Spectral–timing Analysis Of Kilohertz Quasi–periodic Oscillations In Neutron Star Low Mass X-Ray Binaries

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SPECTRAL–TIMING ANALYSIS OF KILOHERTZ QUASI–PERIODIC OSCILLATIONS IN
NEUTRON STAR LOW MASS X-RAY BINARIES

by

JON S. TROYER

DISSERTATION

Submitted to the Graduate School,

of Wayne State University,

Detroit, Michigan

in partial fulfillment of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

2018

MAJOR: Physics

Approved by:

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Advisor

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ACKNOWLEDGEMENTS

I would like to thank many of the faculty in the Department of Physics and Astronomy for freely giving their time and knowledge in order to assist me on the road to this manuscript. This includes the members of my committee: David Cinabro and Claude Pruneau who offered great feedback while I built materials for my job search in addition to teaching more than a few of my courses. Also, Scott Payson who was always willing to talk and help keep things in perspective.

I would also like to thank the co-authors of my publications, especially Philippe Peille who graciously gave of his time to help steer me through the many obstacles of spectral-timing. Thanks also to Misty Bentz who gave me a real introduction to just how much work co-author comments could be.

Thanks also to the Compact Objects in Michigan confederation of faculty for putting on a really great event each year. Those meetings gave me important opportunities to present my research in a “friendly” environment.

Finally, my advisor Ed Cackett. He wore the hat of boss/mentor/friend with professionalism and grace. Ed is a world-class researcher with superior work ethic, career-minded vision, and just enough humility to make him bearable. That last part is in jest of course. There are so many good things to say about Ed it’s difficult to land on the right words. I would simply say he is among the highest quality people I have ever known.
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CHAPTER 1 ACCRETION IN NEUTRON STAR LOW-MASS X-RAY BINARY (LMXB) SYSTEMS

1.1 Accretion as a Window to General Relativity and Dense Nuclear Matter

Accretion occurs when matter falls on to an object under the influence of gravity and can happen in many astronomical objects including neutron stars, stellar mass black holes (BH), and the supermassive black holes (SMBH) residing in the centers of Active Galactic Nuclei (AGN). As matter is drawn onto the object, it forms an accretion disk while conserving angular momentum. Over time, gravitational potential energy is converted to kinetic and viscous internal energy of the accretion disk with a net transfer of angular momentum to the edge of the disk. The resulting heating of the disk is dramatic, with an energy conversion efficiency greater than nuclear fusion processes. To get a feel for this, consider an order of magnitude estimate. The amount of energy released as matter loses gravitational potential energy while accreting onto a compact object ($\Delta E_{\text{acc}}$) is:

$$\Delta E_{\text{acc}} = \frac{GM_{co}m}{R_{co}}$$

(1.1)

where: $G$ is Newton’s gravitational constant, $M_{co}$ is the mass of the compact object, $m$ is the mass of a particle of accreting matter, and $R_{co}$ is the radius of the compact object. For a neutron star, $R_{co} \simeq 10$ km, $M_{co} \simeq 1.4M_\odot$, where $M_\odot$ is the mass of our own sun ($\sim 1.9 \times 10^{30}$ kg), the resulting $\Delta E_{\text{acc}} \simeq 2 \times 10^{20}$ ergs per gram accreted. If we now consider the energy release from nuclear fusion, using the most efficient hydrogen burning process
in astrophysics where four hydrogen nuclei create a helium nucleus, the yield ($\Delta E_{\text{fusion}}$) is: $\Delta E_{\text{fusion}} = 0.007mc^2$, where $c$ is the speed of light. In this case, $\Delta E_{\text{fusion}} \simeq 6 \times 10^{18}$ ergs per gram or about 30 times less than the equivalent accretion yield. A similar order-of-magnitude calculation can be found in Frank et al. (2002).

The primary motivation for studying accretion is the window it provides to observe the physics of strong gravity and dense matter associated with neutron stars and black holes. These objects showcase extreme conditions that elude reproduction in any terrestrial experiment. In order to study the physics of such an object, we must turn to astronomical techniques. Such techniques cannot rely on imaging alone due to the limitations on tele-
scope technology - compact objects are too far away to spatially resolve. To accomplish
this, we must first understand how the neutron star - or any compact gravitational object
- affects its surroundings. If we can measure these effects and gain a clear picture of the
associated physical processes, we can study these types of objects. One example of the
effect of a compact gravitational object on its surroundings is accretion.

General relativity (GR) has been directly tested in regions of space with weak gravi-
tational fields, where $\frac{GM}{R} \ll c^2$, but the motion of particles in regions of strong grav-
tational fields has yet to be observed. The gravitational field strength can also be char-
acterized by two parameters: gravitational potential $\varepsilon$, where $\varepsilon = \frac{GM}{rc}$, and spacetime
curvature $\xi$, where $\xi = \frac{GM}{r^3c^2}$, in both cases, $M$ is the mass of the compact object and
$r$ is some distance from that object. A strong field exists when both these parameters are
high, as illustrated in Figure 1. Additionally, GR predicts the existence of event horizons,
precessional motion – like the precession of the perihelion of Mercury in our solar system,
and inertial frame dragging – the twisting of spacetime due to the spin of the black hole –
which have also not been directly observed. It is also possible that Einstein’s theory does
not work in very strong fields. Indeed GR is predicted to breakdown in the strong field
regime at a gravitational singularity (Psaltis, 2008). By studying the electromagnetic (EM)
signatures of particles as they move near a compact object, i.e. the accretion flow, these
important tests of GR can be investigated. In particular, neutron stars offer a means of test-
ing GR in fields several orders of magnitude higher in strength than any nearby (within
the solar system) tests.

Neutron stars are among the most extreme objects in the universe. Assuming a mass
of $1.4 \, M_\odot$ and putative 10 km radius, the average density of a neutron star is $6.65 \times 10^{17}$
Figure 2: Mass versus radius relationships for proposed equations of state derived from various nuclear models. Hadronic model curves are shown in black and strange quark matter (SQM) in green. Various constraints are shown to: ensure a black hole is not formed, a finite pressure exists at the center of the neutron star, ensure the interior sound speed is less than the speed of light, and rotational forces do not rip the star apart. Figure taken from Lattimer & Prakash (2016).
kg m$^{-3}$. In comparison, the radius of an atomic nucleus follows the relationship $r = r_o A^{1/3}$, where $r_o = 1.2$ fm, so for $A = 1$, the number density $n = 3/4\pi r_o^3$ is $1.4 \times 10^{44}$ fm$^{-3}$ and using a nucleon mass of $1.67 \times 10^{-27}$ kg, the nuclear density $\rho_{nuc} \sim 2.3 \times 10^{17}$ kg m$^{-3}$. Thus, neutron stars are more dense than a typical atomic nucleus. The types and behavior of subnuclear particles that exist in the interior of a neutron star are not well understood. The knowledge of the equation of state (EOS), i.e. the compressibility of matter under these conditions, is vital in order to correctly determine the nuclear model describing this exotic matter. See Lattimer & Prakash (2016) for a recent review. By studying the orbital motion close to the neutron star via accretion, estimates of both the mass ($M$) and radius ($R$) can be made. The mass-radius ($M - R$) relationship can be used to constrain the neutron star EOS and provide crucial insight into the physics of dense matter. Figure 2 illustrates several candidate EOS that can potentially be constrained by the observation of neutron star masses and radii. Only one of these candidate E.O.S. would describe the matter in the interior of a neutron star.

In addition to compact objects, other areas of astrophysics require a model of the accretion process. These include: star formation as well as solar system and planetary formation. Therefore, understanding how observations are linked to the physics of accretion provides an important tool of astrophysical study.

One particular type of object useful in probing the accretion process is a neutron star low mass X-ray Binary (LMXB) system, illustrated in Figure 3. In these systems, a stellar companion with $M \leq M_\odot$ orbits a neutron star and accretion occurs as the outer portion of stellar matter is pulled onto the neutron star by gravity. These objects are numerous and
can typically accrete matter at a few 10s of percent of the Eddington limit. The Eddington limit is the theoretical accretion rate limit where the force of gravity is exactly countered by the emitted radiation pressure and is on the order of \(10^{38}\) erg s\(^{-1}\) for a 1.4\( M_\odot\) neutron star. The viscosity of the disk produces heat and the disk emits radiation thermally which we can observe and study. By gaining a more complete understanding of accretion we are better able to interpret observations of these types of objects. The temperature of the accretion disk is expected to be a few keV in neutron star LMXB systems, emitting brightly in the X-ray portion of the EM spectrum.

Significant gravitationally powered accretion can occur in such systems which contain a neutron star with a relatively weak magnetic field \(\simeq 10^{8-9}\)G. In such neutron star systems, \(\simeq 90\%\) of the gravitational potential energy is converted to kinetic and internal energy in the inner \(\simeq 100\) km, which is \(\simeq 1\%\) of the accretion disk radius. In most accretion models of neutron star LMXBs, the accretion disk consists of a Keplerian flow of plasma that is truncated at the neutron star surface or boundary layer, or at some distance from the surface where the flow proceeds with an inward radial velocity greater than the Keplerian velocity or the flow is expelled by the neutron star’s magnetic field.

### 1.2 The Geometry of Accretion

Prior to further discussion, it is important to develop a picture of the accretion process. In close binary systems, where the separation between the primary and the secondary is on the order of the larger star, the teardrop shaped gravitational potential between the two can distort the outer layers of one or both stars. Neutron star LMXBs are indeed close binary systems, with only the secondary – a main sequence star – having appreciable
extent. The gravitational potential shape producing the distortion of the secondary is called its Roche lobe. If the outer layers of the secondary overflow its Roche lobe and intersect the inner Lagrange point between the two stars, mass transfer will occur. Orbital motion in LMXBs prevents matter from falling directly on the primary, due to the negligible extent of the neutron star. Thus, material begins to orbit the neutron star and forms an accretion disk. The standard picture of such an accretion disk is derived from the work of Shakura & Sunyaev (1973), (see Fabian, 2016, for a recent review of the current accretion picture in black hole systems).

The study of accretion disks is primarily focused on black hole systems and indeed we expect many similarities between neutron star accretion disks and those of black holes. The picture or the accretion processes includes a geometrically thin, optically thick disk that may extend, in the case of a black hole system, to the innermost stable circular orbit.
(ISCO). This orbital distance is derived from the GR equations of motion and is often expressed in terms of the Schwarzschild radius \( R_S = \frac{2GM}{c^2} \). The ISCO for a non-rotating black hole is \( 6 \, R_S \) and relativistic frame-dragging can reduce the ISCO in spinning black holes. In neutron star systems, the stellar surface is the closest the accretion flow can approach. The ISCO for a \( 1.4 \, M_\odot \) neutron star is \( 6 \, R_S \) or \( \sim 12 \, \text{km} \), which is about the same extent as the expected neutron star radius. However, the stability of the orbit near the neutron star surface or ISCO of a black hole can be degraded by external factors including: loss of accreting material, magnetic interactions, jets, luminosity driven radiation pressure (see e.g., Miller & Miller, 2015). Indeed, oscillations associated with instabilities in the inner accretion flow would carry frequency signatures commensurate with kilohertz quasi-periodic oscillations (kHz QPOs) (see Section 1.3). Admittedly, such a casual relationship is far from conclusive (Méndez, 2006).

The standard picture of a flat disk extending near to the neutron star surface can only occur in systems with weak magnetic fields (\( B \sim 10^{8-9} \, \text{G} \)). In systems with high magnetic field strengths, typically associated with younger, high-mass X-ray binary pulsars, the magnetic field disrupts the accretion flow far from the neutron star surfaces and tends to funnel the flow along magnetic field lines, creating a unique non-disk accretion structure close to the neutron star.

The accretion disk is expected to radiate like a multi-color blackbody. One can understand the expected temperature profile for an accretion disk by considering it as a series of concentric annuli, each a blackbody radiator, with the temperature of each annulus decreasing with distance from the compact object. The spectral signatures of accreting objects, in addition to a blackbody component, also suggest the occurrence of Comp-
tonization processes. The conversion of gravitational potential to viscous internal energy of the accretion disk would result in maximum disk temperature in the soft X-ray range ($\sim 1$ keV). The harder, power law portion of the X-ray spectrum seen in accreting compact objects implies a high-temperature corona of electrons that Compton upscatter the accretion disk photons (see Miller, 2007, and references therein, for a review of the X-ray spectra of accretion disks). X-ray spectra observed in accreting LMXBs systems typically also require a reflection component in addition to the power law (Comptonization) and disk component. Indeed, Fe fluorescence lines are routinely observed in these systems (see Cackett et al., 2010, and references therein, for a review of the Fe K detection in neutron star systems). This requires a compact, high-energy X-ray source since the disk emission alone lacks the photon energies sufficient to produce Fe K emission. The GR signatures of the Fe K emission place this emission source near the ISCO in black hole systems. So, while the corona may extend over the disk itself and the geometry of the corona is not known, there must be a corona (or other high energy X-ray source) in the innermost region of the compact object (see e.g., Reynolds, 2014).

The above discussion is generally applicable to both neutron star and black hole accreting systems. However, unique to neutron star systems are both its physical surface as well as the boundary layer. While the surface emission is unobservable when the system is in states of high accretion rates, the boundary layer region is important when the accretion rate is high. This region is expected to arise at the point where the Keplerian velocity of the accretion flow exceeds the neutron star spin frequency and have a surface area comparable to the neutron star (Inogamov & Sunyaev, 1999). Here, accreting material will decelerate and spread over the neutron star surface. Upwards of 50% of the gravitational
Figure 4: A conceptual illustration of accretion geometry and emission. Photons generated via Comptonization in the corona or thermally in the neutron star boundary layer can be directly observed and also act as a reflection source for disk emission. This leads to various fluorescence line emission, dominated by Fe K. Additionally Comptonization, associated with a power law spectral component may be created in an extended corona.
potential energy would be released in the boundary layer region (see Gilfanov et al., 2003; Gilfanov & Sunyaev, 2014, and references therein). This would result in a significant luminosity source thus appearing in the overall X-ray spectrum of neutron star systems and potentially act as the disk illumination source (e.g., Inogamov & Sunyaev, 2010). The boundary layer spectrum is expected to be similar to the disk spectrum resulting in ambiguities when attempting to decompose the X-ray spectra of neutron star systems (e.g., Gierliński & Done, 2002).

Finally, ejection of material from accreting neutron star binary systems is routinely seen. This ejecta can take the form of collimated outflows (i.e. jets), detected primarily in the radio band since the early 1990s (e.g., Stewart et al., 1993). Jets are thought to be powered by the rotation of the neutron star (Miller & Miller, 2015), but the possibility exists that jets can also be accretion-powered based on optical and IR band spectra that possess properties of jets (Russell et al., 2007). Additionally, non-collimated flows (i.e. winds) in accreting neutron star binary systems, detected via blue-shifted absorption lines, have also been detected (e.g., Miller et al., 2016).

Overall, observational evidence suggests the existence of all the previously described components of an accreting neutron star binary system, which is shown schematically in Figure 4.

The distance scale of the inner accretion flow is of the order of the neutron star radius. This implies dynamical velocities and timescales of the order of $\simeq 0.5 \, c$ and $\simeq 100 \, \mu s$ respectively (van der Klis, 2000; Wagoner, 2003). We therefore expect signals that carry the casual signatures of this region to have the same timescale. The shortest timescale (highest frequency) oscillations that have been observed in neutron star LMXBs are kilohertz
quasi-periodic oscillations (kHz QPOs).

1.3 Kilohertz Quasi-Periodic Oscillations (kHz QPOs)

kHz QPOs are high frequency X-ray oscillations observed in neutron star LMXBs and were discovered shortly after the launch of NASA’s Rossi X-ray Timing Explorer (RXTE) (Bradt et al., 1993) in December 1995. See van der Klis (1998) for a history of the early days of RXTE’s discoveries of kHz QPOs. The discovery of two distinct kHz QPOs in nearly every neutron star LMXB system containing QPOs led to twin kHz QPO becoming a signature of neutron star systems (van der Klis, 2006). See Figure 5 for an example of twin kHz QPOs seen in the X-ray power spectrum of Scorpius X-1 (Sco X-1). The kHz QPOs occur in the $300 - 1200$ Hz range and were quickly thought to be associated with orbital frequencies of the inner accretion flow - a characteristic shared by a majority of the models that attempt to explain the origin of kHz QPOs (see e.g., Lin et al., 2011).

