X-ray Timing of Stellar Mass Black Holes

… a white paper for the 2010 Decadal Review by:

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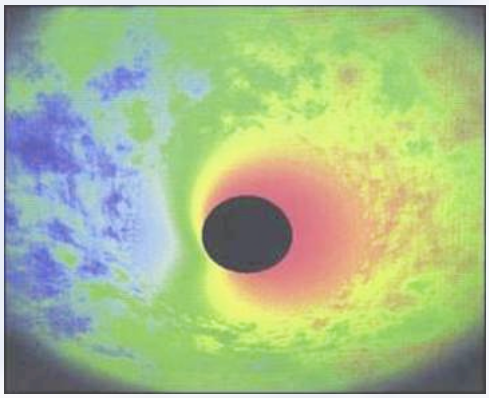

1 Abstract

X-ray timing observations of accreting stellar mass black holes have shown that they can produce signals with such short time scales that we must be probing very close to the innermost stable circular orbit that is predicted by the theory of General Relativity (GR). These signals are quasi-periodic oscillations (QPOs), and both the high-frequency variety (HFQPOs, which have frequencies in the 40–450 Hz range) as well as the 0.1–10 Hz low-frequency type have the potential to provide tests of GR in the strong field limit. An important step on the path to GR tests is to constrain the physical black hole properties, and the straightforward frequency measurements that are possible with X-ray timing may provide one of the cleanest measurements of black hole spins. While current X-ray satellites have uncovered these phenomenona, the HFQPOs are weak signals, and future X-ray timing missions with larger effective area are required for testing the candidate theoretical QPO mechanisms. Another main goal in the study of accreting black holes is to understand the production of relativistic jets. Here, we have also made progress during the past decade by finding clear connections between the radio emission that traces the strength of the jet and the properties of the X-ray emission. With new radio capabilities just coming on-line, continuing detailed X-ray studies of accreting black holes is crucial for continuing to make progress.

2 Introduction and Scientific Goals

Studies of accreting stellar mass black holes address some of the most significant questions in astrophysics, including probing regions of strong gravity close to the black hole as well as improving our understanding of ubiquitous phenomena such as accretion disks and jets. The few dozen black holes (BHs) or black hole candidates (BHCs) that we have found in the Galaxy [29] show X-ray variability on time scales from milliseconds to years as they accrete matter from their binary stellar companions. Their X-ray fluxes can vary by factors of more than a billion, becoming, at times, the brightest sources in the X-ray sky.

That these sources have great potential for helping us to learn about fundamental physics has not gone unnoticed, and accreting BHs received significant attention in the 2000 Decadal Review. The panel on High-Energy Astrophysics from Space included BH science in forming its list of "astrophysics challenges" [4]. Specifically, these include the challenge to "form an indirect image of the flow of gas around a black hole" and to "understand how jets are created and collimated." With X-ray timing at the millisecond level, we are probing the regions of the accretion flow at the very inner edge of the disk. Not only do we know that there is variability coming from these regions, but there are signals at specific frequencies (quasi-periodic oscillations or QPOs) that provide quantitative constraints on the properties of the inner disk.

In the following, we first discuss the major progress that has been made using X-ray timing to study BHs over the past decade. We then focus on opportunities X-ray timing can provide in the next decade related to the goals of testing General Relativity (GR) in the strong field limit and understanding jets. Finally, we discuss the observational requirements that an X-ray timing mission would need to take advantage of these opportunities.

3 Black Holes in 2010: Discoveries and Progress to Date

X-ray binaries provide the best opportunities for constraining the **mass** of stellar-mass BHs. In the past decade, almost 20 confirmed and candidate BHs were observed in outburst, including 10 new discoveries. Eleven new sources were added to the list of dynamically confirmed BHs, doubling the total number. The dependence of X-ray timing properties on BH mass is clearly demonstrated by comparing the timing properties of stellar-mass BHs and the BHs in AGN. Using the break frequencies observed in BH power density spectra (PDSs), it has been shown that, after correcting for mass accretion rate, AGN behave like scaled-up stellar-mass BHs [23]. Similarly, QPOs have been used to argue that at least some Ultra-Luminous X-ray sources (ULXs) harbor intermediate-mass black holes [5].

