIS-S). For TE mode observations, a 350-row subarray was used, yielding a 1.24 second frame time. In CC mode, spatial information is collapsed into 1 row, reducing the frame time to 2.85 msec.
Figure 2-1: Two of GX 13+1’s Z track CDs with the color-coded points corresponding to 6 of the Chandra observations that occurred simultaneously with RXTE monitoring. In several observations, including ObsID 11816, the source only moved slightly along the Z track during the course of the observation (from the lower HB to the upper NB), while in ObsID 11817 the source moved along the entire horizontal branch, from the NB/HB vertex to the NB/FB vertex.

The Chandra data were downloaded from the Chandra Data Archive\textsuperscript{3} and reprocessed using the TGCat [Huenemoerder et al., 2011] run\_pipe script with CIAO 4.9 [Fruscione et al., 2006] and CALDB 4.5.0 in ISIS\textsuperscript{4} version 1.6.2-30 [Houck and Denicola, 2000]. Our GX 13+1 HETGS data processed with CIAO 4.9 differs slightly from data processed with older version of CIAO due to changes in the correction for contaminant build-up on Chandra’s optical blocking filter. The most significant deviations approach the 10% level at long wavelengths (> 8 Å) for both the High Energy Grating (HEG) and Medium Energy Grating (MEG) first orders.

The zero-order position determines the absolute accuracy of the wavelength measurements. As GX 13+1’s zeroth order is significantly piled-up in TE mode observations, we cannot use a centroid calculation due to the distorted point spread function. We used findzo to calculate the zero-order position from the intersection of the MEG spectrum and the ACIS frame-shift streak, which provides a zero-order position accuracy of less than 0.1 ACIS-S detector pixels, corresponding to 0.001 Å for the HEG and MEG first orders. First-order redistribution matrix files (RMFs) and ancillary response files (ARFs) were created with the run\_pipe script.

\footnotesize{\textsuperscript{3}http://cxc.harvard.edu/cda/}

\footnotesize{\textsuperscript{4}http://space.mit.edu/cxc/isis/}
D’Aï et al. [2014] reported a dipping event approximately halfway through ObsID 11814. Dips have been associated with spectral changes in both the warm absorber and neutral absorption column [Díaz Trigo et al., 2006]. We removed the dip event and performed spectral analysis only on the non-dipping spectrum. We excluded a total of 1.05 ks to remove the dip itself as well as the ingress and egress based on times reported by D’Aï et al. [2014].

We used the AGLC script\(^5\) in ISIS to create the ACIS-S grating light curves and compute hardness ratios. Hardness ratios are defined as the number of hard counts (3-8 keV) divided by the number of soft counts (0.5-3 keV). The count rate varied on the level of 15%, but we found no significant changes in the source’s intensity or spectral hardness, so we analyzed observations whole, except for ObsID 11814 as stated above.

The Chandra HETGS observation details are listed in Table 2.1, along with the source’s position along its Z track during simultaneous RXTE observations; for ObsID 13197 there was no simultaneous RXTE coverage. GX 13+1 exhibits significant secular motion of its Z track on the timescales of days or longer. Fridriksson et al. [2015] organized the source’s RXTE data into 6 different color diagram (CD) tracks. Correlating the source’s RXTE position on the Z tracks during our Chandra HETGS observations, see Figure 2-1, ObsIDs 2708, 11815 and 11816 fall on one Z track that has less distinct branches [Homan et al., 2016]. GX 13+1 moved along the horizontal branch (HB) and normal branch (NB) on another Z track during ObsIDs 11814, 11817 and 11818.

2.3 Analysis & Results

All spectral analysis was performed within ISIS. Errors on fit parameters were calculated with conf_loop and correspond to the 90% confidence bounds (\(\sigma = 1.6, \Delta \chi^2 = 2.71\)). All quoted chi-squared values, \(\chi^2 (dof)\), are reduced. We used the model_flux ISIS tool to calculate (absorbed) fluxes and (unabsorbed) luminosities.

\(^5\)http://space.mit.edu/cxc/analysis/aglc/aglc.html
Luminosities for the 0.5-10 keV and 8-10 keV energy bands are calculated assuming a distance of 7 kpc. The Eddington fraction \((L_X/L_{Edd})\) assumes an Eddington luminosity, \(L_{Edd}\), of \(2 \times 10^{38}\) erg s\(^{-1}\) for a 1.4 \(M_\odot\) NS with a hydrogen-rich photosphere.

While the HEG has twice the spectral resolution as the MEG and experiences less pile-up, our spectral analysis benefited from the additional MEG counts. Continuum and line parameters were better constrained when both HEG and MEG first orders (±1) were used\(^6\). ObsID 13197 was a CC mode calibration observation; two arms (MEG −1 and HEG +1) fell of the CCD, leaving only the MEG +1 and HEG −1 orders.

### 2.3.1 Continuum Fitting

#### 2.3.1.1 ISM Absorption

The neutral absorption column towards GX 13+1 is known to be large, with published values in the range of \(N_H = (3 - 5) \times 10^{22}\) cm\(^{-2}\) \((N_{H,22} = 3 - 5\); Ueda et al. 2001, Schulz et al. 2016). We used the absorption model \(tbnew\) v2.3, with the abundances set to those of Wilms et al. [2000] and the cross-sections set to Verner et al. [1996].

We fit all 5 TE mode Chandra HETG observations jointly with a \(diskbb+bbodyrad\) continuum, modified by the \(tbnew\) ISM absorption as well as a pile-up model (see 4.3.3) and absorption features modeled by negative gaussians. For a range of fits with the continuum parameters left free or tied between observations, we obtained column densities between \(N_{H,22} = 4.6 - 5.0\). To avoid degeneracies in continuum parameters when fitting the low-energy (< 2 keV) portion of the spectrum, we fixed the \(tbnew\) hydrogen column density for GX 13+1 to the value of \(N_{H,22} = 4.8\) for all future fits.

We also found the reduced \(\chi^2\) value was always improved when the silicon abundance in \(tbnew\) was allowed to vary, yielding silicon overabundances between 1.8-2.1, with an average value of 2.0. The required silicon abundance is due \(tbnew\)'s incomplete modeling of the Si K-edge [Schulz et al., 2016]. Additional structure in the Si

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\(^6\)The only exceptions are the Fe 26 and Fe 25 absorption lines and the broad iron emission line, for which we excluded the MEG due to its low effective area at 7 keV.
K-edge, i.e. the near and far edge absorption is apparent, including a line at 1.865 keV likely associated with a moderately ionized plasma in GX 13+1. We did not attempt to model the silicon edge beyond allowing for the overabundance in \( tb_{\text{new}} \).

### 2.3.1.2 Pile-up

As GX 13+1 is bright (\( \approx 0.2 \) Crab) and 5 of the 7 observations were taken in TE mode, spectra can suffer from significant pile-up. Pile-up has effects of energy and event grade migration that reduce the total source count rate and distorts the observed spectral shape\(^7\). We used the ISIS convolution model \texttt{simple_gpile2} to quantify and mitigate the pile-up effects [Nowak et al., 2008, Hanke et al., 2009]. The maximum pile-up fraction for a gratings arm is given by: 

\[ P_{\text{max}} = 1 - e^{-\beta C_{\text{max}}} \]

where \( C_{\text{max}} \) is the maximum spectral count rate and \( \beta \) is the pile-up model parameter. The TE mode observations experienced peak pile-up at 3 Å (\( \approx 4.1 \) keV) and global pile-up fractions of 10-20%.

While the CC mode observations have a significantly shorter frame time making pile-up essentially negligible, they do not help us quantify the pile-up effects on the continua of the TE mode observations due to contamination by an X-ray scattering halo. GX 13+1 is highly absorbed and the CC mode continua include the dispersed scattering halo, which is difficult to model.

### 2.3.1.3 Continuum Models

We fit the uncombined HEG and MEG \( \pm 1 \) orders with matched spectral grids across the 1.65 - 9 Å (1.4 - 7.5 keV) range, corresponding to a resolution of 0.023 Å across our energy band. Each bin contained a minimum of 20 counts which allowed us to use \( \chi^2 \) statistics.

The GX 13+1 \textit{Chandra} continuum was consistent with multiple model prescriptions as the large ISM absorption (\( N_{\text{H,22}} > 1 \)) reduces the soft X-ray sensitivity

\(^7\)http://cxc.harvard.edu/ciao/download/doc/pileup_abc.pdf
Table 2.2: Continuum Parameters for DiskBB+BB and BB+PL models

| ObsID | Si Abund | BB kT (keV) | BB norm (km²) | Disk T_in (keV) | Disk Norm (km²) | F_0.5-10/F_8-10/BBa | L_0.5-10/L_8-10b | \( \chi^2 \) (dof) |
|-------|----------|-------------|---------------|----------------|-----------------|---------------------|-----------------|----------------|-----------------|
| 2708  | 2.1 ± 0.1| 2.17 ± 0.17 | 6 ± 2         | 1.59 ± 0.15    | 130 ± 9         | 0.032/0.031 0.018/0.021 | 6.97/0.93 0.24 | 6.95/0.57 1.16 (5871) |
| 11815 | 2.1 ± 0.1| 1.81 ± 0.07 | 17 ± 1        | 1.44 ± 0.01    | 177 ± 8         | 0.025/0.027 0.017/0.017 | 7.02/0.87 0.36 | 7.12/0.53 1.14 (5871) |
| 11816 | 2.1 ± 0.1| 2.13 ± 0.11 | 11 ± 1        | 1.42 ± 0.01    | 179 ± 39        | 0.023/0.025 0.016/0.015 | 7.15/1.03 0.39 | 7.16/0.63 1.17 (5871) |
| 11814 | 2.0 ± 0.1| 1.85 ± 0.04 | 21 ± 1        | 1.22 ± 0.01    | 226 ± 14        | 0.024/0.025 0.019/0.017 | 5.99/0.87 0.56 | 6.00/0.53 1.14 (5871) |
| 11817 | 2.0 ± 0.1| 1.90 ± 0.08 | 13 ± 1        | 1.55 ± 0.01    | 121 ± 13        | 0.023/0.026 0.017/0.016 | 6.79/0.91 0.34 | 6.67/0.56 1.14 (5871) |

| ObsID | Si Abund | BB kT (keV) | BB norm (km²) | \( \Gamma \) | PL norm (km²) | \( \beta \) | \( \beta \) | F_0.5-10/F_8-10/BBb | L_0.5-10/L_8-10b | \( \chi^2 \) (dof) |
|-------|----------|-------------|---------------|----------|-------------|----------|----------|---------------------|----------------|----------------|-----------------|
| 2708  | 1.9 ± 0.1| 1.03 ± 0.02 | 210 ± 9   | 1.72 ± 0.03 | 1.52 ± 0.03 | 0.034/0.034 0.020/0.024 | 7.19/1.12 0.40 | 7.35/0.69 1.16 (5871) |
| 11815 | 1.9 ± 0.1| 1.02 ± 0.02 | 226 ± 9   | 1.75 ± 0.03 | 1.57 ± 0.03 | 0.028/0.029 0.020/0.020 | 7.26/1.08 0.42 | 7.55/0.66 1.15 (5871) |
| 11816 | 1.9 ± 0.1| 1.00 ± 0.02 | 199 ± 11  | 1.66 ± 0.03 | 1.53 ± 0.02 | 0.025/0.027 0.018/0.018 | 7.37/1.22 0.33 | 7.53/0.75 1.17 (5871) |
| 11814 | 1.8 ± 0.1| 1.01 ± 0.03 | 135 ± 9   | 1.65 ± 0.03 | 1.25 ± 0.03 | 0.028/0.030 0.024/0.022 | 5.91/1.01 0.31 | 6.03/0.62 1.15 (5871) |
| 11817 | 1.8 ± 0.1| 1.05 ± 0.02 | 181 ± 8   | 1.64 ± 0.03 | 1.29 ± 0.03 | 0.026/0.028 0.019/0.019 | 7.04/1.12 0.40 | 7.01/0.69 1.14 (5871) |

*aBlackbody fraction of the 0.5-10 keV flux

*bLuminosities are corrected for absorption.
Figure 2-2: Combined HEG & MEG ± 1 orders for all 5 TE mode observations (data plotted in black) fit with a disk plus blackbody continuum and gaussian absorption features (shown in red). The continuum model without simple gpile2, plotted in blue, shows how the spectrum would appear without pile-up. The disk and blackbody contributions are plotted in green and orange, respectively. The low-wavelength residuals in the iron region (< 2 Å) can be improved with a broad emission line when only the HEG data are fit. Additional structure in the silicon edge is seen in the residuals near 6.6 Å.
and limits our ability to distinguish between continuum models. We found the diskbb+bbbodyrad and bbodyrad+powerlaw continuum models, the most common models for NS LMXBs accreting at high rates, performed equally well. The continuum parameters can be found in Table 5.1. We explored single-component continuum models, but a powerlaw or blackbody yielded poor fits ($\chi^2 > 2$); a pure multicolor disk (diskbb) with $T_{in} \approx 1.9$ keV worked very well, with only 2 of the 5 TE observations' fits improved by adding another component.

The accretion disk plus blackbody continuum fit to the TE mode observations is shown in Figure 2-2. In a multicolor disk plus blackbody model, the multicolor disk is the accretion disk while the blackbody is likely boundary layer emission from the NS. The blackbody temperature varies between 1.8 and 2.2 keV, and in the brighter observations ($F_{0.5-10} > 6 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$), the blackbody contributes 25 – 40% of the total flux. The multicolor disk has a lower temperature than the blackbody component and an emission area about 10× larger. While both the blackbody and disk exhibit changes in temperature and emitting area, the 0.5-10 keV absorption-corrected luminosity is relatively constant across all observations, $L_{X,0.5-10 \text{ keV}} \approx (6-7.2) \times 10^{37}$ erg s$^{-1}$. The 8-10 keV flux is also relatively constant in all observations, with slight variations between $(9-10) \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$. This means there is likely no significant change in the ionization state of the disk wind plasma associated with the iron absorption, which is the most sensitive to the hard flux ($> 8$ keV). In the Chandra observations, GX 13+1 is found at similar flux levels in the 1-10 keV range as the XMM observations of March and September 2008. Díaz Trigo et al. [2012] reported 2-10 keV unabsorbed fluxes $(8 - 10) \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$ while we observe GX 13+1 with 0.5-10 keV unabsorbed fluxes of $(10 - 12) \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$.

For a blackbody and powerlaw continuum, we interpret the blackbody as boundary layer emission and associate the nonthermal emission with an accretion disk corona (ADC). The blackbody temperature does not vary, while the emitting area decreases with the 0.5-10 keV luminosity; overall, the blackbody’s contribution to the flux remains in the 30 – 40% range in all observations.

We focus on the 2-component model diskbb+bbbodyrad model in our future contin-
uum prescription for GX 13+1. X-ray instruments with larger bandpasses, such as RXTE-PCA (3-40 keV) and XMM-EPIC (0.3-10 keV), find two components are necessary to fit GX 13+1’s 1.5-10 keV continuum [Díaz Trigo et al., 2012, Homan et al., 2016], with an additional powerlaw necessary to fit the high-energy (> 10 keV) spectrum.

2.3.2 Direct Line Fits

We first focused on known absorption features in GX 13+1’s spectrum, i.e. those identified by Ueda et al. [2004]. We combined all HEG and MEG $m = \pm 1$ orders using the ISIS combine datasets function. Using a powerlaw to fit the local continuum within $\pm 1$ Å of the line center, we fit a gaussian function to the absorption feature ignoring nearby absorption features and edges. Line shifts, turbulent velocities (computed from the gaussian FWHM) and equivalent widths (EWs) were calculated for each absorption feature in each observation. In the TE mode observations we note that pile-up has the effect of reducing an absorption feature’s EW due to the fact that the local pile-up fraction is proportional to the local count rate. This means that the local continuum is more suppressed relative to the absorption feature which reduces the observed EW. We do not attempt to correct our quoted EWs for pile-up.

Our gaussian line parameters are shown in Table 2.3. The Kα transitions of Fe 26, Fe 25, Ca 20, S 16, Si 14 and Mg 12 were detected in all of the Chandra HETG observations. The Kα Ar 18 is weakly present in ObsID 11816 and absent in ObsID 11814. The prevalence of absorption features in the GX 13+1 spectra is in contrast to the XMM observations analyzed in Díaz Trigo et al. [2012], where the only disk wind absorption features present are the the Kα and Kβ transitions of Fe 26 and Fe 25. The Chandra HETG observations lack the signal-to-noise above 8 keV to study the iron Kβ transitions, if present.

The Fe 26, Fe 25, S 16 and Si 14 equivalent widths across the 2 week observation period in July and August 2010 are shown in the top of Figure 2-3. The solid dashed
Table 2.3: Gauss line parameters

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Line</th>
<th>(v_{out}) km s(^{-1})</th>
<th>(v_{turb}) km s(^{-1})</th>
<th>EW eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2708</td>
<td>Fe-XXVI</td>
<td>610 ± 80</td>
<td>1210 ± 150</td>
<td>47.0 ± 3.0</td>
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<tr>
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<td>Fe-XXV</td>
<td>860 ± 160</td>
<td>1250 ± 280</td>
<td>23.0 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Ca-XX</td>
<td>550 ± 140</td>
<td>410 ± 210</td>
<td>2.7 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>Ar-XVIII</td>
<td>440 ± 180</td>
<td>210 ± 100</td>
<td>1.1 ± 0.4</td>
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<tr>
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<td>480 ± 70</td>
<td>450 ± 140</td>
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<tr>
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<td>Si-XIV</td>
<td>490 ± 50</td>
<td>460 ± 90</td>
<td>2.6 ± 0.3</td>
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<tr>
<td></td>
<td>Mg-XII</td>
<td>310 ± 160</td>
<td>600 ± 260</td>
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<tr>
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<td>Mg-XII</td>
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<td>370 ± 180</td>
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<td>1200 ± 170</td>
<td>40.0 ± 3.0</td>
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<td>810 ± 400</td>
<td>1.3 ± 0.7</td>
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<td>Ar-XVIII</td>
<td>530 ± 280</td>
<td>370 ± 180</td>
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<td>320 ± 160</td>
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<td>1.6 ± 0.5</td>
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<td>Si-XIV</td>
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<td>530 ± 140</td>
<td>2.2 ± 0.3</td>
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<tr>
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<td>Mg-XII</td>
<td>280 ± 290</td>
<td>540 ± 270</td>
<td>1.0 ± 0.5</td>
</tr>
<tr>
<td>11817</td>
<td>Fe-XXVI</td>
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<td>810 ± 180</td>
<td>33.0 ± 3.0</td>
</tr>
<tr>
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<td>Fe-XXV</td>
<td>590 ± 230</td>
<td>1240 ± 380</td>
<td>17.0 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Ca-XX</td>
<td>560 ± 290</td>
<td>200 ± 100</td>
<td>1.3 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>Ar-XVIII</td>
<td>280 ± 360</td>
<td>450 ± 220</td>
<td>1.1 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>S-XVI</td>
<td>390 ± 100</td>
<td>110 ± 50</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>Si-XIV</td>
<td>380 ± 50</td>
<td>330 ± 100</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>Mg-XII</td>
<td>320 ± 100</td>
<td>50 ± 20</td>
<td>0.8 ± 0.2</td>
</tr>
<tr>
<td>11818</td>
<td>Fe-XXVI</td>
<td>390 ± 100</td>
<td>530 ± 270</td>
<td>31.0 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Fe-XXV</td>
<td>810 ± 210</td>
<td>700 ± 350</td>
<td>15.0 ± 3.0</td>
</tr>
<tr>
<td></td>
<td>Ca-XX</td>
<td>510 ± 310</td>
<td>80 ± 40</td>
<td>1.9 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>Ar-XVIII</td>
<td>410 ± 380</td>
<td>470 ± 240</td>
<td>0.9 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>S-XVI</td>
<td>220 ± 340</td>
<td>1130 ± 570</td>
<td>2.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>Si-XIV</td>
<td>380 ± 70</td>
<td>240 ± 120</td>
<td>1.4 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>Mg-XII</td>
<td>410 ± 90</td>
<td>40 ± 20</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>13197</td>
<td>Fe-XXVI</td>
<td>870 ± 200</td>
<td>1210 ± 460</td>
<td>40.0 ± 7.0</td>
</tr>
<tr>
<td></td>
<td>Fe-XXV</td>
<td>880 ± 220</td>
<td>1280 ± 440</td>
<td>33.0 ± 6.0</td>
</tr>
<tr>
<td></td>
<td>Ca-XX</td>
<td>700 ± 150</td>
<td>450 ± 220</td>
<td>4.6 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>Ar-XVIII</td>
<td>420 ± 200</td>
<td>520 ± 260</td>
<td>2.7 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>S-XVI</td>
<td>490 ± 160</td>
<td>610 ± 310</td>
<td>3.1 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>Si-XIV</td>
<td>590 ± 60</td>
<td>400 ± 130</td>
<td>2.7 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>Mg-XII</td>
<td>400 ± 190</td>
<td>530 ± 260</td>
<td>1.5 ± 0.6</td>
</tr>
</tbody>
</table>
Figure 2-3: Top: The scaled equivalent widths of the Fe 26 (black), Fe 25 (green), S 16 (red), and Si 14 (blue) absorption features in the observations spanning 2 weeks in July-August 2010 (ObsIDs 11815, 11816, 11814, 11817 and 11818). The long-dashed lines show each absorption line’s EW in the 2001 observation (ObsID 2708); the dotted lines indicate values measured in the 2011 observation (ObsID 13197). Bottom: Line blueshifts calculated from gaussian fits to the Fe 26 absorption line (black) and an average blueshift of the S 16 and Si 14 lines (red). There is evidence of an offset between the faster iron lines and the slower silicon and sulfur lines, as well as a decrease in all the lines’ blueshifts between 30 July (ObsID 11816) and 5 August 2010 (ObsID 11818).
lines indicate the line’s EW in the 2001 observation (ObsID 2708) and the dotted line shows the line’s EW in 2011 (ObsID 13197). Despite the observations occurring almost 8 years apart, ObsID 2708 (8 October 2002) and ObsID 11815 (24 July 2010) exhibit all 4 major absorption features with almost identical EWs.

There is no clear timescale of variability, but there are significant changes in the absorption features’ properties between observations, which occur, at minimum, approximately 2 days apart. Between ObsIDs 11815 and 11816, separated by 6 days, the Fe 25, S 16, and Si 14 EWs all decrease while the Fe 26 EW is relatively constant. If all of the observed absorption features are produced by a single absorption zone, this trend in the EWs requires that the plasma’s ionization state increases along with a decrease in the column density; this would allow the Fe 26 line EW to remain constant while producing a decrease in the S 16, Si 14 and Fe 25 EWs. Alternatively, if the Fe 26 absorption feature is produced by a different absorber than the lower ionization absorption features, this would imply that a decrease in the column density of the respective absorbing region could produce the observed decrease in the S 16, Si 14 and Fe 25 EWs while not necessarily producing any change in the Fe 26 EW.

We compared the blueshifts of the Fe 26 line and an average of the S 16 and Si 14 line shifts, shown in the bottom plot of Figure 2-3. The iron lines appear to exhibit larger blueshifts (500 - 1200 km s\(^{-1}\)) and turbulent velocities (1000 km s\(^{-1}\)) than absorption features with lower ionization energies, including S 16 and Si 14 (with \(v_{out} \approx 300 - 600 \text{ km s}^{-1}\) and \(v_{turb} \approx 300 - 550 \text{ km s}^{-1}\)). The trend in the turbulent velocities may be related to the decreasing spectral resolution at lower wavelengths in the iron region or may indicate distinct absorption zones with different outflow velocities and turbulent velocities in the disk wind. However, the error bounds on the velocities prevent us from claiming the existence of two kinematic components. We do see systematic changes in the outflowing plasma’s blueshift between observations. The average blueshift between the two sets of lines increases from \(\approx 675 \rightarrow 850 \text{ km s}^{-1}\) between 24 and 30 July (ObsIDs 11815 and 11816) while the average blueshift decreases to \(\approx 350 \text{ km s}^{-1}\) six days later (ObsID 11818).
2.3.2.1 Manganese and Chromium Lines

In the 2001 Chandra observation of GX 13+1 (ObsID 2708), Ueda et al. [2004] reported Mn 25 and Cr 24 absorption with equivalent widths of 3.6 and 4.1 eV, respectively. In our analysis of ObsID 2708, we were able to fit absorption features with EWs of $3.5 \pm 0.9$ and $3.4^{+0.9}_{-1.6}$ eV but we consider the manganese line consistent with noise. As ObsID 2708 exhibits similar continuum parameters and fluxes as the other observations, we combined all TE mode HEG ±1 orders to increase the SNR in the 1.9 – 2.1 Å band, see Figure 2-4. No Mn 25 absorption is present, while a possible narrow ($\sigma < 0.005$ Å) Cr 24 line is observed at 2.088 Å; the line energy corresponds to a blueshift of $\approx 700$ km s$^{-1}$, which is consistent with the blueshifts we observed in the individual TE mode observations ($500 - 1000$ km s$^{-1}$).
2.3.2.2 Broad Iron Emission Line

Broad iron emission lines are common to both BH and NS LMXBs [White et al., 1986, Asai et al., 2000]. In NS binaries, possible origins include the inner accretion disk, an accretion disk corona, and an ionized accretion disk wind, the line broadened by relativistic, Compton scattering and electron down scattering mechanisms, respectively.