The first model to gain popularity was the sonic point model (Miller et al., 1998). In the sonic point model, the upper kHz QPO is associated with the Keplerian velocity of the inner accretion flow and the lower kHz QPO arises from a beat-frequency process involving the accretion flow Keplerian velocity and the neutron star spin frequency. This model predicts a constant kHz QPO peak frequency separation ($\Delta \nu$). After the discovery of non-constant QPO peak separation in the LMXB 4U 1608–52 in Méndez et al. (1998c), this model needed modification. In 2001, Lamb & Miller (2001) sought to relax the constraints on the two frequencies. This version introduced gas drifts that could perturb either the Keplerian frequency, or the beat frequency. Additional observational evidence in the form a twin kHz QPO discovery in an accreting millisecond pulsar (Wijnands et al., 2003), which
provided a solid neutron star spin measurement, could not be reconciled with the model. This prompted Lamb & Miller (2003) to abandon the original sonic-point beat frequency model in favor of a spin-resonance model. In this model, vertical motion is excited in the disk where the Keplerian frequency resonates with the neutron star spin frequency. If the accretion flow is smooth, this model becomes consistent with Lamb & Miller (2001). If the flow is clumpy, the modulation is changed so that the beat frequency is the difference between the Keplerian frequency and half the neutron star spin frequency.

Overall, there are over eleven major classes of models that attempt to explain the temporal behavior of kHz QPO frequency, or QPO timing. See van der Klis (2000, 2006) for a review of various kHz QPO models. In 2011, a comparative study done by Lin et al. (2011) tested the predictive power of the various orbital frequency kHz QPO models. The result was that no model satisfactorily reproduced the QPO data in the two sources they considered. One of the major deficiencies of orbital motion models is their lack of a concise predictive signature that can be tested against observation, i.e., the distinction between the expected behaviors of the QPOs across models is blurred. Moreover, it is unclear how the various phenomenon associated with these models couple to the X-ray radiative processes (Kumar & Misra, 2014).

In addition to orbital motion models, there are models that do not associate the kHz QPOs with the orbital frequencies of the inner accretion flow (see e.g., Kumar & Misra, 2014). These models seek to explain the kHz QPOs in terms of their radiative mechanisms. To better understand the potential emission mechanisms associated with kHz QPOs, we next discuss the time-averaged energy spectra of neutron star LMXBs.
1.4 The Spectra of Neutron Star LMXBs

The spectra of neutron star LMXBs clearly show a thermal Comptonized component, which can be fit by a power law, or in some cases approximated by a single temperature blackbody. Additionally, there is a softer component that can be fit well with a multi-colored blackbody. Lastly, the precision of spectral fits are enhanced by the addition of a disk reflection component. In LMXBs, the thermal Comptonized component is associated with a corona of hot plasma or boundary layer and the multicolor blackbody with the accretion disk. (see e.g., Mitsuda et al., 1984; Mitsuda & Tanaka, 1986). See Figure 6 for an example.

Indeed, much work has been done in classifying the spectral shape of LMXBs (see e.g., Lin et al., 2007). This led to categorization of LMXBs based on the shape of their color-
Figure 6: The fitted spectrum of the neutron star LMXB 4U 1608–52 from Cackett (2016). The top panel shows the spectral decomposition. The black curve is the overall spectrum. In blue is the single temperature blackbody component approximating an optically thick Comptonizing source – the corona or boundary layer. In red, the multicolor blackbody component – the accretion disk, and in orange the disk-reflection component. The bottom panel shows the ratio of the modeled fit to the observed spectrum.
1.5 kHz QPO Timing and Spectral Dependence

Tying kHz QPOs to the energy spectrum will be a vital part in understanding their origin. Both the energy spectra and power spectra of neutron star LMXBs are seen to vary over a wide range of timescales. The power spectrum of a source is found via Fourier decompo-
osition of the object’s lightcurve (LC). The lightcurve is a measure of intensity as a function of time, and one of the main products present in an astronomical observation. The power spectrum thus measures the variability power of a source as a function of Fourier frequency, i.e. timescale. The variability of neutron star LMXBs can occur on timescales of hours – weeks in which these objects change the overall shape of their energy spectra. These changes trace out characteristic tracks on the color-color and hardness-intensity diagrams. The phenomenology of the timing properties in the power spectrum – both the broadband noise and the properties of all QPOs present – also depend on source state and their position on the color-color diagram (e.g. Méndez et al., 1999; van Straaten et al., 2000; Di Salvo et al., 2001, 2003; Altamirano et al., 2008). This phenomenology was studied intensely for over 20 years and is still evoked in current research. As recently as 2016, van Doesburgh & van der Klis (2016) comprehensively tested a relativistic-precession model (one of the classes of orbital motion models) using QPO frequencies – both neutron star and black hole LXMBs can exhibit a multitude of lower frequency QPOs – and data grouped by source state.

Regardless of the source state and QPO phenomenological relationships, kHz QPOs are most likely associated with the thermal Comptonization component of the spectrum. This is the dominant component of the X-ray spectrum in many source states. Additionally, studies have shown the fractional root mean square (RMS) amplitude (the power spectrum expressed as a fraction of count rate) of kHz QPOs increases steadily from ∼ 3 keV to 12 keV in nearly all sources (see e.g., Berger et al., 1996; Méndez et al., 2001) suggesting a source with energy commensurate with thermal Comptonization rather than soft, black-body emission.
1.6 Spectral–Timing Analysis

Spectral analysis usually focuses on fitting physical models to the time averaged energy spectrum, including the disk, boundary layer, corona, reflection etc. However, there can be significant degeneracies in this approach. Timing, on the other hand, has mostly been phenomenological, characterizing QPO properties through fitting Lorentzians, and seeing how those properties change with state. However, timing studies rarely connect to the energy spectrum of the emission. Until recently, the two approaches have largely been separate. Performing spectral-timing analyses allows one to connect the two worlds, and understanding which components of the energy spectrum are related to the QPO, and how those components are connected to each other.

Any model that we hope to apply to kHz QPOs must explain in a global sense, the many correlations between kHz QPO frequency and other lower frequency oscillations and also the correlations between source state and kHz QPO appearance and properties. Additionally, we must also link up any model explaining kHz QPOs to a spectral component of these objects. In that respect, kHz QPOs are most likely associated with thermal Comptonization since studies have shown the fractional RMS amplitude of kHz QPOs increases steadily from $\sim 3$ keV to 12 keV in nearly all sources (see e.g., Berger et al., 1996; Wijnands et al., 1997; Zhang et al., 1996; Méndez et al., 2001) suggesting a source with energy commensurate with thermal Comptonization rather than soft, black-body emission. Additionally, Gilfanov et al. (2003); Revnivtsev & Gilfanov (2006) showed that the RMS energy spectrum of neutron star LMXBs are consistent with a thermal Comptonization spectrum, which they suggest is due to the neutron star boundary layer (BL). As previously stated, conser-
vative arguments place the emission power of the BL as at least half of the total accretion powered emission (e.g., Sunyaev & Shakura, 1986). Specifically, Gilfanov et al. (2003) showed that the RMS energy spectrum of kHz QPOs in 4U 1608−52 and GX 340+0 are consistent with Comptonized emission. Peille et al. (2015) showed the energy-dependent covariance spectra (see Chapter 2) for 4U 1608−52 and 4U 1728−34 are also consistent with Comptonized emission. See Gilfanov & Sunyaev (2014) for a review of neutron star BL physics.

For a physical picture where thermal accretion disk photons are Compton scattered by a hot corona or boundary layer to higher energies, delays between variations of higher-energy photons and variations of lower-energy photons are expected to arise. There are several physical explanations for correlated lags, and the search for conclusive evidence of the correct picture is a topic of ongoing research. One possibility follows from the fact that in order to obtain higher energies, a photon arriving in the corona must undergo a larger number of scattering events, which means that it resides longer within the corona. Detailed analysis of Comptonization models suggest that this delay should scale with $\sim \log \frac{E_{\text{high}}}{E_{\text{low}}}$ (Nowak & Vaughan, 1996). However, a majority of time lags measured in kHz QPOs have been soft (Lee et al., 2001). Soft lags, by convention, indicate variations in the lower-energy photons lag those of the higher-energy photons. Hard lags occur when the opposite is true. The measurement of time lags between correlated variability in different energy bands helps inform how the spectra change as a function of energy and Fourier frequency (time scale). These time lags are a product of spectral-timing analysis. See Chapter 2 for the details of spectral-timing analysis.

The first energy-dependent soft lags of a neutron star LMXB 4U 1608−52 were found
in Vaughan et al. (1998). After which, soft lags were found in other neutron star LMXB systems (Kaaret et al., 1999; Barret, 2013; de Avellar et al., 2013; Peille et al., 2015), black hole binaries and AGN (see Uttley et al., 2014, for a review of time lags in black hole systems).

While Vaughan et al. (1998) and Kaaret et al. (1999) were the first works to study time lags in kHz QPOs in 4U 1608–52 and 4U 1636–53 respectively using 3–4 energy bins, more recent analyses that have greatly expanded the energy resolution have been done for a total of three neutron star LMXBs. Time lags associated with kHz QPOs have been studied in 4U 1608–52 in de Avellar et al. (2013) and Barret (2013), in 4U 1636–53 in de Avellar et al. (2013, 2016a), and 4U 1728–34 in Peille et al. (2015). These studies have all shown soft broadband lags for the lower kHz QPO. Also, when lag as a function of energy is computed for the lower kHz QPOs, a near monotonic trend of lag with energy, with the higher energy photons arriving first. The magnitudes of the soft broadband lags have all been on the order of the size scale of the neutron star inner accretion disk/boundary layer. In cases where the upper kHz QPO is detected – the upper kHz QPO is systematically weaker for all sources – the broadband lags are hard and lag increases with energy (see e.g., Peille et al., 2015). The interpretation of time lags is unclear and the complete picture of the source of time lags is likely complex, involving a combination of several physical processes.

The problem of observed soft lags and Comptonization models that predicted hard lags was addressed by Lee et al. (2001). In this model, soft lags were predicted and provided a good fit to the data for the lower kHz QPO in 4U 1608–52 (Vaughan et al., 1998). In this model, the primary oscillations manifest in Comptonizing temperature variations, and
soft lags can occur if a significant fraction of the Comptonized flux impinges back on the seed photon source. This model does not give detailed information regarding the source geometry and could not reliably constrain the corona temperature. If the Comptonizing temperature were greater than the 25 keV assumed, there would be significant effects on the model accuracy (Lee et al., 2001).

Additional spectral-timing analysis beyond time lags was done in Gilfanov et al. (2003) and Peille et al. (2015) for two sources: 4U 1608−52 and 4U 1728−34. This included producing a detector response-folded covariance spectra. Typically, fractional RMS normalization of the power spectrum is used to study the timing properties of kHz QPOs. However, using a different normalization for the power spectrum, Méndez et al. (1997), Revnivtsev et al. (1999), and Gilfanov et al. (2003) were all able to illustrate the use of the Fourier frequency resolved spectrum as the energy-dependent RMS amplitude in a given frequency range. The advantage of this normalization over fractional RMS normalization is that the power spectrum can be folded with the instrument response to yield an energy-dependent spectrum. There are a few caveats to the interpretation of the spectra created in this fashion that will be discussed in Chapter 2.

The covariance spectrum was introduced in the compact objects spectral-timing community by Wilkinson & Uttley (2009) and later examined in detail by Uttley et al. (2014). Essentially, the covariance spectrum is equivalent to the RMS spectrum, with higher signal-to-noise (S/N) when the two signals are coherent. The details of the calculation of the covariance spectrum, the meaning of coherence, and its effect on the interpretation of the covariance spectrum will be discussed in Chapter 2. Gilfanov et al. (2003) showed that the RMS spectrum and Peille et al. (2015) confirmed that the covariance spectrum of
kHz QPOs were consistent with Comptonized blackbody emission from the boundary layer without contribution from the accretion disk. This is consistent with the behavior seen in the fractional RMS (covariance) that has been measured in neutron star LMXBs. Fractional RMS (covariance) drop at energies below $\sim 10$ keV, behavior likely arising from dilution of the variability by the accretion disk, and begins to flatten above $\sim 10$ keV.

The usefulness of the response-folded covariance spectrum is that it can be compared side-by-side with the time-averaged spectrum. In this way, comparisons between variable and non-variable spectral features can be made. What Peille et al. (2015) showed, for the lower kHz QPO, was a harder covariance spectrum compared with the time-averaged spectrum for the objects 4U 1608−52 and 4U 1728−34. This is similar to the results obtained by Gilfanov et al. (2003) using the response-folded RMS spectrum for 4U 1608−52. Additionally, Peille et al. (2015) showed a better spectral-fit was obtained when the seed photon temperature of these two components are decoupled. For that analysis, the covariance seed photon temperature was found to be systematically higher than the mean seed photon temperature.

There are several conclusions that can be drawn about the physical processes of the kHz QPOs from the various spectral-timing information gathered to date from the small-number of LMXBs studied. Considering the lag–energy spectrum first, the shape of the lag–energy spectrum is markedly different for lower kHz QPOs when compared to upper kHz QPOs. This suggests that different physical processes might be responsible for their production. Barret (2013) suggested the soft lags associated with the lower kHz QPO could be produced via reverberation. See Blandford & McKee (1982) for a discussion of reverberation and reverberation mapping analysis techniques used in astrophysics.
Figure 8: Comparison of the lag energy spectrum of the lower kHz QPO in 4U 1608-52 with modeled general relativistic reverberation lags. Figure from Cackett (2016). The model follows the data to energies $\sim 8$ keV where they diverge. This indicates that reverberation alone cannot explain the origin of the lags.

1.7 Reverberation

The essential idea behind reverberation is that a central, variable luminosity source is incident upon a body of matter which reflects the incident source. Reflection in this context is the induced fluorescent and backscattered emission as well as thermal emission due to radiative heating of the reflecting matter (Uttley et al., 2014). This reflection is the “echo” produced by the primary source of variable emission. There can also be line emission in the reflected spectrum, which is typically dominated by Fe K$\alpha$ due to its high yield and abundance. Line emission can occur in the innermost accretion flow and is a powerful diagnostic of relativistic effects occurring there (see Fabian & Ross, 2010, for a review).

If the reflected and incident luminosity sources can be correlated, a time lag can be measured. This time lag is interpreted as the light-crossing time between source and re-
flector. See Figure 4. In the context of neutron star LMXB systems, the primary variability source could be the X-ray luminosity produced by the boundary layer and reflection could occur when that source is incident upon the accretion disk. However, the lag–energy spectrum of the lower kHz QPO continues to decrease above energies where the accretion disk emission should contribute. This suggests some other mechanism, aside from reverberation, must be in place to produce the lags.

Cackett (2016) showed that the lag–energy spectrum of 4U 1608–52 could not be explained by reverberation alone. In that work, reverberation was modeled using a general-relativistic ray-tracing impulse response model. This type of model generates the reflected response of the accretion disk to a delta function burst associated with some incident luminosity source. The model captures the relativistic physics that is expected to occur in the vicinity of a LMXB accretion disk as well as the effects of dilution. Dilution occurs because a portion of the primary, hard, power-law component associated with Comptonization is also contained in the reflection emission band. This can effect the magnitude of the lags as well as alter the shape of the lag–energy spectrum. When comparing the lags, Cackett (2016) found the lags measured using data from 4U 1608–52 provided a good fit to the model for energies up to $\sim 8$ keV. Above this energy, the lags expected from reverberation monotonically increased while the lags measured from the data decreased. See Figure 8.

The lag–energy spectrum of the upper kHz QPO is a more viable candidate to explain in the context of reverberation. These lags are relatively flat at lower energies, gradually increasing at higher energies. This means the highest energy photons arrive after the full-energy continuum. The overall shape of the upper kHz QPO in 4U 1728–34 done in Peille et al. (2015) is qualitatively similar to that modeled by Cackett (2016) and work
quantitatively comparing the lags is ongoing.

1.8 Links to Thermal Comptonization

The spectra of kHz QPOs is dominated by Comptonization as seen in Gilfanov et al. (2003) and Peille et al. (2015), so it is natural to look for possible source of lags there. As detailed in Peille et al. (2015), oscillations in the temperature of the photons seeding the Comptonization process seem to be excluded by data. Such oscillations predict a dip in the RMS spectrum that is not present in any data (Lee et al., 2001).

Oscillations could occur in the rate at which the boundary layer (or other Comptonizing region) is heated. This was also investigated by Lee et al. (2001) as well as Kumar & Misra (2014). These studies indicated that such oscillations could produce both hard and soft broadband lags. Soft lags are produced if a significant fraction of the Comptonized photons feedback to their source, i.e. the accretion disk. The variability needed to produce the QPO implies a compact ($\sim 1$ km) oscillating region. Such a scenario, as pointed out in Peille et al. (2015), could be supported by the finding of a seed photon temperature that is systematically higher for the QPO. Thus, a composite Comptonizing region might exist with a inner core that modulates the seed photons on the QPO timescale - and create the soft lags associated with the lower kHz QPO. The outer region, at a lower temperature would then create the portion of the X-ray spectrum not on the kHz QPO timescale. However, this scenario produces an RMS spectrum that increases above 10 keV, something not present in the data. See Figure 9.