Dedicated monitoring of transient sources, in which their evolution over periods of weeks to months is followed on a $\sim$daily basis, have been critical in improving our understanding of the correlated behavior of X-ray timing and spectral properties, i.e., the **black-hole X-ray states**. This has led to a clear organization of BH behavior into three active states [29]. Each state displays different combinations of energy spectra, PDSs, and multi-wavelength properties, implying major differences in accretion geometry and radiation mechanisms. They provide unique applications for studying the effects of GR as they allow for more focused attempts to model their characteristics. For example, accretion disk spectra from the thermal state are being used to measure **black-hole spin** [21, 19], as are the broad iron lines found in the steep power-law state [26]. This is also where the high-frequency oscillations that are a main topic of this white paper are found.

Simultaneous coverage of outbursts at other wavelengths has led to a **unified model for jet formation** in stellar-mass BHs [9]. A steady radio jet is observed in the hard spectral state, while violent, relativistic jet ejections are observed during the transitions from the spectrally hard to spectrally soft states. Radio/X-ray luminosity relations initially observed in stellar-mass BHs [11] have now been extended to include AGN [25, 8], suggesting a scale invariance of the jet-accretion coupling in accreting black holes .

High-frequency QPOs ($\nu > 30$ Hz) have been discovered in 7 BH transients (see Figure 1), five of these in the last decade. In 4 of those sources, pairs of HFQPOs have been observed, with the frequencies being consistent with a 3:2 ratio. While the single peaks have been observed to drift in frequency by up to 15%, the frequencies of the pairs are very stable on time scales of years. There are indications [29] that the frequencies of the pairs scale inversely with the mass of the black hole, as determined from dynamical measurements of the binary companion. This scaling, combined with the frequencies and stability, suggest that the QPO pairs are rooted in GR, and the properties of HFQPOs have sparked theoretical interest, leading to models that incorporate GR phenomena (e.g., [37, 31]). While neutron star systems also exhibit QPOs, their properties are clearly different from the BH HFQPOs. We expect the BH systems to be cleaner, without intrinsic magnetic fields or solid surfaces, so the stable frequencies of HFQPOs may be more likely to be fundamentally related to strong gravity.

While HFQPOs are restricted to a narrow range of X-ray properties, **low-frequency QPOs** ($<$30 Hz) are found at some level in all BH states. The most common type of LFQPO can be followed in frequency from the hardest spectral state to the softest spectral state as it increases from $\sim$0.1 Hz up to $\sim$10 Hz, tracing changes in the size of the inner disk or Comptonizing corona. Phase-resolved spectroscopy reveals rapid changes in the strength of the iron line [27], which has been modeled in terms of a tilted accretion disk in strong gravity (e.g., [32, 10]).