A broad iron emission line has previously been seen in the GX 13+1 spectrum with multiple X-ray instruments including ASCA, XMM-EPIC, RXTE-PCA and Chandra-HETGS [Asai et al., 2000, Ueda et al., 2001, Sidoli et al., 2002, Díaz Trigo et al., 2012, D'A1 et al., 2014]. A 1994 ASCA observation revealed an emission line with energy 6.42 ±0.08 keV, σ < 220 eV, and EW=19±8 eV [Asai et al., 2000, Ueda et al., 2001]. The emission line was statistically required in multiple XMM-EPIC observations, although the nearby Fe Kα absorption and the instrument’s low energy resolution made it difficult to constrain the line parameters. The emission line was variable, exhibiting energies in the range of 6.5-6.8 keV, σ=0.7-0.9 keV, and large equivalent widths of 100-200 eV [Sidoli et al., 2002, Díaz Trigo et al., 2012]. The broad emission line was found to be consistent with inner accretion disk atmosphere/coronal models, broadened by Compton scattering, but the correlation between the emission and absorption line equivalent widths suggest a common origin in the outer disk (i.e. an accretion disk wind).

An emission line was not statistically required for our continuum fits, but we did see an excess in positive residuals in the 6-7 keV (≈1.8-2 Å) range in the observations. We were able to constrain a gaussian emission line in our fits of the HEG spectrum (±1 orders) with the accretion disk component fixed to the values found in Section 2.3.1.3; see Table 2.4 for the emission line’s parameters. We note that the emission feature is best constrained in ObsID 11816, the brightest observation, with an EW of 20 eV, while the emission feature is weakest in the faintest observation (ObsID 11814), with an EW of 7 eV. Figure 2-5 shows the combined spectrum from the TE mode observations in the iron region with and without the emission feature. The
unreduced $\chi^2$ value decreased from 6920.4 (dof=5872) to 6791.4 (dof=5869) when the emission line was included in the continuum model, showing that the iron line feature improved the fit. We found the broad line had typically energies 6.45-6.6 keV, $\sigma$=0.1-0.3 eV, and equivalent widths of 20-40 eV. While the Chandra HETG line energies are consistent with the Diaz Trigo et al. [2012] results, our widths and EWs are significantly lower, even considering the large XMM error bounds.

### 2.3.3 Photoionization Model

In essentially all LMXB disk winds, the absorbers have temperatures below the threshold of a collisionally ionized plasma ($k_B T_e \approx E_I$, where $T_e$ is the electron temperature, $E_I$ is the ionization energy of the plasma ions). We modeled the absorption line features with the photoionized plasma warmabs (v.2.27) multiplicative component in ISIS. Simultaneously fitting the continuum and the absorption features, the combined function followed the prescription: \textit{simple\_gpile2} / $\text{tbnew} \times (\text{warmabs} \times (\text{diskbb} + \text{bbbodyrad}))$.

#### 2.3.3.1 XSTAR Parameters

The warmabs model fits the plasma's bulk properties: ionization state, column density, outflow velocity and turbulent velocity broadening. The ionization state is characterized by the ionization parameter:

$$\xi = \frac{L}{n_e R^2}, \quad (2.1)$$
Figure 2-5: Combined TE mode observations, HEG ±1 orders from 1.7 – 2.0 keV. Top: When only the local Fe 26 and Fe 25 absorption features are fit, there is an excess of positive residuals in the 1.75 – 1.95 Å range. The data has been heavily binned to make the residual pattern more apparent. Bottom: Adding an emission line centered at 1.87 Å (indicated by the dashed vertical line) improved the fit.
which depends on the ionizing luminosity \((L)\), the electron density \((n_e)\) and the distance from the ionizing source \((R)\) [Tarter et al., 1969].

The \textit{warmabs} model fits for the plasma’s physical properties using files containing pre-calculated ion level populations. Ion level populations used in our \textit{warmabs} fits were calculated with XSTAR v2.33 [Bautista and Kallman, 2001, Kallman and Bautista, 2001]. XSTAR simulates a spherical gas shell with a uniform density, illuminated by a central ionizing source. We simulated plasmas with a range of physical properties and illuminated by different types of ionizing spectra, to explore the effects on the resulting \textit{warmabs} fit parameters. We ran XSTAR with a column density of \(N_H = 10^{17} \text{cm}^{-2}\) to remain within the optically thin limit \((\lesssim 10^{24} \text{cm}^{-2}\) for ionization parameters \(2.5 \leq \log \xi \leq 5\)).

Measurements of the disk wind plasma density are rare, as the vast majority of the absorption features are not sensitive to density. A measurement of the wind plasma density \((\log n = 14 \text{ cm}^{-3})\) has only been made for one source, BH LMXB GRO J1655-40, due to the presence of rare density-sensitive absorption features in its soft state spectrum [Miller et al., 2008]. In principle, the high density and ionization suggest a magnetically-driven wind, although a detailed analysis of the ionizing radiation field and multiwavelength SED indicates that Compton heating cannot be ruled out (Neilsen et al. 2016; see also Shidatsu et al. 2016). Simulations of accretion disks and thermally launched winds predict plasma densities at lower values in the range of \(\log n = 11 - 13 \text{ cm}^{-3}\). Densities of \(\log n = 12 \text{ cm}^{-3}\) are commonly used in disk wind studies, and we adopt this value in our analysis.

In XSTAR we simulated plasmas illuminated by different types of ionizing spectra across the 1eV to 100 MeV energy range, including a generic powerlaw \((\Gamma = 2)\), our \textit{Chandra} continuum for GX 13+1, and an \textit{RXTE} GX 13+1 continuum. It is common to run XSTAR simulations with a powerlaw ionizing spectrum, and while LMXB spectra can be roughly approximated by a powerlaw, it is not a physically consistent model, especially across the broad energy range across which the ion populations are generated. The \textit{Chandra} input spectrum was based on the multicolor disk plus blackbody spectrum (Section 2.3.1.3) since the \textit{powerlaw} component in the
Figure 2-6: Thermal stability curves for different ionizing spectra. A powerlaw (red curve) generates a plasma with a significantly higher temperatures than a thermal ionizing spectra (blue and green curves). The black lines are lines of constant ionization parameter (log $\xi = 3, 4$ for bottom/top, respectively; the thermal stability curves span ionization parameters $2 \leq \log \xi \leq 5$. All plasmas have densities of $10^{12}$ cm$^{-3}$.

*bbbodyrad+powerlaw* continuum model produces an unphysical ionizing spectrum at low energies ($< 3$ keV). The *RXTE* 3-40 keV spectrum includes the *Chandra* multi-color disk and blackbody as well as a high-energy powerlaw component that is cut off below the blackbody temperature [Homan et al., 2016].

*XSTAR* calculates hydrogen column densities, gas temperatures and ionization parameters for each spatial region in the slab of plasma. From these outputs we generated thermal stability curves, log($\xi$) vs log($T$), for different ionizing spectra, shown in Figure 2-6. Portions of the thermal stability curves with negative derivatives correspond to unstable solutions. It is generally agreed that one does not expect to observe ion signatures corresponding to plasmas with temperatures and ionization parameters along the unstable branch. This phenomenon has been invoked to explain the absence of ionized absorption features in BH LMXB’s hard state spectra. Unstable solutions correspond to a large range of unstable ionization parameters.
(3.55 \leq \log \xi \leq 4.2). This range happens to correspond with the peak fractions of many H-like and He-like ion species, making them essentially unobservable, which is in agreement with the absence of disk wind absorption features observed in the hard state [Chakravorty et al., 2013].

From Figure 2-6 it is obvious that the nonthermal powerlaw ionizing spectrum produces very different plasma behavior (red curve), occupying a temperature domain hotter for any given ionization parameter, compared to a realistic thermal ionizing spectrum (blue and green curves). The thermal curve differences between the Chandra and RXTE ionizing spectra are small, likely because the high-energy powerlaw in the RXTE spectrum does not significantly increase the hard flux compared to the extrapolated Chandra spectrum (without a powerlaw component). We use the Chandra continuum as the ionizing spectra. As GX 13+1’s spectrum did not change significantly between any of the observations, the ionizing spectrum input into XSTAR is essentially the same from one observation to another. To aid in comparing differences in warmabs parameters between observations, we used the population file generated with the ObsID 11815 ionizing spectrum in all of our warmabs fits.

The exact shape of the thermal curves are subject to uncertainties. Primarily, we have extrapolated the 1-7.5 keV Chandra spectrum to the 1 ev→1 MeV energy range to generate the ionizing spectrum, which is inaccurate. In addition, we have already acknowledged the high obscuration along the line of sight and degeneracies in fitting the Chandra continuum with multiple model prescriptions providing equally acceptable fits; thus even our knowledge of the ionizing spectrum in the X-ray regime is not fully specified. The shape of the stability curve along with the size of the instability region may change with a more accurate ionizing spectrum, but Figure 2-6 is a good place to start.

2.3.4 Warm Absorber Fits

In our warmabs modeling, we allowed for warm absorber column densities between \( N_H = 10^{20-24} \text{ cm}^{-2} \), ionization parameters \( \log \xi = 2.5 - 5.0 \), outflow velocities 0-1350 km s\(^{-1}\), and turbulent velocities 0 – 1500 km s\(^{-1}\). In fits with a single warm absorber,
we were able to constrain the broad emission feature, but including the emission line neither improved our fits nor changed our continuum or warmabs fit parameters. For the sake of simplicity, we did not attempt to fit for the gaussian emission line in the fits with warmabs components.

We found our warmabs fits were not significantly affected by our XSTAR choice of plasma electron density or column density in our XSTAR, but did depend on our incident ionizing spectrum. For a powerlaw ionizing spectrum, one absorber could produce all 7 accretion disk wind absorption features at their observed line widths and depths, while a more physically-motivated ionizing spectrum of a disk plus blackbody requires multiple absorbers to produce all 7 major features.

In the case of a powerlaw ionizing spectrum, the absorber has a high column density of $N_{H,22} = 80$ with an ionization parameter of $\log \xi = 3.6$, $v_{\text{turb}} \approx 500$ km s$^{-1}$, and $v_{\text{out}} \approx 600$ km s$^{-1}$. With an ionizing spectrum extrapolated from our Chandra continuum, a single warmabs components can produce absorption close to the observed levels, but the correct Fe 25/Fe 26 ratio is not produced. Additionally, the turbulent velocities (WA $v_{\text{turb}} \approx 100$ km s$^{-1}$) are a fraction of the values computed from our gaussian fits (FWHM $\Rightarrow v_{\text{turb}} \approx 500$ km s$^{-1}$). Fit parameters for a single warmabs component are shown in Table 2.5. The lower ionization energy lines are visibly too narrow; the warmabs fit is shown in blue in Figure 2-7. We found these issues arose in all of the observations when fit with a single warmabs component.

We calculated an average turbulent velocity for each observation based on our gaussian fits to the S 16 and Si 14 features as they are the strongest absorption lines in the portion of the spectrum with the highest spectral resolution. Fixing the warmabs $v_{\text{turb}}$ parameter to our gaussian velocity widths, the high ionization parameters required to produce the iron lines ($\log \xi \approx 4.1$), significantly under-fit the sulfur, silicon and magnesium lines. We conclude that more than one absorber is required to produce all the absorption features at their velocity-broadened widths and equivalent widths. In Figure 2-7, the warmabs fit with a fixed turbulent velocity is shown in red.

All of our XSTAR simulations and aforementioned warmabs modeling have as-
Figure 2-7: Chandra HETG data for ObsID 11815 are shown in black for the iron line region (top), S 16 (middle) and Si 14 absorption features. The warmabs model in blue shows a fit with a single absorber; the iron lines are well-fit, but the absorber has a small turbulent velocity ($v_{\text{turb}} \approx 100$ km s$^{-1}$) and the predicted sulfur and silicon lines are too narrow. In red we have plotted the resulting fit when the warmabs $v_{\text{turb}}$ parameter is fixed to the turbulent velocity value calculated from the gaussian line fits (490 km s$^{-1}$); the produced sulfur and silicon absorption is far below what is observed. These results demonstrate at least 2 absorbers are required to fit the iron, sulfur and silicon lines to match their observed velocity-broadened and equivalent widths.
Table 2.5: *Single warmabs component fits with the turbulent velocity parameter free.*

<table>
<thead>
<tr>
<th>ObsID</th>
<th>$N_H$</th>
<th>$\log \xi$</th>
<th>$v_{turb}$</th>
<th>$v_{out}$</th>
<th>Ca Abund.$^8$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2708</td>
<td>26</td>
<td>3.95</td>
<td>210</td>
<td>600</td>
<td>1.85</td>
<td>1.17</td>
</tr>
<tr>
<td>11815</td>
<td>31±2</td>
<td>3.97±0.02</td>
<td>97±25</td>
<td>653±11</td>
<td>2.06±43</td>
<td>1.15</td>
</tr>
<tr>
<td>11816</td>
<td>17</td>
<td>4.04</td>
<td>200</td>
<td>900</td>
<td>1.80</td>
<td>1.17</td>
</tr>
<tr>
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<td>18</td>
<td>3.97</td>
<td>144</td>
<td>570</td>
<td>1.65</td>
<td>1.17</td>
</tr>
<tr>
<td>11817</td>
<td>28</td>
<td>3.98</td>
<td>133</td>
<td>510</td>
<td>1.32</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Assumed standard Wilms solar abundances [Wilms et al., 2000]. If we allow the warm absorber’s abundances to vary and fix the turbulent velocity to $v_{turb} \approx 500$ km s$^{-1}$, one absorber can provide reasonable fits to all of the absorption features. Allowing only the iron abundance to vary required iron abundances 40% relative to solar, although the Si 14 absorption line is still underfit. With the iron abundance relative to solar fixed to unity and allowing the calcium, argon, sulphur, silicon and magnesium (i.e. the other major absorption feature elements) abundances to vary require overabundances (2-5)$\times$ solar values. We acknowledge that a single absorber with super-solar Ca, Ar, S, Si & Mg abundances is a possible solution to the absorption complex modeling, but we continued to search for solutions with non-variable abundances, finding that multiple absorption zones are required.

The Fe 26 absorption feature’s large equivalent width (30-45 eV) and, in particular, its width relative to Fe 25 in GX 13+1’s spectrum, is the first indication that a warm absorber with ionization parameter $\log \xi \gtrsim 4$ was present. All accretion disk wind LMXBs show absorption lines from Fe 25 and/or Fe 26, which can be modeled by photoionized plasmas with $\log \xi \gtrsim 3$. Unlike most BH and NS disk wind sources where only iron lines are observed, GX 13+1’s spectrum exhibits significant absorption from ions with lower ionization parameters (for example, the Si 14 K$\alpha$ absorption line is at $\approx 2$ keV with equivalent widths of 1.2-2.9 eV), indicating a less ionized plasma is also present.

We found adding a second *warmabs* component did not offer a complete solution.

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$^8$Overabundance required by *warmabs*. 

65
One absorber produced the iron lines but the second absorber producing the silicon and sulfur lines generates too much Fe 25 absorption. While the 2-\textit{warmabs} component model provided more accurate turbulent velocities, it could not produce the correct iron line ratio. In the two absorber model, the iron lines are associated with a highly ionized absorber ($\log\xi \approx 4.1, N_{\text{H},22} \approx 10 - 20$), while the silicon, sulfur, magnesium, calcium and argon lines are partially produced by a much less ionized absorber ($\log\xi \approx 3.15, N_{\text{H},22} \approx 0.9 - 10$). The two components exhibit similar turbulent velocities ($v_{\text{turb}} \approx 250 - 600 \text{ km s}^{-1}$), while the more highly ionized absorber has a larger blueshift ($v_{\text{outflow}} \approx 700 - 1100 \text{ km s}^{-1}$) than the less ionized component ($v_{\text{outflow}} \approx 400 - 700 \text{ km s}^{-1}$).

In a solution with three \textit{warmabs} components, one highly ionized absorber ($\log\xi \approx 4.3, N_{\text{H},22} \approx 20$) generates almost exclusively Fe 26 Ka absorption, a second absorber ($\log\xi \approx 3.5, N_{\text{H},22} \approx 0.7 - 1.2$) produces significant Fe 25 absorption along with some of the lower energy lines (S 16, Si 14, etc) and a third absorber produces ($\log\xi \approx 3.3, N_{\text{H},22} \approx 0.2 - 0.9$) the rest of the S 16, Si 14 and Mg 12 absorption features, generating absorption lines with widths matching their gaussian broadening and full equivalent width. Similar to our findings with a two \textit{warmabs} component model, the component associated with the Fe 26 line had a larger blueshift ($v_{\text{out}} = 750 - 1260 \text{ km s}^{-1}$) than the 2 components associated with the lower ionization lines ($v_{\text{out}} = 510 - 840 \text{ km s}^{-1}$).

For both the two and three \textit{warmabs} component solutions, we find the low ionization component $\log\xi \approx 3.4$ produces Si 13 absorption around 1.865 keV (6.65 Å) in the silicon edge, as predicted by Schulz et al. [2016].

### 2.3.5 Variability and the RXTE CD

Accretion disk wind absorption line variability, attributed to changes in accretion flow, has been seen on both short ($\approx \text{ks}$) and long (days$\rightarrow$months) timescales. On timescales down to tens of seconds, Neilsen et al. [2011] correlated dramatic cyclical changes with a period $\approx 50 \text{ s}$ in the illuminating continuum to changes in the accretion disk wind column density in GRS 1915+105. On timescales of tens of ks in GRS 1915+105, Lee et al. [2002] found changes in the accretion disk flux and the accretion
disk wind density drive changes in the iron absorption features.

In previous analyses of GX 13+1, variability has been claimed on day and kilosecond timescales [Díaz Trigo et al., 2012, Ueda et al., 2004]. While Sidoli et al. [2002] found no significant changes on day timescales in the Fe 25 and Fe 26 Kα EWs, Díaz Trigo et al. [2012] found significant correlations between the hard flux (6-10 keV) and the ionization state and column density of the absorber in their 5 XMM EPIC observations, which were taken days to weeks apart from one another. Ueda et al. [2004] claimed variability in the absorber’s ionization on timescales of 5 ks in the 2002 HETGS observation of GX 13+1; changes in the iron lines’ ratio appeared to be correlated with the continuum flux.

We compared our measured wind properties with GX 13+1’s position along its Z tracks, which are plotted in Figure 2-1. All of the Chandra observations occurred while GX 13+1 was on the normal and horizontal branches; blueshifted absorption features detected in all of these observations suggests these branches are both strongly associated with an accretion disk wind. Strong radio emission commonly associated with jets has also been observed at the vertex of the normal and horizontal branches along one of the Z tracks [Homan et al., 2004], which suggests accretion disk winds and jets can be simultaneous in LMXBs and is the subject of the work of Homan et al. [2016].

During some of the Chandra observations, GX 13+1 exhibits significant movement along the CD. While the GX 13+1 light curves do not suggest significant changes or trends in the source’s intensity during the observations despite the known motion along the Z track, we tested whether the accretion disk wind exhibits variability on small timescales as reported by [Ueda et al., 2004] by breaking the observations into 10 ks time segments. Figure 2-8 shows the Fe 26 and Fe 25 Kα lines’ EWs versus the hard 8-10 keV flux in each 10 ks segment.

For the majority of the Chandra observations, we observed no significant variability in the iron line EWs during the course of the observation, as well as no clear change in the hard flux. For example, in ObsID 11816, the Fe 26 and Fe 25 EWs were consistent with 43 eV and 10 eV, respectively, during each time step while the hard
flux also remained constant. The lack of change in the hard flux is consistent with the source's minimal vertical movement along the CD during ObsID 11816, where it remained mostly on the HB. ObsID 11817, however, shows a correlation between the Fe 26 EW and the hard flux. The 8-10 keV flux decreases over the course of the observation ($9.2 \rightarrow 8.3 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$) while the equivalent width increases from 27 eV to 43 eV. The corresponding change in the Fe 25 Kα is less clear, but appears to either increase less significantly or remain constant. ObsID 11817 corresponds to GX 13+1 moving downwards along the normal branch during which the hard color decreases, in agreement with the observed decrease in the hard flux.

In the scenario where one absorber produces both the Fe Kα lines as in our 2-component warmabs model, the equivalent width ratio (Fe 25 EW / Fe 26 EW) is a probe of the ionization state. The errors of the EW ratios, however, are too large to interpret relative changes in the absorption features during any of the observations. The definite changes in the Fe 26 EW and the lack of correlated changes in the Fe 25 EW between the 10 ksec time chunks supports the 3 absorption zone warmabs model. In this scenario, two different absorption zones produce the Fe 25 and Fe 26 Kα lines, so we would not expect trends in the EW ratio. Additionally, the decrease in the Fe 26 Kα EW with the increase in hard flux in ObsID 11817 is consistent with the absorption zone becoming overionized; this behavior is predicted by the 3-warmabs model, where an increase in the ionization state of the the most ionized zone ($\log \xi \approx 4.3$) leads to a decrease in the Fe 26 EW. Alternatively, the reduction of the Fe 26 EW could be produced by a decrease in the accretion disk wind column, rather than a change in the ionization state.

While GX 13+1 is largely non-variable during the Chandra observations, we do, however, see definite variability in the Fe 26 EW between observations. In ObsID 11814 the Fe 26 EW was $\approx 35$ eV, about half of the Fe 26 EW in the beginning of ObsID 11815.
Figure 2-8: Fe 26 (star symbols) and Fe 25 (filled circles) EWs versus the 8-10 keV flux in each 10 ks time interval of the 5 TE mode observations. In ObsIDs 11814 and 11816, neither the Fe 26 nor Fe 26 EWs exhibit variability over the course of the 30 ks observations, while in ObsID 11817 the Fe 26 EW decreases as the hard flux increases.
2.4 Discussion

As the number of high-resolution observations of disk wind systems has grown over the past decade, it has become increasingly clear that disk winds play a critical role in the overall accretion process in both BH and NS LMXBs. GX 13+1 is one of only 3 NS narrow absorption line systems that shows a definitive outflow (IGR J17480-2446 [Miller et al., 2011] and Cir X-1 [Brandt and Schulz, 2000] are the others). In contrast, all BH narrow line systems exhibit blueshifts [Díaz Trigo and Boirin, 2016]. GX13+1 is bright, accreting at more than 50% Eddington and displays seven major absorption features, the most amongst NS disk wind systems, revealing a detailed view of the absorbing plasma's properties. Its simultaneous Chandra HETG and RXTE observations offer the unique chance to study the disk wind properties along the source's horizontal and normal branches.

The abundance of high signal-to-noise observations of GX 13+1 have allowed us to perform a detailed analysis of the disk wind absorption spectrum in GX 13+1. We have fit the Chandra 1.5-7.5 keV spectrum and performed direct line fits of the seven strongest absorption features, including hydrogen- & helium-like iron Kα lines and the Kα lines from hydrogen-like Ca, Ar, S, Si and Mg. Through careful photoionization modeling of the absorption features, we found multiple absorbers were required to produce the observed disk wind signature.

2.4.1 Multiple Absorbers in Accretion Disk Winds

Previous analyses of the accretion disk wind in GX 13+1 required only one warm absorber, while we find at least 2 absorbers are necessary. The disagreement may be a result of inherent variability or our improved treatment of the ionizing spectrum. In 5 XMM observations Díaz Trigo et al. [2012] found significant absorption due to the Kα and Kβ transitions of Fe 25 and Fe 26. Evidence of absorption due to Si 13 and S 16 was present in several observations, while additional features possibly corresponding to Si 14, S 15 and Ca 20 were present in only one observation which also had the lowest measure ionization parameter of all the observations (log ξ =
Upper limits on Mg 12 absorption (EW < 2.5 eV) were compatible with the Mg 12 equivalent width predicted by a single, highly ionized absorber with log $\xi = 4$ [Díaz Trigo et al., 2012]. If only one absorber was indeed present in the XMM observations, it would indicate variability in the wind's ionization state, as the lower ionization components we see in our Chandra observations are absent. However, the low energy resolution of the XMM EPIC observations makes the detection of the narrow, less ionized absorption features unlikely even if they were present.