Overall, no single model can reproduce the characteristics of both the lower and upper kHz QPOs. It is likely they are produced by different physical mechanisms and perhaps
Figure 9: Comparison of fractional RMS and lags between data from 4U 1608−52 and thermal Comptonization model. Figures from Lee et al. (2001). The numbered curves represent different parameterizations of the model. The model fits the data if a significant fraction of the Comptonized photons impinge back on the source. 4U 1608−52 data originally seen in Vaughan et al. (1998). Note how the modeled fractional RMS continues to increase above ∼ 10 keV while the data levels off.

equally likely that combinations of different physical processes occurring simultaneously produce the QPOs. The correlations of the frequencies of the lower and upper kHz also suggest an overarching property of the LMXB might contribute to their respective sources, i.e. mass accretion rate. What is clear is that only four LMXB sources have been studied in detail using spectral-timing analysis techniques. Additional LMXBs that exhibit kHz QPOs must be studied to fully explore their possible physical origins.

1.9 Motivation for Thesis

The motivation for this thesis is to extend the body of spectral-timing analysis to include LMXB sources where kHz QPOs are detected. By measuring the spectral-timing properties of additional sources, the hope is to gain further insight into the origin of kHz QPOs and the physical processes underlying their creation. The high frequency nature of kHz QPOs
means they can be used to probe the inner accretion flow of neutron stars. Thus they can provide both clues to the geometry of these regions yielding insights into the spatial extent of neutron stars. Such insights could provide valuable constraints of the equation of state of ultra-dense matter and potentially answer vital question about the nature of such matter. Additionally, the EM emission of kHz QPOs carries signatures of the behavior of matter in a strong gravity environment and could provide important validation of the theory of general relativity.
CHAPTER 2  ANALYSIS OF KHZ QPOS IN LOW-MASS X-RAY BINARY SYSTEMS

2.1 Rossi X-ray Timing Explorer (RXTE)

In order to analyze kHz QPOs signals an instrument with micro-second timing resolution is required. Nearly all studies of kHz QPOs have been done using data from the Rossi X-ray Timing Explorer (RXTE) (Bradt et al., 1993), seen in Figure 10. This telescope was launched in 1995, and provided 16 years of X-ray data with superior time resolution until it was decommissioned in 2012. Coupled with modest energy resolution, RXTE is the only instrument to date that has been capable of providing data of sufficient quality to study the spectral-timing properties of kHz QPOs. While loaded with both a high-energy instrument, the High Energy X-ray Timing Experiment (HEXTE) (Gruber et al., 1996) and an All Sky Monitor (ASM) (Levine et al., 1996), the instrument useful for spectral-timing analysis was the Proportional Counter Array (PCA) (Jahoda et al., 1993). The PCA consisted of an array of five Xenon gas filled proportional counters, and had an energy range of 2 − 60 keV, time resolution of 1 µs, and energy resolution < 18 % at 6 keV. A diagram of a single detector in the PCA is shown in Figure 11. Prior to telemetry back to Earth, the signal from the PCA was processed by the Experimental Data System (EDS) (Bradt et al., 1993), consisting of eight Event Analyzers (EA), six of which were dedicated to the PCA and could process the same incoming events independently. RXTE did not possess any imaging capability. The detectors used a collimator to achieve a full-width half maximum of one degree.
Figure 10: An image of the Rossi X-ray Timing Explorer (RXTE). RXTE was launched in December 1995 and provided unprecedented X-ray timing resolution until it was decommissioned in 2012. Image Credit: NASA.

2.1.1 Event Mode Data Reduction

While the EDS processed data using various data modes, the analyses performed in this manuscript is restricted to those data processed using the Science Event mode. In this case, each photon arrival time and energy are collected and stored. The photon energy information is stored in a PCU channel. The conversion from channel to energy is done using the response (RSP) file. The response matrix contained in the response file is the product of the the redistribution matrix function (RMF) and the ancillary response file (ARF). The ARF corrects for the collimator response and detector windows and the RMF is a matrix of probabilities that a photon sorted into a particular channel has a specific energy. The RSP file is created using the FTOOL `pcarsp`, which applies the latest detector calibration and accounts for conditions at the time of observation. An FTOOL is a computational script used to process astronomical observation files and are available from via NASA HEASARC website. More information about the RXTE satellite can be found at `https://heasarc.gsfc.nasa.gov`. 
2.2 Detection of kHz QPOs

Analysis of high frequency data is most efficiently done using Fourier analysis techniques. The first step is to create the power spectrum for the observation or series of observations of interest.

2.2.1 Power Spectra

Selecting observations that cover the full RXTE/PCA energy channel range (64 channels), the power spectrum, formally the power spectral density function (PSD), is created over the desired energy range. For analysis of kHz QPOs this is nominally 3 – 20 keV. Following Uttley et al. (2014), this is done by first computing the discrete Fourier transform (DFT) of a light curve, over a time period (T). In this case, a light curve is photon count rate as a function of time. All analyses in this manuscript use a DFT time of 4 seconds. For a light curve with points $x(t)$, the DFT $X$ for $N$ contiguous data points with separation $\Delta t$ is
given by:

$$X_n = \sum_{k=0}^{N-1} x_k \exp(2\pi i nk/N) \text{ for } n = 0, 1, \ldots, N - 1$$  \hspace{1cm} (2.1)$$

where \(x_k\) is the measured count rate, and \(X_n\) is DFT at each Fourier frequency \(f_n = \frac{n}{N\Delta t}\), with \(n = 1, 2, 3, \ldots, N/2\). The observation time, \(T_{obs} = N\Delta t\) and the Nyquist frequency is, \(f_{Ny} = 1/(2\Delta t)\). This is the highest frequency needed to fully describe the underlying signal. The input signal is real, therefore only the positive portion of the summation in Equation 2.1 is needed. For all analysis, the observation time is fixed at 4 s, and the Nyquist frequency at 2048 Hz. This means the signal is sampled (\(\Delta t\)) every \(\sim 244 \mu s\), and the raw frequency spacing is 0.25 Hz.

An estimate of the PSD is obtained from the modulus squared of the DFT, called the periodogram, and given by:

$$|X_n|^2 = X_n^*X_n$$  \hspace{1cm} (2.2)$$

where the asterisk denotes complex conjugation. There are choices for the normalization of the PSD to be used. One often used normalization is the Leahy normalization (Leahy et al., 1983). The power spectrum is then:

$$P_n = \frac{2\Delta t|X_n|^2}{N}$$  \hspace{1cm} (2.3)$$

While lacking a physical meaning, Leahy normalization provides many computational advantages. The main advantage is that a pure noise spectrum has a power of 2. Additional normalizations can be used as well. One other useful normalization is called the fractional
root mean square (RMS) normalization and is given by:

\[
P_n = \frac{2\Delta t|x_n|^2}{N\langle x \rangle^2}
\]  

(2.4)

where the periodogram is normalized by the mean count rate (\(\langle x \rangle\)). Thus the power spectrum is expressed in units of fractional variance per Hz. Integrating this over a range of frequencies yields the fractional RMS variability.

### 2.2.2 Noise and Detection of Signals in the Power Spectrum

When measuring variability in astrophysical sources, noise is present. Indeed, any measurement taken will be a superposition of the intrinsic signal of interest and noise from all sources under the assumption that the noise processes are random and independent of the signal. For kHz QPOs, the dominate noise source is Poisson counting noise (see e.g., van der Klis, 1998). Thus, the power spectrum can be written \(P_n = P_{n,\text{noise}} + P_{n,\text{signal}}\). For a Leahy normalized power spectrum, the mean signal \(\langle P_n \rangle\) and signal standard deviation \((\sigma_p)\) are (see Leahy et al., 1983, Appendix A):

\[
\langle P_n \rangle = 2 \quad \sigma_p = 2
\]  

(2.5)

This relationship is true for all frequencies and independent of the observation time. The meaning here is that the power spectrum is intrinsically noisy. In practice, the noise is reduced by binning the power spectrum. This is done in both frequency and independent observation segments. In this case, the binned power spectrum is given by:
\[ P_j = \frac{1}{KM} \sum_{n=1}^{K} \sum_{m=1}^{M} P_{n,m} \]  

(2.6)

where \( P_j \) is the power spectrum in frequency bin \( j \), \( K \) is the number of Fourier frequencies per bin, and \( M \) is the number of lightcurves of length \( T_{\text{obs}} \) per bin. Binning the power spectrum in this fashion reduces the error by a factor of \( \sqrt{1/KM} \). An example analysis could use 1 Hz binning and an average time of 1024 s. Thus \( K = 4 \) and \( M = 256 \), using a 4 s observation time, and \( KM = 1024 \). In this regime when considering the detection of a non-noise feature, the \( \chi^2 \) distribution is close to Gaussian, and the probability significance (\( \sigma \)) is then:

\[ \sigma = \frac{P_{\text{excess}} \sqrt{MW}}{2} \]  

(2.7)

where \( P_{\text{excess}} = P_j - 2 \).

When searching the power spectrum for signals, the probability that a noise feature (\( P_{\text{noise}} \)) will manifest a power excess above a threshold (\( \sigma_{\text{thresh}} \)) for a number of frequencies tested (\( N_{\text{test}} \)) is given by:

\[ P_{\text{noise}} = 1 - (1 - P_{\sigma_{\text{thresh}}})^{N_{\text{test}}} \]  

(2.8)

In the analyses in this manuscript a significance threshold of \( \sigma_{\text{thresh}} = 5.5 \) is used. When searching for QPO signals, the power spectrum is scanned within a nominal frequency range between of 300 – 1200 Hz. When using 1 Hz frequency bins to search for kHz QPOs, the probability of a random noise fluctuation being positively detected as a QPO signal is \( P_{\text{noise}} < 4 \times 10^{-5} \).
Figure 12: Shown are three power spectra from the LMXB 4U 1728–34. These were taken from the RXTE/PCA OBSID 20083-01-04-020 which occurred on October 1st, 1997. Each panel shows a 1024 s averaged power spectrum and follow in sequence from the top to bottom panels over the course of the one hour observation. In black are the power spectra data and red are the fitted Lorentzian profiles of the kHz QPOs. This illustrate the characterization of kHz QPOs and the temporal behavior of kHz QPO detections. Note that the upper kHz QPO is not significantly detected in the first 1024 s and then becomes detectable in the last two power spectra of the observation.
2.2.3 Characterization of the kHz QPO Signal

Once the power spectrum has been scanned and a significant power excess has been detected, a constant plus Lorentzian profile is fit to the power spectrum. The form of the fitted function is:

\[
S(f) = a + \frac{R\omega}{2\pi[f - f_o]^2 + (\omega/2)^2}
\]  

(2.9)

where \(a\) is a constant to account for Poisson noise. In a Leahy normalized power spectrum, \(a = 2\), \(\omega\) is the FWHM of the Lorentzian profile, \(R\) is the integrated power of the QPO in Leahy normalization, and \(f_o\) is the frequency where the power excess was detected.

The profile is then fit using either a Chi–squared minimization, given by Equation 2.10.

\[
\chi^2 = \sum_{i=1}^{N} \frac{(y_i - f(x_i; \vec{\theta}))^2}{\sigma_i^2}
\]  

(2.10)

where the individual data values are \(y_i\), the frequencies are \(x_i\) mapped into power by the Lorentzian function \(f\), with parameters \(\vec{\theta}\), and errors on the frequencies equal to \(\sigma_i\). The \(\chi^2\) function is then minimized in order to determine the parameters \(\vec{\theta}\).

Alternatively, the maximum likelihood estimation (MLE) method can be used. This method is described in detail in Barret & Vaughan (2012), and consists of maximizing the likelihood function. In practice, the log of the likelihood function is used and then minimized. The log-likelihood equation is shown in Equation 2.11.

\[
\mathcal{L} = -2\ln\mathcal{L} = 2M \sum_{j=1}^{N} \left[ \frac{P_j}{S_j} + \ln S_j + \frac{1}{M - 1} \ln P_j + c(M) \right]
\]  

(2.11)
where $\mathcal{L}$ is the likelihood function and $\mathcal{S}$ is the log-likelihood function, $S_j$ are the modeled values of the PDS given by the MLE parameters $\hat{\theta}_i = [\hat{a}, \hat{\omega}, \hat{R}, \hat{f}_0]$, $M$ is the number of periodograms averaged, $c$ is a constant that is only a function of $M$. Maximizing the likelihood function ($\mathcal{L}$) is equivalent to minimizing the log likelihood function ($\mathcal{S}$). The IDL$^1$ POWELL minimization routine is used to perform the minimization. The errors on the MLE parameters are found by computing the Fisher matrix ($F$), shown in equation 2.12. The Fisher matrix yields the confidence intervals for each MLE parameter. For a set of model parameters $\{\hat{\theta}_i\}$, with errors $\{\sigma_i\}$, the Fisher matrix ($F$) is:

$$\sigma_i = F^{-1}_{ii} = \left\langle -\frac{\partial^2 \mathcal{L}}{\partial \theta_i \partial \theta_j} \right\rangle$$

(2.12)

As described in Barret & Vaughan (2012), the MLE method is superior to an ordinary $\chi^2$ minimization when averaging a relatively small number of power spectra when uncertainties are not Gaussian deviates. For the analyses in this manuscript, the difference in the MLE method and $\chi^2$ minimization are expected to be minimal. An example of a kHz QPO detection and characterization is shown in Figure 12.

2.2.4 Shift and Add Technique

Once a QPO profile is computed from a binned power spectrum $P_j$, we can begin to track the QPO characteristics. In the case of analyses presented here, every significantly detected QPO represents an average of several DFTs of an observation. QPO frequency is well known to exhibit variation as a function of time (see Belloni et al., 2005), the drift in frequency over short time scales tends to spread the power over a wider frequency range.

$^1$IDL or Interactive Data Language is an analysis-oriented programming language widely-used in astrophysics
An illustration of this is shown in Figure 13. It is of interest to understand the intrinsic properties of the QPO. The shift-and-add technique was originally used by Méndez et al. (1998a). This technique shifts the binned power spectra to the same arbitrary frequency and then averages them together, obtaining a PDS with much higher signal-to-noise ratio. This technique has been used extensively for the past 20 years to reconstruct the intrinsic properties of QPOs. A fit of the shift-and-added PDS yields the intrinsic QPO parameters and is what will be used to analyze all the energy-dependent spectral-timing properties of the kHz QPOs in this manuscript.

2.3 Spectral-Timing Analysis Overview

2.3.1 Cross-Spectrum

See Nowak et al. (1999); Uttley et al. (2014) for a detailed review of spectral-timing analysis techniques. For two DFTs $X(f)$ and $Y(f)$ computed for the same time intervals, but different energy bands the cross spectrum can be calculated:

$$C(f) = X^*(f) \times Y(f)$$

with the asterisk indicating complex conjugation. The phase of the cross spectrum, $\phi(f)$, can be understood by considering the complex exponential representation of $X(f)$ and $Y(f)$. For example, the Fourier transform of the light curve $x(t)$ can be represented by:

$$X_n = A_{X_n} e^{-i\psi_n}$$

where $A_{X_n}$ is the Fourier amplitude and $\psi_n$ is the phase at frequency $f_n$. For a random noise
Figure 13: An illustration of the variation of kHz QPO frequency with time. Figure from Barret et al. (2005) for observations of the lower kHz QPO in 4U 1608−52. The bottom axis counts the number of power spectra extracted from the data. The top axis is the mean time and date of each observation segment. The y-axis shows the QPO frequency.
signal, the phase $\psi_n$ would vary randomly between $-\pi$ and $\pi$. For a linearly correlated light curve $y(t)$, at frequency $f_n$, the Fourier transform is:

$$Y_n = A_n e^{-i(\psi_n + \phi_n)}$$

(2.15)

where $\phi_n$ is the added phase shift of the correlated light curve. When the cross spectrum is calculated, the random noise portion of the phase ($\psi_n$) cancels, leaving the phase lag $\phi_n$. The phase lag is then converted to a time lag

$$\tau(f) = \frac{\phi(f)}{2\pi f}$$

(2.16)

Therefore, at each Fourier frequency ($f$) a time lag is calculated. This allows inspection of time lag as a function of Fourier frequency. Additionally, the energy dependence of the time lags can be explored by computing the cross spectrum for various energy bands. This amounts to repeating the analysis between multiple energy bands. Understanding the energy dependence helps establish which component of the emission is contributing to the time delay. Formally, the average cross-spectrum ($\bar{C}_{XY}$) when averaging $K$ frequency binned and $M$ DFT binned power spectrum is computed by:

$$\bar{C}_{XY} = \frac{1}{KM} \sum_{n=1}^{K} \sum_{m=1}^{M} C_{XY,n,m}$$

(2.17)

For a coherent signal, any uncorrelated noise cancels, and the phase lag measurement will be independent of that noise. The meaning of coherence is discussed in Section ??.