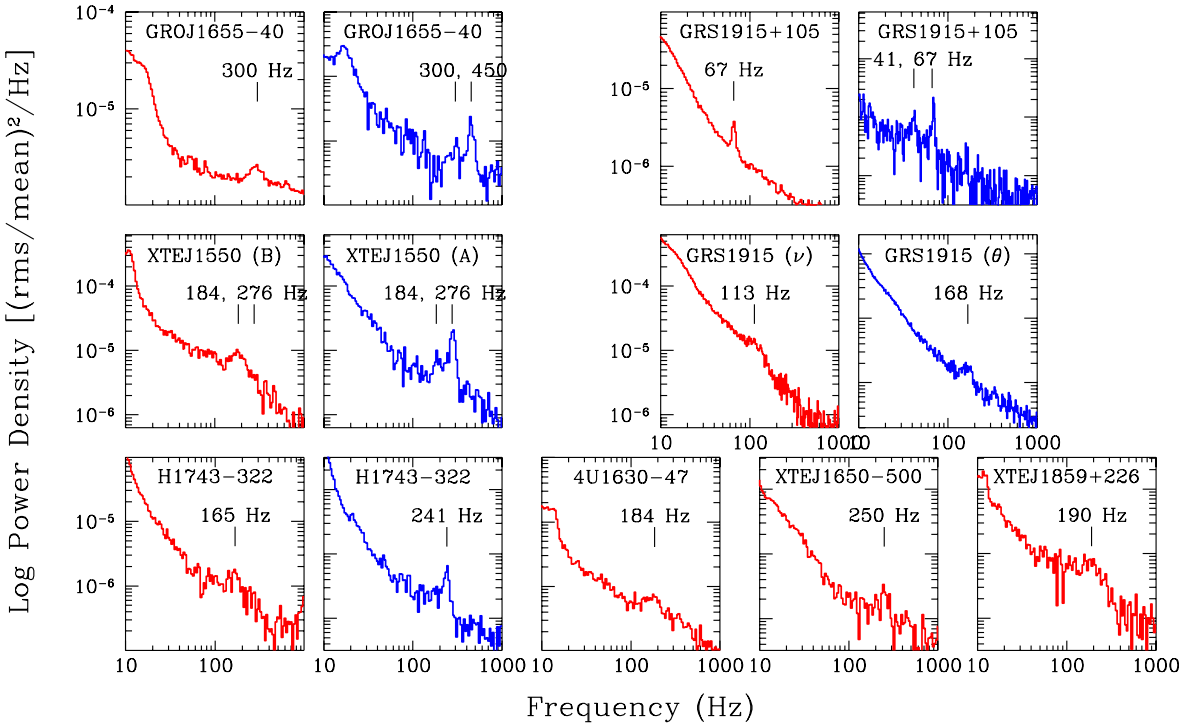

Figure 1: HFQPOs detected in the X-ray PDS of BH and BHC systems. This figure shows the entire sample of HFQPOs detected at high significance. Blue traces are used for PDS for 13–40 keV. Red traces show PDS for a broader energy range, either 2–30 or 6–30 keV [29].

4 X-ray Timing and Black Hole Astrophysics in the Next Decade

In the next decade, we must accelerate progress for quantitative applications with GR in investigations of accreting BHs. The radiation properties of matter in strong gravity can be used to conduct fundamental investigations in physics, while constraining the physical properties of the BHs, i.e., mass (M) and spin[1]. Modeling relativistic accretion disks and broad iron Kα emission lines in X-ray spectra are current techniques for measuring BH parameters. We must continue to develop these approaches, as well as engaging in additional techniques, such as interpretations of QPOs and X-ray polarimetry. For all of the models used to interpret the data, there are concerns about assumptions and systematic uncertainty. Thus, it is necessary to use multiple techniques and to obtain measurements of BH parameters whenever possible. This motivates the strategy to **focus on BH spin** [29], and to capitalize on the continuing enterprises that seek BH mass measurements.

The primary focus of this white paper is the opportunity for advancement related to X-ray timing measurements, and the HFQPOs represent one of the most enticing opportunities. HFQPOs potentially offer the most accurate constraints on BH mass and spin, since the frequencies are measured in a straightforward manner, with no distortions due to distance, reddening, or other effects common in astrophysics. The expected link between **HFQPOs and strong gravity** is based on two arguments. First, there is the relationship between frequency and BH mass mentioned above (although this is still based on a small number of systems). Second, HFQPO frequencies are as

[1]The dimensionless spin parameter is $a_* = cJ/GM^2$, where J is the BH angular momentum, c is the speed of light, G is the gravitational constant, and the value of a_* lies between 0 and 1.

fast as the dynamical frequencies associated with the inner edge of the accretion disk. GR theory imposes an inner boundary condition in the form of an innermost stable circular orbit (ISCO) that is outside the event horizon. For example, for the cases, $a_* = \{0.0, 0.5, 1.0\}$, the event horizons lie at $\{2.0, 1.9, 1.0\}$ $R_{\rm g}$ and the ISCO radii are $\{6.0, 4.2, 1.0\}$ $R_{\rm g}$, where $R_{\rm g} \equiv GM/c^2$. For a given BH with the same illustrative spin values, the maximum orbital frequency has values $\nu_{\rm ISCO} = \{220, 351, 1615\}$ Hz $(M/10\,{\rm M}_\odot)^{-1}$. GR also predicts that small orbital perturbations do not produce closed orbits, and separate oscillation frequencies would be observed for the radial (ν_R) and polar (ν_θ) coordinates (e.g., [24]). Both are slower than the Keplerian frequency (ν_ϕ), while all three coordinate frequencies depend on both the BH mass and spin.