Ueda et al. [2004] analyzed the first Chandra HETGS observation of GX 13+1 performed in 2001. They did not perform a warmabs modeling of the 9 absorption features they identified. Instead, using XSTAR they estimated the photoionized absorber had an ionization parameter of log $\xi \approx 4.2 - 4.5$ in order to produce the observed iron lines ratio. From $\xi$, they computed the elemental abundances for all absorption line ions which they then converted to abundances, comparing to the Wilms et al. [2000] ISM and solar values, finding them in agreement. Our analyses with standard abundances, however, requires multiple absorption zones with different ionization states to produce the observed absorption complex.

As previously discussed in Section 2.3.3.1, a pure powerlaw ionizing spectrum used as input in XSTAR calculation leads to significantly different warmabs parameters compared to a realistic ionizing spectrum. D'Al et al. [2014] performed a warmabs analysis of ObsID 11814 and found that one absorber with log $\xi \approx 3.6$ could reproduce the observed absorption lines, assuming a $\Gamma = 2$ power law ionizing spectrum. However, we found that a power law ionizing spectrum leads to significantly different parameters compared to a more realistic spectrum based on the best-fit continuum; this is in part because the power law is unphysical and requires a low-energy cut-off.

The warmabs model has been applied to this set of Chandra HETGS GX 13+1 observations [Madej et al., 2014], and the analysis only required one absorber, but it is not clear whether all absorption features other than the Fe 25 and Fe 26 $\alpha$ lines are well-fit. Problematically, the population files generated for the warmabs analysis were created with a large column density ($N_H = 10^{24}$ cm$^{-2}$), approaching the optically thick regime whereas XSTAR is only supposed to be applied to optically
thin plasmas.

In the best fits to our data, we found at least two absorption zones with different ionization parameters were required to produce the observed disk wind signature. Multiple absorbers have been seen in disk wind systems before. Evidence of multiple velocity components was seen in LMXB BH GRO J1655-40 [Kallman et al., 2009, Neilsen and Homan, 2012]. Taking a closer look at the iron line region (6-8 keV) in the third-order HEG spectra of 4 BH disk wind systems, including GRO J1655-40, Miller et al. [2015] found fits with 2 or more absorption zones significantly improved their fits.

Among NS systems with narrow line absorption features, 3 have one low ionization component (log $\xi < 3$) and one high ionization component (log $\xi > 3$) [Díaz Trigo and Boirin, 2016]. Díaz Trigo et al. [2006] found 2 ionization zones in NS MXB 1658-258 (one with log $\xi = 3.8$, $N_{H,22} = 10$ and another with log $\xi = 3.1$, $N_{H,22} = 3$), although no significant blueshifts were detected so the source is known as having a warm atmosphere rather than a disk wind outflow. Absorption features associated with ions observed in GX 13+1’s spectrum, including S 16, S 14 and Mg 12, have also been observed in the NS binaries 4U 1916-05 and Cir X-1. In 4U 1916-05, an accretion disk atmosphere source, the Fe 25 and Fe 26 features were produced by an absorber with log $\xi \approx 4.15$ while the S, Si, Mg and Ne lines were associated with a much less ionized component, log $\xi \approx 3$ [Iaria et al., 2006]. Similarly, in GX 13+1 we found absorption zones with log $\xi = 3.2-3.5$ produced the less ionized features. In Cir X-1, the absorption features were very broad (FWHM $\approx 2000$ km s$^{-1}$ compared to the 400-600 km s$^{-1}$ we observe in GX 13+1) and exhibited strong P-Cygni profiles, supporting the interpretation that the lines are due to an accretion disk wind [Brandt and Schulz, 2000, Schulz and Brandt, 2002].

Observing multiple absorption zones in a accretion disk wind will provide multiple measurements of the plasma’s outflow velocities and ionization parameters and will help probe the disk wind structure and, hence, the wind launching mechanism. Our analysis highlights the importance of not using an approximated ionizing spectrum, such as a powerlaw, in the XSTAR analysis. A reanalysis of the warm absorber
modeling in disk wind sources may reveal multiple absorption components previously not identified. Future X-ray instruments with higher energy resolution and larger effective area will allow us to see more and more absorption line components, as weak lines become visible and blended lines become resolved [Kallman et al., 2009].

In disk wind and disk atmosphere systems where multiple absorbers provide the best fit to absorption line complex, the absorption zones are usually typified by distinct ionization states or by outflow velocity. In GX 13+1, the absorption zones differ by the associated column, ionization state and velocity. These multiple absorption zones may be a natural signature of a smooth outflow. Simulations of Compton-heated winds suggest the absorption line complex may be characterized by two or three ionized zones [Giustini and Proga, 2012, Higginbottom and Proga, 2015]. Alternatively, the different ionization zones may correspond to "clumps" of outflowing material, challenging the assumptions of a continuous and homogenous outflow. In this scenario, one might expect strong temporal variability in the absorption line features due to the noncontinuous outflow of absorbing material. As we see the same absorption features in all 7 observations that span almost 10 years of monitoring, and model the absorption zones with similar ionization parameters and column densities, this suggests a relatively continuous and smooth outflow as opposed to separate physical clumps of outflowing material.

2.4.2 Disk Wind Launching Mechanism

Compton heating and magnetic driving are considered the most viable mechanisms in X-ray binary disk wind systems. For several BH wind systems (e.g. GRO J1655-40 and GRS 1915+105), there have been claims of magnetic driving based on small inferred wind launching radii (Miller et al. 2006, 2016b, but see also Neilsen et al. 2016 and Shidatsu et al. 2016 for an alternative explanation). Unusual wind properties or changes in wind properties within a single outburst have also driven the formulation of hybrid wind theories. GRO J1655-40’s disk wind with only 2 absorption features in one observation and 2 weeks later showing over 90 absorption features can be explained by a switch between a Compton wind to a magnetically driven wind
Previous studies of the disk wind in GX 13+1 have found the wind is consistent with Compton heating [Díaz Trigo et al., 2012, Sidoli et al., 2002, Díaz Trigo et al., 2012, Madej et al., 2014], although Ueda et al. [2004] proposed radiation-driven wind based on a model where radiation driving could be effective at sub-Eddington luminosities. The question of the wind launching mechanism in any disk wind system is often answered by determining the wind launching radius; the launching radius \( R_L = \sqrt{\frac{L}{n\xi}} \) is approximated as the radius we observe the innermost absorption region which is estimated from the definition of the ionization parameter (Eqn. 2.1). As previously discussed in Section 2.3.3.1, the largest uncertainty in disk wind observations is the plasma density. It is also the largest uncertainty in determining the wind launching radius, and hence the wind mechanism. We have no independent measurement of the plasma density in GX 13+1, so for this reason and for consistency we use the same electron density we used to calculate our population levels in XSTAR, \( n = 10^{12} \text{ cm}^{-3} \).

Uncertainty in the bolometric luminosity is the second largest source of error in determining the wind launching radius. The bolometric luminosity is estimated from the X-ray luminosity, which can be significantly underestimated when there is a high opacity along the line of sight, the exact conditions when observing highly-inclined disk wind systems [Díaz Trigo and Boirin, 2016]. While there is a large neutral column density \( (N_{\text{H}}) \approx 4.8 \) towards GX 13+1, as well as a warm absorber with an even larger column density \( (N_{\text{H}}) \approx 30 \), we benefit from luminosity measurements from the simultaneous RXTE observations, rather than trying to extrapolate our Chandra spectrum to obtain a broadband flux. Homan et al. [2016] found that GX 13+1 was accreting at nearly its Eddington limit, \( L = (1.2 - 1.3) \times 10^{38} \text{ erg s}^{-1} \approx 0.7 - 0.8 L_{\text{Edd}} \) across 0.1-100 keV; this value is likely a lower bound on the luminosity as the accretion disk’s flux has not been corrected for inclination. The highest ionization parameter we detected in our observations of GX 13+1 was \( \log \xi \approx 4.3 \). Re-writing the launching radius in terms of our estimates for the density and luminosity, we find
\[ R_L = 7 \times 10^{10} \times \left( \frac{L}{1.3 \times 10^{38} \text{ erg s}^{-1}} \right)^{\frac{1}{2}} \times \left( \frac{n}{10^{12} \text{ cm}^{-3}} \right)^{-\frac{1}{2}} \times \left( \frac{\xi}{10^{4.3} \text{ erg cm s}^{-1}} \right)^{-\frac{1}{2}} \text{ cm.} \]  
\[ \text{(2.2)} \]

Our launching radius is consistent with other published estimates, \( R_L \approx 10^{10-11} \) cm [Ueda et al., 2004, Díaz Trigo et al., 2012, D’Aì et al., 2014], despite the variety of luminosities and densities used to estimate the radius. Compton-heated winds can be launched outside of the \( 0.1 \times \) Compton radius, \( R_C \) [Begelman and McKee, 1983]. The Compton radius, \( R_C \), is given by:

\[ R_C = 10^{10} \times \left( \frac{M_{NS}}{M_\odot} \right) \times \left( \frac{T_C}{10^8 \text{ K}} \right)^{-1} \text{ cm}, \]  
\[ \text{(2.3)} \]

where \( M_{NS} \) is the NS mass and \( T_C \) is the Compton temperature defined as:

\[ T_C = \frac{1}{4k_B} \int_0^\infty \frac{h\nu L_\nu d\nu}{\int_0^\infty L_\nu d\nu}. \]  
\[ \text{(2.4)} \]

From our Chandra observations, we calculate a typical Compton temperature of \( 1.3 \times 10^7 \) K, which translates to a Compton radius of \( 8 \times 10^{10} \) cm and is comparable with our wind launching radius. As a Compton driven wind can be launched just beyond \( 0.1 R_C \), this means a Compton wind can be launched an order of magnitude closer to the central NS than our calculated wind launching radius.

Furthermore, at increasing Eddington fractions, electron (radiation) pressure likely contributes to the wind driving. The electron pressure reduces the local effective gravity and, hence, the local escape velocity; this effect makes it easier for Compton-heated winds to be launched at smaller and smaller radii [Proga and Kallman, 2002, Homan et al., 2016, Done et al., 2016]. An approximate theoretical correction factor to the Compton radius due to the effects of radiation pressure is given by

\[ \bar{R}_C \approx R_C \left( 1 - \frac{L}{0.71L_{\text{Edd}}} \right), \]  
\[ \text{(2.5)} \]

where \( R_C \) is our Compton radius from Eqn 2.3 [Done et al., 2016]. The Compton radius moves inwards as the source brightens while the launching radius moves outwards.
As GX 13+1 has a luminosity of at least $0.5 \, L_{\text{Edd}}$, it is well within the regime where electron pressure becomes significant. Our Compton radius is likely at least an one order of magnitude smaller than our estimate with no electron pressure taken into consideration, making it even more robust to the Compton-heated wind criterion $R_L > R_C$.

The estimated wind launching radius is also well within the accretion disk extent, $R_C < R_L < R_{\text{Disk}}$. The disk size can be estimated from the radius of the Roche Lobe ($R_{Lb}$) as $R_{\text{Disk}} \approx 0.8R_{Lb}$. For an orbital period of 24 days, a NS mass of 1.4 M$_\odot$ and a binary mass ratio, $q$, of 1 leads to a semimajor axis, $a$, of $3.5 \times 10^{12}$ cm. We estimate a Roche lobe radius of approximately $1.3 \times 10^{12}$ cm [Eggleton, 1983] and, hence, an approximate accretion disk extent of $10^{12}$ cm, which is at least an order of magnitude larger than our wind launching radius. Thus, the condition $R_C < R_L < R_{\text{Disk}}$ is met and the accretion disk wind in GX 13+1 is consistent with a Compton-heated wind.

### 2.4.3 Disk Wind Mass Loss

GX 13+1 is one of the few NS systems with an accretion disk wind and the outflow is consistent with a Compton wind. In general, if the accretion disk is too small relative to the Compton radius, a Compton-heated wind cannot be launched although mass loss via jets is still possible. The accretion disk size may explain why blueshifts are not detected in $\approx 70\%$ of high inclination NS LMXBs that exhibit narrow absorption features [Díaz Trigo and Boirin, 2016], indicating an ionized plasma is present but is in a static configuration as an accretion disk atmosphere rather than an outflow. Indeed, comparing the Compton radii and the accretion disk size in 7 BH and NS warm absorber systems, including GX 13+1, Díaz Trigo and Boirin [2016] found systems whose absorption lines are not measurably blueshifted have disk sizes comparable or significantly less than the Compton wind launching radius ($R_{\text{Disk}} \lesssim 0.1R_C$).

Constraining the fraction of NS LMXBs that have disk outflows is critical to understanding the contribution of disk winds to galactic feedback. The mass driven from the binary system by a radial wind is given by
\[ \dot{M}_{\text{Wind}} = 4\pi m_p v_{\text{outflow}} \frac{L \Omega}{\xi 4\pi}. \]  

(2.6)

Assuming a maximal covering fraction of unity will give us an upper limit on the mass loss rate. As before, we will use the plasma properties for the more highly ionized component in GX 13+1 and a bolometric luminosity of $1.2 \times 10^{38}$ erg s$^{-1}$ [Homan et al., 2016] with a $v_{\text{out}}$ of 1000 km s$^{-1}$, we find $\dot{M}_{\text{Wind}} < 2 \times 10^{-7} M_\odot$ yr$^{-1}$. For a more realistic disk wind covering fraction of $\frac{\Omega}{4\pi} \approx 0.4$, we estimate $\dot{M}_{\text{Wind}} \approx 6 \times 10^{-8} M_\odot$ yr$^{-1}$. This estimate assumes a homogenous and symmetric absorber. Other studies of GX 13+1 have inferred disk wind outflow rates between $(0.8 - 2) \times 10^{-8}$ $M_\odot$ yr$^{-1}$ [Ueda et al., 2004, Díaz Trigo et al., 2012], but still comparable to the mass accretion rate.

The wind’s kinetic luminosity is given by

\[ L_{\text{kinetic}} = \frac{1}{2} \dot{M}_{\text{Wind}} v_{\text{outflow}}^2. \]

(2.7)

so even though the wind carries substantial mass from the system, the relatively low outflow velocity, using 1000 km s$^{-1}$ as an upper limit, translates to a kinetic luminosity of $L_{\text{kinetic}} \approx 10^{-4} L_{\text{Edd}}$. This finding has been seen in the other BH and NS disk wind systems [Ponti et al., 2016]. While the low kinetic luminosity may mean accretion disk winds do not significantly contribute to galactic feedback, the kinetic luminosity of the wind relative to the source luminosity is consistent with a Compton-heated wind. The kinetic luminosity of a Compton wind cannot exceed the luminosity intercepted by the outer disk which heats the accretion disk and powers the wind. Assuming a disk flaring angle of 10$^\circ$ and efficiencies of $1 - 10\%$, converting the illuminating luminosity to kinetic power predicts Compton disk wind kinetic luminosities in the range of $10^{-5.5} \rightarrow 10^{-3.5} L_{\text{Edd}}$ (see Figure 3 in Ponti et al. [2016]).
Chapter 3

Spectral Softening Between Outburst and Quiescence in SAX J1750.8-2900

Abstract

Tracking the spectral evolution of transiently accreting neutron stars between outburst and quiescence probes relatively poorly understood accretion regimes. Such studies are challenging because they require frequent monitoring of sources with luminosities below the thresholds of current all-sky X-ray monitors. We present the analysis of over 30 observations of the neutron star low-mass X-ray binary SAX J1750.8-2900 taken across four years with the X-ray telescope aboard *Swift*. We find spectral softening with decreasing luminosity both on long (~1 year) and short (~days to week) timescales. As the luminosity decreases from $4 \times 10^{36}$ erg s$^{-1}$ to $\sim 1 \times 10^{35}$ erg s$^{-1}$ (0.5-10 keV), the power law photon index increases from 1.4 to 2.9. Although not statistically required, our spectral fits allow an additional soft component that displays a decreasing temperature as the luminosity decreases from $4 \times 10^{36}$ to $6 \times 10^{34}$ erg s$^{-1}$. Spectral softening exhibited by SAX J1750.8-2900 is consistent both with accretion emission whose spectral shape steepens with decreasing luminosity and also with being dominated by a changing soft component, possibly associated with accretion onto the neutron star surface, as the luminosity declines.

3.1 Introduction

Low-mass X-ray binaries (LMXBs) are powerful and strongly variable X-ray sources that provide a means to study accretion flows over a wide luminosity range and on relatively short timescales. Neutron star LMXBs consist of a neutron star accreting via Roche-lobe overflow from its low-mass ($\lesssim 1 M_\odot$) companion. In transient LMXBs, the accretion rate onto the neutron star surface varies by many orders of magnitude, but the systems spend the majority of their time in a low-luminosity, $10^{31} - 10^{33}$ erg s$^{-1}$ (0.5-10 keV unabsorbed luminosity, denoted by $L_X$), state of quiescence during which there is little or no accretion. In outburst, these systems undergo intense accretion for periods of weeks to months (to years in the extreme case of quasi-persistent transients), with typical X-ray luminosities of $10^{36} - 10^{38}$ erg s$^{-1}$. In this work, we focus on the intermediate luminosity range between outburst and quiescence of $10^{34} - 10^{36}$ erg s$^{-1}$.

Limited instrumental sensitivity and/or observation time makes it difficult to study neutron star transients during their, often rapid (lasting less than several weeks), transition from outburst to quiescence. Hence, the accretion processes and emission sources in this luminosity regime are not well-understood. However, as more and more neutron star binaries are being monitored between outburst and quiescence, there is growing evidence that these systems may share the common behavior of spectral softening with decreasing luminosity. Spectral softening between outburst and quiescence has been documented in detail for transient black hole binaries [Yuan et al., 2007, Wu and Gu, 2008, Plotkin et al., 2013] and for individual neutron star transients [Armas Padilla et al., 2011, 2013, Linares et al., 2014]. It has recently been proposed as a feature exhibited by most neutron star transients between luminosities of $10^{36}$ and $10^{34}$ erg s$^{-1}$ [Wijnands et al., 2015]. In black hole systems, the softening is commonly attributed to radiatively inefficient accretion flows. The underlying mechanism(s) responsible for the softening in neutron star systems is likely more complicated due to the presence of the neutron star surface and magnetic field.

A better understanding of accretion at luminosities between $10^{34}$ and $10^{36}$ erg s$^{-1}$
may provide insight into accretion processes at even lower luminosities while the systems are in quiescence. In addition to thermal emission from the neutron star surface, many quiescent transients display a non-thermal, high-energy spectral tail above 2 keV which can be modeled with a power law \( (\Gamma = 1 - 2)^2 \). Nonthermal and thermal emission may be variable both in their total flux and relative flux contribution over short and long timescales, as has been found in the well-studied neutron star transient Cen X-4 [Cackett et al., 2010]. Several quiescent transients have also exhibited flares, sudden increases in flux reaching ten or more times the typical quiescent emission levels and exponentially decaying over the course of a few days [Fridriksson et al., 2011, Degenaar and Wijnands, 2013a, Coti Zelati et al., 2014]. The physical origin of the non-thermal emission in quiescence is not entirely understood, but is generally attributed to ongoing accretion [Campana et al., 1998a], while flares are interpreted as sporadic increases in the accretion rate onto the neutron star, although the physics of disk instabilities at low accretion rates is not well-understood.

More frequent and deeper observations of neutron star LMXBs between their quiescent and outburst states, as well as observations of flares in quiescence, are critical to constraining the physical origins of the hard and soft spectral contributions, together with their evolution in time. Such work is necessary to understand the nature of accretion at all luminosities. In particular, it can help in identifying the accretion regimes that heat the neutron star crust, which has important implications for equilibrium temperature measurements of the crust and studies of the thermal evolution of transient neutron stars.

SAX J1750.8-2900 was first detected in outburst in 1997 by the Wide Field Cameras on board BeppoSAX and has since been detected in outburst an additional 3 times with both long (4-5 months) and short (≤ 1 month) outburst durations. The presence of type I X-ray bursts revealed that the source is a neutron star LMXB [Natalucci et al., 1999]. Using RXTE observations of its 2001 outburst, the second recorded for this source, Galloway et al. [2008] analyzed photospheric radius expansion bursts to establish a distance of 6.79 ± 0.14 kpc for hydrogen-
poor burning. In March 2008, SAX J1750.8-2900 entered its third known outburst [Markwardt and Swank, 2008] with a reported flux of 230 mCrab corresponding to a luminosity $3.1 \times 10^{37}$ erg s$^{-1}$ (2-10 keV, $d = 6.79$ kpc), similar to the peak flux exhibited in previous outbursts. By August 2008 the source fell below the RXTE detection threshold and was reported to be returning to quiescence [Linares et al., 2008a]. SuperAGILE reported a 60 seconds long burst on October 9, 2008 [Pacciani et al., 2008] indicating the system had rebrightened. The return to outburst was also seen in two Swift XRT observations on October 1$^{st}$ and 8$^{th}$ [Linares et al., 2008b]. By mid-February 2009, SAX J1750.8-2900 had returned to quiescence [Lowell et al., 2012].

Over a year after the end of its last reported outburst, SAX J1750.8-2900 was observed for the first time in quiescence in April 2010 with XMM with a bolometric luminosity of $1.05 \pm 0.12 \times 10^{34} \, (D/6.79 \, \text{kpc})^2 \, \text{erg s}^{-1}$ ($L_X = 8.9 \times 10^{33} \, \text{erg s}^{-1}$), making it the most luminous quiescent neutron star known [Lowell et al., 2012]. The spectrum was well-fit with a neutron star atmosphere model with a high effective temperature ($kT_{\text{eff}} = 148$ eV). Under the assumption the source had undergone no additional heating (i.e. accretion) since outburst, Lowell et al. [2012] claimed that the neutron star crust and core were in equilibrium and, thus, the high surface temperature reflected a hot neutron star core.

In the two years after the XMM observation, SAX J1750.8-2900 exhibited a short outburst (< 1 month) and a flare in quiescence. A February 2011 increase in activity reported by IBIS/INTEGRAL [Fiocchi et al., 2011] was confirmed as a faint outburst by Swift XRT with $L_X = 1.05 \times 10^{36}$ erg s$^{-1}$ for a source distance of 6.79 kpc [Natalucci et al., 2011]. In March 2012, the detection by Swift XRT of a low-level flare (with characteristic $L_X = (3 - 4) \times 10^{34}$ erg s$^{-1}$ assuming $d = 6.79$ kpc) lasting between 5 and 16 days indicated the system may undergo small accretion events between outbursts [Wijnands and Degenaar, 2013].

No orbital parameters are known for this neutron star binary and no observations of the companion star exist except for reports of a near-IR candidate counterpart [Torres et al., 2008]. The line-of-sight towards SAX J1750.8-2900 suffers from high-
extinction \((A_V^3 = 13.0-15.1)\), consistent with the high column density, \(N_H > 10^{22}\), which may limit observations of the optical counterpart.

In this work we present a detailed spectral analysis of the neutron star LMXB SAX J1750.8-2900, observed with Swift XRT over the course of four years. We have tracked the X-ray spectral evolution of SAX J1750.8-2900 over three orders of magnitude in luminosity between outburst and quiescence, detecting spectral softening with decreasing luminosity. We interpret the spectral softening as being generated by changes in soft and hard accretion-powered emission as the mass accretion rate decreases, and we investigate the potential crustal heating effects due to accretion at sub-outburst rates.

### 3.2 Observations & Analysis

We analyzed all Swift XRT [Burrows et al., 2005] observations where SAX J1750.8-2900 was in the field of view (FOV), which yielded 27 source detections out of a total of 38 observations. Five observations had SAX J1750.8-2900 more than 7 arcminutes off-axis (i.e., inside but near the edge of the FOV), but we included them in our analysis as luminosity upper limits. The data set spans over four years of activity, between March 2008 and September 2012, with a total exposure time of almost 70 ks. The long-term soft and hard X-ray light curves from SAX J1750.8-2900 measured with RXTE PCA and Swift BAT [Krimm et al., 2013], respectively, covering the timespan of our Swift observations are shown in Figure 3-1. The majority of our Swift XRT observations cover the tail end of the 2008 outburst and the return to outburst just several weeks later in October; the remaining observations primarily occurred in February and March 2012. A log of the Swift XRT observations is presented in Table 3.1.