A geometric illustration of phase lag can be seen in Figure 14.
2.3.2 Root Mean Square Variability - RMS spectrum

The variable power of a signal can be expressed via the rms-squared variability or what is normally called the rms spectrum. From the fractional rms normalized power spectrum computed using Equation 2.4, the fractional rms-square variability can be found by integrating the power spectrum over a desired frequency range (see e.g., Belloni & Hasinger, 1990; Miyamoto et al., 1992). By multiplying the fractional-rms by the mean count rate or flux, one then obtains the absolute rms-square variability spectrum. The absolute rms spectrum is useful when attempting to model the variability. The rms spectrum will be discussed more in Section 2.4.3.
2.3.3 Coherence - Definition and Interpretation

Coherence describes the degree to which the non-noise dominated cross-spectra are phase invariant and is necessary to quantify the error on the phase of the cross-spectrum. Formally, the raw coherence ($\gamma^2$) in frequency bin $j$ is computed by:

$$
\gamma_j^2 = \frac{|\tilde{C}_{XY_j}|^2 - n_j^2}{\tilde{P}_X \tilde{P}_Y}
$$

(2.18)

where $n^2$ is a bias term due to the contribution of noise to the cross-spectrum.
of this term can be found in Vaughan & Nowak (1997). It is computed in frequency bin $j$:

$$n_j^2 = \frac{[\bar{P}_{Xj} - P_{X,\text{noise}}]P_{Y,\text{noise}} + (\bar{P}_{Yj} - P_{Y,\text{noise}})P_{X,\text{noise}}]}{KM} \quad (2.19)$$

The $1\sigma$ error on the phase of the cross-spectrum ($\Delta \phi$) in frequency bin $j$ is computed using the raw coherence given in Equation 2.18.

$$\Delta \phi_j = \sqrt{\frac{1 - \gamma_j^2}{2\gamma_j^2KM}} \quad (2.20)$$

The raw coherence used in computing the phase lag errors does not have Poisson noise subtracted from the powers in the denominator of Equation 2.18. To get the coherence attributable to the source itself, one must compute the intrinsic coherence. The intrinsic coherence is then:

$$\gamma_j^2 = \frac{|\bar{C}_{XYj}|^2 - n_j^2}{(P_{Xj} - P_{X,\text{noise}})(P_{Yj} - P_{Y,\text{noise}})} \quad (2.21)$$

For two signals with $\gamma^2 = 1$, perfect intrinsic coherence, the combined cross-spectrum will yield the correct interpretation of the phase lag. As the coherence drops between two signals, due to a breakdown of coherence at the source or some form of correlated noise, the phase of the cross spectrum will be distributed closer to random between $-\pi$ and $\pi$ to the point when $\gamma^2 \rightarrow 0$, and the phase lag is truly randomly distributed within that range.

A geometric illustration of coherence can be seen in Figure 15.

### 2.4 Spectral-Timing Products

Using the analysis methods described above, various output products can be computed. Once the kHz QPO has been detected in the broad energy power spectrum and its profile
is found, the cross spectrum is computed and averaged over the FWHM of the QPO. The most direct output product is the examination of time lag as a function of kHz QPO frequency. The following discussion invokes, where applicable, the specific values used in this manuscript.

2.4.1 Frequency Dependence of Lags: Lag/Frequency

Frequency dependent lags are computed by first extracting the power spectra from two broad-energy bins for each averaged segment of the light curve where a significant QPO is detected. The low energy bin contains the power spectra with energies from $3 \rightarrow 8$ keV and the high energy bin contains power spectra from $8 \rightarrow 30$ keV nominally. The $3$ keV lower limit is selected because it is the lowest energy where RXTE is well calibrated. The $30$ keV upper limit is selected because this is where noise begins to dominate the QPO emission. In some cases where the QPO is weakly detected, this limit is lowered to $20$ keV. Thus, we have two averaged PDS, one low energy and one high energy, recall Equation 2.6 for how the PDS is averaged. We then compute the cross spectrum at each frequency and then average the cross spectra over the FWHM of the fitted QPO profile. In this way, we compute one lag for each significantly detected averaged QPO. The $1 \sigma$ errors on the lags are computed using Equation 2.20. This technique is similar to the one used by Barret (2013).

The lags are typically averaged and binned to aid in analyzing trends. All studies of kHz QPOs (e.g., Barret, 2013; de Avellar et al., 2013; Peille et al., 2015) have shown soft average lags for the lower kHz QPOs and hard or zero average lags for the upper. The term soft lag is used to indicate the correlated variations in the higher energy bin occur before those in the lower energy bin. Hard lag is the term used to describe the converse.
Figure 16: Lower kHz QPO lags as a function of frequency for 4U 1608−52. Figure from Barret (2013). The lower shows the lags for each significantly detected lower kHz QPO from a 128 s averaged power spectrum. The upper panel shows the lags binned into ten adjacent frequency bins, clearly showing a trend of lag with frequency.
Figure 17: Lower kHz QPO lags as a function of energy for 4U 1608–52. Figure from Barret (2013). For the lower kHz QPO range shown and using 128 s averaged power spectra, the lags decrease with energy. This spectrum has the best statistics for a contiguous pointing of RXTE of any object.

In the case of Barret (2013), some lag dependence on frequency was seen in the LMXB 4U 1608–52. In all other studies, lags show no significant dependence on kHz QPO frequency. An example of a lag/frequency spectrum is shown in Figure 16.

2.4.2 Energy Dependence of Lags: Lag/Energy Spectrum

We can also explore the lag dependence on energy. For each averaged power spectrum where a significant QPO is detected, the power spectrum is extracted from all available energy bins within the range of 3 – 20 keV. Typically, the highest energy used here is lowered from 30 keV to further improve signal statistics because noise dominates at these energies. The cross spectrum is computed between a single energy bin, called the channel of interest (CI) and the remaining energy range with the CI subtracted. This is called the reference band. The CI is subtracted from the reference band to prevent the addition of
correlated noise (see e.g. Uttley et al., 2014). The 1σ errors on the lags are computed using Equation 2.20. An example of a lag/energy spectrum is shown in Figure 17.

2.4.3 Covariance Spectrum

Lastly, following directly from the cross-spectrum calculation, frequency and energy-dependent covariance spectra can be calculated. The covariance spectrum is similar to an rms-spectrum, with a higher signal-to-noise ratio. The higher signal to noise arises because the rms spectrum is the variability computed from each energy channel independently while the covariance spectrum shows the variability in each channel that is correlated with the reference band. See Wilkinson & Uttley (2009); Uttley et al. (2011, 2014) for further details. Indeed, in the case of perfect coherence, the covariance spectrum is equivalent to the rms-spectrum (see e.g., Gilfanov et al., 2003). The covariance spectrum shows the spectral shape of the variability components correlated with the reference band. In absolute units, which is useful for modeling the covariance spectrum and comparing with the time-averaged spectrum, the covariance spectrum is given by:

\[
\text{Cov}_f(f_j) = \langle x \rangle \sqrt{\Delta f_j (|\bar{C}_{XY}(f_j)|^2 - n^2) / \bar{P}_Y(f_j) - \bar{P}_{Y,\text{noise}}}
\]  

(2.22)

where \(\langle x \rangle\) is the mean value of the light curve in counts per second, \(\Delta f_j\) is the frequency bin width and the subscript \(Y\) denotes the reference band that has been corrected by subtracting the CI. The error on the covariance spectrum is:

\[
\Delta \text{Cov}_f(f_j) = \sqrt{(|\bar{C}_{XY}(f_j)|^2 \sigma^2_{Y,\text{noise}} + \sigma^2_Y(f_j) \sigma^2_{X,\text{noise}} + \sigma^2_{X,\text{noise}} \sigma^2_{Y,\text{noise}}} / 2KM \sigma_Y^2(f_j)
\]  

(2.23)

where \(\sigma^2_X\) and \(\sigma^2_Y\) denote the noise-subtracted absolute rms-squared of the CI and reference
band respectively. Using the fractional rms-squared normalized power spectra $P_X$ and $P_Y$, we then have $\sigma_{X,\text{noise}}^2 = P_{X,\text{noise}}(x) \Delta f_j$. The reference band signal and noise rms are calculated similarly.

Thus, in the assumption of unity coherence, the covariance spectrum can be used to investigate the variability power of the kHz QPO. Like the lag calculation, the covariance can be computed as a function of frequency or energy. An example of the application of the covariance spectrum is shown in Figure 18.

In the following Chapter, an example of the spectral-timing analysis process is presented from previously published work on the LMXB Aquila X-1 (Aql X-1).
CHAPTER 3 SPECTRAL–TIMING ANALYSIS OF THE LOW-MASS X-RAY BINARY AQUILA X-1 (AQL X-1)


3.1 Introduction

In this work, we searched the RXTE/PCA archive for observations of the LMXB Aquila X-1 (Aql X-1) for kHz QPOs. The goal of this paper was to characterize the average spectral–timing products of kHz QPOs detected in Aql X-1. What follows are the details of the analytic process and the results of that analysis.

Specifically, we computed the lag/frequency, lag/energy, and covariance spectra for the observations where kHz QPOs were detected. This allowed comparison between the spectral–timing properties of Aql X-1 and the other previously studied LXMBs detailed later in this chapter, as well as the opportunity to discuss the interpretation of these spectral–timing analysis products.

We also took the step of performing a side-by-side analysis of the covariance spectra and time-averaged spectra for various sets of observations. This allowed us to perform spectral fits to quantify parameters associated with the accretion geometry, comparing those of the average spectrum to those of the kHz QPO (covariance) spectrum.

3.2 Data Analysis

3.2.1 Overview

We searched the entire RXTE/PCA archive for observations of Aql X-1 in modes compatible with spectral-timing analysis. In all cases, we required better than 125 $\mu$s timing
resolution and 64 energy channels. Once such observations were identified, we required significantly detected kHz QPOs in order to obtain sufficient statistics for meaningful analysis. Using Barret et al. (2008), we were able to select observations with significantly detected QPOs up to July 2007.\textsuperscript{2} It should be noted that in the case of Aql X-1, only a single kHz QPO - likely the lower kHz QPO (Méndez et al., 2001) - is detected well enough to perform spectral-timing analysis (Barret et al., 2008). Following Barret (2013), we evaluated kHz QPOs by computing the power spectral density (PSD) for each time bin of the lightcurve. We used a binning time of 256 s, ensuring the bins did not cross individual observations. We computed the discrete Fourier transform, calculated the periodogram (Uttley et al., 2014), and left it in counts units. We then searched the PSD for power excess and used the $\chi^2$ method to fit a constant plus a Lorentzian with three parameters: centroid frequency ($\nu$), full-width half maximum frequency ($\Delta\nu$), and normalization ($I_{lor}$). Thus, we obtained a single QPO frequency for each 256 s bin. A QPO is considered significant if the ratio $I_{lor}/\Delta I_{lor} \geq 3.0$.

For observations with significantly detected QPOs, there are several ways of presenting the data. The first is by combining observations within a single OBSID. For RXTE, an OBSID is a grouping of observations within a single, contiguous pointing. In this case there are no issues of changing source state or instrument response since the time intervals between exposures are much shorter than the observation times. Problems arise however in obtaining sufficient S/N to obtain meaningful results. In order to expand our analysis, the approach we take is to combine observations in which the instrument response does not vary signif-

\textsuperscript{2}We searched all mode compatible observations after July 2007. There was a single OBSID (94076-01-05-00) with a single observation where the lower kHz QPO was significantly detected. However, due to the short duration (2.3 ks) of this observation, we could not produce any spectral-timing products because of the limited statistics.
Table 1. Aql X-1 Observation Group 1: Observation Properties

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Date</th>
<th>Event Mode</th>
<th>Exposure</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td>20092-01-01-02</td>
<td>08/13/1997</td>
<td>1434551</td>
<td>911</td>
<td>3</td>
</tr>
<tr>
<td>20092-01-02-01</td>
<td>08/15/1997</td>
<td>2378037</td>
<td>1391</td>
<td>1</td>
</tr>
<tr>
<td>20092-01-02-03</td>
<td>08/17/1997</td>
<td>1470468</td>
<td>833</td>
<td>3</td>
</tr>
<tr>
<td>20092-01-05-01</td>
<td>09/06/1997</td>
<td>22695778</td>
<td>14263</td>
<td>3</td>
</tr>
<tr>
<td>20098-03-07-00</td>
<td>02/27/1997</td>
<td>5888675</td>
<td>4538</td>
<td>14</td>
</tr>
<tr>
<td>20098-03-08-00</td>
<td>03/01/1997</td>
<td>5793703</td>
<td>5776</td>
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</tr>
<tr>
<td>30072-01-01-01</td>
<td>03/03/1998</td>
<td>2498232</td>
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<tr>
<td>30072-01-01-02</td>
<td>03/04/1998</td>
<td>3310253</td>
<td>1510</td>
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</tr>
<tr>
<td>30072-01-01-03</td>
<td>03/05/1998</td>
<td>3168559</td>
<td>1314</td>
<td>6</td>
</tr>
</tbody>
</table>

Significantly. Since the spectral properties of the source itself can change between observations, what we present is an average over the times selected. The criteria we used to choose how to combine observations was to first verify that the energy channels of interest were the same. We considered energies from $3 - 20$ keV, above which the background begins to dominate. Even with the same energy channels, between observations the energy ranges in each bin fluctuate by small amounts. It is therefore necessary to rebin in energy so that the energy range fluctuation per bin is much smaller than the energy bin width (see e.g., Peille et al., 2015). Within all observation groups, the maximum fractional fluctuation of the centroid energy of a bin is $0.17\%$ and the maximum fluctuation of an energy bin width is $0.18\%$. Overall we present three contiguous observational groupings shown in Tables 1, 2, and 3. All uncertainties throughout the paper are quoted at the $1\sigma$ level.

### 3.2.2 Data Reduction

To produce the spectral-timing products, we use the RXTE/PCA event mode data listed in Tables 1, 2, and 3. First, in order to determine the conversion from channel to energy, we extract spectra and create associated response matrices using `seextract` and `pcarsp`. 
Table 2. Aql X-1 Observation Group 2: Observation Properties

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Date</th>
<th>Event Mode</th>
<th>Exposure</th>
<th>Significant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm/dd/yyyy</td>
<td>Counts</td>
<td>Time (s)</td>
<td>QPOs</td>
</tr>
<tr>
<td>40047-02-05-00</td>
<td>05/31/1999</td>
<td>13061454</td>
<td>9456</td>
<td>2</td>
</tr>
<tr>
<td>40047-03-02-00</td>
<td>06/03/1999</td>
<td>13043680</td>
<td>10777</td>
<td>4</td>
</tr>
<tr>
<td>40047-03-03-00</td>
<td>06/04/1999</td>
<td>12172425</td>
<td>9831</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 3. Aql X-1 Observation Group 3: Observation Properties

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Date</th>
<th>Event Mode</th>
<th>Exposure</th>
<th>Significant</th>
</tr>
</thead>
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<td>Counts</td>
<td>Time (s)</td>
<td>QPOs</td>
</tr>
<tr>
<td>50049-02-13-00</td>
<td>11/07/2000</td>
<td>5828947</td>
<td>3011</td>
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<tr>
<td>50049-02-15-03</td>
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<td>7268319</td>
<td>5456</td>
<td>14</td>
</tr>
<tr>
<td>50049-02-15-04</td>
<td>11/14/2000</td>
<td>4918301</td>
<td>5034</td>
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<tr>
<td>50049-02-15-05</td>
<td>11/15/2000</td>
<td>9864954</td>
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<tr>
<td>50049-02-15-06</td>
<td>11/16/2000</td>
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<td>70069-03-01-01</td>
<td>03/07/2002</td>
<td>2727478</td>
<td>2429</td>
<td>6</td>
</tr>
<tr>
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<td>03/07/2002</td>
<td>1836713</td>
<td>1647</td>
<td>3</td>
</tr>
<tr>
<td>70069-03-02-01</td>
<td>03/10/2002</td>
<td>1460966</td>
<td>813</td>
<td>4</td>
</tr>
<tr>
<td>70069-03-03-06</td>
<td>03/18/2002</td>
<td>918008</td>
<td>918</td>
<td>2</td>
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<tr>
<td>70069-03-03-07</td>
<td>03/18/2002</td>
<td>3268159</td>
<td>3264</td>
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<tr>
<td>70069-03-03-09</td>
<td>03/19/2002</td>
<td>1388293</td>
<td>1288</td>
<td>3</td>
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<tr>
<td>70069-03-03-14</td>
<td>03/21/2002</td>
<td>2092049</td>
<td>2690</td>
<td>2</td>
</tr>
</tbody>
</table>
We applied good time intervals (GTI) to account for PCUs turning on and off, Earth limb avoidance, and avoidance of the South Atlantic Anomaly (SAA). From the response matrices we get the energy range associated with each binned channel, and determine the absolute channel values using chantrans.

For each observation group, we analyzed all event mode files and computed the fast Fourier transform (FFT) at 4.0 seconds (s) intervals which are then averaged over 256 s bins. Data gaps in the GTIs are windowed and the averaged FFTs are not permitted to cross observations. Each 256 s bin was then searched for excess power and fit with a 3−parameter Lorentzian as described above. We discarded any QPOs with significance < 3.0. Any bursts were not included in our analysis.