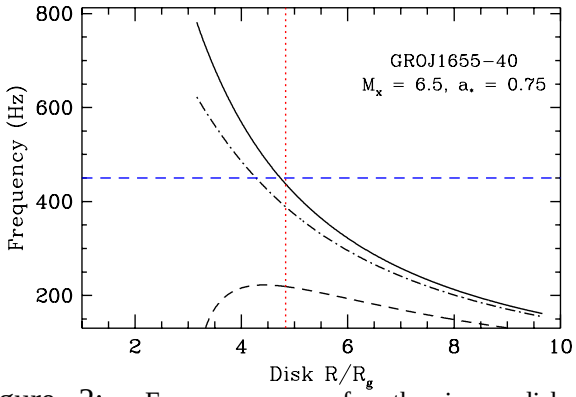

Figure 2: Frequency map for the inner disk of GRO J1655–40. The black curves show the 3 coordinate frequencies: ν_ϕ (solid), ν_θ (dot-dash), and ν_R (dashed). The latter frequency falls to zero at the ISCO, and for this case $R_{ISCO} = 3.16\,R_{\rm g}$. The vertical, red line shows the location in the disk for maximum energy release in the Kerr metric ($R_x = 4.83\,R_{\rm g}$), and this location happens to be very close to the location where the upper HFQPO frequency (450 Hz) from this BH intersects the curve for ν_ϕ.

We can now illustrate the expected origin of HFQPOs with the help of Figure 2. We choose the BH GRO J1655–40, adopting the optically determined mass (6.5 ${\rm M}_\odot$) and the spin value inferred from the analysis of the thermal state X-ray spectra ($a_* \sim 0.75$). The curves for the coordinate frequencies (ν_ϕ, ν_θ, and ν_R) vs. disk radius are shown. The orbital frequency (ν_ϕ) at the radius in the disk where the accreting matter would experience maximum energy loss is 437 Hz, which is remarkably close to one of the HFQPO pairs (300 and 450 Hz) actually measured for this X-ray source. It has also been noted that observed oscillations are unlikely to be faster than the dynamical frequency (ν_ϕ) at the radius where the QPO originates [34]. In Figure 2, this would imply (for 450 Hz) $R_{QPO} < 5R_{\rm g}$. Furthermore, this HFQPO may exclude the possibility of $a_* = 0$ for GRO J1655–40, since in that case (for 6.5 ${\rm M}_\odot$) $\nu_{max} = \nu_{ISCO} = 338$ Hz. HFQPOs transport us to realms where $R < 10R_{\rm g}$, and a proper interpretation would yield immediate constraints on BH spin when the mass is known.

Thus, the **key questions** for HFQPO investigations are: what theoretical models can explain these oscillations? And what new observations can be made to point us in the right direction? A general theory of oscillation modes for accretion disks in the Kerr metric has been developed [17, 38]. The turnover of the ν_R curve in Figure 2 illustrates the natural capacity of a relativistic accretion disk to trap and grow high-frequency oscillations. Using linear perturbation theory, the normal disk modes were calculated, but the predictions are not consistent with the 3:2 ratio seen for the HFQPO pairs. It has also been suggested that HFQPOs arise from a **non-linear resonance** mechanism [1], since resonances are known to exhibit oscillations with commensurate frequencies. Resonances were first discussed in terms of specific radii where GR coordinate frequencies scale with a 3:1 or a 3:2 ratio. These simple ideas have been replaced by considerations of resonances in fluid flow (e.g., [18]). Other models utilize variations in the geometry of accretion. In one model, state changes are invoked that thicken the disk into an **accretion torus**, where the normal modes can yield oscillations with a 3:2 frequency ratio [30, 3]. It is also possible that HFQPOs exhibit properties of a **magnetized accretion disk**, e.g., the rotating magnetic spiral waves in the accretion