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3http://irsa.ipac.caltech.edu/applications/DUST/
Figure 3-1: Light curves for SAX J1750.8-2900 from RXTE PCA (top) and the Swift BAT monitor (bottom). In April 2010, indicated by the diamond symbol, SAX J1750.8-2900 was observed in quiescence with XMM and Lowell et al. [2012] reported a quiescent luminosity of $L_X = 9 \times 10^{33}$ erg s$^{-1}$. The red vertical line symbols in the bottom panel indicate all 27 Swift XRT observations with source detections, analyzed herein. Within this set of observations, SAX J1750.8-2900 had luminosities between $10^{34}$ and $10^{37}$ erg s$^{-1}$ (see Table 3.2).
3.2.1 Source Detection & Spectral Extraction

All observations were re-processed with the xrtpipeline tool (v.0.12.6). The source was identified in photon counting (PC) mode observations with the sosta tool set to a signal-to-noise threshold limit of 2.0 in XImage (v.4.5.1).

Pile-up corrections were made for PC mode observations with count rates greater than 0.5 s\(^{-1}\) within a circular region with a 20-pixel (47 arcsec) radius centered on the source. The extent of the piled-up region was determined following the Swift XRT Pile-Up thread\(^4\). In these observations, an annulus with an inner radius set to exclude the piled-up pixels (radius of 3 pixels for mild pile-up and up to 12 pixels for the most severe case of pile-up, ObsID 31166001) and an outer radius of 30 pixels (45 pixels for 31166001) was used for the source region. The background spectra were extracted from two circular regions, both with radii of 45 pixels. All PC mode observations with count rates between 0.004 and 0.5 s\(^{-1}\) (i.e., not affected by pile-up) had spectra extracted from a circular region with a 20-pixel radius centered on the source, and the background was extracted from two circular regions, both with radii of 35 pixels. Potentially nearby X-ray sources (within 15 arcseconds) were identified using Simbad\(^5\) and were avoided in any of the source and background regions.

Window timing (WT) mode observations only incur pile-up for count rates above 100 s\(^{-1}\); all SAX J1750.8-2900 count rates were below 10 s\(^{-1}\). Thus, no pile-up corrections were required in this mode. Both the source and background spectra in WT mode were extracted from circular regions with 30-pixel radii.

After extracting the source and background spectra in XSelect (v.2.4b) with standard event grades 0-2 for WT and 0-12 for PC modes, we created exposure maps and ancillary files using the xrtexpomap and xrtmkarf tools, respectively, using the most recent RMFs (v.14 for PC mode and v.15 for WT mode) and enabling the vignetting and PSF correction options. Whenever possible, we grouped energy bins to a minimum of 20 counts per bin using the grppha tool. In cases where there were only dozens of counts, we binned as low as 5 counts per bin. We confirmed that

\(^4\)http://www.swift.ac.uk/analysis/xrt/pileup.php
\(^5\)http://simbad.u-strasbg.fr/simbad/
Table 3.1: Exposures and background corrected count rates for all observations with and without SAX J1750.8-2900 detections. 95% upper count rate limits (indicated by the '<' symbol) are given in cases where the source was not detected above the SNR threshold (≤ 2). The '*' indicates the far off-axis observations (>7') with SAX J1750.8-2900 within the FOV.

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Observation Date</th>
<th>Mode</th>
<th>Exposure (ks)</th>
<th>Count Rate (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31166001</td>
<td>2008-03-17</td>
<td>PC</td>
<td>1.0</td>
<td>3.36 ± 0.06</td>
</tr>
<tr>
<td>31174001</td>
<td>2008-03-24</td>
<td>PC</td>
<td>0.7</td>
<td>1.56 ± 0.05</td>
</tr>
<tr>
<td>31174001</td>
<td>2008-03-24</td>
<td>WT</td>
<td>0.3</td>
<td>5.71 ± 0.14</td>
</tr>
<tr>
<td>31174002</td>
<td>2008-03-25</td>
<td>PC</td>
<td>0.9</td>
<td>1.38 ± 0.04</td>
</tr>
<tr>
<td>31174002</td>
<td>2008-03-25</td>
<td>WT</td>
<td>0.1</td>
<td>3.96 ± 0.23</td>
</tr>
<tr>
<td>31174003</td>
<td>2008-08-14</td>
<td>PC</td>
<td>1.9</td>
<td>0.06 ± 0.01</td>
</tr>
<tr>
<td>31174004</td>
<td>2008-08-15</td>
<td>PC</td>
<td>1.9</td>
<td>0.04 ± 0.01</td>
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<tr>
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<td>PC</td>
<td>2.0</td>
<td>0.06 ± 0.01</td>
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<tr>
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<td>PC</td>
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<td>0.05 ± 0.01</td>
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<tr>
<td>31174007</td>
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<tr>
<td>31174008</td>
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<td>0.12 ± 0.01</td>
</tr>
<tr>
<td>31174009</td>
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<td>0.08 ± 0.01</td>
</tr>
<tr>
<td>31174010</td>
<td>2008-08-24</td>
<td>PC</td>
<td>1.8</td>
<td>0.06 ± 0.01</td>
</tr>
<tr>
<td>31174011</td>
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<td>PC</td>
<td>2.1</td>
<td>0.13 ± 0.01</td>
</tr>
<tr>
<td>31174012</td>
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<td>PC</td>
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<td>0.12 ± 0.01</td>
</tr>
<tr>
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<td>PC</td>
<td>1.9</td>
<td>0.11 ± 0.01</td>
</tr>
<tr>
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<td>0.08 ± 0.01</td>
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<tr>
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<td>0.050 ± 0.0003</td>
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<tr>
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<td>2008-09-03</td>
<td>PC</td>
<td>2.3</td>
<td>0.14 ± 0.01</td>
</tr>
<tr>
<td>31174017</td>
<td>2008-09-05</td>
<td>PC</td>
<td>0.7</td>
<td>0.05 ± 0.01</td>
</tr>
<tr>
<td>31174018</td>
<td>2008-09-11</td>
<td>PC</td>
<td>1.8</td>
<td>0.07 ± 0.01</td>
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<tr>
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<td>2008-10-01</td>
<td>PC</td>
<td>2.0</td>
<td>0.74 ± 0.02</td>
</tr>
<tr>
<td>31174020</td>
<td>2008-10-08</td>
<td>PC</td>
<td>1.9</td>
<td>0.62 ± 0.02</td>
</tr>
<tr>
<td>31174021</td>
<td>2011-02-19</td>
<td>PC</td>
<td>3.9</td>
<td>0.46 ± 0.01</td>
</tr>
<tr>
<td>31174023</td>
<td>2011-09-30</td>
<td>PC</td>
<td>0.5</td>
<td>&lt;0.018</td>
</tr>
<tr>
<td>31174024</td>
<td>2012-02-14</td>
<td>PC</td>
<td>3.8</td>
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</tr>
<tr>
<td>31174025</td>
<td>2012-02-26</td>
<td>PC</td>
<td>2.6</td>
<td>&lt;0.003</td>
</tr>
<tr>
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<td>2012-02-29</td>
<td>PC</td>
<td>0.3</td>
<td>&lt;0.023</td>
</tr>
<tr>
<td>31174027</td>
<td>2012-03-03</td>
<td>PC</td>
<td>3.2</td>
<td>0.002 ± 0.001</td>
</tr>
<tr>
<td>31174028</td>
<td>2012-03-06</td>
<td>PC</td>
<td>2.8</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>31174030</td>
<td>2012-03-17</td>
<td>PC</td>
<td>3.1</td>
<td>0.018 ± 0.003</td>
</tr>
<tr>
<td>31174031</td>
<td>2012-03-20</td>
<td>PC</td>
<td>1.0</td>
<td>0.006 ± 0.003</td>
</tr>
<tr>
<td>31174032</td>
<td>2012-03-22</td>
<td>PC</td>
<td>1.0</td>
<td>&lt;0.006</td>
</tr>
<tr>
<td>43649001</td>
<td>2012-05-22</td>
<td>PC</td>
<td>0.5</td>
<td>&lt;0.019*</td>
</tr>
<tr>
<td>32427001</td>
<td>2012-06-17</td>
<td>PC</td>
<td>0.8</td>
<td>&lt;0.009*</td>
</tr>
<tr>
<td>32427002</td>
<td>2012-06-22</td>
<td>PC</td>
<td>0.7</td>
<td>&lt;0.008*</td>
</tr>
<tr>
<td>32427003</td>
<td>2012-08-15</td>
<td>PC</td>
<td>0.1</td>
<td>&lt;0.042*</td>
</tr>
<tr>
<td>32427004</td>
<td>2012-09-04</td>
<td>PC</td>
<td>0.5</td>
<td>&lt;0.010*</td>
</tr>
<tr>
<td>Quiescence</td>
<td>-</td>
<td>PC</td>
<td>12.3</td>
<td>0.0011 ± 0.0004</td>
</tr>
<tr>
<td>Flare</td>
<td>-</td>
<td>PC</td>
<td>5.1</td>
<td>0.012 ± 0.002</td>
</tr>
</tbody>
</table>
the spectral parameters obtained with binning to fewer than 20 counts per bin were consistent with the spectral parameters from fits of unbinned spectra.

### 3.2.1.1 Non-detections and combined observations

In 11 out of a total of 38 observations, we did not detect our source. We were able to place upper limits on SAX J1750.8-2900's activity using a circular extraction region with a radius of 15 pixels centered on the published Chandra coordinates for SAX J1750.8-2900 [Chakrabarty et al., 2008]. Following the prescription of Gehrels [1986], we placed the 95% upper limits on the source count rate (denoted by < in Table 3.1).

We combined observations with no source detection and observations with faint source detections at low intensities (with count rates < 0.02 s\(^{-1}\)) during the February and March 2012 period to increase the source counts and perform spectral fits. Observations 31174030, 31174031 and 31174032, corresponding to March 17-22, exhibited elevated count rates compared to previously exhibited quiescent levels (< 0.002 s\(^{-1}\)); we combined these three observations to form a 'Flare' spectrum. We formed a 'Quiescent' spectrum by summing all observations immediately prior to the flare with count rates (including upper limits) less than 0.004 s\(^{-1}\) for a total exposure time of 12.3 ks (corresponding to ObsIDs 31174024-25 and 31174027-28). Spectra for the flare and quiescence were generated by summing observations' event files in XSelect followed by summing their exposure maps in XImage. The source and background spectra were extracted following the same procedure previously outlined for PC mode observations with clear source detections using a circle with a 10-pixel radius as the source region.

The source intensity as a function of the observation date for our entire data set is shown in Figure 3-2.

### 3.2.2 Spectral Analysis

All spectral analysis was performed using XSpec v.12.7.0 [Arnaud, 1996]. We used the \texttt{tbabs} multiplicative model to account for interstellar absorption and set our abun-
Figure 3-2: SAX J1750.8-2900’s count rate light curve: The downward arrows indicate the upper 95% count rate limits for all observations without source detections (see Section 3.2.1.1), and the inset shows the activity between August and October 2008 where the bulk of our observations occur. The numbers indicate the approximate groups of observations with similar spectral properties and luminosities.

dances to those of Wilms et al. [2000] and used the cross-sections from Verner et al. [1996]. All quoted luminosities are the 0.5-10 keV unabsorbed luminosities (unless a different energy range is specified), calculated with the cf1ux convolution model assuming a source distance of 6.79 kpc [Galloway et al., 2008]. The Eddington fraction \((L_X/L_{Edd})\) assumes an Eddington luminosity, \(L_{Edd}\), of \(2 \times 10^{38}\) erg s\(^{-1}\) for a 1.4 M\(_\odot\) neutron star with a hydrogen-rich photosphere. Errors on fit parameters correspond to the 90% confidence bounds \((\Delta \chi^2 = 2.71)\) and all chi-squares, \(\chi^2 (dof)\), are reduced.

### 3.2.2.1 Hardness Ratio

In order to study the evolution of the average spectral slope or "hardness" in a model-independent way, we calculated the hardness ratio (HR) for each observation. We have defined the hardness ratio as the ratio of hard (2-10 keV) to soft counts (0.5-2 keV), which we calculated within XSpec from background-corrected source spectra binned
to 1 count per bin to avoid having empty bins.

*Swift* XRT analysis guides warn of soft spectral 'bump' below 1 keV for highly absorbed sources \((N_H > 10^{22} \text{ cm}^{-2})\) when using the standard WT mode event grades 0-2 selection. We investigated the grades 0-2 versus grade 0 extractions for our two WT mode observations and found no significant difference in the hardness ratios between the two grade selections (ObsID 31174001 HR = 5.7 ± 0.4 vs 5.95 ± 0.5, 31174002 HR = 6.6±1.3 vs 6.1±1.1 for grades 0 and 0-2, respectively) or in parameters obtained from spectral fits (for example, a simple absorbed power law). Thus, we used the standard WT event grades 0-2 extraction in our analysis.

### 3.2.2.2 Column Density Constraints and Spectral Modeling

The column density towards SAX J1750.8-2900 is poorly constrained; published values range from \(N_H = (2.5 - 6.0) \times 10^{22} \text{ cm}^{-2}\), henceforth noted as \(N_{H,22} = 2.5 - 6.0\) [Natalucci et al., 1999, Lowell et al., 2012] and are strongly dependent on the spectral model used. From a quiescent *XMM* observation, Lowell et al. [2012] obtained \(N_{H,22} = 5.9 \pm 0.5\) with the *NSATMOS* model [Heinke et al., 2006], while a blackbody fit yielded \(N_{H,22} = 4.0^{+1.1}_{-0.9}\).

Fitting individual observations with an absorbed power law with no fixed inputs led to large uncertainties in the spectral parameters. In order to obtain better constraints, we fit groups of observations with a single model and tied certain parameters between all observations within the group. We formed the groups by initially fitting all individual observations with an absorbed power law fixing the column density to \(N_{H,22} = 5\) (the average of the values obtained by Lowell et al. 2012) while leaving the photon index and normalization free to vary; we then sorted the observations by their 2-10 keV unabsorbed luminosities. Plotting the 2-10 keV unabsorbed luminosities against the powerlaw photon index, we found 7 distinct clusters of observations in the

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6http://www.swift.ac.uk/analysis/xrt/digest_cal.php
7We first attempted to sort the observations by their 0.5-10 keV unabsorbed luminosity, but found a weaker correlation between the luminosity and spectral shape (i.e. photon index). For highly absorbed sources \((N_{H,22} \gtrsim 3)\) and soft spectra \((\Gamma \gtrsim 2)\), a power law model leads to large 0.5-2 keV unabsorbed fluxes due to the divergence of the power law flux at low energies. Thus, we found a stronger spectral dependence on luminosity when we excluded the low-energy flux contribution by looking at the 2-10 keV unabsorbed luminosity.
photon index-luminosity parameter space and divided our set of observations into 7 spectral and luminosity groups, shown in Table 3.2.

We also attempted a single component fit with a blackbody model (bbodyrad), but found it did not provide acceptable fits across our dataset’s entire luminosity range. At high luminosities ($L_X > 10^{37}$ erg s$^{-1}$, the blackbody yielded a significantly worse fit than a power law ($\chi^2 = 1.2$ vs 0.9). Additionally, column densities required for the blackbody fits ($N_{H,22} \lesssim 2.5$) were lower than even the low-end of published estimates.

We performed a new power law fit for each group, tying the photon index while leaving the normalization free. For the two brightest groups (6 and 7) we left the absorption parameter free (but tied if there were multiple observations in the group) and found consistent values for the column density, $N_{H,22} = 4.2 \pm 0.4$ and $4.4 \pm 0.4$. We fixed all future column densities to $N_{H,22} = 4.3$, the average value from our two brightest groups.

While the group fits provided tight constraints on SAX J1750.8-2900’s average spectral changes with luminosity, to examine the source’s variability on shorter timescales we fit the individual observations with an absorbed power law, fixing the column density while leaving the photon index and normalization free to vary. Due to insufficient source counts, we were unable perform spectral fits for ObsIDs 31174024-31174032 in an attempt to track the changes in the photon index before, during and after the flare. Instead, we used a count rate-flux conversion to estimate the system’s luminosity. Using WebPimms (v4.6a)$^8$, we converted the observed count rate/upper limit to a luminosity based on the published blackbody quiescent fit result of Lowell et al. [2012] ($kT_{\text{eff}}^{\infty} = 331$ eV and $N_{H,22} = 4$), shown in Figure 3-3. The quiescent and flare spectra formed by combining observations (Section 3.2.1.1), however, had enough counts to perform power law fits.

While the power law model worked well for both the group and individual fits (we obtained $\chi^2 \sim 1$), we investigated whether multiple spectral components were present by performing a multicomponent model fit to the grouped observations where our

$^8$http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html
Figure 3-3: The 0.5-10 keV unabsorbed luminosity estimates for SAX J1750.8-2900 between February and March 2012, including the flare reported by Wijnands and Degenaar [2013] which begins as early as March 6. Both luminosity upper limits (indicated by the downward pointing arrows) and luminosity estimates for observations with source detections (diamond symbols) were calculated from the count rate-flux conversion based on a blackbody with $kT_{\text{eff}} = 331$ eV. The shaded region is bounded by the quiescent luminosities reported by Lowell et al. [2012] for blackbody ($L_X = 2.8 \times 10^{33}$ erg s$^{-1}$) and neutron star atmosphere models ($L_X = 8.9 \times 10^{33}$ erg s$^{-1}$).
Figure 3-4: Hardness ratio as a function of count rate: As the count rate decreases between $1.5 - 0.05 \text{ s}^{-1}$, the hardness ratio also decreases, indicating the source softens as its intensity declines. This behavior is intrinsic to the source as the hardness ratio is independent of a spectral model. The source may soften further towards quiescence (down to a count rate of $0.001 \text{ s}^{-1}$) but we discuss the limitations of interpreting the softening with low count spectra in Section 3.3.1.1.

the statistics were good enough to constrain additional parameters. We added a blackbody component (bbbodyrad) to the existing powerlaw. When tying the blackbody temperature and normalization across all observations within a group, we were able to constrain the soft component’s temperature, emitting area (i.e. the blackbody model’s normalization) and its fractional contribution to the total unabsorbed flux for groups 3-6.

3.3 Results

In our set of observations, SAX J1750.8-2900’s count rate and luminosity span over 3 orders of magnitude with ranges of $0.001 \text{ to } 6 \text{ s}^{-1}$ and $L_X$ between $10^{34}$ to $10^{37}$ erg s$^{-1}$. Observed at the beginning of the March 2008 outburst with $L_X = (4 - 30) \times 10^{36}$ erg s$^{-1}$, the source declined in intensity and luminosity in August 2008 ($L_X \sim 1 \times 10^{35}$ erg s$^{-1}$) until it re-brightened in October 2008. In March 2012, SAX J1750.8-2900’s
activity was below the RXTE PCA and Swift BAT sensitivity thresholds, but its quiescent activity ($\lesssim 10^{34}$ erg s$^{-1}$) was still marginally detectable with Swift XRT. Our observations were all well-fit by a pure power law, and in some cases, we were able to fit groups of observations with a power law plus blackbody model.

### 3.3.1 Spectral Softening, Hardening and Variability

We find a clear softening towards lower luminosities of the X-ray spectrum of SAX J1750.8-2900. Hardness ratios and photon indices decrease and increase, respectively, as the system’s unabsorbed luminosity decreases.

In Figure 3-4, as the source’s intensity decreases, $1.5 \rightarrow 0.05$ counts s$^{-1}$, the spectrum softens as the hardness ratio decreases by nearly a factor of 3, from $8 \rightarrow 3$. The results presented in Figure 3-4 use hardness ratios and count rates for pile-up corrected spectra and are therefore independent of the spectral model used. Further softening at even lower count rates ($< 0.05$ s$^{-1}$) is discussed in the next section.

#### 3.3.1.1 Model 1: Power law behavior

The softening behavior is also evident in the power law spectral parameters both when observations are fit as groups and individually. Power law parameters obtained from group fits are shown in Table 3.2 and plotted in Figure 3-5, while power law fits to individual spectra are contained in Table 3.3 and plotted in Figures 3-5 and 3-6 for the full data set and the August to October 2008 period, respectively. As seen in Figure 3-5, as the 0.5-10 keV unabsorbed luminosity decreases, $L_X = 4 \times 10^{36} \rightarrow 1 \times 10^{35}$ erg s$^{-1}$, the photon index increases from 1.4 to 2.9.

Below an intensity of 0.05 s$^{-1}$ and a luminosity of $\sim 5 \times 10^{34}$ erg s$^{-1}$, the spectral parameters and hardness ratios suffer from large uncertainties due to the low number of counts, making the softening trend less obvious. Lowell et al. [2012] and Wijnands and Degenaar [2013] found that SAX J1750.8-2900’s 2010 and 2012 quiescent spectra, respectively, were well-fit with a thermal spectral model (either NSATMOS
Table 3.2: Power Law and Power Law + Blackbody Fits - Grouped Observations

<table>
<thead>
<tr>
<th>Group Low (^{a}) High</th>
<th>Model 1: ( \text{tbabs} \ast \text{powerlaw} )</th>
<th>Model 2: ( \text{tbabs} \ast (\text{powerlaw} + \text{bbodyrad}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_{H,22} ) ( \Gamma ) ( L_X ) ( \chi^2 ) (dof)</td>
<td>( N_{H,22} ) ( \Gamma ) ( kT ) ( \text{BB-Norm} ) ( L_X ) ( F_{PL} ) ( F_{BB} ) ( \chi^2 ) (dof) F-Test ( ^{e} ) HR</td>
</tr>
<tr>
<td>1 0.001 0.01</td>
<td>4.3 4.1 ± 1.6 0.11 ±0.46 15.1 (18) ( ^{f} )</td>
<td>-</td>
</tr>
<tr>
<td>2 0.01 0.1</td>
<td>4.3 1.7 ± 0.5 0.16 ±0.08 68.4 (59) ( ^{g} )</td>
<td>-</td>
</tr>
<tr>
<td>3 0.1 0.3</td>
<td>4.3 2.9 ± 0.2 0.97 ±0.21 9.9 (108)</td>
<td>4.3 2.5 ±0.8 0.49 ±0.15 6.2 ±8.1 0.6 ±0.2 66 ± 32 % 34 ± 32 % 0.9 (106) 2e-3 3.1 ± 0.8</td>
</tr>
<tr>
<td>4 0.3 5</td>
<td>4.3 2.2 ± 0.1 1.26 ±0.17 1.0 (144)</td>
<td>4.3 1.6 ±0.4 0.55 ±0.08 6.7 ±0.3 1.0 ±0.1 62 ± 12 % 38 ± 12 % 0.8 (142) 7e-9 4.6 ± 0.9</td>
</tr>
<tr>
<td>5 5 20</td>
<td>4.3 1.6 ± 0.1 15.4±0.66 1.0 (231)</td>
<td>4.3 1.6±0.2 1.04±0.17 4.4±3.4 14.4±0.7 79±7 % 21±7 % 0.8 (229) 5e-2 7.5 ± 0.6</td>
</tr>
<tr>
<td>6 20 100</td>
<td>4.4 ± 0.4 1.4 ± 0.1 44.57±0.34 1.0 (216)</td>
<td>4.3 1.6±0.3 1.89±0.52 1.7±1.5 44.6±3.5 77±11 % 23±11 % 1.0 (215) 8e-6 6.9 ± 0.6</td>
</tr>
<tr>
<td>7 100 500</td>
<td>4.2 ± 0.4 1.6 ± 0.1 253.13±19.75 0.9 (139)</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^{a}\)Group luminosity bounds in units \(10^{35} \text{ erg s}^{-1}\) for the 2-10 keV unabsorbed luminosity obtained with a power law fit.

\(^{b}\)Blackbody temperature (keV)

\(^{c}\)Percent contributions of the powerlaw component to the total 0.5-10 keV unabsorbed luminosity.

\(^{d}\)Percent contributions of the blackbody component to the total 0.5-10 keV unabsorbed luminosity.

\(^{e}\)F-test probability that the added component (i.e. blackbody) improves the fit by chance.

\(^{f}\)C-statistic

\(^{g}\)C-statistic
or \texttt{bbodyrad}). In particular, for the deep \textit{XMM} quiescent observation where more stringent limits on the nonthermal component could be placed, no additional power law was necessary and a power law component had a maximum contribution of 4\% to the total flux [Lowell et al., 2012]. The thermal nature of the quiescent spectrum combined with our low hardness ratio (HR = 1.1) suggest it is possible that the softening continues towards quiescence near $L_X \sim 10^{34}$ erg s$^{-1}$. The flare, however, appears inconsistent with the softening behavior. It exhibits a higher hardness ratio and lower photon index than the trend would predict given the event’s luminosity, but the error bars are large for both parameters, so we are unable to claim that the flare is an exception to the softening trend with such limited statistics.