3.2.3 Lags vs. Frequency

To establish the presence of any lags, and if there is any frequency dependence, we computed lags between two broad energy bins: 3 – 8 keV and 8 – 20 keV. See Section 2.4.1 for details of calculating the broad energy lags. We computed the cross spectrum for each 256 s data segment between the two energy bins and averaged across the QPO FWHM. In order to correct for dead time induced cross-talk (van der Klis et al., 1987; Peille et al., 2015), we subtracted Fourier amplitudes between 1350 Hz–1700 Hz from the cross-spectrum. We then compute the time lag from the phase of the cross spectrum. To further characterize the results and highlight any possible trends, we fit a straight line to the data and found fits consistent with no significant dependance of the lag on QPO frequency. The mean lags for observation group 1, 2, and 3 are 28 ± 4 µs, 38 ± 8 µs and 29 ± 5 µs, respectively, and the mean lag when considering all observations together is 30 ± 3 µs. Additionally, we rebinned the lag-frequency data using 10 equally-spaced frequency bins.
to further illustrate the consistency of lag with frequency. The lag frequency data for each observation group are shown in Figure 19 and the lag frequency data combining observations are show in Figure 20. The average lags are all soft lags and positive by convention, indicating that the higher energy band variations lead the lower energy band variations.

3.2.4 Lag Energy Spectrum

In order to compute the full lag-energy spectrum, we computed the cross-spectrum within the FWHM of the mean QPO frequency, for each 256 s segment of data, between each energy band — channel of interest (CI) — and the remaining energy channels (3 – 20 keV) — reference band. See Section 2.4.2 for details of calculating the lag/energy spectrum. We rebinned in energy, decreasing the number of bins by a factor of 2 in order to increase the signal to noise ratio per bin and to reduce the effect of small energy fluctuations that occur at the channel boundaries between observations mentioned previously. We then averaged the centroid QPO frequencies and shifted and added (Méndez et al., 1998b) each cross spectrum to the mean QPO frequency. We eliminate correlated errors (Uttley et al., 2011, 2014) by not including the CI in the reference band. We then computed the time lag from the phase of mean cross spectrum. The lag-energy spectra, shown in Figure 21, all show nearly monotonic trends with energy, where the highest energy photons arrive before the lower energy photons. We fit each lag-energy spectrum with a straight line to characterize any trend(s). The data were fit to the function \( y = A + Bx \) and are shown in Figure 21. The fit parameters are shown in Table 4. The best-fitting linear relations are consistent between all 3 observation groups.
Figure 19: Frequency-dependent lags for each observation group. Each data point (small black dot) is the lag from a 256 s bin with a significantly detected kHz QPO. The mean lag between the 3 – 8 keV and 8 – 20 keV bands are shown in red. Additionally, the lags are binned into 10 equally-spaced frequency bins (blue triangles) between the minimum and maximum QPO frequency.
Figure 20: Lag as a function of frequency for all observation groups combined. The mean lag is shown in red. The rebinned data are shown in blue triangles.

Table 4. Aql X-1 Lag/Energy Linear Fit Parameters

<table>
<thead>
<tr>
<th>Observation Group</th>
<th>A (µs)</th>
<th>B (µs keV⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49 ± 8</td>
<td>−6 ± 1</td>
</tr>
<tr>
<td>2</td>
<td>70 ± 17</td>
<td>−9 ± 2</td>
</tr>
<tr>
<td>3</td>
<td>53 ± 10</td>
<td>−7 ± 1</td>
</tr>
</tbody>
</table>

Note. — Parameters are from the best fit relation $y = A + Bx$
Figure 21: Lag-energy spectrum for each observation group. The lags are computed with respect to a 3 – 20 keV reference band. By convention, positive lags indicate photons from that energy bin arrive after the reference band. Hence the highest energy photons arrive first. Note that the highest energy bin for observation group 2 could not be calculated due to poor S/N. The best fit linear relations are also shown. The best fit parameters are listed in Table 4.
3.2.5 Covariance Spectrum

The covariance spectrum (Wilkinson & Uttley, 2009; Uttley et al., 2011) is yet another analysis tool useful in understanding the nature of kHz QPOs and is computed quite easily alongside the lag-energy spectrum. The equations and methodology for calculating a covariance spectrum are given in detail in Uttley et al. (2014) and Section 2.4.3. The covariance spectrum describes the spectral shape of the portion of the CI which is correlated with the reference band. Put another way, it is equivalent to the rms spectrum when both are correlated. The first covariance spectrum of a kHz QPO was computed for 4U 1608−52 and 4U 1728−34 in Peille et al. (2015). We computed the raw covariance spectrum over the same energy range, and with the same binning and frequencies as the lag-energy spectrum.

In order to compare the covariance spectrum with the time-averaged spectrum, we need to fold the covariance spectrum through the instrument response for the same observation interval. In this way, we can investigate the amount of correlated variability present in each segment of the spectrum. To get an average instrument response for the covariance spectrum over the observation interval, we expanded the individual response matrices and averaged each entry across observations within a group by weighting it with the fraction of significant QPO time.

We extracted the Standard 2 spectra for all observations, adding 0.6% systematic errors and creating background and response files for each. We used the most recent bright background model and SAA history. We verified that the shape of the responses within each observation group were the same (ignoring normalization), with the exception of
Figure 22: Covariance in relative RMS units, which can be thought of the fraction of the spectrum that is variable on the kHz QPO timescale. The mean spectrum rebinned to match the covariance spectrum binning. We note an increase in fractional RMS (covariance) with energy up to approximately 12 keV where it levels off.

Observation Group 3, and added the spectra, background and responses.

To calculate the fractional rms (covariance) we calculate the ratio of the covariance spectrum to the mean spectrum by first rebinning the mean spectrum to match the covariance spectrum binning. The fractional rms for Aql X-1 is shown in Figure 22. This shows an increase in the fraction of the spectra that is variable with increasing energy, fractional rms (covariance), which becomes nearly constant above $\sim 12$ keV. This compares well to previous analyzes of the energy-dependence of the rms in kHz QPOs (e.g., Méndez et al., 2001).

Observation Group 3 showed (3) distinct instrument response profiles in their Standard 2 spectra, which made combining these spectra impossible. We attempted to break this observation group into (3) corresponding groups, but lack of statistics prevented meaningful calculation of the lag/energy and covariance spectra. We could therefore not perform any
3.2.6 Spectral Analysis

We simultaneously fit the mean spectra with the covariance spectra over the $3-20$ keV (above $20$ keV the background dominates) energy range using XSPEC 12.8.2 (Arnaud, 1996). We use the model combination $\text{phabs*(diskbb+nthcomp+gaussian)}$ for the fits (see Zdziarski et al., 1996; Zycki et al., 1999, for a description of $\text{nthcomp}$), though we note that the X-ray spectra of LMXBs are degenerate and can be fit equally well by other model choices (e.g., Lin et al., 2007). We fix the photoelectric absorption column density at $0.3 \times 10^{22}$ cm$^{-2}$ (Kalberla et al., 2005). For the Fe-line component we use a simple Gaussian model, with centroid constrained between $6.4$ keV and $6.97$ keV. Following Gilfanov et al. (2003); Peille et al. (2015) for the covariance spectrum, we use the model combination $\text{phabs*nthcomp}$ initially with the idea that the covariance spectra might represent the boundary layer emission.

We find as in Gilfanov et al. (2003); Peille et al. (2015) for 4U 1608–52 and 4U 1728–34, good fits with the chosen model configuration. We attempted fitting schemes by systematically untying one parameter at a time. These were: the electron temperature ($kT_e$), photon index ($\Gamma$) and seed photon temperature ($kT_{\text{seed}}$). In order to obtain a good fit, only the seed photon temperature can be untied between the spectra. All other configurations resulted in poor fits. We find as in Peille et al. (2015) the seed photon temperature to be systematically higher for the covariance spectrum. Additionally, in the case of observation group 1, the spectra are fit better when an Fe K Gaussian is included in the covariance spectrum. In this case, we tied the Gaussian centroid and width of both spectra allowing only the normalizations to vary. With the additional Gaussian in the covariance spectrum,
Figure 23: Upper Panels: Time-averaged spectrum (black triangles) and covariance spectrum (red squares) for observation group 1 (top) and observation group 2 (bottom). Solid lines indicate the best-fitting overall model. The nthcomp (black dashed), disk blackbody (blue dotted) and Gaussian (green dashed dotted) components for the time-averaged component are shown, while the nthcomp (red dashed) and Gaussian (magenta dashed dotted) components are shown for the covariance spectrum. There is no Gaussian for the covariance spectrum for observation group 2. Bottom Panels: Ratio of the data to the best-fitting model.
we get a change of $\Delta \chi^2 = 10.1$ for 1 additional degree of freedom, which corresponds to a better fit at the 2.4$\sigma$ confidence level using an F-test. In order to further test the presence of the covariance gaussian, we compared fits with no parameters tied between the mean spectrum and covariance spectrum with and without covariance Gaussian. In this case we also obtain better fits including the covariance Gaussian with $\Delta \chi^2 = 6.21$ for 1 additional degree of freedom. This corresponds to a better fit at the 2.0$\sigma$ confidence level using an F-test. The spectral decompositions are shown in Figure 23 and the best-fitting parameters are listed in Table 5. The model begins to over estimate the covariance spectrum at higher energies. This is an artifact produced by allowing only a single model parameter to be free for the fits. This artifact vanishes when both $\Gamma$ and $kT_{seed}$ are freed, with a negligible $\Delta \chi^2$.

Finally, it should be noted that modeling a covariance spectrum with an XSPEC model implicitly assumes that only the normalization is oscillating, but the covariance spectra could also be produced by the average spectrum changing shape, e.g. the seed photon temperature or the optical depth.

### 3.3 Discussion

We have analyzed all RXTE data of Aql X-1 that show significant kHz QPOs and that were in modes with adequate resolution in time ($\leq 125 \mu s$) and energy (64 channels). This work was motivated by the desire to expand the scope of spectral–timing analysis of kHz QPOs to a wider array of neutron star LMXB systems. We only analyzed the lower kHz QPO of Aql X-1 due to the poor S/N of the upper kHz – which was only discovered in Barret et al. (2008). All analyses are associated with the lower kHz QPO. As in Barret (2013); de Avelllar et al. (2013); Peille et al. (2015), for objects 4U 1608–52, 4U 1636–53, and
Table 5. Aql X-1 Spectral Fit Parameters

<table>
<thead>
<tr>
<th>Obs. group</th>
<th>1*</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_H (10^{22} cm^{-2})</td>
<td>0.3 (fixed)</td>
<td>0.3 (fixed)</td>
<td>0.3 (fixed)</td>
</tr>
<tr>
<td>kT_{disk} (mean)</td>
<td>0.64 ± 0.04</td>
<td>0.65^{+0.07}_{-0.04}</td>
<td>0.67 ± 0.04</td>
</tr>
<tr>
<td>Norm_{disk}</td>
<td>980^{+420}_{-288}</td>
<td>950^{+370}_{-360}</td>
<td>900^{+300}_{-240}</td>
</tr>
<tr>
<td>kT_{seed} (mean)</td>
<td>1.09 ± 0.06</td>
<td>1.09^{+0.08}_{-0.06}</td>
<td>1.13^{+0.07}_{-0.06}</td>
</tr>
<tr>
<td>kT_{seed} (cov)</td>
<td>1.65 ± 0.05</td>
<td>1.62 ± 0.04</td>
<td>1.54 ± 0.1</td>
</tr>
<tr>
<td>kT_e (tied)</td>
<td>3.3 ± 0.13</td>
<td>3.27^{+0.37}_{-0.26}</td>
<td>3.4^{+0.5}_{-0.3}</td>
</tr>
<tr>
<td>Norm_{nthcomp} (mean)</td>
<td>(6.7^{+0.9}_{-1.2}) \times 10^{-2}</td>
<td>(6.7^{+0.5}_{-0.6}) \times 10^{-2}</td>
<td>(7.0 \pm 0.1) \times 10^{-2}</td>
</tr>
<tr>
<td>Norm_{nthcomp} (cov)</td>
<td>(2.0 \pm 0.2) \times 10^{-3}</td>
<td>(2.01 \pm 0.09) \times 10^{-3}</td>
<td>(1.7 \pm 0.3) \times 10^{-3}</td>
</tr>
<tr>
<td>\Gamma (tied)</td>
<td>2.99 ± 0.2</td>
<td>2.97 ± 0.02</td>
<td>3.1^{+0.1}_{-0.2}</td>
</tr>
<tr>
<td>E_{line} (tied)</td>
<td>6.54^{+0.08}_{-0.1}</td>
<td>6.53^{+0.09}_{-0.3}</td>
<td>6.55 ± 0.05</td>
</tr>
<tr>
<td>\sigma_{line} (tied)</td>
<td>0.69^{+0.15}_{-0.14}</td>
<td>0.70^{+0.19}_{-0.13}</td>
<td>0.49^{+0.04}_{-0.09}</td>
</tr>
<tr>
<td>Norm_{E_{line}} (mean)</td>
<td>(2.0^{+1.0}_{-0.4}) \times 10^{-3}</td>
<td>(2.2 \pm 0.4) \times 10^{-3}</td>
<td>(1.6^{+0.4}_{-0.3}) \times 10^{-3}</td>
</tr>
<tr>
<td>Norm_{E_{line}} (cov)</td>
<td>(4.8 \pm 3) \times 10^{-4}</td>
<td>0.0 (fixed)</td>
<td>0.0 (fixed)</td>
</tr>
<tr>
<td>\chi^2</td>
<td>1.59(44)</td>
<td>1.78(45)</td>
<td>1.56(35)</td>
</tr>
</tbody>
</table>

Note. — Obs. group 1* includes a Gaussian in modeling the covariance spectrum. All other fits have no Gaussian in the covariance spectrum model. All energies are given in keV.
4U 1728–34 respectively, we found soft lags between the high energy X-ray photons and low energy X-ray photons. The magnitude of lags in Aql X-1 were on the order of 30 µs and comparable to all the previous studies of neutron star LMXB systems. Additionally, over the QPO frequencies, we find large dependencies of lag on frequency are excluded, consistent with de Avellar et al. (2013); Peille et al. (2015). We note that Barret (2013) does find some variation of lag with QPO frequency, since that work used a larger data set for 4U 1608–52 than de Avellar et al. (2013). See Barret (2013) for a discussion of the magnitude of the average lag and its implication on the geometry of neutron star systems.

The shape and magnitude of the lag-energy spectra for Aql X-1 is also consistent with the other objects previously mentioned. This includes a smooth decrease in the lags toward higher energies. The exact mechanism and source of lags is poorly understood. One possibility is that thermal Comptonization in the boundary layer causes the lags. See Lee et al. (2001); Kumar & Misra (2014, 2016) for a discussion of different models of Comptonization and how they produce lags. Another possible explanation of the production of lags is X-ray reflection. In the reflection scenario, soft lags are thought to be associated with reverberation. Here, a hard source of photons – possibly the neutron star boundary layer formed at the point where the faster Keplerian motion of the accretion flow encounters the slower rotating neutron star surface – impinges on and is reprocessed by the accretion disk. Whereas hard lags are thought to arise due inward propagating accretion rate variations which modulate the hard Comptonized flux via seed photon fluctuations. Additionally, lags can also be due to intrinsic, coherent spectral softening (Kaaret et al., 1999) or due to temperature oscillations between two different non-isothermal Comptonizing sources (e.g., de Avellar et al., 2013; Peille et al., 2015) which might indicate a composite
Peille et al. (2015) point out that because the lag-energy spectrum drops at energies where the accretion disk does not contribute a significant amount of flux, there must be some property associated with Comptonization alone that must contribute to the lags. Also, relative rms (covariance) increases above energies where the accretion disk should contribute to the flux and therefore the variations there are likely modulated by a harder source of photons, possibly the boundary layer (see e.g., de Avellar et al., 2013). Recently, Cackett (2016) modeled the lag-energy spectrum of 4U 1608–52 in order to test whether reverberation could produce the observed lags. While finding that reverberation could account for the lags below 8 keV, the behavior of the lags above 8 keV was markedly different than predicted.

Our spectral fits of the mean and covariance spectra in Aql X-1 yield similar results as Peille et al. (2015). We find systematically higher seed photon temperatures for the covariance spectra over the mean spectra. Additionally, the covariance spectra are harder than the mean spectra, a result seen in all neutron star LMXBs to date and is well fit by a thermal Comptonized component (Gilfanov et al., 2003; Peille et al., 2015). The implications of these findings are discussed in detail in Peille et al. (2015).