In addition to the general trend of softening as the luminosity decreases over an order of magnitude, we found softening occurred on very short timescales (on the order of days to weeks), as well as spectral hardening as the luminosity increased on similar timescales. While the 2-10 keV luminosity was more strongly variable than the 0.5-10 keV luminosity (see Figure 3-6), between August and October 2008, which corresponds to groups 3 and 4, hardness ratios and photon indices were correlated and anti-correlated, respectively, with the 0.5-10 keV luminosity$^9$ which varied between $5.9 \times 10^{34}$ and $1.6 \times 10^{35}$ erg s$^{-1}$.

For example, SAX J1750.8-2900 softened between August 25-29 (ObsIDs 31174011-4015); as the intensity, hardness ratio (6.3 $\rightarrow$ 3), and 0.5-10 keV luminosity decreased ($L_X = (1.42 \rightarrow 0.96) \times 10^{35}$ erg s$^{-1}$) while the photon index increased (2.0 $\rightarrow$ 2.9). Immediately after the softening, the spectrum hardened; between August 29 - September 3 (ObsIDs 31174015-4016), SAX J1750.8-2900’s luminosity increased to $1.6 \times 10^{35}$ erg s$^{-1}$, while the hardness ratio increased to 5.4 and the photon index decreased to $\Gamma = 2.0$.

$^9$As mentioned in 3.2.2.2, the suppressed variation in the 0.5-10 keV unabsorbed luminosity may be due to the large 0.5-2 keV unabsorbed flux contribution in a power law fit to highly absorbed, soft spectra.
Figure 3-5: **Model 1, Power Law:** Hardness ratios (model-independent) and photon indices from a power law fit versus the unabsorbed 0.5-10 keV luminosity, also given in terms of the Eddington fraction ($L_X/L_{Edd}$). Empty symbols indicate values for the individual observations and the symbol color represents its luminosity group. Black filled circles are the results for the fits of the grouped observations (with the group numbers adjacent). Spectral softening, first evident in the hardness ratio-count rate relation in Figure 3-4, is further supported by the anti-correlation and correlation of the hardness ratio and photon index, respectively, with the luminosity between $4 \times 10^{36}$ and $10^{35}$ erg s$^{-1}$. 
Figure 3-6: **Model 1, Power Law**: Between August and October 2008, the hardness ratios and photon indices obtained with a power law model show signs of correlation and anti-correlation, respectively, with the 0.5-10 keV unabsorbed luminosity, indicating the spectrum softens (hardens) as the luminosity decreases (increases) on timescales from days-weeks. Also plotted in the bottom panel is the 2-10 keV unabsorbed luminosity, which shows stronger variation in time.
Table 3.3: Model 1: Power Law Fits - Individual Observations

<table>
<thead>
<tr>
<th>Group</th>
<th>ObsID</th>
<th>$N_{H,22}$</th>
<th>$\Gamma$</th>
<th>$L_X^{10}$</th>
<th>$\chi^2$ (dof)</th>
<th>HR</th>
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<td>Quiescence</td>
<td>4.3</td>
<td>4.1±1.6</td>
<td>0.11$^{+0.46}_{-0.08}$</td>
<td>15.1 (18)</td>
<td>1.1±0.8</td>
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<td>Flare</td>
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<td>1.7±0.5</td>
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<td>68.4 (59)</td>
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<td>1.16$^{+0.64}_{-0.60}$</td>
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<td>0.96$^{+0.23}_{-0.19}$</td>
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<td>0.96$^{+0.42}_{-0.34}$</td>
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<td>2.5±0.3</td>
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<td>1.0 (15)</td>
<td>4.1±0.8</td>
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<td>1.5 (28)</td>
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<td>4.1±0.7</td>
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<td>2.0±0.2</td>
<td>1.42$^{+0.20}_{-0.18}$</td>
<td>0.9 (16)</td>
<td>6.3±1.2</td>
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<td>2.0±0.2</td>
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<td>5.4±0.8</td>
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<td>1.5±0.1</td>
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<td>1.0 (80)</td>
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<td>15.79$^{+0.41}_{-0.71}$</td>
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<td>8.5±0.7</td>
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<td>18.68$^{+0.99}_{-0.97}$</td>
<td>0.6 (53)</td>
<td>6.6±0.5</td>
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<td>0.8 (47)</td>
<td>7.5±0.7</td>
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<td>1.4±0.1</td>
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</tr>
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<td>7</td>
<td>31166001</td>
<td>4.2$^{+0.4}_{-0.4}$</td>
<td>1.6±0.1</td>
<td>253.13$^{+19.75}_{-16.60}$</td>
<td>0.9 (139)</td>
<td>6.2±0.3</td>
</tr>
</tbody>
</table>

3.3.2 Model 2: Soft emission and thermal contributions

We were able to fit a soft component (modeled with a blackbody) in addition to the hard emission (modeled with a powerlaw) when fitting several of the groups of observations. There was no change in the chi-squared value compared to the pure power law fit, indicating there is no strong model preference. The multicomponent fit parameters are shown in Table 3.2 and spectra with their group fits (either powerlaw or powerlaw plus blackbody models) are shown in Figure 3-7.

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12Unabsorbed 0.5-10 keV luminosity in units of $10^{35}$ erg s$^{-1}$
12C-statistic
12C-statistic
Figure 3-7: Swift XRT folded spectra of SAX J1750.8-2900 used in this work, together with our best-fit model functions. Observations were combined into 7 groups (Sec. 3.2.2, Table 3.2). Groups 1, 2 and 7 are fit with an absorbed power law, while with groups 3-6 we were able to constrain an additional soft component, and so we plot their `powerlaw + bbodyrad` fits. Adding a soft component improved residuals slightly, but overall the spectra and their residuals are similar between the single and multicomponent fits. Groups 1 and 2 are plotted together but are fit separately and binned for display only.
Despite group 7 being the brightest observation, it had fewer source counts than any of groups 3, 5 or 6. We were unable to calculate the lower error bound on the blackbody temperature when we performed a powerlaw plus blackbody fit, indicating the blackbody component was not definitively detected in this observation. For a blackbody normalization of 5 (an average of the normalizations found in fits on groups 3-6), the blackbody had a temperature upper limit of 2.45 keV and maximal flux contribution of 25%.

Luminosity-photon index relations for the power law and the power law plus blackbody models are compared in the top panel of Figure 3-8. With the addition of the soft component, between $4 \times 10^{36}$ and $1 \times 10^{35}$ erg s$^{-1}$, the photon index was consistent with being constant ($\Gamma \sim 1.6$). At a luminosity of $L_X = 6 \times 10^{34}$ erg s$^{-1}$, however, the power law component softened ($\Gamma = 2.5_{-1.2}^{+0.8}$) although the error bars are large and still consistent with the photon index at higher luminosities.

Shown in the middle panel of Figure 3-8, the blackbody component exhibited a decreasing temperature ($1.9 \rightarrow 0.5$ keV, plotted in red) at lower luminosities ($L_X \sim 4 \times 10^{36} \rightarrow 6 \times 10^{34}$ erg s$^{-1}$). The blackbody’s contribution to the total flux (i.e. the thermal flux fraction, plotted in black) tends towards higher fractions at lower luminosities, although the uncertainties are large. We could only fit for an additional soft component in groups 3-6, but we have also plotted the quiescent thermal fraction (with a lower limit of 96% as the quiescent spectrum was thermal with a maximum power law contribution of 4%) and luminosity from the Lowell et al. [2012] results. We estimated the lower limit to the thermal fraction of the flare by simply dividing the quiescent thermal luminosity by the flare luminosity.

In the bottom panel of Figure 3-8, we plot the power law and blackbody components’ 0.5-10 keV luminosities as a function of the total 0.5-10 keV luminosity. When we performed a simple linear fit, we found the power law flux declines more rapidly than the thermal flux (a slope of 1.1 versus 0.70 for the blackbody flux), which is consistent with the thermal flux fraction increasing towards lower luminosities. If we express each component’s luminosity in terms of the quiescent thermal luminosity (right axis, bottom panel), we find that for groups 3 and 4 the thermal luminosity is
2-4 times the quiescent luminosity, indicating that the quiescent emission contributes significantly to the thermal luminosity (approximately 50% and 25% of the thermal luminosity at $6 \times 10^{34}$ erg s$^{-1}$ and $1 \times 10^{35}$ erg s$^{-1}$, respectively).

3.4 Discussion

Our set of Swift XRT observations of SAX J1750.8-2900 span over 4 years and 3 orders of magnitude in luminosity, which allows us to explore a wide range of accretion rates and timescales. We find that the source softens between outburst and quiescence, $L_x = 10^{-2} \rightarrow 10^{-3} L_{\text{NS}}^{\text{Edd}}$, and the softening mechanism generates spectral variability on multi-day timescales.

3.4.1 Spectral softening between outburst and quiescence

Spectral softening is a nearly universal behavior in black hole transient systems as they enter quiescence [Wu and Gu, 2008, Plotkin et al., 2013] and now a trend seen across dozens of neutron star transients [Wijnands et al., 2015]. In black hole binaries, one interpretation of the spectral softening during the transition from the hard state to quiescence involves the changing opacity of an inner advection-dominated accretion flow (ADAF), although jets may also play a role in the softening near quiescence. The anti-correlation between the photon index and luminosity typically spans $L_x/L_{\text{BH}}^{\text{Edd}} = 10^{-2} \rightarrow 10^{-5}$ for $\sim 10 M_\odot$ black holes, while below $L_x/L_{\text{BH}}^{\text{Edd}} = 10^{-5}$, there is evidence the spectrum does not soften further into quiescence but that the photon index remains constant [Plotkin et al., 2013].

While both neutron star and black hole transients exhibit increasing photon indices towards lower luminosities, the softening mechanism(s) are not necessarily expected to be the same, largely due to the differences in emission sources between the two types of transients. Gathering observations of neutron star transients with luminosities between $10^{34} - 10^{36}$ erg s$^{-1}$ and comparing to the photon index-luminosity relation for black holes found by Plotkin et al. [2013], Wijnands et al. [2015] found that softening black hole and neutron star transients are distinctly separate popu-
Figure 3-8: Model 2, Power law + Blackbody: The top panel shows the difference in the power law photon index behavior between the two models: pure power law (plotted in grey) and power law plus blackbody (black). When a soft component (i.e. blackbody) is included in the fit, the photon index is essentially constant between $L_X = 4 \times 10^{36} \rightarrow 10^{35}$ erg s$^{-1}$. In the middle panel are the thermal fraction (black) and blackbody temperature (red) as a function of the total 0.5-10 keV unabsorbed luminosity. The soft component’s temperature is lower at lower luminosities, which is expected if the soft component is associated with accretion onto the neutron star surface. Bottom panel: Luminosity from each of the power law (blue) and blackbody (red) components in the power law plus blackbody model plotted along with a linear fit, along with the Lowell et al. [2012] NSATMOS thermal luminosity (at $\sim 10^{34}$ erg s$^{-1}$). The power law flux declines more rapidly than the flux from the thermal component.
lations. Black holes are significantly harder ($\Gamma \lesssim 2$) than neutron star transients ($2 \lesssim \Gamma \lesssim 3$) below $10^{35}$ erg s$^{-1}$.

With the exception of accretion disk emission, black hole transients are almost entirely sources of nonthermal emission and can be modeled with a pure power law at luminosities below an Eddington fraction of 1%. Neutron star LMXBs, however, have both nonthermal and thermal emission, although it is unclear which component dominates in different luminosity and accretion regimes. Due to the neutron star's solid surface, there are multiple sources of soft X-ray emission across a range of luminosities: boundary layer emission [Lin et al., 2007], thermal surface emission due to heat generated by pycnonuclear reactions deep within the neutron star crust [Brown et al., 1998], and a blackbody-like spectrum due to low-level accretion [Zampieri et al., 1995], while accretion can produce nonthermal emission at almost any luminosity. Changes in multiple or just one of these sources can contribute to the spectral softening. Attempts to track the thermal and nonthermal contributions as a function of time and luminosity are further complicated when there is insufficient spectral quality to constrain both components. Despite these obstacles, there is growing evidence suggesting that changes in a soft component's properties is largely responsible for spectral softening [Armas Padilla et al., 2013, Bahramian et al., 2014, Wijnands et al., 2015] and that the component is powered by accretion rather than heat release from the neutron star crust, while there may be simultaneous changes in the nonthermal emission associated with accretion.

Softening has been observed in neutron star LMXBs over luminosities of $10^{36} \rightarrow 10^{34}$ erg s$^{-1}$, similar to the range where we have detected softening in SAX J1750.8-2900 between outburst and quiescence. In Figure 3-9 we have plotted the photon indices and luminosities for SAX J1750.8-2900's power law fits, along with the published power law parameters for several other NS LMXBs that have exhibited spectral softening. For a more complete comparison of spectral softening in a dozen neutron star transients, see Figure 1 in Wijnands et al. [2015].
3.4.1.1 Soft Component’s Role in Softening

In most of the neutron star softening sources, a power law provided adequate, if not good, fits to most of the observations. However, at lower luminosities (≤ 10^{35} erg s^{-1}) and with higher SNR spectra, many sources required an additional soft spectral component, indicating the spectra are not entirely non-thermal, and the softening cannot be accurately modeled by a power law with a steepening photon index, as is the case with softening black hole transients.

In deep *XMM* observations of neutron star transients XTE J1709-267 and IGR J1794-3030, Degenaar et al. [2013] and Armas Padilla et al. [2013] achieved the sensitivity to constrain both hard and soft spectral components; both sources exhibited a decaying thermal temperature and constant photon index while the total flux decreased over the course of approximately 10 hours. Due to the similarities between the two systems’ behaviors, Armas Padilla et al. [2013] credited the spectral changes in both sources to a decrease in the mass accretion rate onto the neutron star surface which produced a soft component with a decreasing temperature, while the nonthermal flux due to accretion also decreases.

With SAX J1750.8-2900 when adding a blackbody, we found almost no change in the chi-squared values, indicating there was no model preference between a pure power law and the power law plus blackbody and that the additional soft component was not statistically required. Thus, the softening in SAX J1750.8-2900 from our data can be accurately described by a steepening photon index towards lower luminosities. However, it is worth noting that when we included a blackbody component, we find the soft component’s behavior is similar to that seen in other softening neutron star transients where additional soft components are statistically required, and the behavior is consistent with the interpretation that the soft component is generated by accretion onto the neutron star. In SAX J1750.8-2900, as the total luminosity decreased, the blackbody displayed lower temperatures and its flux contribution increased, indicating the strength of the component was increasing relative to the hard component. Between \( L_X \sim 10^{36} \) and \( 10^{35} \) erg s^{-1}, the photon index of the power law
component was essentially constant revealing that an increasingly dominant thermal component may contribute significantly to the softening. We are unable to comment on the behavior of the power law component's photon index above \( L_x \sim 5 \times 10^{36} \text{ erg s}^{-1} \) and below \( \sim 5 \times 10^{34} \text{ erg s}^{-1} \), as we either were unable to constrain both power law and blackbody components or the photon index suffered from large uncertainties.

3.4.1.2 Variability and Spectral Hardening

Rapid, non-monotonic variability, as well as alternating spectral softening and hardening with decreasing and increasing luminosity seen in SAX J1750.8-2900 strongly support the theory that accretion generates the spectral softening. With our dense set of observations between August and October 2008 (Figure 3-6), we found SAX J1750.8-2900's luminosity and spectral hardness varied on timescales as short as a day; such rapid variability can be generated by changes in the accretion rate onto the
neutron star. Additionally, SAX J1750.8-2900 displays alternating spectral hardening and softening over the course of days and weeks, which has not been seen in other neutron stars on such timescales.

Spectral hardening with increasing intensity has been observed in the neutron star LMXB Swift J174805.3-244637 as its rise to the hard state was monitored with Swift XRT \cite{Bahramian2014}. As its luminosity increased from $L_X = 4 \times 10^{34} \rightarrow 10^{36} \text{ erg s}^{-1} (\sim 2 \times 10^{-4} \rightarrow 4 \times 10^{-3} L_{Edd})$ the photon index decreased ($\Gamma = 2.6 \rightarrow 1.7$) when fit with a pure power law. Using more complex models with a soft component, Bahramian et al. \cite{Bahramian2014} found an increasing thermal temperature with increasing luminosity, which cannot be produced via a cooling neutron star crust since the observations are at the onset outburst. While we could not track the rapid day-to-day variations in the soft component as SAX J1750.8-2900 hardened, the similarities between SAX J1750.8-2900 and Swift J174805.3-244637 further support the interpretation that the spectral changes are produced by hard and soft emission powered by a varying mass accretion rate onto the neutron star surface.

While we found SAX J1750.8-2900 to be variable during August to October 2008, its average luminosity was approximately $10^{35} \text{ erg s}^{-1}$, which shows that underluminous accretion flows ($L_X/L_{Edd} < 0.1\%$) can be stable under certain conditions. Namely, SAX J1750.8-2900 remained at $L_X \sim 10^{35} \text{ erg s}^{-1}$ for over one month (Figure 3-6) in contrast with the rapid decay to quiescence ($\lesssim 1 \text{ week}$) seen in other neutron star transients (Aql X-1, Campana et al. \cite{Campana2014}; SAX J1810.8-2069 Linares et al. \cite{Linares2007}; 4U 1608-52 Linares et al. \cite{Linares2009}).

3.4.2 Accretion and the Origin of the Soft Component

In many of the existing discussions of softening neutron star LMXBs, emission associated with accretion onto the neutron star surface has been cited as the possible soft component detected in the spectra. The spectrum generated by spherical accretion onto an unmagnetized neutron star has been a long-standing issue. Zel'dovich and Shakura \cite{Zeldovich1969} demonstrated that freely, radially infalling ions onto a neutron star produced a blackbody spectrum with a high-energy tail due to Comp-
tonization with luminosities of $\sim 10^{35} - 10^{38}$ erg s$^{-1}$. Similar results were obtained by subsequent studies even when additional physics were included. Zampieri et al. [1995] extended simulations to even lower mass accretion rates down to luminosities of $\sim 10^{31} - 10^{32}$ erg s$^{-1}$ and found the emergent spectra were significantly hardened compared to a blackbody at the neutron star effective temperature. Deufel et al. [2001] considered the case of non-spherical accretion from a hot accretion flow (ADAF) surrounding the neutron star. The hot ions heat the surface layer to produce a blackbody-like spectra with a high-energy Comptonized tail, highlighting the contribution of neutron star surface to the hard emission in LMXBs. Further investigations are required to determine how the surface emission is modified by the accretion flow. But in all cases, accretion onto the neutron star surface produces a hardened blackbody-like spectrum and, at high accretion accretion rates, a significant high-energy tail.

We note that at luminosities above $L_X \sim 10^{36}$ erg s$^{-1}$, corresponding to groups 5-7, there is not a significant change in the hardness ratio or spectral parameters (photon indices, blackbody temperatures, etc.) for either the powerlaw or powerlaw plus blackbody models, despite over an order of magnitude change in luminosity. This 'plateau' in spectral parameters could suggest that the emission, whether entirely nonthermal or a combination of thermal and nonthermal sources, above $10^{36}$ erg s$^{-1}$ only changes in brightness without a substantial change in the accretion flow properties.

### 3.4.3 Sub-Outburst Accretion and Crustal Heating Implications

Accretion in the outburst state dominates the thermal evolution of transiently accreting neutron stars. During outburst, the accreted material compresses the upper layers of the neutron star, inducing pycnonuclear reactions in a process known as deep crustal heating [Brown et al., 1998]. The heat generated by the reactions is conducted throughout the neutron star and is partially radiated away at the surface, emerging
as a thermal spectrum. From the time-averaged outburst accretion rate, which is determined by the outburst history, one can estimate the neutron star’s quiescent luminosity and surface temperature due to deep crustal heating. Time-averaged accretion rates due to sub-outburst accretion, however, are less well-known as there are typically large uncertainties in the accretion events’ properties, such as duration, intensity and recurrence times as this type of low-level activity is difficult to observe with all-sky X-ray monitors.

The heating problem is particularly important in SAX J1750.8-2900 because it exhibits two forms of accretion outside of outburst: sustained (> 1 month) accretion at $10^{35}$ erg s$^{-1}$ and a low-level flare in quiescence, while also having one of the highest reported surface temperatures for a neutron star in quiescence [Lowell et al., 2012]. The system warrants an investigation as to whether these forms of low-level accretion could be frequent enough to produce shallow heating in the crust and contribute to the high thermal luminosity.

The intensity and type of accretion flow that manifests in quiescent transients has been a long-standing issue. A hard power law component often seen in quiescent neutron star spectra has commonly been attributed to ongoing accretion. It has been recently proposed that the hard, high-energy tail is produced by thermal bremsstrahlung emission from a radiatively-inefficient accretion flow [Chakrabarty et al., 2014]. SAX J1750.8-2900, however, does not show signs of nonthermal emission in quiescence nor does it show signs of spectral variability, which is another sign of ongoing accretion. The 2010 and 2012 quiescent luminosities were consistent [Lowell et al., 2012, Wijnands and Degenaar, 2013] further supporting the claim that accretion is not continuous during quiescence in SAX J1750.8-2900, although the Wijnands and Degenaar [2013] luminosity has large uncertainties.

While SAX J1750.8-2900 does not exhibit the characteristic signs of continuous accretion in quiescence, the detection of a flare [Wijnands and Degenaar, 2013] suggests accretion is at least sporadic. Flaring activity of similar intensity and duration as in SAX J1750.8-2900 has been exhibited in several X-ray neutron star transient systems, including KS 1741-293 [Degenaar and Wijnands, 2013a] and XTE 1701-462
[Fridriksson et al., 2011]. While we lack the statistics to monitor the progression of the flare in SAX J1750.8-2900, Fridriksson et al. [2011] studied the hardness-intensity diagram of a flare observed in XTE 1701-462 that reached a peak luminosity 20 times higher than the system’s quiescent level. Both the thermal and non-thermal fluxes increased, albeit differently, strongly suggesting the flare was accretion-powered.

With our Swift XRT constraints on the accretion events (the quiescent flare and \( L_X = 10^{34} - 10^{36} \) erg s\(^{-1}\) activity) we can estimate their associated time-averaged accretion rates and compare to that of outburst, which is expected dominate the thermal evolution of the neutron star. We roughly approximated the flare as having a duration of 16 days (the longest possible duration in order to calculate an accretion rate upper limit) with a constant flux (\( \sim 4 \times 10^{-12} \) erg s\(^{-1}\) cm\(^{-2}\) our 0.5-10 keV unabsorbed flux estimate for the flare) and a (highly unconstrained) recurrence rate of 3 times per year. Bolometric corrections are model and luminosity dependent, but we use the ratio between the unabsorbed bolometric and 0.5-10 keV quiescent fluxes reported by Lowell et al. [2012] as a correction estimate (B.C. = 1.2 for the NSATMOS fluxes). After we convert the flare’s flux to a bolometric luminosity, we subtract the bolometric luminosity associated with the neutron star surface emission in quiescence (i.e. the Lowell et al. [2012] quiescent luminosity). Assuming an accretion efficiency of \( \epsilon = 0.2 \), we find a time-averaged accretion rate of \( \dot{M} = 1 \times 10^{-13} \) M\(_\odot\) per year (using \( L_{Bot} = \epsilon \dot{M} c^2 \)); even a recurrence rate of 10 flares per year only yields \( \dot{M} = 3 \times 10^{-13} \) M\(_\odot\) per year which is nearly 2 orders of magnitude smaller than our outburst averaged accretion rates, \( \dot{M} = 0.4 - 2.2 \times 10^{-10} \) M\(_\odot\)/year.

We estimated the outburst \( \dot{M} \) based on an outburst duration of 4 months with an occurrence rate of once every 4 years. We have detected SAX J1750.8-2900 in outburst with luminosities between \( L_X = 0.4 - 2.5 \times 10^{37} \) erg s\(^{-1}\), corresponding to range of accretion rates previously stated. Lowell et al. [2012] computed an outburst mass accretion rate of \( 2 \times 10^{-10} \) M\(_\odot\) per year which is in agreement with our estimates. For SAX J1750.8-2900’s activity between August and October 2008, we estimated a maximum rate of \( \dot{M} = 2 \times 10^{-12} \) M\(_\odot\) per year based on a duration of 60 days (August and September) with a typical \( L_X = 10^{35} \) erg s\(^{-1}\) and a recurrence time of once per
year. If this behavior is only associated with outbursts, then we'd expect a lower occurrence rate (once per 4 years) and a lower mass accretion rate ($\sim 4 \times 10^{-13} M_\odot$).

Although there are large uncertainties in our assumptions (recurrence times, durations, etc.) we find that sub-outburst accretion events lead to mass accretion rates at least an order of magnitude lower than rates associated with the outburst state. This supports the claim that the thermal evolution of the neutron star in SAX J1750.8-2900 is most heavily dependent on outburst accretion and that low-level accretion has little to no effect on the long term crustal temperature. Our conclusion is in agreement with Fridriksson et al. [2011], who performed a similar analysis based on flares exhibited by XTE J1701-462 and found that low-level accretion is unlikely to have a significant effect on the equilibrium surface temperature. We do not, however, address the immediate crustal heating effects due to small accretion events, such as flares, as they require much more detailed observations and calculations.

3.5 Conclusions

In our Swift XRT study of SAX J1750.8-2900's X-ray spectral behavior over four years of activity, we have found that the source softens as its luminosity decreases between $L_X = 4 \times 10^{36} \rightarrow 10^{35}$ erg s$^{-1}$. This trend is consistent with the spectral softening observed in individual neutron star LMXB systems, as well as the cumulative softening behavior exhibited by over one dozen transients between the luminosities of $10^{36}$ and $10^{34}$ erg s$^{-1}$. Our data is consistent with both the softening being due to a steepening power law towards lower luminosities and a thermal component becoming more apparent in the spectrum. The soft component may be associated with accretion onto the neutron star surface and has been definitively detected in other softening neutron star transients, which supports the interpretation that the thermal emission is driving the softening as the luminosity decreases.
Chapter 4

Multi-temperature Thermal Quiescent Emission in Cen X-4

Abstract

Cen X-4 is one of the most well-studied neutron star low-mass X-ray binaries, but the origin of its quiescent thermal emission is still under debate. Its soft quiescent X-ray emission is often well-fit with a neutron star surface emission model and the radiated energy is associated with latent heat deposited during outburst. Cen X-4’s flux and spectral variability in quiescence, however, has been attributed to low-level accretion and conflicts with the constant thermal flux predicted by the neutron star surface emission theories. We report on new analysis of a 2013 XMM EPIC observation when Cen X-4 was at its brightest quiescent luminosity ever recorded, $L_X = 1 \times 10^{33}$ erg s$^{-1}$. While a single thermal component attributed to neutron star surface emission provides an adequate fit to the soft X-ray spectrum, we find a better continuum model includes two thermal components differing in their temperature and emitting areas. We interpret the hotter, smaller emission component as a possible hotspot on the neutron star surface associated with magnetically channeled accretion. The additional thermal component could also be associated with a boundary layer produced by quiescent accretion.

4.1 Introduction

A quiescent neutron star (NS) low-mass X-ray binary (LMXB) typically exhibits both thermal and nonthermal emission, each contributing approximately half the total flux and both exhibiting variability on timescales of hundreds of seconds to years.
[Campana et al., 1998b, Cackett et al., 2010, Bernardini et al., 2013]. The thermal emission has temperatures in the \(\sim 50-150\) eV range, and the nonthermal component, often modeled with a powerlaw, dominates the spectrum above 2 keV. The thermal component has typically been associated with emission from a cooling NS surface. While origin of the nonthermal emission is more controversial, recent work suggests it is associated with a low-level accretion onto the NS [Chakrabarty et al., 2014, D’Angelo et al., 2015].

In the past 20 years, the NS LMXB Cen X-4 has been observed in quiescence 9 times with *Chandra* and *XMM*. The system’s proximity (\(\sim 1\) kpc), low absorption (\(N_H < 10^{21}\) cm\(^{-2}\)) and brightness (\(L_X = 10^{32}-10^{33}\) erg s\(^{-1}\)) make it ideal for studies of quiescent NS emission and low-level accretion flows. Joint *XMM* and *NuSTAR* observations revealed a high-energy cut-off in the powerlaw spectrum [Chakrabarty et al., 2014]. Compton scattering and synchrotron emission were ruled out as sources of the high-energy radiation, while thermal bremsstrahlung emission from a boundary layer or accretion flow could explain the spectral component’s flux and energy-cutoff [Chakrabarty et al., 2014]. The hard and soft quiescent emission have been found to vary together [Cackett et al., 2010, Bernardini et al., 2013], favoring a boundary layer connected with the low-level accretion as the origin of the nonthermal emission [D’Angelo et al., 2015].

Cen X-4 was discovered in 1969 during a bright outburst that lasted over two months [Conner et al., 1969, Evans et al., 1970]. It exhibited its last outburst in 1979 [Kaluzienski et al., 1980] and has been in quiescence ever since. Type 1 X-ray bursts were observed during both of the 1969 and 1979 outbursts [Belian et al., 1972, Matsuoka et al., 1980], which placed limits on the surface dipole magnetic field (\(B_{\text{surf}} < 10^{10}\) G, Joss and Li 1980) and the source distance (\(d = 1.2 \pm 0.3\) kpc, Chevalier et al. 1989). From optical photometry and spectroscopy, Shahbaz et al. [2014] found a secondary star-to-neutron star binary mass ratio of 0.1755, with a NS mass of 1.94\(^{+0.37}_{-0.85}\) M\(_{\odot}\) and a binary inclination of \(i = 32^\circ \pm 8^\circ\).

We have re-analyzed the quiescent *XMM* soft X-ray spectrum of Cen X-4. While previous analyses modeled the soft spectrum with a simple neutron star atmosphere
model, in this paper we present evidence that the soft thermal emission from the NS in Cen X-4 consists of two distinct components with different temperatures. We interpret the higher temperature component as a hotspot on the NS surface heated by magnetically channeled accretion. We discuss the implications of the accretion heating, with respect to previous deep pulsation searches of Cen X-4’s quiescent spectrum.

4.2 Observations

We have re-analyzed the joint *XMM* EPIC (ObsID 0692790201) and *NuSTAR* dataset of Cen X-4 from 2013 January 21. As this was the brightest quiescent X-ray observation of Cen X-4 ever recorded, it is ideal for searching for structure in the spectrum. All three imaging instruments (pn, MOS1, MOS2) were operated in full-frame mode with a thin optical-blocking filter, resulting in a timing resolution of 73 ms for the pn camera and 2.6 for the MOS cameras.

Since we are primarily interested in the soft X-ray spectrum below 2 keV, we re-reduced the *XMM* data with the latest calibration tools. We reprocessed the data with the *epproc* and *emproc* processes in *XMM-Newton* Scientific Analysis System (SAS) v16.0.0 with the most recent calibration files as of 2017 March 10. For the pn data, we excluded times with a 10-12 keV count rate above 0.75 counts s⁻¹, to reduce the flaring background. For the MOS data, we excluded times with a 10-12 keV count rate above 0.2 counts s⁻¹.

We used the *eregionanalyse* tool to optimize the source extraction region. For our pn data, we extracted the source from a circular region (center coordinates: 14:58:21.99/-31:40:08.67) with a radius of 83". The background spectrum is extracted from a nearby region on the same CCD as the source; we used a circular region with a radius of 188". The MOS source and background spectra with circular from source regions with radii of 82" and 135", respectively. We were left with net exposure times of 26.8 ks and 31 ks for pn and MOS, respectively. Standard event filing (i.e. 'FLAG== 0 && PATTERN<= 4' were applied. We used the *rmfgen* and *arfgen* to
Table 4.1: XMM EPIC Observations

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Obs. Date</th>
<th>Mode</th>
<th>Exposure 1 (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0067750101</td>
<td>2001 August 20</td>
<td>Full Frame</td>
<td>53 (19)</td>
</tr>
<tr>
<td>0144900101</td>
<td>2003 March 1</td>
<td>Timing</td>
<td>84 (32)</td>
</tr>
<tr>
<td>0692790201</td>
<td>2013 January 21</td>
<td>Full Frame</td>
<td>35 (27)</td>
</tr>
</tbody>
</table>

produce the redistribution matrix files (RMFs) and ancillary response files (ARFs). The 2013 XMM observation details are listed in Table 4.1, along with two other XMM observations we consider in this analysis.

The NuSTAR observation (ObsID 30001004002) had an on-source exposure time of 114 ks (See Figure 1 of Chakrabarty et al. 2014). We used the same NuSTAR reduction as presented in Sec. 2.1 of Chakrabarty et al. [2014].

All spectral analysis was performed within ISIS\(^2\) version 1.6.2-30 [Houck and Denicola, 2000]. Errors on fit parameters were calculated with \texttt{conf\_loop} and correspond to the 90% confidence bounds ($\sigma=1.6$, $\Delta\chi^2 = 2.71$). All quoted chi-squared values, $\chi^2 (dof)$, are reduced. We used the \texttt{cflux} convolution model to get the (unabsorbed) fluxes in the 0.3-10 keV energy range and calculated the luminosities assuming a distance of 1.2 kpc.

4.3 Analysis & Results

4.3.1 Residual Pattern in the Soft PN Spectrum

Typically, NS LMXB quiescent spectra are modeled with a thermal neutron star atmosphere and a high-energy powerlaw with a slope in the range of $1 < \Gamma < 3$. In their analysis of this XMM EPIC and NuSTAR Cen X-4 dataset, Chakrabarty et al. 2014 modeled the soft X-ray portion of the spectrum ($< 5$ keV), using both the \textsc{nsatmos} [Heinke et al., 2006] and \textsc{zamp} thermal components [Soria et al., 2011]. \textsc{nsatmos} models thermal emission from a neutron star surface, processed by a pure-hydrogen atmosphere, while \textsc{zamp} models a neutron star accreting at low-rates.

\(^1\)Filtered pn exposure used in spectral analysis is given in parenthesis.

\(^2\)http://space.mit.edu/cxc/isis/
Chakrabarty et al. 2014 found both thermal model provided essentially identical fits to the soft spectrum. For the NSATMOS model, Chakrabarty et al. 2014 fixed the NS mass to 1.9 $M_\odot$, the distance to 1.2 kpc and assumed uniform surface emission (i.e. norm parameter = 1). Depending on their high-energy continuum model they found (unshifted) NS surface temperatures $\log T_{\text{eff}} = 6.18 - 6.2$ (0.123 - 0.129 keV), a NS radius $R_{NS} = 8.1 - 9.2$ km and $\text{tbnew}$ column densities $N_H = (0.087 - 0.092) \times 10^{22}$ cm$^{-2}$.

As shown by Chakrabarty et al. 2014, the absorbed neutron star atmosphere and bremsstrahlung model provides a good fit to the 0.3-79 keV X-ray spectrum. We found similar parameters when applying the same continuum model (see Table 4.2). However, a closer inspection with heavy binning applied to the spectrum revealed a systematic wavy structure in the low-energy residuals below 2 keV, shown in the left of Figure 4-1. The residual pattern is consistent with the presence of an additional thermal component. We first consider whether the residuals could be due to calibration or pile-up.

4.3.2 EPIC Calibration

While significant work is currently focused on the EPIC pn PSF at high energies (< 5 keV), we are not aware of significant calibration problems that affect the soft X-ray spectrum and could produce the observed residual signal in our Cen X-4 spectrum. There have been known gain offsets associated with the silicon and oxygen K-shell edges at 0.54 keV and 1.84 keV, respectively, more so in windowed mode pn observations. We allowed for a gain offset with the $\text{gainshift}$ kernel in ISIS in our single thermal component model (i.e. NSATMOS + brems), but the offset was less than 34 eV and did not change our fit parameters or the residual pattern.

4.3.3 Pile-up

Pile-up has multiple effects, including reducing the observed flux due to photon loss and energy distortion. If a source is bright enough, two photons can hit a pixel within
a single read-out cycle; the event is processed with an energy equal to the sum of the energies of the two incident photons. Our analysis is particularly focused on the soft X-ray spectrum (< 5 keV), so we want to make sure pile-up does not introduce any spectral distortions due to multiple low-energy photons being shifted to the hard portion of the spectrum. As this particular observation of Cen X-4 is relatively bright and its count rate is near the pile-up threshold of the pn camera (2 cts s$^{-1}$)\(^3\), there is a reasonable concern that the data could be affected by pile-up.

While we want to eliminate the risk of pile-up effects, we also want to maximize our source counts to improve our constraints on the soft X-ray spectrum. Previous analyses of the *XMM* observation used annular source extraction regions, excluding the inner 10" to reduce any possible pile-up effects [Chakrabarty et al., 2014, D’Angelo et al., 2015]. In our analysis, we have performed several tests to determine whether the pn spectrum experiences pile-up, as well as to quantify the pile-up fraction, if any.

We first used the SAS `epatplot` task which reveals irregularities in the pattern distribution caused by pile-up. Observed-to-model fraction ratios for single and double events should be consistent with unity; ratios below one and larger than one for single and double events, respectively, indicate the spectrum is affected by pile-up. We obtained ratios of 0.985 ± 0.006 and 1.044 ± 0.010 for single and double events for a circular extraction region centered on the source. The ratios did not change for annular extraction regions, excluding the central source counts; thus, we conclude that pile-up is not significant in this observation.

Additionally, as single event spectra (i.e. 'PATTERN=0') are less sensitive to pile-up, we also extracted a source spectrum with only 'PATTERN=0' events. Comparing the two spectra of single events only versus single and double events, we found no significant difference in the spectral parameters or the residual pattern in the 0.3-2 keV energy range.

Finally, we also performed detailed simulations of EPIC event files using *Simula-

\(^3\)https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/epicmode.html
tion of X-ray Telescopes\(^4\) (SIXTE). Simulations of a 100 ks observation of Cen X-4 found pile-up fractions of 2\% and 5\% of pn and MOS single event spectra; MOS spectra experience more pile-up because of the smaller pixel size and longer read out time. For pile-up fractions of a few percent, we expect only minor flux suppression due to pile-up, not changes in the spectral shape. Multiple tests for pile-up in the 2013 XMM EPIC spectrum are all consistent with low-level or negligible pile-up.

As we have ruled-out spectral distortion due to pile-up or calibration effects, we conclude that the residual pattern is not instrumental and has an astrophysical origin.

### 4.3.4 Modeling the Residuals in pn Data

We aim to provide a physically consistent explanation behind the signal we have identified in the 0.3-2 keV EPIC residuals. Our first step is to generate a spectral model that provides a better fit to the data (probed by the \(\chi^2\) value) and suppresses the wavy pattern seen in the residuals. We will show that residual pattern can be all but eliminated when a continuum model with two thermal components as opposed to one is adopted for the quiescent spectrum.

We first tried improving the fit using standard quiescent NS LMXB models, allowing additional model parameters to vary and different high-energy model combinations as used in Chakrabarty et al. [2014]. We implemented both NSA [Zavlin et al., 1996] and NSATMOS NS thermal emission models, allowing the NS mass and radius to vary as well as the emitting area. We fit the XMM and NuSTAR data with all five of the different components used model the high-energy X-ray spectrum (see Table 1; Chakrabarty et al. 2014), but found no significant change in the 0.3-2 keV residuals.

In all of our subsequent modeling, we adopted the thermal bremsstrahlung model for the hard X-ray spectrum and froze the model parameters to the fit values from Chakrabarty et al. 2014.

Figure 4-1 (left panel) shows the residual in the pn data and all of the fits in Table 4.2 are from EPIC pn and NuSTAR joint fits. While we do not include the MOS 1 & 2 data in our figures and tables, we note that we do see the same residual pattern in

\(^4\)http://www.sternwarte.uni-erlangen.de/research/sixte/index.php
Figure 4-1: Left: The 2013 XMM pn spectrum fit with a \textit{NSATMOS} + \textit{bremss} model; the NS atmosphere model contribution is plotted in green. When the residuals are heavily binned, a significant pattern becomes apparent in the 0.3-2 keV band, indicating the \textit{NSATMOS} model is an incomplete fit to the low-energy portion of the spectrum. Right: The pn spectrum fit with a \textit{blackbody(1) + blackbody(2) + bremss} model. The fit is improved compared to a NS atmosphere model ($\chi^2 = 1.16 \rightarrow 1.10$), and the residual pattern is no longer present. The hotter blackbody component is plotted in blue, the larger, cooler blackbody is plotted in green and the total model, including the bremsstrahlung component, is plotted in red.
Table 4.2: Thermal Continuum Models

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{H,22}$</th>
<th>$kT_1$</th>
<th>norm$_1$</th>
<th>$M_{NS}/R_{NS}$</th>
<th>$kT_2$</th>
<th>norm$_2$</th>
<th>$L_{NS}$</th>
<th>$kT_3$</th>
<th>norm$_3$</th>
<th>$L_3$</th>
<th>$L_X$</th>
<th>$\chi^2$ (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS(1)</td>
<td>0.84$^{+0.06}_{-0.00}$</td>
<td>152$^{+9}_{-8}$</td>
<td>1.9*/7.5$^{+0.1}_{-0.3}$</td>
<td>8.4$^{+0.2}_{-0.5}$</td>
<td>207$^{+2}_{-3}$</td>
<td>201$^{+11}_{-14}$</td>
<td>15.3$^{+0.2}_{-0.1}$</td>
<td>14.5$^{+0.4}_{-0.4}$</td>
<td>1.10 (421)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB(1)+BB(3)</td>
<td>1.28$^{+0.12}_{-0.01}$</td>
<td>95$^{+4}_{-4}$</td>
<td>4797$^{+1346}_{-1051}$</td>
<td>4.2$^{+0.9}_{-0.8}$</td>
<td>212$^{+4}_{-3}$</td>
<td>155$^{+47}_{-66}$</td>
<td>6.3$^{+1.7}_{-1.2}$</td>
<td>13.4$^{+0.5}_{-0.3}$</td>
<td>1.12 (420)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[NS(1)-BB(2)]+BB(3)</td>
<td>1.10$^{+0.06}_{-0.01}$</td>
<td>179$^{+3}_{-8}$</td>
<td>1*</td>
<td>2.52$^{+0.01}<em>{-0.02}$/8.36$^{+0.01}</em>{-0.01}$</td>
<td>179</td>
<td>155$^{+37}_{-66}$</td>
<td>6.3$^{+1.7}_{-1.2}$</td>
<td>13.4$^{+0.5}_{-0.3}$</td>
<td>1.12 (420)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**XMM EPIC pn 2001**

<table>
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<tr>
<th>Model</th>
<th>$N_{H,22}$</th>
<th>$kT_1$</th>
<th>norm$_1$</th>
<th>$M_{NS}/R_{NS}$</th>
<th>$kT_2$</th>
<th>norm$_2$</th>
<th>$L_{NS}$</th>
<th>$kT_3$</th>
<th>norm$_3$</th>
<th>$L_3$</th>
<th>$L_X$</th>
<th>$\chi^2$ (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS(1)</td>
<td>0.90$^{+0.12}_{-0.01}$</td>
<td>135$^{+19}_{-17}$</td>
<td>1.9*/7.2$^{+0.2}_{-0.4}$</td>
<td>3.7$^{+0.3}_{-0.2}$</td>
<td>198$^{+9}_{-7}$</td>
<td>79$^{+17}_{-16}$</td>
<td>2.1$^{+0.7}_{-0.1}$</td>
<td>6.1$^{+0.5}_{-0.7}$</td>
<td>0.96 (208)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB(1)+BB(3)</td>
<td>1.14$^{+0.12}_{-0.02}$</td>
<td>104$^{+10}_{-10}$</td>
<td>1540$^{+654}_{-617}$</td>
<td>2.1$^{+0.7}_{-0.2}$</td>
<td>222$^{+31}_{-17}$</td>
<td>23$^{+7}_{-10}$</td>
<td>1.0$^{+0.4}_{-0.6}$</td>
<td>6.2$^{+0.6}_{-0.1}$</td>
<td>0.96 (207)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[NS(1)-BB(2)]+BB(3)</td>
<td>1.18$^{+0.01}_{-0.02}$</td>
<td>162$^{+3}_{-53}$</td>
<td>1*</td>
<td>2.36$^{+0.33}<em>{-0.08}$/7.86$^{+0.04}</em>{-0.02}$</td>
<td>162</td>
<td>23$^{+7}_{-10}$</td>
<td>3.5$^{+0.5}_{-0.3}$</td>
<td>2.1$^{+0.7}_{-0.1}$</td>
<td>0.96 (207)</td>
<td></td>
<td></td>
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</table>

**XMM EPIC pn 2003**

<table>
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<tr>
<th>Model</th>
<th>$N_{H,22}$</th>
<th>$kT_1$</th>
<th>norm$_1$</th>
<th>$M_{NS}/R_{NS}$</th>
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<th>norm$_2$</th>
<th>$L_{NS}$</th>
<th>$kT_3$</th>
<th>norm$_3$</th>
<th>$L_3$</th>
<th>$L_X$</th>
<th>$\chi^2$ (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS(1)</td>
<td>0.80$^{+0.10}_{-0.00}$</td>
<td>138$^{+9}_{-18}$</td>
<td>1*</td>
<td>1.9*/6.9$^{+0.3}_{-0.2}$</td>
<td>2.9$^{+0.2}_{-0.2}$</td>
<td>4.1$^{+0.2}_{-0.2}$</td>
<td>0.98 (210)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

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(a) (1) indicates the NS surface emission component, modeled with bbodyrad or NSATMOS. (2) is the NS surface emission blocked by the hotspot which is indicated by (3)

(b) All temperatures are given in units of eV.

(c) 0.5-10 keV neutron star luminosity in units of $10^{32}$ erg s$^{-1}$.

(d) Total model 0.5-10 keV luminosity, units of $10^{32}$ erg s$^{-1}$. 

| Joint XMM EPIC pn & NuSTAR 2013 | XMM EPIC pn 2001 | XMM EPIC pn 2003 |
the MOS data as the pn, albeit with a lower significance. We used the constant model in ISIS to allow for offsets between the EPIC datasets; both MOS 1 & 2 constant factors were consistent with 1. The fact that we see the same residual signal in the pn and MOS data supports our conclusion that the modulation is not a calibration issue. We focused our analysis on the pn data as the the pn camera has about twice the effective area as MOS in the 0.3-2 keV energy range, which makes it better able to constrain the low-energy behavior.

At first glance, the excess in the residuals at 0.5 and 1.5 keV in the pn data resembles what one would expect if a single thermal component is not broad enough to fit the low-energy spectrum. Similarly, the residual pattern could be produced if a single thermal component is fit to a spectrum produced by two thermal components. We first fit the soft X-ray continuum with two blackbodies ($bbodyrad(1) + bbodyrad(2)$) without constraints on the thermal temperatures or emission areas. We found a significant improvement in the goodness-of-fit and, most importantly, flatter 0.3-2 keV residuals. The fitted spectrum and residuals are shown in the right panel of Figure 4-1, and the fit parameters are listed in Table 4.2. The ratio between the emission areas of the 'hot' and 'cold' blackbodies is only 0.04.

If we interpret the larger, cooler blackbody as surface emission from the NS, the small ratio of the two blackbodies’ emission areas indicates the hotter component could be a hotspot, possibly generated by magnetically channeled accretion onto a NS polar cap. We attempted to fit the larger blackbody with a NS atmosphere component to obtain a more physical model of the emission components. The $NSATMOS + bbodyrad$ model, however, did not improve the fit or the residual pattern compared to the single $NSATMOS$ model. We also attempted to fit both of the thermal components with NS atmosphere models ($NSATMOS(1) + NSATMOS(2)$); one component modeling the NS surface with uniform emission (i.e. the normalization parameter set to 1) and the other component modeling smaller blackbody with an emission factor < 0.1 to reflect the small area ratio found with the double blackbody fit. The NS mass and radius parameters were tied between the NS atmosphere models. No combination of fixing or tying parameters yielded a fit that improved the residual pattern.
In our final model involving a NS atmosphere component, we subtracted the NS surface emission blocked by the potential hotspot, based on the formulation used by Elshamouty et al. [2016b] to model the effect of hotspots on quiescent spectral measurements (their Eqn. 2):

\[ F_{\text{obs}} = F_{\text{NS}} + F_{\text{spot}} - F_{\text{backspot}} \]  

(4.1)

where \( F_{\text{NS}} \) is the flux from the entire NS with a uniform surface temperature \( T_{\text{NS}} \), \( F_{\text{spot}} \) is the flux from the hotspot with temperature \( T_{\text{spot}} \), and \( F_{\text{backspot}} \) is the flux emission of the spot area with (lower) temperature \( T_{\text{NS}} \). In our model, \( (\text{NSATMOS} - \text{BBODYRAD}(1) + \text{BBODYRAD}(2)) \), we tied the temperature between the NS atmosphere component and \( \text{bbbodyrad}(1) \), and tied the normalizations of the two blackbody components; all other parameters were free to fit, except for the distance parameter in the \( \text{NSATMOS} \) model. This model improved the continuum fit compared to a single NS atmosphere component and flattened the 0.3-2 keV residuals. The hotter blackbody had similar parameters to those found in the double blackbody fit.