Finally, we have discovered that in one set of observations, the covariance spectrum is better fit with a combination of a thermal Comptonized component and a Fe K line Gaussian profile. This hints at the possibility of a reflection/reverberation signature that contributes to the lags, at least in part, or that some other mechanism can modulate the Fe K line at the frequency of the lower kHz QPO. Interestingly, by taking the ratio or the iron line normalization in the time averaged and covariance spectra, the fractional RMS
is \( \simeq 24\% \) which is much higher than the observed fractional RMS which never exceeds \( \simeq 10\% \) in this component of the spectrum; see Figure 22. This implies that Fe K line is more variable at the QPO frequency than the overall hard emission. We do not have a physical explanation of this.

Currently, there are no models that explain all the spectral-timing properties of neutron star LMXBs.

### 3.4 Conclusion

We have studied the spectral-timing properties of the neutron star LMXB Aql X-1. We found similar behavior in the lag-frequency and lag-energy relationships as well as covariance spectral decompositions as seen previously in other neutron star LMXBs that have been studied. This adds an additional source to those where detailed spectral-timing analysis of kHz QPOs has been done, and provides further support for the conclusions reached in all cases. Specifically, the covariance spectra is well fit by a thermal Comptonized component and spectral fits indicate a higher seed photon temperature for the covariance spectrum. This implies a possible composite boundary layer emitting region.

We also find for one set of observations, the covariance spectrum is fit better with a thermal Comptonized component and Fe K line with 2.4\( \sigma \) confidence. The implications of this are less clear. While tempting to attribute this to reverberation, more information is needed. Moreover, neither 4U 1608–52, nor 4U 1728–34 show this feature in their respective covariance spectra. Spectral-timing analysis of additional sources is needed to determine if this result is more common in neutron star LMXBs. Also, future missions with better spectral resolution – while maintaining the high timing capability of \textit{RXTE} – might
unlock this feature and help answer questions about the fundamental nature of accretion and emission of these objects.

In the next chapter, we undertake a systematic approach to the study of spectral–timing products in LXMBs. In this approach, we develop spectral–timing products for many different LMXB systems in order to gain insights into the commonalities and/or differences that may manifest.
4.1 Introduction

In this work, we performed a large-scale analysis of LMXBs in the RXTE/PCA archive. The goal of this work was to develop average spectral–timing products for as many different LMXB systems as possible. This would allow us to examine spectral–timing products on a source-by-source basis in a quantitatively consistent manner. We would then be able to compare and contrast the results, with the possibility of gaining insights in the interpretation of the various spectral–timing results.

Specifically, we computed the average: intrinsic coherence, fractional RMS and covariance, lag/frequency, and lag/energy relationships for (14) different LMXBs for the lower kHz QPO. We split the analysis in order to study lower kHz QPOs separately from uppers. We derived the same set of results for (6) LMXBs for the upper kHz QPO.

4.2 Analysis Overview

We searched the entire RXTE/PCA archive for event mode observations of neutron star LMXB systems. In order to provide meaningful and consistent spectral-timing products, we considered only observations where the full 64 channel RXTE/PCA energy bands were available. We also required observations with as good or better than 125 $\mu$s time resolution. The list of neutron star LMXB sources we considered as well as the nature of the observational limitations present in the RXTE/PCA archive are shown in Table 6. In a small
Table 6. Neutron Star Low-Mass X-ray Binaries Considered for Analysis

<table>
<thead>
<tr>
<th>Object ID</th>
<th>Source Classification</th>
<th>Event Mode Obs.</th>
<th>Present?</th>
<th>Full Energy Range Available?</th>
<th>kHz QPOs Detected?</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1608-52</td>
<td>Atoll</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>4U 1636-53</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>4U 0614-09</td>
<td>Atoll</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>4U 1728-34</td>
<td>Atoll</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>4U 1702-43</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>4U 1820-30</td>
<td>Atoll</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Aql X-1</td>
<td>Atoll</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>4U 1735-44</td>
<td>Atoll</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>XTE J1739-285</td>
<td>Burster</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>EXO 1745-248</td>
<td>Burster</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>4U 1705-44</td>
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<td>SAXJ1748.9-2021</td>
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<td>HIR J17191-2821</td>
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<td>Yes</td>
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<td>4U 1915-05</td>
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<td>SAXJ1808.4-3658</td>
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<tr>
<td>SAXJ1750.8-2990</td>
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<tr>
<td>RXJ1709.5-2639</td>
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<td>Cyg X-2</td>
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<tr>
<td>EXO 0748-676</td>
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<tr>
<td>MXB 1659-298</td>
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<tr>
<td>XTE J1723-376</td>
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<tr>
<td>2S 0918-549</td>
<td>Burster</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>IA 1246-588</td>
<td>Burster</td>
<td>Yes</td>
<td>Yes</td>
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<td>MXB 1730-33</td>
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<tr>
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<tr>
<td>GX 349+2</td>
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<td>4U 1746-37</td>
<td>Atoll</td>
<td>No</td>
<td>No</td>
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</table>

Note. — Source Classification from Liu et al. (2007). While all objects considered are present in the RXTE/PCA archive, additional columns indicate the presence of observation files in the Event mode necessary for analysis. Additionally, where event mode files are present, we indicate when these have the full RXTE/PCA energy range available. Finally, we also show whether or not we were able to detect kHz QPOs from these observations in the manner described in Section 4.2. In some cases, while we were able to detect kHz QPOs, there was not sufficient detected QPO observation time to obtain spectral–timing results. Those sources shown in bold are the ones where we present analysis.

The number of cases objects present in the archive did not have event mode data available.

Once observations meeting the above criteria were identified, we created their associated response matrices using the FTOOL pcarsp to determine the channel-to-energy conversion matrix. Barycentric correction was then performed using the FTOOL faxbary. We applied good time intervals (GTI) to avoid the Earth’s limb, South Atlantic Anomaly (SAA), and to remove any thermo-nuclear bursts that occurred.

We computed the discrete Fourier transform (DFT) over 4.0 s intervals, with a Nyquist frequency of 2048 Hz, and averaged these in order to obtain 1024 s spectra. This average
time was adopted to facilitate easier detection of the upper kHz QPOs. We binned the average power spectrum in 1 Hz bins. The power spectrum was initially computed over the 3 – 30 keV energy range. We searched the power spectra for excess power between 300 – 1300 Hz and fit a single Lorentzian profile using the maximum likelihood estimator (MLE) method as described in Barret & Vaughan (2012). We attempted a fit with a double Lorentzian profile in cases where a second excess power was found. In this way, each 1024 s power spectrum was characterized by one, two, or no candidate kHz QPOs. Only individual 1024 s spectra where the QPO was significantly detected were considered for further analysis. A QPO is considered significant if the ratio of the fitted Lorentzian normalization ($I_{lor}$) to the error in the normalization ($\Delta I_{lor}$) is: $I_{lor}/\Delta I_{lor} \geq 3.0$ (Boutelier et al., 2010).

The initial detections of kHz QPOs in the sources we analyze are well-documented in van der Klis (2000) with the following exceptions: Kaaret et al. (2007) for XTEJ1739–285, Mukherjee & Bhattacharyya (2011) for EXO1745–248, Altamirano et al. (2010b) for SAXJ1748.9–2021, and Altamirano et al. (2010a) for IGR J17191–2821.

Within a single event mode file, each 1024 s spectra with a significantly detected QPOs was shifted-and-added (see Méndez et al., 1998b) to the mean QPO frequency. In the case where QPO classification was ambiguous, the highest duty cycle frequency was used to calculate the mean. For dual detections, the lowest frequency QPOs were used to calculated the mean. The resulting spectrum was again fit with a single or double Lorentzian profile using the MLE. We used these profiles to classify the QPOs of each event file. This provided cleaner profiles with higher S/N over individual spectra while still maintaining temporal continuity of the observation.
kHz QPOs are not detected in all sources. We emphasis that we only searched *event mode* observations with the previously mentioned constraints for kHz QPOs and attempted no detailed reconstruction of the QPO. Additionally, we only performed single detections on 1024 s observation segments, while other studies might average over longer periods of time to detect kHz QPOs. Finally, in some cases, kHz QPOs were detected in only a small number of averaged spectra and thus too few data points were available for meaningful spectral-timing analysis.

### 4.3 kHz QPO Classification

We wish to partition the analysis products by QPO type (lower or upper kHz QPO). Therefore, following Peille et al. (2015) in the case where a single kHz QPO is significantly detected in an event file, we classify that QPO using the quality factor (Q) parameter. Quality factor is defined as the ratio of the QPO frequency to its full-width half-maximum (FWHM). In cases where two kHz QPOs are simultaneously detected, the quality factor is not needed as the classification is obvious. For a single kHz QPO detection, we look to the relationship between quality factor and QPO frequency. The distinction between lower and upper kHz QPO can be generally inferred from this relationship. Barret et al. (2006) demonstrated that the lower and upper kHz QPOs follow distinct tracks on this diagram. Using this relationship for each source, we set quality factor limits in order to classify single kHz QPO detections. We compute the quality factor of the QPOs detected in each event file. These plots are shown in Figure 24. Looking at each object individually, we set frequency ranges for lower and upper kHz QPOs. We also conservatively set allowed ranges of Q to ensure unambiguous classification.
Once the kHz QPOs were classified, we were able to organize the event files for each object in order to combine observations with lower kHz QPOs and observations with upper kHz QPOs. These event files were used in the computation of various spectral-timing products described in Section 4.4.

4.4 Spectral-Timing Products

For each object, we combined all the event files for each QPO type across the entire RXTE/PCA archive. This is necessary because in many cases the QPO is only weakly detected and spectral-timing analysis requires a significant number of counts in order to constrain the results. To allow meaningful comparisons from source to source we perform an identical analysis on all objects.

Having identified all kHz QPOs present in the data, we next produce a range of spectral-timing products of interest. See Nowak et al. (1999); Uttley et al. (2014) for a review of spectral-timing analysis methods. We calculate both the power spectra and cross spectra in each energy band of interest. The detector response varied over the multi-year range of data we averaged. Therefore, it was necessary to rebin the channel-to-energy conversion matrices to accommodate both small fluctuations in the energy boundaries of observations with identical channels and allow averaging of observations with different channel-to-energy conversion matrices. All spectra were normalized using fractional RMS normalization (Miyamoto et al., 1991). We subtracted Fourier amplitudes were no source signal is nominally present (1350 Hz – 1700 Hz) from the cross-spectra in order to correct for dead time induced cross-talk (van der Klis et al., 1987; Peille et al., 2015).

We are interested in the energy-dependence of most of the spectral-timing products,
Figure 24: Quality factor versus kHz QPO frequency for the (14) objects studied. Quality factor is the ratio of the QPO frequency to the FWHM ($\nu/\Delta \nu$). Each point represents a single shift-and-added event mode file using 1024 s spectra with a significantly detected kHz QPO. The different quality factor tracks (see e.g., Barret et al., 2006) are used to classify the QPOs as lower or upper in cases where the QPOs are ambiguous. Limits in quality factor (Q) and frequency ($\nu$) were adopted from a visual-inspection of the data in the case of a single kHz QPO detection. In all cases, a minimum quality factor of 5 was employed to ensure a good detection. No maximum Q was used to filter detections of lower kHz QPOs. The vertical red dashed lines indicate the frequency boundaries of the lower kHz QPOs. The vertical blue dashed lines indicate the frequency boundaries of the upper kHz QPOs. The horizontal red dashed line indicates the minimum quality factor for lower kHz QPOs. The horizontal blue dashed line indicates the maximum quality factor for upper kHz QPOs.
thus we have power- and cross-spectra in both a channel-of-interest (CI; a specific energy bin) and the reference band. Using the above convention, lightcurve \( p(t) \) would represent the CI and \( q(t) \) the reference band. The reference band covers the full \( 3 - 20 \) keV energy range with the CI subtracted. Not only does this convention increase the S/N over the use of a single channel reference band, it also eliminates correlated errors (e.g., Uttley et al., 2014).

We shifted-and-added (Méndez et al., 1998b) both the power spectra and the cross spectra of the reference band and the CI to the center frequency of the classified QPO frequency range of each object. We did this separately for the lower and upper kHz QPOs and only for spectra where a QPO was detected significantly as defined in Section 4.2. After shifting all the spectra, we fit a single Lorentzian at the center frequency in order to characterize the FWHM of the shift-and-added QPO. Averaging across one FWHM, we then computed the intrinsic coherence (Vaughan & Nowak, 1997), covariance (Wilkinson & Uttley, 2009) as well as the fractional RMS, and lags (Nowak & Vaughan, 1996; Vaughan et al., 1998). The details of the intrinsic coherence results are shown in Section 4.4.1, the RMS and covariance results in Section 4.4.2, a look at the frequency-dependence and energy-dependence of the lags are shown in Section 4.4.3 and 4.4.4 respectively. Unless otherwise stated, all errors reported are at the \( 1\sigma \) level.

### 4.4.1 Intrinsic Coherence

The intrinsic coherence provides a quantitative measure of how one signal is related to another by linear transformation (e.g., Vaughan & Nowak, 1997). Generally speaking, if we wish to interpret the various spectral-timing products, especially time lags, as a result of some type of physical process, i.e. energy-dependent Comptonization delays or light-travel
time delays due to spatial separation of one or more emitting regions, it is crucial that the underlying signals have near unity coherence. In other words, if intrinsic coherence is not near unity, any lag measurement is essentially meaningless, because we lose the underlying attachment of the two signals to a direct physical process. Thus, understanding the coherence of the kHz QPOs across the energy range of interest is an important place to start. Both Vaughan et al. (1998) and Kaaret et al. (1999) showed that kHz QPOs in 4U 1608−52 and 4U 1636−53 have high (near unity) coherence. Additionally, de Avellar et al. (2013) nicely showed the frequency dependence of the coherence across the kHz QPO profile. In Figure 1 of that paper, the unity coherence of the QPOs is illustrated. See Section 2.3.3 for details of the calculation of the intrinsic coherence.

The average coherence as a function of energy for the lower and upper kHz QPOs are shown in Figures 25 and 26 respectively. Here, we adopt confidence limits for the high-signal, high-coherence regime as defined in Nowak & Vaughan (1996) for all values of coherence due to the difficulties in quantifying the coherence confidence limits outside of this regime (e.g., Vaughan & Nowak, 1997). Thus, confidence limits for low values of coherence should be interpreted accordingly.

General speaking, we find both kHz QPOs show high coherence across a majority of the energy range we use. Objects with larger amounts of data generally show more well-constrained coherence, with a preference of higher coherence in the middle of the energy range covered. Additionally, in many sources we note a drop in coherence and/or a drop in well-defined coherence (large error bars at high coherence) at energies above ∼ 15 keV.
Figure 25: Average intrinsic coherence as a function of energy for the lower kHz QPOs. Intrinsic coherence measures the degree to which two signals are related by linear transformation. In this case, one signal is the CI and the other is the reference band. In general, objects with larger numbers of observations tend to have coherence near unity. This is likely simply due to more signal available. Additionally, in all cases, intrinsic coherence tends to drop at low energies (∼3 keV) and above (∼15 keV).
Figure 26: Average intrinsic coherence as a function of energy for the upper kHz QPOs. Intrinsic coherence measures the degree to which two signals are related by linear transformation. In this case, one signal is the CI and the other is the reference band. In general, objects with larger numbers of observations tend to have coherence near unity and more well-constrained coherence. This is likely simply due to more signal available. Additionally, in all cases, intrinsic coherence tends to drop at low energies (∼3 keV) and above (∼15 keV).
4.4.2 Covariance

The covariance measures the variability power in an energy bin that is correlated with the reference band (see Wilkinson & Uttley, 2009; Uttley et al., 2011, 2014). For high coherence signals, the covariance is essentially the RMS spectrum with intrinsically higher S/N (Uttley et al., 2014). It is well known that the RMS spectrum of kHz QPOs increases with increasing energy up to $\sim 15$ keV, where it levels off (see e.g., Berger et al., 1996; Zhang et al., 1996; Wijnands et al., 1997; Méndez et al., 2001). Peille et al. (2015) showed similar behavior in the fractional covariance for 4U 1728−34. Our results are generally consistent with this behavior with a few exceptions noted below. See Section 2.4.3 for details of the calculation of the covariance.

In order to illustrate the usefulness and limitations of the covariance statistic, we have computed both the RMS and covariance in fractional RMS units. These data for the lower and upper kHz QPOs are shown in Figures 27 and 28 respectively.

A drop in covariance is seen in many objects at high energies. We also note that there is sometimes a divergence between the RMS and covariance. These are both likely due to a drop in coherence seen at those energies. For example, see Figure 25. However in some cases, the fractional RMS appears to also decrease. This occurs mainly in the highest energy bin. As previously noted, the nature of the large amount of data that we average makes the results sensitive to the exact energy bin boundaries chosen. Additionally, at higher energies, the statistical uncertainty of the RMS calculation is high, thus the individual energy bin values should be considered somewhat less reliable than the overall trend in the results.Interestingly, Mukherjee & Bhattacharyya (2012) find indications that
Figure 27: Average fractional RMS and covariance in fraction RMS units as a function of energy for the lower kHz QPOs. Fractional RMS is shown in red squares and covariance in black dots. In general, objects show increasing fractional variability with increasing energy. The divergence of fractional RMS and covariance implies a drop in coherence, seen here at the lowest energy bins and the highest. This behavior is consistent with the behavior of the coherence seen in Figure 25. At energies above ~5 keV, the covariance falls off generally, while the fraction RMS levels off or increases while becoming less well-constrained. The drop in covariance at high energies generally tracks the drop in intrinsic coherence which muddles the interpretation of the covariance and renders these data points unreliable. Undefined RMS values due to poor S/N are not shown.
fractional RMS may decrease above $\sim 20$ keV. We also find the behavior of the fractional RMS/covariance similar between all objects and QPO type.

An increase in fractional RMS/covariance with energy is indicating that the fraction of kHz QPO signal that is variable is increasing with energy. If one assumes that the accretion disk is constant on the timescale of the kHz QPO and it is the Comptonized emission that is variable, then as the flux from the accretion disk drops with increasing energy, the RMS/covariance rises. A flattening off will happen once the accretion disk is no longer significantly contributing to the flux. This idea is further supported by both Peille et al. (2015) and Troyer & Cackett (2017) who show the response-folded covariance spectra of kHz QPOs are consistent with Comptonized emission and do not require a disk component, as well as Gilfanov et al. (2003) who also show the RMS spectrum to be consistent with
4.4.3 Lags vs. Frequency

To establish the presence of any lags, and search for any frequency dependence, we computed lags between two broad energy bins: \(3 - 8\) keV and \(8 - 20\) keV. We considered lower kHz QPOs separately from uppers. We were able to derive lower kHz QPO lag vs frequency relationships for 14 objects and upper kHz QPO lag vs frequency relationships for 6 objects. The lag vs frequency relationships for the lower kHz QPOs and the upper kHz QPOs are shown in Figures 29 and 30 respectively. A positive lag indicates that the higher-energy band photon variability arrives before the lower-energy band photon variability. We binned the lag/frequency data into a maximum of eight bins in an effort to highlight any frequency dependence. See Section 2.4.1 for details of the calculation of the broad-energy lags.

In general, the lags for the lower kHz QPOs show positive average lags, i.e. so-called ‘soft lags’ where the lower energy photons lag the higher energy ones. This result is seen in all previously published work where such lags have been computed (Barret, 2013; de Avellar et al., 2013; Peille et al., 2015; de Avellar et al., 2016b; Troyer & Cackett, 2017). The upper kHz QPOs suffer from reduced quality and amount of data. In general, we find lags consistent with zero or slightly negative average lags, except in two cases. Zero or slightly negative average lags are also consistent with previously published work and illustrates that the nature of the lags is fundamentally different between the lower and upper kHz QPO (Barret, 2013; de Avellar et al., 2013; Peille et al., 2015; de Avellar et al., 2016b; Troyer & Cackett, 2017). Moreover, the values of the average lags are consistent with all comparable previous analyses which include: 4U 1608–52, 4U 1636–53, 4U 1728–34,
and Aql X-1. Both 4U 1608–52 and 4U 1702–43 show positive average lags for the upper kHz QPOs. In both cases, there are relatively few data and the upper kHz QPOs are very weakly detected as evidenced by their poorly constrained coherence.

While in some cases significant upper kHz QPOs are found in event file shift-and-added spectra shown in Figure 24, an individual 1024 s spectrum with a significant upper kHz QPO may not exist and thus not appear in the lag vs. frequency analysis.

There are hints of frequency-dependence is seen in the lower kHz QPOs of 4U 1608–52, 4U 1820–30, 4U 0614+09, and Aql X-1, where there is a decrease in lag as a function of kHz QPO frequency. For 4U 1608–52, this was noted previously by Barret (2013). The uneven sampling of lags across frequency makes a robust determination of frequency dependence problematic. Indeed, de Avellar et al. (2013) showed no dependence of lags on frequency for 4U 1608–52 using a smaller data set than Barret (2013). Additionally, de Avellar et al. (2013) showed a slight decrease in lower kHz QPO lags for 4U 1636–53 above 850 Hz with no frequency dependence for the upper kHz QPO. de Avellar et al. (2016b), who computed phase lags, find no significant frequency dependence for either the lower or upper kHz QPOs in 4U 1636–53. Both de Avellar et al. (2013) and de Avellar et al. (2016b) use different energy bin boundaries than this work. For 4U 1728–34, Peille et al. (2015) find no frequency dependence for the lower kHz QPO lags and the possibility of a slight decrease of the lags at higher frequency for the upper kHz QPO. In Aql X-1, Troyer & Cackett (2017) find no significant frequency dependence on the lags for the lower kHz QPO.

In an effort to further characterize the frequency-dependence of the lags, we performed linear fits. In four objects: EXO 1745–248, 4U 1705–44, SAXJ1748.9-2021, and
Figure 29: Broad energy lags as a function of kHz QPO frequency for the lower kHz QPO. Each small dot represents a single 1024 s spectrum with a significantly detected lower kHz QPO. The data, where practical, are binned in a maximum of eight equally-spaced frequency bins shown in large blue squares. The average lag with error is shown in red and the values of the average lags are shown in Table 7. A positive lag indicates that variability in the higher energy band (8 – 20 keV) arrives before variability in the lower energy band (3 – 8 keV). In general, lower kHz QPOs show positive average lags. In all cases, there is either a slight decrease in lags as a function of QPO frequency or no significant frequency dependence. In objects with more than (5) data points, the linear fit parameters are also shown in Table 7.
Figure 30: Broad energy lags as a function of kHz QPO frequency for the upper kHz QPO. Each each small dot represents a single 1024 s spectrum with a significantly detected upper kHz QPO. The data are binned in a maximum of eight equally-spaced frequency bins shown in large blue squares. The average lag with error is shown in red and the values of the average lags are shown in Table 8. A positive lag indicates that variability in the higher energy (8 – 20 keV) band arrives before variability in the lower energy band (3 – 8 keV). The upper kHz QPOs show lags which are consistent with 0 except in the cases where the upper kHz QPOs are weakly detected, i.e. 4U 1608−52 and 4U 1702−43. In all cases, there is not significant dependence on frequency on lag. The linear fit parameters are also shown in Table 8.

Table 7. Lower kHz QPO Lag/Frequency Data.

<table>
<thead>
<tr>
<th>Object ID</th>
<th>Average Broad Energy Lag (μs)</th>
<th>Best Fit Slope (μs/Hz)</th>
<th>Intercept (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1608−52</td>
<td>23.7 ± 1.3</td>
<td>−0.09 ± 0.02</td>
<td>96.3 ± 1.3</td>
</tr>
<tr>
<td>4U 1636−53</td>
<td>16.5 ± 0.8</td>
<td>−0.02 ± 0.02</td>
<td>36.0 ± 0.8</td>
</tr>
<tr>
<td>4U 0614+09</td>
<td>46.8 ± 4.0</td>
<td>0.07 ± 0.1</td>
<td>−0.8 ± 4.1</td>
</tr>
<tr>
<td>4U 1728−34</td>
<td>9.5 ± 1.6</td>
<td>0.01 ± 0.03</td>
<td>1.9 ± 1.6</td>
</tr>
<tr>
<td>4U 1702−43</td>
<td>35.6 ± 2.8</td>
<td>0.03 ± 0.04</td>
<td>14.7 ± 2.9</td>
</tr>
<tr>
<td>4U 1820−30</td>
<td>5.4 ± 3.1</td>
<td>−0.26 ± 0.07</td>
<td>193 ± 3</td>
</tr>
<tr>
<td>Aql X-1</td>
<td>29.2 ± 3.0</td>
<td>−0.15 ± 0.04</td>
<td>154 ± 3</td>
</tr>
<tr>
<td>4U 1735−44</td>
<td>6.9 ± 3.1</td>
<td>0.12 ± 0.08</td>
<td>−82.5 ± 3.2</td>
</tr>
<tr>
<td>XTEJ1739−285</td>
<td>9.6 ± 9.3</td>
<td>−0.3 ± 0.2</td>
<td>267 ± 10</td>
</tr>
<tr>
<td>EXO 1745−248</td>
<td>18.9 ± 10.1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>4U 1705−44</td>
<td>−84.3 ± 35.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SAXJ1748.9−2021</td>
<td>26.6 ± 23.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>IGRJ17191−2821</td>
<td>−1.4 ± 9.5</td>
<td>3.4 ± 2.5</td>
<td>−73 ± 10</td>
</tr>
<tr>
<td>4U 1915−05</td>
<td>27.2 ± 32.8</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Table 8. Upper kHz QPO Lag/Frequency Data.

<table>
<thead>
<tr>
<th>Object ID</th>
<th>Average Broad Energy Lag (μs)</th>
<th>Best Fit Slope (μs/Hz)</th>
<th>Best Fit Intercept (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1608−52</td>
<td>38.2 ± 9.3</td>
<td>−0.13 ± 0.65</td>
<td>144 ± 9</td>
</tr>
<tr>
<td>4U 1636−53</td>
<td>2.6 ± 4.8</td>
<td>−0.01 ± 0.08</td>
<td>12.4 ± 4.8</td>
</tr>
<tr>
<td>4U 0614+09</td>
<td>6.8 ± 8.3</td>
<td>−0.10 ± 0.10</td>
<td>90.0 ± 8.5</td>
</tr>
<tr>
<td>4U 1728−34</td>
<td>−2.9 ± 2.8</td>
<td>−0.04 ± 0.04</td>
<td>30.0 ± 2.7</td>
</tr>
<tr>
<td>4U 1702−43</td>
<td>53.2 ± 19.6</td>
<td>0.10 ± 0.41</td>
<td>−25 ± 21</td>
</tr>
<tr>
<td>4U 1820−30</td>
<td>−11.4 ± 24.0</td>
<td>0.13 ± 0.16</td>
<td>−136 ± 28</td>
</tr>
</tbody>
</table>

4U 1915−05, we assessed the number and range of data too small to provide a useful characterization of the data. The best-fit slope and intercept contain no straight-forward physical significance and are only used as a way to characterize the data. A more detailed interpretation of the fit parameters requires, in the case of lag/frequency data, an underlying assumption that decrease in lags would represent a decrease in distance scale associated with the increasing QPO frequency. There is no statistically significant frequency-dependence seen for the lags. The best-fit slope and intercept information can be found in Table 7 for the lower kHz QPOs and Table 8 for the upper kHz QPOs.

Overall, we find and previous studies support, no strong frequency dependence on the lags. While the data do not formally exclude a frequency dependence on the lags, because of the paucity of high-quality data for most of the sources, we chose to not employ frequency binning on any analyses. This allows for increased S/N when averaging the data and enables a systematic method of analysis across all sources.

4.4.4 Energy-Dependent Lags

Energy-dependent lags offer a way to begin describing the role of various time-dependent physical process involved in the creation of kHz QPOs. These data illustrate the time lag in each energy bin relative to the reference band. They should be read as relative lags,
Figure 31: Energy-dependent lags for the lower kHz QPO. A positive value of lag in an energy bin indicates that the variability in that bin arrives after the variability in the reference band. In general, lower kHz QPOs show lags with a decreasing trend as energy increases. In order to further characterize the lags, we performed a linear fit in all cases. The best-fit line is shown in red. The best-fit intercept and slope with confidence limits are shown in Table 9.
Figure 32: Energy-dependent lags for the upper kHz QPO. In general, upper kHz QPOs show lags which are consistent with zero lag. In order to characterize the lags, we performed a linear fit in all cases. The best-fit line is shown in red. The best-fit intercept and slope with confidence limits are shown in Table 10.

with the most negative lag being the photons that arrive first. We show lags as a function of energy for the lower and upper kHz QPOs in Figures 31 and 32 respectively. To further characterize the data, we performed linear fits and show the best-fit slope and intercept as well as then number of significant QPO spectra we averaged to obtain the lag/energy spectrum in Tables 9 and 10 for the lower and upper kHz QPOs respectively. The best-fit slope and intercept contain no straight-forward physical significance and are only used as a way to characterize the data. The lags are calculated in a relative way, so that the values are dependent on the reference band chosen and thus they do not translate in a physically meaningful way. See Section 2.4.2 for details of the calculation of the lag/energy spectrum.

For the lower kHz QPOs, the trend is generally monotonically decreasing lags with
Table 9. Lower kHz QPO Lag/Energy Data.

<table>
<thead>
<tr>
<th>Object ID</th>
<th>Number of Significant QPOs</th>
<th>Best Fit Slope ($\mu s/keV$)</th>
<th>Best Fit Intercept ($\mu s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1608−52</td>
<td>89</td>
<td>$-4.9 \pm 0.6$</td>
<td>$37.3 \pm 2.6$</td>
</tr>
<tr>
<td>4U 1636−53</td>
<td>742</td>
<td>$-3.2 \pm 0.3$</td>
<td>$24.3 \pm 1.3$</td>
</tr>
<tr>
<td>4U 0614+09</td>
<td>114</td>
<td>$-8.1 \pm 1.0$</td>
<td>$54.4 \pm 4.9$</td>
</tr>
<tr>
<td>4U 1728−34</td>
<td>174</td>
<td>$-2.2 \pm 0.4$</td>
<td>$20.3 \pm 1.4$</td>
</tr>
<tr>
<td>4U 1702−43</td>
<td>112</td>
<td>$-6.4 \pm 0.7$</td>
<td>$52.9 \pm 3.2$</td>
</tr>
<tr>
<td>4U 1820−30</td>
<td>147</td>
<td>$-1.1 \pm 0.4$</td>
<td>$8.9 \pm 1.7$</td>
</tr>
<tr>
<td>Aql X-1</td>
<td>92</td>
<td>$-5.6 \pm 0.7$</td>
<td>$42.5 \pm 3.3$</td>
</tr>
<tr>
<td>4U 1735−44</td>
<td>110</td>
<td>$-0.9 \pm 0.5$</td>
<td>$8.1 \pm 1.8$</td>
</tr>
<tr>
<td>XTEJ1739-285</td>
<td>22</td>
<td>$-0.5 \pm 1.5$</td>
<td>$4.0 \pm 5.9$</td>
</tr>
<tr>
<td>EXO1745-248</td>
<td>4</td>
<td>$-1.5 \pm 1.1$</td>
<td>$11.6 \pm 4.1$</td>
</tr>
<tr>
<td>4U 1705−44</td>
<td>2</td>
<td>$6.5 \pm 3.9$</td>
<td>$-54.5 \pm 17.9$</td>
</tr>
<tr>
<td>SAXJ1748.9-2021</td>
<td>4</td>
<td>$-0.4 \pm 3.6$</td>
<td>$-2.4 \pm 12.4$</td>
</tr>
<tr>
<td>IGRJ17191-2821</td>
<td>18</td>
<td>$-0.08 \pm 1.41$</td>
<td>$2.7 \pm 5.2$</td>
</tr>
<tr>
<td>4U 1915−05</td>
<td>3</td>
<td>$-4.0 \pm 3.7$</td>
<td>$35.4 \pm 16.7$</td>
</tr>
</tbody>
</table>

Table 10. Upper kHz QPO Lag/Energy Data.

<table>
<thead>
<tr>
<th>Object ID</th>
<th>Number of Significant QPOs</th>
<th>Best Fit Slope ($\mu s/keV$)</th>
<th>Best Fit Intercept ($\mu s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1608−52</td>
<td>8</td>
<td>$-2.3 \pm 1.2$</td>
<td>$15.0 \pm 5.4$</td>
</tr>
<tr>
<td>4U 1636−53</td>
<td>104</td>
<td>$0.63 \pm 0.57$</td>
<td>$-5.0 \pm 2.0$</td>
</tr>
<tr>
<td>4U 0614+09</td>
<td>114</td>
<td>$-0.5 \pm 1.1$</td>
<td>$2.3 \pm 5.5$</td>
</tr>
<tr>
<td>4U 1728−34</td>
<td>130</td>
<td>$0.8 \pm 0.3$</td>
<td>$-7.2 \pm 1.3$</td>
</tr>
<tr>
<td>4U 1702−43</td>
<td>112</td>
<td>$-6.4 \pm 0.7$</td>
<td>$52.9 \pm 3.2$</td>
</tr>
<tr>
<td>4U 1820−30</td>
<td>12</td>
<td>$-1.1 \pm 1.7$</td>
<td>$10.1 \pm 7.0$</td>
</tr>
</tbody>
</table>
increasing energy. The lag of each energy bin – channel of interest (CI) – is measured with respect to the CI-subtracted reference band energy range (3 – 20 keV). Therefore, the variability at lower energies lags the variability at higher energies, with the highest energy photons arriving first. The upper kHz QPOs generally show lags that are flat and in some cases show an increase in the lags at higher energies albeit with poorer statistics than lower kHz QPO. This is consistent with the results of de Avellar et al. (2013) and Peille et al. (2015), which show different behavior of energy-dependent lags of the lower and upper kHz QPO for 4U 1608–52, 4U 1636–53, and 4U 1728–34. This implies that the physical mechanisms responsible for the creation of lower and upper kHz QPOs are likely different.