4.4 Discussion

As a result of the joint \textit{XMM} and \textit{NuSTAR} observations of Cen X-4, Chakrabarty et al. [2014] found that a single powerlaw was an incomplete description of the hard X-ray quiescent spectrum. Models that included a high-energy cut-off provided a better fit and provided insight into the nature of the hard X-ray emission. In our analysis of Cen X-4’s soft X-ray spectrum, we have found that two thermal components provide a better characterization of the quiescent emission than the typical single neutron star atmosphere model. We propose that the hotter emission component is likely a hotspot on the NS surface, most likely a magnetic polar cap.
Figure 4-2: The 2001 XMM pn spectrum fit with a $NSATMOS + powerlaw$ model. We see evidence of the same wavy residual pattern as in the 2013 observation.

4.4.1 Other Observations of Cen X-4

As the pattern is significant in the 0.3-2 keV residuals of the 2013 pn data, we also looked to see whether other archival observations of Cen X-4 show evidence of the same structure in the residuals.

There are 7 XMM EPIC and 2 Chandra ACIS observations of Cen X-4 in quiescence, making it one of the most observed quiescent NS LMXBs. The 2013 EPIC observation captured Cen X-4 at its brightest quiescent luminosity ever detected, while Cen X-4 was observed at its second and third brightest quiescent flux levels in 2001 August (EPIC ObsID 0067750101) and 2003 March (EPIC ObsID 0144900101). The 0.3-10 keV unabsorbed luminosities were $3.7 \times 10^{32}$ erg s$^{-1}$ and $1.5 \times 10^{32}$ erg s$^{-1}$, respectively [Cackett et al., 2010].

We looked for structure in the $NSATMOS + powerlaw$ fit residuals of these observations, which would indicate whether the two-temperature thermal components are also present at lower fluxes relative to the 2013 level. We see evidence of the
residual pattern in the 2001 data, with the excess residuals peaking around the same energies (0.5 and 1.5 keV) as in 2013 (see Figure 4-2). Even though $\chi^2$ value indicates the single thermal component plus powerlaw provides an adequate fit to the data, a two blackbody plus powerlaw model did better. We were able to suppress the wavy residual pattern, and the model parameters (listed in Table 4.2) have similar values to the 2013 fits. A $\text{NSATMOS} - \text{BB}(1) + \text{BB}(2)$ model also improved the residuals of the 2001 data.

In the 2003 pn data, we found no evidence of the structure in the residuals. The continuum fit with a $\text{NSATMOS} + \text{powerlaw}$ model provides a good fit ($\chi^2=0.98$) and is shown in Figure 4-3. We simulated the 2013 double blackbody model parameters at the 2003 flux levels ($\approx 70\%$ lower) to determine whether one would expect to detect both two thermal components when Cen X-4 is fainter. To match the total 2003 flux, we simulated two scenarios: the two blackbodies with reduced temperatures or the two blackbodies with reduced normalizations. For either case, we found the double blackbody model improved the fit compared a single NS atmosphere model in fewer than 20\% of the 100 simulated trials. The simulations indicate that we would not expect to detect the second thermal component at the 2003 flux.

### 4.4.2 Accretion Hot Spot

The small emission area of the hot blackbody component is suggestive of a hot spot, like a magnetic polar cap. Thermal emission attributed to accretion hotspots has been modeled spectrally and detected via timing searches at luminosities $\lesssim 10^{33}$ erg s$^{-1}$ in isolated pulsars [Bogdanov and Grindlay, 2009], as well as accreting NS pulsars in HMXBs and LMXBs [Elshamouty et al., 2016a, Bogdanov, 2013, Archibald et al., 2015]. All of the NS in LMXBs that have shown evidence of magnetically channeled accretion are known pulsing systems with spin frequencies in the range of 150 – 600 Hz. Accreting millisecond X-ray pulsars (AMXPs) are a subclass of transient NS LXMBs that exhibit coherent X-ray pulsations in outburst [Patruno, 2010] and have magnetic fields strong enough ($B \approx 10^{8-9}$ G) to channel accreted material onto the magnetic poles, heating the immediate NS surface such that a hotspot forms.
Figure 4-3: The 2003 timing mode XMM pn spectrum fit with a NSATMOS + powerlaw model. A good fit is achieved and the residuals show no signs of the pattern seen in the 2013 and 2001 observations.
In our analysis of the bright XMM quiescent observation of Cen X-4, we have detected potentially two sources of thermal emission. A continuum model with two blackbodies implies a temperature differential of $\approx 100$ eV and emission area ratio of $\approx 5\%$, indicating the hotter component is likely confined to a small fraction of the NS surface. The emission area ratio allows us to estimate the angular radius of the spot ($\rho$) and we find $\rho \sim 23^\circ$, which is in the estimated range of angular sizes for polar cap models [Lyne and Graham-Smith, 2006, Elshamouty et al., 2016b].

The X-ray/radio luminosity correlation of Cen X-4 through outburst and quiescence is in agreement with other non-pulsing NSs rather than a MXP [Tudor et al., 2017]. Most previous X-ray observations of Cen X-4 did not have the timing sensitivity to detect millisecond pulsations. The one exception is the 2003 XMM observation, which placed an upper limit on the pulsed fraction of less than 7% [D’Angelo et al., 2015], which has been interpreted as evidence against the magnetic regulation of the quiescent accretion flow in Cen X-4.

However, our inference of an accretion hotspot is not at odds with constraints on the pulsed fraction of Cen X-4’s quiescent spectrum. First of all, the 2013 XMM observation occurred when the source was significantly brighter than the 2003 XMM observation. The 2003 observation is the only quiescent observation of Cen X-4 which has the timing resolution ($\approx 30$ $\mu$s) necessary to perform a millisecond pulsation search. Based on simulations of fainter quiescent spectra with multiple thermal components, albeit with potentially naive assumptions of how the hotspot’s properties evolve with flux, we have already shown that we do not expect to spectrally detect the hotspot emission at the 2003 quiescent flux levels.

Based on the upper limit on the pulsed fraction reported by D’Angelo et al. [2015], Elshamouty et al. [2016b] placed limits on the temperature differential between a possible hotspot and NS surface emission ($\approx 10$ eV), as well as the maximum hotspot temperature (130 eV). The hotspot simulations, however, used canonical NS mass and radius values ($M = 1.4 M_\odot$, $R = 11.5$ km), as well as uniform distributions in $\cos(i)$ inclination space that favor inclinations of 90°. Cen X-4’s relatively low inclination ($i = 32^\circ$), reduces the expected pulsed fraction. Additionally, the NS’s
potentially high-mass (1.9 M\(_{\odot}\); Shahbaz et al. 2014) and small-size (\(R < 10\) km; Chakrabarty et al. 2014 as well as this work) compared to the simulated NS parameters have the effect of increasing the NS’s compactness and surface gravity, both of which suppress the pulsed fraction (see Figures 6 and 7 of Elshamouty et al. [2016b]). All of these effects decrease the restrictions on the possible hotspot’s properties while still producing a pulsed fraction that is less than 6%. It is also worth noting that while the accretion and pulsations physics may be fundamentally different between pulsars and non-MSXPs systems, low pulsed fractions (< 10%) do not completely rule out the presence of hotspots. At a an X-ray luminosity of \(5 \times 10^{33}\) erg s\(^{-1}\), pulsations were detected in MSXP XSS J12270-4859 with a pulsed fraction of 7.7% [Papitto et al., 2015].

The presence of accretion hotspots on the surface of NSs has significant implications for our understanding of the thermal evolution of the NS in quiescent LMXBs. Previously, NS surface emission was only associated with heat deposited during outburst via deep crustal heating, and the NS temperature and luminosity has been used as a direct probe of the system’s outburst history [Tomsick et al., 2004]. The presence of accretion hotspots leads to the possibility that NSs undergo continued accretion heating during quiescence.

While Cen X-4 has been observed numerous times already, our findings of a potential quiescent accretion hotspot makes Cen X-4 a candidate for continued observation. In particular, observations with \(XMM\) while Cen X-4 is bright (\(L_X \approx 10^{33}\) erg s\(^{-1}\)) may confirm the spectral detections of the multiple thermal components. Cen X-4 is an ideal source for future observations with \(NICER\). We have found spectral evidence of magnetic hotspots while Cen X-4 is in quiescence; these hotspots should produce pulsations. \(NICER\)'s large effective area (more than twice that of \(XMM\) EPIC-pn) in the 0.2-12 keV band and excellent timing resolution (100 nanoseconds) is perfectly suited to performing a deep pulsation search of Cen X-4 quiescence.

### 4.4.3 Boundary Layer

D’Angelo et al. [2015] suggested the high-energy thermal bremsstrahlung emission
in Cen X-4 could be associated with an accretion flow boundary layer. They also predicted additional an nonthermal emission component that would be produced by a radiatively inefficient accretion flow, but were unable to detect it in their analysis of the 2013 XMM and NuSTAR data.

As the evidence for low-level accretion flows in quiescent NS LXMBs mounts, there is the question of whether the thermal emission is actually emission from the NS surface [Cackett et al., 2010, D’Angelo et al., 2015]. The lack of boundary layer models for low accretion rates onto a NS makes it difficult to attribute any of the quiescent emission components to a boundary layer, but studies of particle bombardment onto a NS surface by Zampieri et al. 1995 and Deufel et al. [2001] found the emission could take the form of a modified blackbody. We note that our multi-temperature continuum models could be produced by some combination of emission from the NS surface, a boundary layer and an accretion hotspot.
Chapter 5

Quiescent Thermal Emission from SAX J1810.8-2609

Abstract

We have observed the neutron star low-mass X-ray binary SAX J1810.8-2609 in quiescence with XMM-Newton. SAX J1810.8-2609 is one of the faintest non-pulsing neutron star low-mass X-ray binaries in quiescence and has no detectable thermal emission, in disagreement with theoretical predictions. We found SAX J1810.8-2609 at the same $0.5-10$ keV, unabsorbed luminosity as the previous quiescent observation in 2003, $L_X = 2 \times 10^{32}$ erg s$^{-1}$. We show that the spectrum requires both thermal and nonthermal components, each contributing approximately half the total emission. The low neutron star luminosity is likely due to a low time-averaged outburst mass accretion rate, $M \approx 2 \times 10^{-12} M_\odot$, as opposed to more exotic explanations such as a heavy neutron star or a hybrid neutron star crust.

5.1 Introduction

Transient neutron star (NS) low-mass X-ray binaries (LMXBs) exhibit periods of low and high accretion rates onto the NS surface known as quiescence and outburst, characterized by luminosities in the ranges of $10^{31-33}$ erg s$^{-1}$ (0.5-10 keV) and $10^{36-38}$ erg s$^{-1}$, respectively. The sources spend most of their time in quiescence, with outburst periods typically lasting weeks to months. NS LMXBs can be distinguished by the peak luminosity reached in outburst. Bright/very bright transients have peak persis-
tent outburst emission in the range of $L_X = 10^{37-39}$ erg s$^{-1}$; faint transients peak in the range of $10^{36-37}$ erg s$^{-1}$ and very-faint transients peak $10^{34-36}$ erg s$^{-1}$. For faint and very faint NS LMXBs, the low outburst luminosity makes it difficult to monitor their outburst activity, especially when the outbursts are short (< week long). Their peak outburst flux can be near or below the sensitivity threshold of most X-ray surveys. Additionally, the outburst durations are often comparable to the monitoring cadences, making these sources easier to miss.

Accretion flows at low rates are not well understood. This regime includes the quiescent state of NS LMXBs, where the accretion rate onto the neutron star surface is very low. The quiescent X-ray spectrum is typically characterized by two components: one nonthermal and one thermal. The nonthermal component, often modeled with a powerlaw, dominates the spectrum above 2 keV and has been attributed to the low-level accretion flow near the NS [Menou et al., 1999]. More recent observations of the high-energy (> 10 keV) behavior of the nonthermal component have associated it with thermal bremsstrahlung emission [Chakrabarty et al., 2014] possibly produced by the NS boundary layer [D'Angelo et al., 2015]. Observationally, the nonthermal emission’s contribution to the total unabsorbed flux has been found to increase to larger fractions (approaching 100%) towards lower luminosities below $10^{33}$ erg s$^{-1}$ [Jonker et al., 2004a]. At even lower quiescent luminosities (below $\approx 10^{32}$ erg s$^{-1}$), a radio pulsar may turn on [Stella et al., 1994, Campana et al., 1998b], producing significant nonthermal synchrotron emission not associated with the thermal bremsstrahlung emission.

Despite the nonthermal component’s increasing contribution to the quiescent flux at lower luminosities, transiently accreting NSs are expected to exhibit a minimum thermal luminosity set by their time-averaged outburst mass accretion rate. While low-level accretion onto the neutron star can potentially produce thermal emission in quiescence [Zampieri et al., 1995], even in the complete absence of quiescent accretion the NS is expected to radiate a stable level of thermal emission. The energy source is latent heat deposited in the inner crust during accretion. Known as deep crustal heating, matter accreted during outbursts compresses the upper layers of the NS,
activating density-sensitive pycnonuclear reactions [Brown et al., 1998]. The heat is conducted throughout the NS and partially radiated away at the surface, emerging as a thermal spectrum with a predicted surface temperature in the X-ray band.

For a given outburst history (parameterized by a time-averaged accretion rate $\dot{M}$), one can estimate the quiescent NS thermal luminosity $L_{NS}$. The calculation requires assumptions about the heat released by the pycnonuclear reactions per accreted nucleon (commonly assumed $Q_{nuc} \approx 1$ MeV / $m_p$; Brown et al. 1998), as well as standard cooling mechanisms active within the neutron stars which, in turn, depends on the neutron star composition. Many NS LMXB transients, including most accretion-powered millisecond pulsars (AMXPs), only have upper limits measured for their thermal luminosities, and even these upper limits fall below the standard cooling predictions (see Figure 8; Heinke et al. 2010). AMXPs typically exhibit faint ($L_X < 10^{32}$ erg s$^{-1}$), hard ($\Gamma = 1 - 2$) spectra in quiescence with little or no NS thermal emission. These systems are identified as pulsars by pulsations detected in outburst and, in some cases, radio emission in low-luminosity quiescent states. Some NS LMXBs that have not exhibited pulsations in outburst, and, thus, are not likely AMXPs, including XTE J2123-058, SAX J1810.8-2609, and EXO 1747-214 are also faint in quiescence with low or nonexistent constraints on the thermal surface emission [Tomsick et al., 2004, Jonker et al., 2004b, Tomsick et al., 2005]; they, too, disagree with deep crustal heating predictions.

NS LMXBs whose faint quiescent thermal emission is in conflict with standard heating and cooling models may harbor massive NSs [Colpi et al., 2001], NSs with hybrid crusts [Wijnands et al., 2013] or have very poorly constrained outburst histories. Enhanced cooling mechanisms (i.e. the direct Urca process) may produce low-temperature NSs below standard cooling model predictions; due to the high density thresholds of the reactions ($\rho > 1.3 \times 10^{15}$ g cm$^{-3}$), they are only thought to occur in massive NSs, $M_{NS} > 1.7 M_\odot$ [Colpi et al., 2001]. Alternatively, deep crustal heating may not be fully active in LMXBs with hybrid NS crusts. In young LMXBs where the NS has not been accreting for a long time ($\lesssim 10^8$ years) and also in systems with very low outburst accretion rates ($\dot{M} \lesssim 10^{-12}$ M$_\odot$ yr$^{-1}$), the NS has not accreted enough
companion material to activate all the pycnonuclear reactions [Wijnands et al., 2013]. Heating is suppressed and the result is a cold neutron star, $L_{NS} \lesssim 10^{31}$ erg s$^{-1}$. Deep crustal heating predictions of the quiescent NS thermal luminosity also rely on the time-averaged outburst accretion rate. For most NS LMXBs, there are large uncertainties in the outburst history because the outburst activity over the past 30-40 years is assumed to be the same as the activity over the past several thousand years. The outburst history uncertainty is large particularly for faint or very faint transients, because their low outburst luminosities can be missed by X-ray monitoring.

SAX J1810.8-2609 is an X-ray transient discovered with the Wide Field Camera onboard the BeppoSAX satellite [Ubertini et al., 1998]. The source exhibited a type-I X-ray burst, identifying SAX J1810.8-2609 as a NS LMXB [Ubertini et al., 1998, Cocchi et al., 1999]. The burst showed signs of photospheric radius expansion, and a source distance of $d = 4.9 \pm 0.3$ kpc was determined [Natalucci et al., 2000]. The persistent outburst emission was approximately $9 \times 10^{35}$ erg s$^{-1}$ (2-10 keV), and the outburst lasted at least 13 days. A later look at the RXTE ASM light curves indicates the source may have been in outburst as early as 1997 December 18, corresponding to an outburst duration of $\gtrsim 90$ days [Tomsick et al., 2004]; the X-ray luminosity was also estimated from the 1.5-12 keV ASM light curve to be $L_{peak} = 10^{37}$ erg s$^{-1}$ for a distance of 4.9 kpc.

SAX J1810.8-2609 went into outburst again in 2007 and 2012. A Swift monitoring program for very-faint X-ray transients (VFXTs) was triggered on 9 August 2007 [Degenaar et al., 2007]. INTEGRAL observations occurred between 25 August and 30 September 2007 [Fiocchi et al., 2008]. Due to the low outburst luminosity, $L_X \approx 2 \times 10^{36}$ erg s$^{-1}$ (20-100 keV), and the low long-term averaged mass accretion rate ($\dot{M} \approx 10^{-12}$ M$_{\odot}$), Fiocchi et al. [2008] classified SAX J1810.8-2609 as a faint X-ray transient. The source was not detected in Swift XRT observations 3 and 5 November 2007, indicating SAX J1810.8-2609 was returning to quiescence [Linares et al., 2007] after an outburst duration of 85-92 days. In the combined spectrum of the two XRT observations, the source was detected with a luminosity of $L_X = 4.3 \times 10^{32} (d/4.9\text{kpc})^2$ erg s$^{-1}$ [Linares et al., 2007].
In 2012, SAX J1810.8-2609 was monitored with MAXI between 7-24 May and likely had $L_X \gtrsim 10^{36}$ erg s$^{-1}$ (2-20 keV) for the entire duration [Degenaar and Wijnands, 2013b]. A Swift XRT observation 12 May 2012 found SAX J1810.8-2609 with $L_X = 2.7 \times 10^{37} (d/5.7$kpc$)^2$ erg s$^{-1}$ (2-10 keV), consistent with the peak luminosity measured during the MAXI monitoring ($L_X = 2 \times 10^{37} (D/5.7$kpc$)^2$ erg s$^{-1}$). The 2012 outburst was an order of magnitude brighter than the peak luminosities in the previous 2 outbursts and designates SAX J1810.8-2609 as a bright X-ray transient rather than a faint X-ray transient.

SAX J1810.8-2609 has only been observed once previously while in quiescence. In 2003, a 35 kilosecond Chandra observation revealed the quiescent spectrum was not consistent with pure thermal emission [Jonker et al., 2004b]; blackbody and neutron star atmosphere models lead to poor chi-squared values ($\chi^2 > 1.5$). The spectrum was well-fit with a single power law. While the power law’s high photon index ($\Gamma = 3.3 \pm 0.5$) suggested a thermal component was present, adding a soft component was not statistically required. With fewer than 150 source counts and fitting a spectrum binned to fewer than 10 counts per bin, only weak constraints could be placed on an additional soft component. SAX J1810.8-2609’s 0.5-10 keV unabsorbed luminosity was estimated to be $1 \times 10^{32}$ erg s$^{-1}$, assuming a distance of 4.9 kpc. The thermal component contributed approximately half of the unabsorbed flux, which is treated as an upper limit to the system’s NS thermal luminosity. Based on deep crustal heating models and assuming standard cooling processes, the low quiescent thermal luminosity of SAX J1810.8-2609 required an extremely low time-averaged mass accretion rate of $\sim 5.7 \times 10^{-13} M_\odot$ yr$^{-1}$ [Jonker et al., 2004b]. In contrast, estimates of the time-averaged mass accretion rate from the outburst history are at least an order of magnitude higher, $(2 - 5) \times 10^{-12} M_\odot$ yr$^{-1}$ [Tomsick et al., 2004, Fiocchi et al., 2008].

We obtained a new observation of SAX J1810.8-2609 in quiescence, which we present here. We find the quiescent spectrum requires a thermal component that is likely a cooling NS. The NS luminosity is in agreement with deep crustal heating and standard cooling predictions, along with its known outburst history.
5.2 Observations

5.2.1 XMM EPIC

SAX J1810.8-2609 was observed on 9 October, 2015 (ObsID 0763100101) with the all three instruments (pn, MOS1, MOS2; Strüder et al. [2001], Turner et al. [2001]) of the European Photon Imaging Camera (EPIC) on board the XMM-Newton focusing X-ray telescope. The 78 ks exposure began at 15:43 UT. All 3 imaging cameras were used in small window mode (63x64/100x100 pixel area for PN/MOS respectively) with a timing resolution of 6 ms for PN and 0.3 s for MOS1 and MOS2. The medium optical-blocking filter was used.

We used the XMM-Newton Scientific Analysis System (SAS) v16.0.0 with the most recent calibration files (as of March 2017) to reprocess the data using epproc/emproc to generate new event files using standard filtering. The beginning of the observation was heavily affected by background flares; for pn/MOS, we excluded times where the 10-12 keV count rate was above 0.05/0.2 cts s$^{-1}$ to provide the best background subtraction. We used the eregionanalyse tool to optimize the source extraction region which was determined to be circles with radii of 11" for both pn and MOS. The background spectrum was extracted from a nearby circular region with radii 35"/20" for pn/MOS. We used the rnfgen and arfgen to produce the redistribution matrix files (RMFs) and ancillary response files (ARFs). The net exposure for pn and MOS instruments were 36 and 51 ks (for each MOS camera). The pn light curve is shown in Figure 5-1.

5.3 Analysis & Results

All spectral analysis was performed within ISIS\textsuperscript{1} version 1.6.2-30 [Houck and Denicola, 2000]. Errors on fit parameters were calculated with conf\_loop and correspond to the 90\% confidence bounds ($\sigma=1.6$, $\Delta \chi^2 = 2.71$). All quoted chi-squared values, $\chi^2 (dof)$, are reduced. We used the cflux convolution model to calculate (absorbed)

\textsuperscript{1}http://space.mit.edu/cxc/isis/
Figure 5-1: The 0.5-10 keV, background subtracted XMM-pn light curve of SAX J1810.8-2609 with 2 ks bins.

fluxes and (unabsorbed) luminosities. Luminosities for the 0.5-10 keV energy band are calculated assuming a distance of 4.9 kpc.

We first fit the XMM EPIC and Chandra ACIS observations separately. The XMM EPIC data, including all three instruments: pn, MOS 1 and MOS 2, was fit in the 0.5-10 keV energy range and binned to a minimum of 20 counts per bin, which allows us to use the $\chi^2$ statistic to judge the goodness-of-fit. For the PN, MOS 1, and MOS 2 instruments we had 234, 82, and 102 source counts in the 0.5-10 keV range. The Chandra observation had 123 source counts.

In all of our spectral fits, the NS LMXB continuum was multiplied by the $tb_{new}$ model (v2.3) to account for the neutral ISM absorption; the abundances were set to those of Wilms et al. [2000] and the cross-sections set to those of Verner et al. [1996]. Previous observations of SAX J1810.8-2609, in quiescence and in outburst, constrained the column density along the line-of-sight to the range of $(3 - 7) \times 10^{21}$ cm$^{-2}$ [Dickey and Lockman, 1990, Natalucci et al., 2000, Degenaar and Wijnands, 2013b]. When we fit our XMM data with $powerlaw$ and $bbodyrad+powerlaw$ models
with all parameters free, we find column densities in the range of \((2 - 9) \times 10^{21}\) cm\(^{-2}\). We fixed our neutral column density to \(6 \times 10^{21}\) cm\(^{-2}\) in all subsequent spectral fits.

We fit continuum models typically exhibited by NS LMXBs in quiescence: single component nonthermal (powerlaw) and thermal (bbodyrad and NSATMOS), as well as combinations of nonthermal and thermal components. While a bbodyrad model is not a physically accurate model for NS surface emission, it does provide a good fit to thermal emission for faint quiescent spectra with low count numbers. For a blackbody, we allowed the normalization to vary, while for the neutron star atmosphere model, NSATMOS, we fixed the normalization to unity, assuming the entire NS surface produces the thermal emission. NSATMOS and NSA are both models specifically designed for quiescent surface emission; we found no statistical difference in our fits when using the NSATMOS and NSA as the neutron star component, thus we only list results from the NSATMOS fits. NS mass and radius are parameters in the NS atmosphere models, as well as the distance to the system. The distance to SAX J1810.8-2609 was fixed to 4.9 kpc [Natalucci et al., 2000]. We fixed the mass and radius 1.4 \(M_\odot\) and 12 km, adopting the NS values measured from modeling the photospheric radius expansion bursts of SAX J1810.8-2609. Näätänen et al. [2016] and Suleimanov et al. [2017] found \(M = 1.3 - 1.5\) \(M_\odot\) and \(R = 11.5 - 13\) km for the NS in SAX J1810.8-2609 using improved cooling tail modeling of hard state bursts. Results from our continuum fits are listed in Table 5.1. We also calculated the 0.5-10 keV absorbed fluxes, 0.5-10 kev unabsorbed luminosities and the thermal fractional contribution for the 2-component models.