4.5 Discussion

We have performed the first systematic study of the spectral-timing products of kHz QPOs for neutron star LMXBs using data in the entire RXTE/PCA archive. We examined the coherence, covariance, and lags in the lower kHz QPOs for 14 objects and in the upper kHz QPOs of 6 objects. This is a significant increase compared to all previous studies where lags in the lower kHz QPOs have been studied in 4 objects (Barret, 2013; de Avellar et al., 2013; Peille et al., 2015; de Avellar et al., 2016b; Troyer & Cackett, 2017), and in the upper kHz QPOs for 3 objects. We also find similar results between the various sources where we were able to compute spectral-timing products. We summarize the main observational results:

- Both the lower kHz QPOs and upper kHz QPOs are highly coherent over most of the energy range studied (3 – 20 keV), with a potential drop in coherence at the highest
energies in a few objects.

- The fractional covariance of all kHz QPOs generally increases with energy, levels off around 15 keV and in some cases drops towards 20 keV.

- The kHz QPOs generally show no strong frequency dependence in lag between the 3–8 keV and 8–20 keV band, with the caveat that we may be seeing a statistical bias.

- The lower kHz QPO lags generally show a decrease with energy, with the highest energy photons arriving first, while the upper kHz QPO lags are generally consistent with zero lag.

We discuss these more below.

### 4.5.1 Coherence

While generally consistent with unity, our results show the intrinsic coherence is not well-constrained in objects with poor statistics across all energy bands. Generally, the extreme low and high energy bins of all objects lack statistics and thus also show poorly constrained intrinsic coherence.

The lower kHz QPOs are generally easier to detect, have more and higher quality data, and produce more well-constrained coherence. The confidence limits of the intrinsic coherence are difficult to quantify (see e.g., Nowak & Vaughan, 1996; Vaughan & Nowak, 1997; Uttley et al., 2014).

If the drop in intrinsic coherence at higher energies is real, it would have implications of the nature of kHz QPOs. One can describe the causal relationship between the lightcurve in the CI energy band and the reference band via an impulse response function.
The impulse response function depends on the physical processes taking place. Vaughan & Nowak (1997) suggest that in the case of an impulse response function that is temperature-dependent only, a deviation from linear temperature dependance could cause the loss of coherence. Additionally, Vaughan & Nowak (1997) show that for multiple processes occurring in the same energy band, i.e. two independent impulse response functions, coherence would also be lost. Thus another emission process which becomes more significant at these energies might account for the drop in coherence. Higher quality data near 20 keV is needed, perhaps from AstroSAT (Yadav et al., 2016), to provide concrete evidence of a true loss of coherence.

4.5.2 Covariance

The covariance statistic is dependent on the coherence, and thus we expect the covariance to drop when the coherence drops. In the regime of unity coherence, the covariance spectrum becomes equivalent to the RMS spectrum with higher S/N and we generally find good agreement between the covariance and RMS spectra.

The fractional covariance of all kHz QPOs generally follow a similar trend, rising with increased energy and then leveling off around $\sim 15$ keV and in many cases dropping as the energies approach $\sim 20$ keV. This is generally thought to be due to the increased contribution of the Comptonizing source of photons, which is more variable on the timescale of the kHz QPOs, over the accretion disk photons which are relatively constant on these timescales.

The behavior of the covariance is similar between the lower and upper kHz QPOs. This behavior is consistent with Gilfanov et al. (2003) where they show that by subtracting a putative modeled accretion disk from the average spectrum, the result looks like the
response-folded RMS spectrum for all the QPOs (lower, upper, and the 45 Hz hectohertz QPO) they considered.

The fractional RMS/covariance spectra are also very similar for different objects. Gilfanov et al. (2003) also show this result in the similarity of the spectra in the two objects, GX 340+0 and 4U 1608−52, they studied. They conclude that because the accretion rates of these two objects are likely different by a factor of \(\sim 10\), the RMS spectra is only weakly dependent on mass accretion rate. Our results further support this.

Our results also show the expected deviation between the covariance and RMS spectra when the coherence departs from unity. In some cases, however, we see drops in both RMS and covariance near 20 keV where the coherence remains high. It is difficult to assess the significance of this due to the reduced statistics at these energies. The RMS calculation is sensitive to background subtraction at energies where the QPO signal is low, which might account for the drop. The implication would be that there must be a change in the variability timescale of the Comptonized emission at these energies. A drop in fractional RMS at these energies has been reported by Mukherjee & Bhattacharyya (2012) in 4U 1728−34.

4.5.3 Lags

We computed the average lag and also performed a linear fit of the lags. We find either a slight trend of decreasing lags as a function of frequency or no dependence of lag on frequency of both the lower and upper kHz QPOs. This result is consistent with and well-discussed in previous work (see e.g., de Avellar et al., 2013). We therefore do not explore the frequency dependence in the remaining analysis in order to maintain the consistency of analysis when considering the amount and quality of data available for all objects.
The broad-energy lags for the lower kHz QPOs show correlated variations in the high energy band occur on average before those in the low energy band. The average lags are on the order of a few $10^6$ microseconds which is consistent with the putative timescale of the inner accretion flow of a neutron star. The average lags of the upper kHz QPOs are generally consistent with zero, and suffer from fewer and lower quality data than the lower kHz QPOs.

We also study the lags as a function of energy, averaged over all frequencies. The energy-dependent lags between the lower and upper kHz QPOs follow different trends. The lower kHz lags generally decrease monotonically as energy increases. Those objects that do not show a strong trend typically have far fewer lower kHz QPOs detected. The exceptions are 4U 1735−44 and 4U 1820−30, which show little energy dependence despite relatively large numbers of detections as seen in Table 9. Additionally, these objects have the smallest average broad energy lags of all objects with well-constrained, near unity coherence.

The upper kHz QPO lags are not as well constrained and are generally consistent with zero lag, except in the cases of 4U 1608−52 and 4U 1702−43 where the upper kHz QPOs are weakly detected. The objects with the best upper kHz QPO photon statistics, 4U-1636−53 and 4U 1728−34, show slightly increasing lags as a function of energy.

The energy-dependence of the lags has the potential of constraining the geometry and physics of the emission region of kHz QPOs. For example, in the case of reverberation, the parts of the energy spectrum that are dominated by the reflected emission should show the largest lags behind the direct emission component. The energy-dependent lags in 4U 1608−52 were initially suggested to be due to reverberation by (Barret, 2013).
However, models of the expected reverberation lags in 4U 1608–52 found the energy-dependent lags diverged from the modeled lags above $\sim 8$ keV (Cackett, 2016), eliminating reverberation as the sole source of emission for the lower kHz QPO. Moreover, a response-folded covariance spectra, produced for lower kHz QPOs do not show an accretion disk component that would be expected from reverberation (Peille et al., 2015; Troyer & Cackett, 2017). Both these studies found the seed photon temperature of the covariance spectra, which can be thought of as the spectrum of the kHz QPO, was systematically higher than the time-averaged spectra for 4U 1728–34 and Aql X-1 respectively.

Lee & Miller (1998), Lee et al. (2001), and more recently Kumar & Misra (2014, 2016) have applied Comptonization models to the lag/energy and RMS spectra of kHz QPOs. Most of these studies use the RMS spectrum of 4U 1608–52 from Berger et al. (1996) and the lag/energy spectrum from Vaughan et al. (1998). Kumar & Misra (2014, 2016) show that the lag/energy spectra of the lower kHz QPO can be recovered by a Comptonization model in which a fraction of the Comptonized emission impinges back on the seed photon source. This includes time lags where high energy fluctuations lead lower energy fluctuations.

4.6 Conclusion

We have analyzed all RXTE/PCA data for the objects listed in Table 6. We present the first systematic comparison of spectral-timing characteristics of kHz QPOs across many sources. We have shown that the average spectral-timing properties for all sources in the RXTE/PCA archive, which remains the best data set currently available for this kind of study, are very similar. This supports the idea that the production mechanism of kHz
QPOs is the same for all sources. Additionally, we show the both the broad-band lags and the lag/energy spectra for the lower and upper kHz QPOs are markedly different, which supports the idea that the emission mechanisms of the two types of kHz QPOs are different.

We computed the intrinsic coherence, RMS/covariance, frequency-dependent and energy-dependent lags for the lower kHz QPO in 14 objects, with 6 of those yielding results for the upper kHz QPO. We have demonstrated only broad trends in our results. Both high timing and higher energy resolution are required to model spectral-timing results in a robust fashion.

This work was only possible because of the existence of RXTE/PCA, which was uniquely capable of providing data necessary for spectral-timing work of kHz QPOs. While the energy resolution coupled with variations in the detector’s response limits the energy resolution of analyses, we now understand the scope of the requirements needed to fully exploit this type of analysis. Future proposed missions such as STROBE-X (Wilson-Hodge et al., 2017) and eXTP (Zhang et al., 2016), equipped with such capabilities will allow the full exploration of these analytic techniques.
CHAPTER 5  FINAL PERSPECTIVES

5.1 General Remarks

This work represents the first application of spectral–timing analysis techniques to the study of kHz QPOs to a large data set covering observations of multiple neutron star LMXB systems. Prior to this work, the only application of this type of analysis to kHz QPOs was done for a single source with a single paper studying two sources.

The goal of this work was to discover what similarities and differences might exist in the spectral–timing products of kHz QPOs for multiple neutron star LMXB sources, as well as gain insight into the interpretation and meaning of these spectral–timing products. The overarching goal is to attempt to connect these results to the broader nature of the accretion flow in a strong gravity environment. Such insights would facilitate greater understanding of the physics occurring in the strong gravitational regime as well as the nature of neutron star geometry, and by extension, constraints on the equation of state of ultra–dense matter.

The major scientific insights of this work include the demonstration of the commonality of the various spectral–timing products across many sources. This reinforces the idea that the physical mechanism that produce kHz QPOs may be similar for all sources. While the RXTE mission offered the only means to study the kHz QPO phenomenon, there were some limitations to these data. Specifically, detailed conclusions from spectral–timing data can only be drawn from data with both superior time and energy resolution. The energy resolution of RXTE allowed for the quantification of trends in the analysis products as a function of energy. Such results offered great insight into the general nature of kHz QPOs
as detailed in previous chapters, but in most cases, specific quantitative conclusions could not be produced.

A greater understand of kHz QPOs could be gained by the use of these techniques on data that possess not only greater energy resolution, but also a differing energy range. Outside the 3 keV to the effective 20 keV range of data available to RXTE, additional information about the physics of kHz QPOs might lie. Specifically, energies below 3 keV would contain information about the accretion disk and energies above 20 keV the higher range of BL/corona emission (e.g., Lee et al., 2001). Understanding the behavior of spectral–timing products in these other energy ranges would help develop a more complete picture of kHz QPOs.

5.2 The Future

The broader impact of this work is the demonstration of spectral–timing analysis techniques which might be extended to study data from current and next generation telescopes. In addition to STROBE-X and and exTP mentioned in the previous chapter, the Large Area X-ray Proportional Counter (LAXPC) aboard the Indian satellite telescope ASTROSAT (Yadav et al., 2016), is currently conducting observations. With an effective area four times that of RXTE for energies above 20 keV, this mission would be ideal for probing the BL/coronal regions of the spectral–timing spectra. Additionally, the NICER (Arzoumanian et al., 2012) NASA mission is now aboard the International Space Station (ISS). The 0.3 – 10 keV energy range of NICER is ideal for exploring the contribution of the accretion disk to spectral–timing products.

The recent use of phased-resolved spectroscopy (Stevens & Uttley, 2016), which is a
time-domain form a spectral–timing, on the vast lower frequency complex of QPOs as well as kHz QPOs, demonstrates the usefulness of the full range of these techniques.

Spectral–timing is also used to analyze the QPOs of black hole (BH) binary systems. Much effort has been applied to the possible linking of the QPOs present in neutron stars to those present in BH systems (e.g., Motta et al., 2017). By comparing neutron star and black hole systems, where there are some common emission components like the thermal accretion disk, Compton power law and some differences, notably a thermal emission component from the neutron star surface which does not exist for a black hole, one could begin to systematically eliminate some model combinations.

Finally, the development of spectral–timing products would be of enormous use to the more recent modeling efforts occurring. For example, de Avellar et al. (2018) are currently employing a general-relativistic (GR) magneto-hydrodynamic (MHD) model of accretion in a neutron star environment. They have been able to produce a complex of frequencies and harmonics of an axisymmetric tordial plasma geometry. When ultimately coupled with a GR radiative transfer model, synthetic X-ray power spectra will be produced. In addition to other constraint, these power spectra must reproduce the observed spectral–timing products. Thus, these techniques have application in model validation. Any model for kHz QPOs now must not only demonstrate the power spectral properties, but must also explain the energy-dependent lags, and covariance. This makes a much more powerful discriminant between future models.

We are only beginning to see the utility of spectral–timing. The refinement of these techniques, represented in this manuscript, along with access to better quality observational data will be crucial to taking the next step in understanding neutron star physics
and the physics of strong gravity.
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SPECTRAL–TIMING ANALYSIS OF KILOHERTZ QUASI–PERIODIC OSCILLATIONS IN NEUTRON STAR LOW MASS X-RAY BINARIES

by

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May 2018

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Kilohertz quasi-periodic oscillations or kHz QPOs are X-ray intensity variations observed in neutron star low-mass X-ray binary (LMXB) systems. In such systems, matter is transferred from a secondary low-mass star to a neutron star via the process of accretion. kHz QPOs occur on the timescale of the inner accretion flow and may carry signatures of the physics of strong gravity ($c^2 \sim GM/R$) and possibly clues to constraining the neutron star equation of state (EOS). No model to date has been able to illuminate the origin of kHz QPOs. Spectral-timing is a set of analysis techniques useful in deriving information about the nature of physical processes occurring within the accretion flow on the timescale of the kHz QPO. We present a comprehensive study of spectral-timing products of kHz QPOs from systems where data is available in NASA's Rossi X-ray Timing Explorer (RXTE) archive to demonstrate the promise of these techniques and to gain insights regarding the origin of kHz QPOs. Using data averaged over the entire RXTE archive, we show correlated time-lags as a function of QPO frequency and energy, as well as energy-dependent covariance spectra for the various LMXB systems where spectral-timing analysis is possible. The similarity in trends in all sources suggest a common physical origin for kHz QPOs across the
population. The differences in results between lower and upper kHz QPOs lend further support to the evidence of the differing nature of the lower and upper kHz QPOs.
AUTOBIOGRAPHICAL STATEMENT

Name: Jon S. Troyer

Prior to beginning a physics PhD program at Wayne State University, I was a part-time member of the faculty at Eastern Michigan University’s (EMU) Department of Physics and Astronomy, where I taught introductory physics and engineering physics to undergraduates. During this time, I also was employed at X-ray and Specialty Instruments (XSI) Inc. in Ypsilanti, where I assisted in producing stock and custom scientific X-ray sources and detectors.

My career in physics and astronomy began in 2005 when I enrolled in the Physics Masters Degree program at EMU. This marked a transition from a career which began after I enlisted in the United States Navy in 1988 just after graduating from high school. After undergoing nuclear propulsion training, I was accepted to attend the United States Naval Academy where I became a midshipman in the summer of 1991. After graduating with a B.S. in Marine Engineering and a commission as an ensign in the U.S. Navy, I underwent training in nuclear powered submarines. After completion of that training pipeline, I was assigned to the fast attack submarine USS Topeka (SSN 754) home-ported in Honolulu, HI in November 1996. Over the next four years, I took part in three Western Pacific deployments (WESTPAC), qualified engineering officer, and honorably separated from the Navy in 2000.

After separating from the Navy, I began a career as a civilian. I married Sarah Lindsey and we settled into an apartment in northwest Washington D.C. There, I began employment at Systems Planning and Analysis (SPA) Inc. At SPA, I assisted in providing technical and analytical support to executive decision makers throughout the Departments of Defense (DoD), Homeland Security (DHS) and Energy (DoE). It was at this point in my career that I decided on a transition. After three years at SPA, Sarah and I embarked on what would be a 10 month around the world trip. We both transitioned to life in their native Michigan, where Sarah continued a career in law, and I began work on my master’s degree in 2005.

While at EMU, I worked in the plasma lab and focused on characterizing the hollow anode, Argon plasma source in EMU’s laboratory while working with Professor James Carroll. It was shortly after graduating EMU that I began work as a part-time faculty member at EMU and work at XSI.

While immensely enjoying that experience, it became clear that there were no paths to full-time employment. This motivated my to pursue a doctoral degree which would provide the necessary means to attain full-time employment. I began work at Wayne State University (WSU) in 2013, working with Professor Edward Cackett. The focus of my work at WSU has been the study of compact objects, neutron stars and black holes, with specialization in the high frequency X-ray variability of neutron star low mass X-ray binary (LMXB) systems.

Currently I make my home in Plymouth, MI with my wife Sarah and two children Annabelle and Marshall.