Our fits to the XMM spectrum revealed a pure powerlaw is a poor fit, \(\chi^2 = 1.5\); the powerlaw cannot produce the high-energy emission (> 4 keV) seen in the PN data. The high powerlaw index (\(\Gamma = 3.6\)) indicates the spectrum is very soft. Pure thermal continuum models, either a blackbody or neutron star atmosphere, provided even worse fits to the EPIC data, \(\chi^2 = 2.8\) and 2.7, respectively. The thermal continuum models do not produce essentially any significant emission above 3 keV, so yet again the high-energy portion of the spectrum was underfit.

Continuum models with both thermal and nonthermal components provided sig-
Table 5.1: Continuum parameters

<table>
<thead>
<tr>
<th>Model</th>
<th>kT</th>
<th>Norm</th>
<th>Γ</th>
<th>Flux (0.5-10 keV)</th>
<th>$L_X$ (NS Fraction)</th>
<th>Constant</th>
<th>$\chi^2$ (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eV</td>
<td></td>
<td></td>
<td>10^{-14} erg s^{-1} cm^{-2}</td>
<td>10^{32} erg s^{-1}</td>
<td></td>
<td></td>
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<tr>
<td>Joint XMM EPIC &amp; Chandra ACIS</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Powerlaw</td>
<td>3.7^{+0.3}_{-0.3}</td>
<td>1.6 ± 0.2</td>
<td>1.2 ± 1.4</td>
<td>1.10</td>
<td>1.39 (26)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BBodyrad</td>
<td>229^{+35}_{-26}</td>
<td>0.3^{+0.4}_{-0.2}</td>
<td>1.1 ± 0.2</td>
<td>0.8 ± 1.0</td>
<td>1.07</td>
<td>2.88 (26)</td>
<td></td>
</tr>
<tr>
<td>NSATMOS</td>
<td>73^{+1}_{-1}</td>
<td>1*</td>
<td>1.2 ± 0.2</td>
<td>1.0 ± 1.2</td>
<td>1.08</td>
<td>2.81 (27)</td>
<td></td>
</tr>
<tr>
<td>BBodyrad + Powerlaw</td>
<td>143^{+34}_{-38}</td>
<td>4^{+18}_{-3}</td>
<td>2.2^{+1.0}_{-1.1}</td>
<td>2.3 ± 1.0</td>
<td>1.6 ± 1.9 (0.52)</td>
<td>1.07</td>
<td>1.23 (24)</td>
</tr>
<tr>
<td>NSATMOS + Powerlaw</td>
<td>70^{+2}_{-4}</td>
<td>1*</td>
<td>1.2^{+1.0}_{-0.8}</td>
<td>2.6 ± 1.0</td>
<td>1.6 ± 1.9 (0.59)</td>
<td>1.05</td>
<td>1.16 (24)</td>
</tr>
<tr>
<td>XMM EPIC, Binning = 20 cts/bin</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Powerlaw</td>
<td>3.6^{+0.3}_{-0.3}</td>
<td>1.7 ± 0.2</td>
<td>1.4 ± 1.6</td>
<td>1.49</td>
<td>(22)</td>
<td></td>
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<td>BBodyrad</td>
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<td>1.1 ± 0.1</td>
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<td>2.78 (22)</td>
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<tr>
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<td>1.0 ± 1.2</td>
<td>2.69 (23)</td>
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<tr>
<td>BBodyrad + Powerlaw</td>
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<td>4^{+19}_{-3}</td>
<td>2.0^{+1.2}_{-1.0}</td>
<td>2.5 ± 1.0</td>
<td>1.8 ± 2.2 (0.61)</td>
<td>1.38 (20)</td>
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</tr>
<tr>
<td>NSATMOS + Powerlaw</td>
<td>70^{+2}_{-4}</td>
<td>1*</td>
<td>1.3^{+1.0}_{-0.8}</td>
<td>2.8 ± 1.0</td>
<td>1.8 ± 2.0 (0.70)</td>
<td>1.29 (20)</td>
<td></td>
</tr>
<tr>
<td>Chandra ACIS, Binning = 10 cts/bin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powerlaw</td>
<td>3.7^{+0.5}_{-0.5}</td>
<td>1.8 ± 0.4</td>
<td>1.8 ± 2.2</td>
<td>0.83</td>
<td>(9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BBodyrad</td>
<td>201^{+42}_{-32}</td>
<td>0.8^{+1.4}_{-0.5}</td>
<td>1.2 ± 0.2</td>
<td>1.2 ± 1.5</td>
<td>2.21 (9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSATMOS</td>
<td>73^{+2}_{-2}</td>
<td>1*</td>
<td>1.3 ± 0.2</td>
<td>1.3 ± 1.7</td>
<td>1.94 (10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BBodyrad + Powerlaw</td>
<td>123^{+68}_{-113}</td>
<td>7^{+23}_{-7}</td>
<td>3.0^{+1.0}_{-1.2}</td>
<td>2.0 ± 0.6</td>
<td>1.9 ± 2.4 (0.42)</td>
<td>0.86 (7)</td>
<td></td>
</tr>
<tr>
<td>NSATMOS + Powerlaw</td>
<td>56^{+17}_{-47}</td>
<td>1*</td>
<td>3.4^{+0.7}_{-3.0}</td>
<td>1.8 ± 0.5</td>
<td>1.8 ± 2.2 (0.33)</td>
<td>0.90 (7)</td>
<td></td>
</tr>
</tbody>
</table>

*aFor all models: $N_H = 6 \times 10^{21} \text{ cm}^{-2}$, $M = 1.4 M_{\odot}$, $R = 12 \text{ km}$, $D = 4.9 \text{ kpc}$

*bThermal component temperature

cThermal component normalization. For a blackbody, the normalization has been corrected for the source distance and has units km$^2$. For NSATMOS the normalization is fixed to 1.

dAbsorbed

eUnabsorbed luminosity with the thermal fraction in parentheses for 2-component models
significantly better fits to our XMM data, accurately modeling the high-energy portion of the spectrum. The thermal component had temperatures of 144 eV for the blackbody model and 70 eV for the NS atmosphere model. The powerlaw index was significantly harder compared to a pure powerlaw fit with $\Gamma = 2$ and 1.3 when the thermal component is fit with a blackbody and NS atmosphere model, respectively. The absorbed flux and unabsorbed luminosity were the same for both 2-component continuum prescriptions, $F \approx 2.6 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$, $L_x \approx 1 \times 10^{32}$ erg s$^{-1}$. The thermal and nonthermal components each contribute approximately half the unabsorbed flux.

The neutron star atmosphere plus powerlaw model provides a slightly better fit than the blackbody plus powerlaw model, but in both cases, the $\chi^2$ was significantly lower than the fits with a single component continuum. The F-statistic probability for the neutron star atmosphere plus powerlaw fit versus the pure powerlaw fit is 0.05, indicating the addition of the neutron star atmosphere component significantly improved the continuum fit.

The Chandra observation was fit in the 0.5-10 keV energy range. Binning to 20 counts per bin yielded only 5 bins, so we binned the spectrum to 10 counts per bin, as Jonker et al. [2004b] did in their analysis of the same data. Our findings are the same as Jonker et al. [2004b], so we only provide a brief summary. A pure powerlaw continuum yielded a very high ($\Gamma = 3.7$) photon index. Blackbody and neutron star atmosphere models provided poor fits to the Chandra data. Adding a power law component improved the fits compared to single component thermal models, but did not provide a statistical advantage over a pure powerlaw continuum. The unabsorbed flux of our XMM observation is consistent with the Chandra value, indicating the source is found at the same quiescent level in 2015 as it was in 2003.

Due to the similarity in continuum parameters and the source flux between the XMM and Chandra observations, we fit the 2 observation simultaneously. We used the constant model to account for offsets between the datasets; fixing the PN constant parameter to 1.0 and allowing the Chandra constant value to vary. When we allowed for continuum parameters to vary between the two observations (such as powerlaw normalization, thermal component temperature, etc.), we found the parameters were
consistent within their 90% error bounds, so we tied all parameters between the XMM and Chandra datasets. In the joint fits, we binned both XMM and Chandra datasets to a minimum of 20 counts per bin.

Jointly fitting the two observations strengthened the results found when fitting the XMM by itself. The continuum fits are plotted in Figure 5-2. A pure powerlaw model provides a poor fit to the data and a high powerlaw index, $\Gamma = 3.7 \pm 0.3$. Despite the large photon index indicating the spectrum is soft, pure thermal models, either bbodyrad or NSATMOS, were incomplete descriptions of the data; significant residuals above 3 keV require another component to provide an accurate fit. A two-component model with thermal and nonthermal components provided the best-fit to the two datasets. We achieved $\chi^2$ values of approximately 1.2 for bbodyrad+powerlaw and NSATMOS+powerlaw continuum models. The thermal component had temperatures of 140 and 70 eV for blackbody and neutron star atmosphere models, and the nonthermal component had a relatively hard photon index, $\Gamma = 2.2 \pm 1.1, 1.2 \pm 1$ for the 2 thermal models. The absorbed fluxes and unabsorbed luminosities were the same as found when the XMM data was fit alone, $F = 2.45 \times 10^{14}$ erg s$^{-1}$ cm$^{-2}$, $L_X = 1.6 \times 10^{32}$ erg s$^{-1}$. The thermal and nonthermal components contribute equally to the unabsorbed flux.

5.4 Discussion

SAX J1810.8-2609 is a NS LMXB whose previously reported thermal NS luminosity upper limit is in disagreement with widely accepted NS heating and cooling models [Jonker et al., 2004b]. In our new (2015) XMM observation, we find the source at the same quiescent level as the 2003 Chandra observation, $L_X = 2 \times 10^{32}$ erg s$^{-1}$. A 2-component spectrum with a thermal component providing $\approx 50\%$ of the flux provides the best description of the quiescent spectrum. We interpret the thermal component as a cooling neutron star surface.

Despite our observation being heavily affected by background flares that reduced our exposure by nearly half, we obtained twice as many source counts compared
Figure 5-2: Joint continuum fits to the XMM EPIC PN (black), MOS 1/2 (blue) and Chandra ACIS data (red), each binned to a minimum of 20 counts per bin. The continuum was tied between all datasets and we fit with nonthermal (top,left), thermal (both 2, left) and 2-component (right) models. For the two-component continuum, we plot the thermal contribution in green and the nonthermal emission in orange. While the large powerlaw index for a pure powerlaw suggests the spectrum is soft and has significant thermal emission, we found the pure thermal models (i.e. bbodyrad and nsatmos) were not sufficient; high-energy residuals above 3 keV show that an additional powerlaw component is required. The nsatmos+powerlaw fit provides the best fit overall. The neutron star atmosphere and powerlaw components contribute 60% and 40%, respectively, to the unabsorbed flux.
to the previous, and only, quiescent observation performed over 10 years ago. Most significantly, we measured nearly 30 counts above 4 keV (compared to only 4 counts in the Chandra observation), which was necessary to constrain the high-energy portion of the spectrum and distinguish between a completely nonthermal spectrum and a spectrum that required both thermal and nonthermal emission. While a powerlaw provides an equally good fit as a combination model for the 2003 Chandra observation, our 2015 XMM data required both thermal (either a blackbody or a neutron star atmosphere) and powerlaw components to fit the 0.5-10 keV quiescent spectrum. The neutron star atmosphere model had a temperature of 70 eV, which is in the range of previously observed quiescent NS temperatures [Brown et al., 1998, Heinke et al., 2006, Heinke et al., 2003].

With a NS luminosity of \( \approx 10^{32} \) erg s\(^{-1}\), SAX J1810.8-2609 is one of the faintest NSs in a non-AMXP system. It stands out from AMXPs because not only is it not a pulsar (as no pulsations are detected in outburst), its quiescent spectrum when fit with a powerlaw has a very high photon index (\( \Gamma \approx 3.7 \)) indicating significant thermal emission is present. For AMXPs, the quiescent spectra are very hard and almost entirely nonthermal. For example, SAX J1808.4-3658, a well-known AMXP, has an entirely nonthermal quiescent spectrum (\( \Gamma = 1.7 \)) and has stringent upper limits placed on possible thermal emission \( L_{\text{NS}} < 6 \times 10^{30} \) erg s\(^{-1}\) (0.1-10 keV; Heinke et al. 2009). Based on deep crustal heating and standard cooling predictions, the NS luminosity in SAX J1810.8-2609 is at least an order of magnitude fainter than expected given its outburst accretion rate history (see Figure 8 Heinke et al. 2010). Possible explanations for a cold NS include enhanced cooling processes, a hybrid crust, or overestimates of the time-averaged outburst accretion rate.

The density threshold for the direct Urca process is reached inside massive NSs (\( M=1.7-1.8 \ M_{\odot} \)); this enhanced cooling mechanism allows for the heat produced by the pycnonuclear reactions to be radiated away more efficiently and significantly reduces the NS cooling timescale (\( \tau << 10^{4} \) years; Colpi et al. 2001). In our fits we fixed the mass and radius values of the neutron star atmosphere models based on results from burst cooling tail methods. Näättilä et al. [2016] found \( M = 1.4 \pm 0.4 \ M_{\odot} \),

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\( R = 12 \pm 0.5 \text{ km} \) (errors are the 68% confidence level), so a heavy NS in SAX J1810.8-2609 is at the very high-end of acceptable values. Unfortunately, our quiescent data is not able to distinguish between different NS mass and radius values. We were unable to constrain the NS mass even when we fixed the radius parameter. Similarly, a massive NS is disfavored to explain the low thermal quiescent luminosity \( (L_x < 1.4 \times 10^{32} \text{ erg s}^{-1}, \text{bolometric}; \text{Tomsick et al. 2004}) \) for the NS in the LMXB XTE J2123-058. NS mass measurements using a variety of techniques, including radial velocity curves and radio spectroscopy, favor \( 1.5 \pm 0.3 M_\odot \) [Tomsick et al., 2001, 2002, Casares et al., 2002] and \( 1.04 - 1.56 M_\odot \) [Shahbaz et al., 2003].

A hybrid NS crust, where the original crust has not been completely replaced by compressed accreted material, may be able to produce a cool quiescent NS. If less than \( 0.02 M_\odot \) has been accreted, the crust is largely composed of the original NS material and the full range of pycnonuclear reactions will not be activated, resulting in heating less than \( \approx 1.5 \text{ MeV} \) per accreted nucleon assumed with deep crustal heating [Wijnands et al., 2013]. Young systems and those with low outburst accretion rates are the most likely candidates for hybrid crusts; neither type of systems should have accreted enough material to replace the crust during the course of its lifetime. While SAX J1810.8-2609 has a low mass outburst accretion rate compared to other NS LMXBs \( (\dot{M} \lesssim 10^{-11} M_\odot \text{ yr}^{-1}) \), the uncertainties in the source’s outburst history, and a general lack of understanding of the heating and cooling mechanisms in a hybrid NS crust prevents us from evaluating a hybrid crust as a possible explanation for the faint NS in SAX J1810.8-2609.

SAX J1810.8-2609 has relatively short outbursts \( (< \text{ few months}) \) and long quiescent periods \( (> 5 \text{ years}) \), resulting in a low time-averaged accretion rate \( 10^{-12} - 10^{-11} M_\odot \text{ yr}^{-1} \) [Tomsick et al., 2004, Fiocchi et al., 2008]. The time-averaged outburst mass accretion rate (Equation 1 from Tomsick et al. 2004) is given by

\[
\dot{M} = \frac{\bar{L}_{\text{peak}} N t_{\text{obs}} f}{\epsilon c^2 (33 \text{ year})},
\]

where \( \bar{L}_{\text{peak}} \) is the mean peak outburst luminosity, \( N \) is the number of outbursts in
the past 33 years, $t_{outb}$ is the typical outburst duration, $f$ parameterizes the shape of the outburst light curve and $\epsilon$ is the fraction of the accreted rest mass energy that is released during accretion. For NSs, $\epsilon$ is typically 0.2 [Rutledge et al., 2002] and $f$ can be approximated as the mean outburst flux divided by the peak outburst flux. SAX J1810.8-2609 has had 3 outbursts in the past 20 years. The 1998 and 2007 outbursts were classified as faint outbursts with $\bar{L}_{peak} < 10^{36}$ erg s$^{-1}$ [Natalucci et al., 2000, Fiocchi et al., 2008], while a review of the 1998 RXTE monitoring revealed the outburst may have actually been bright, $\bar{L}_{peak} \approx 10^{37}$ erg s$^{-1}$, and longer than previously estimated ($\approx 100$ days). The outburst in 2012 was bright, but may have only lasted approximately 20 days [Degenaar and Wijnands, 2013b]. We estimated the time-averaged mass accretion rate in outburst for a variety of outburst characteristics: bright/faint peak luminosities, long/short in durations (20 days/100 days), and the number of outbursts ranging in the past 33 years from 2-5 for the different outburst types. We calculate mass accretion rates in the range of $(5 - 20) \times 10^{-13} \ M_\odot \ yr^{-1}$.

For a quiescent NS heated by pycnonuclear reactions in the crust (i.e. deep crustal heating), the luminosity associated with the cooling NS, $L_{NS}$ is given by (Eqn. 1 from Rutledge et al. 2002)

$$L_{NS} = 9 \times 10^{32} \left( \frac{\dot{M}}{10^{-11} \ M_\odot \ yr^{-1}} \right),$$  \hspace{1cm} (5.2)

based on 1.45 MeV of heat deposited in the crust per accreted nucleon [Haensel and Zdunik, 1990b]. For a quiescent luminosity of $L_X = 1 \times 10^{32}$ erg s$^{-1}$ and a 50% thermal contribution, Jonker et al. [2004b] inferred an outburst mass accretion rate of $6 \times 10^{-13} \ M_\odot \ yr^{-1}$, which was significantly lower than the accretion rate estimated from outburst activity, although at the time only a single outburst had been observed from SAX J1810.8-2609. Our XMM observation, which has over twice as many counts as the Chandra observation, places the source at $L_X = 2 \times 10^{32}$ erg s$^{-1}$ with a 50% thermal contribution, implying a NS luminosity $L_{NS} \approx 10^{32}$ erg s$^{-1}$, requiring an outburst accretion rate of $\approx 1 \times 10^{-12} \ M_\odot \ yr^{-1}$. This value is within the range our
time-averaged mass accretion rate calculated from its outburst history. Referencing Figure 8 in Heinke et al. [2010], again, we find the new estimates for the cooling neutron star luminosity and the time averaged outburst accretion rate are more in line with standard cooling than previous analyses. We do not need to invoke large outburst recurrence timescales to explain the low outburst accretion rate, as was the case with XTE J2123-058 which requires outburst recurrence timescales of > 70 years [Tomsick et al., 2004].

While our NS quiescent luminosities are consistent with deep crustal heating and standard cooling models, there is also the possibility that the thermal component is not actually emission from the NS surface. Low-level accretion flows can produce a thermal-like spectrum [Zampieri et al., 1995], while D’Angelo et al. [2015] has suggested that the nonthermal and thermal quiescent emission may both be associated with the NS boundary layer. Both scenarios imply the cooling NS has not been detected in SAX J1810.8-2609 in quiescence, pushing the source further into disagreement between standard heating and cooling models and the known outburst history. However, the similarity of the quiescent luminosities between the two quiescent observations does not support the interpretation that accretion produces the observed thermal emission in SAX J1810.8-2609. Two outbursts have occurred between the quiescent observations which were taken over 10 years apart. In both quiescent observations, the source was found with $L_X = 2 \times 10^{32}$ erg s$^{-1}$. The consistency between the two observations supports our interpretation that we have observed the cooling NS surface.
Chapter 6

Conclusion

In Chapter 2, I detailed the accretion disk wind properties in the persistent NS LMXB GX 13+1. I showed that the absorption feature complex imprinted on the X-ray continuum is the result of several ionized zones in the accretion disk wind outflow. Additionally, the wind is consistent with a Compton heated outflow and radiation pressure likely facilitates the wind launching in this source as it accretes at substantial Eddington fraction. While consensus is growing that Compton heating may be a universal wind-launching mechanism, at least in neutron star LMXBs, there are still huge unknowns concerning these substantial outflows in outburst.

There is the question of whether the onset of one outflow is the direct result of the shut down of another outflow. The depletion of the accretion disk via a soft state disk wind may generate jets in the hard state [Neilsen and Lee, 2009]; together, the outflows complement each other to self-regulate the accretion rate onto the central compact object. Additionally, the outflows may be intimately tied to state transitions. Mass loss rates comparable to the accretion rate are thought to cause instabilities in the accretion disk [Begelman and McKee, 1983]. Estimates of the material driven from the accretion disk via a disk wind have been found to be equal or even greater than the accretion rate; thus, it is possible that winds actually trigger the state transitions via disk instabilities [Shields et al., 1986]. While I have tried to produce a comprehensive view of the accretion disk wind in GX 13+1, there is huge amount of work to be done to study the simultaneous accretion disk winds and jets in a
small, but interesting, subset of luminous disk LMXBs. A joint X-ray, radio and optical observation of GX 13+1 along its horizontal and normal Z track branches with coverage provided by Chandra HETG, Very Large Array and Gemini has already been successfully proposed (J. Homan, PI) and will hopefully lead to enlightening results. Additionally, coordinated observations that track a LMXB during its state transition can provide greater insight into the interplay between the outflows.

Additionally, we found evidence that thermal stabilities may play a role in GX 13+1’s accretion disk wind plasma. Plasma instabilities have been invoked to explain the absence of disk winds in the hard states of BH LMXBs [Chakravorty et al., 2013]. Plasmas illuminated by the hard state spectrum are unstable for a large range of ionization parameters which can explain why we do not see accretion disk winds hard states. Stability analysis require detailed knowledge of the ionizing spectrum across a wide energy band (0.01 – 10³ keV). Currently, there are more complete continuum models for BH LMXBs, while NS models are lacking. As GX 13+1 is a source that exhibits simultaneous winds and jets, deciphering the role of plasma instabilities may prove critical to understanding the subset of sources that exhibit winds and jets in their hard spectral states.

In Chapter 3, I focused on the transition from the hard state in outburst to quiescence in SAX J1750.8-2900. While the system is not as bright as in outburst and outflows have likely shut off, the transition is still an interesting phase in the NS LMXB life cycle. I found significant spectral variation accompanied the decrease in flux. The softening X-ray emission may be associated with the accretion flow itself or may be the result of a increasing contribution of a boundary layer. Distinguishing between the two behaviors, in SAX J1750.8-2900 and in other NS LMXBs, will require deeper observations with Chandra or XMM; these instruments have the energy resolution and collective area that will allow us to distinguish between a purely nonthermal spectrum from one with both thermal and nonthermal components.

In Chapters 4 and 5, I turned my studies to quiescent NS LMXBs. One of my primary focuses has been whether the thermal X-ray emission is consistent with a cooling NS, as well as the mass and radius constraints from modeling the surface

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emission. For SAX J1810.8-2609, we obtained the first direct detection of the thermal emission in the quiescent spectrum and found the thermal luminosity is consistent with deep crustal heating predictions and its known outburst history. As there have been significant constraints placed on the NS mass and radius in SAX J1810.8-2609 through burst cooling tail modeling, comparison with a quiescent measurement of the mass and radius is promising. While SAX J1810.8-2609 is relatively unabsorbed, it is still faint in quiescence and will require long ($\sim 100$ ksec) observations with Chandra or XMM to obtain a thermal spectrum sensitive to the mass and radius values.

And finally, my graduate career and thesis has ended with one of the most well-studied quiescent NS LMXBs. Cen X-4 has been the subject of extensive observations, and the source of major breakthroughs in quiescent LMXB properties, including evidence of accretion-induced quiescent variability and thermal bremsstrahlung as the high-energy emission mechanism. We found the source still holds secrets in its spectrum. In a bright quiescent observation, we found a small signal in its residuals that may be the signature of an accretion hot spot or a boundary layer. While Cen X-4 is a source worthy of future Chandra and XMM campaigns, the greatest promise may lie with NICER. If the hot thermal component is associated with an accretion hotspot, we expect to see millisecond pulsations from the rotating NS. As the spectral component is only significantly present in the brightest quiescent observation of Cen X-4, we are also motivated to review quiescent observations NS LMXBs that are bright and variable in quiescence, such as Aql X-1.
Bibliography


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