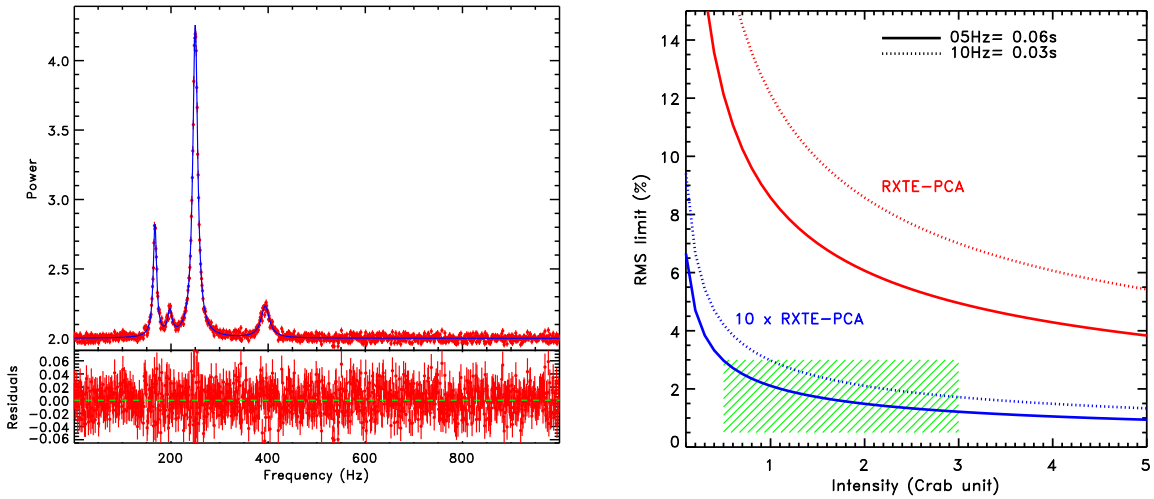

Figure 3: *Left:* Simulated Power Density Spectrum that could be obtained in a 10,000 second exposure by a future X-ray mission with 10 times the effective area of the *RXTE*/PCA. The QPOs at 250 and 167 Hz are analogous to HFQPOs at the 3:2 ratios that have been previously observed. This simulated PDS also has weaker QPOs at 400 and 200 Hz. Detecting such QPOs with frequencies spaced by integer ratios (2:1 in this example) could confirm the non-linear resonance mechanism. *Right:* The rms amplitude limit to detect QPOs on their coherence time scales ($1/\pi\Delta\nu$) for QPO widths of $\Delta\nu = 5$ *(solid lines)* and 10 Hz *(dashed lines)*, as a function of source count rate normalized to the intensity of the Crab. The region where BH QPOs fall is shown as a green-dashed rectangle. The PCA limits are shown in *red*, and the limit that would be obtained with 10 times more effective area is shown in *blue*.

ejection instability (AEI) model [35].

Both the observational and theoretical sides of the HFQPO question suffer from a fundamental problem. The observations of HFQPOs in BHs suffer from chronic signal-to-noise starvation. Half of the detections (see Figure 1) were only achieved after averaging PDSs over several observations. The effort to link oscillations to theory requires a more complete representation of the harmonic structure of HFQPOs that can be compared to predictions derived from full modal analyses. The **current observational deficiencies clearly require new missions with larger collecting area**. As illustrated in Figure 3, a factor of 10 in area would open a new window in the study of millisecond oscillations from accreting systems. In addition, to the possibility of detecting other resonances, detection of the oscillations within time intervals over which they are coherent would permit identification of the mechanism of decoherence and should provide insight to their physical origin. This is a key step in understanding the QPOs so that they can be exploited as tools to study fundamental physics [15]. On the theoretical side, **current models are deficient in terms of specifying the radiation mechanisms** that would imprint a given oscillation mode into the X-ray light curve. This step is critically important, given the fact that HFQPOs and LFQPOs are commonly tied to a hard X-ray component, rather than the thermal component that can be directly attributed to the accretion disk. Such considerations apply to both analytical models and to GR-MHD simulations (see [28]).

Observations of LFQPOs with a large effective area X-ray timing mission also provide a major opportunity for the next decade. The evolution of LFQPO properties as a source moves from one state to another can provide unique insights in the underlying changes in the accretion flow geometry. Moreover, LFQPOs probably also originate close enough to the BH for GR to have a significant effect on the QPO formation. One of the models for LFQPOs in BHs is Lense-Thirring

precession of the inner part of the disk, and if this is correct, then this would provide yet another independent measure of BH spin. Two areas of LFQPO research that can be opened up further by next generation timing instrument are QPO folding (e.g., [36]) and phase resolved spectroscopy. These techniques are intrinsically better suited for LFQPOs than HFQPOs, because of their lower frequencies and higher amplitudes, but require count rates higher than typically obtained with current instrumentation. While crude attempts have been made to measure the energy spectrum of QPOs [12, 27], **phase resolved spectroscopy**, in which spectral changes are followed throughout a QPO cycle, will provide more direct information on the connection between the QPO and the individual spectral component, some of which provide their own spin constraints.

While there are other more advanced time-domain analysis techniques (e.g., phase lags, coherence, etc.) that would benefit from a large effective area X-ray timing mission in the next decade, we close this discussion by emphasizing the link between BH jets and X-ray timing signals on both long and short time scales. Characterizing the connection between jets and spectral states discussed above has depended on multi-wavelength observations, including $\sim$daily monitoring of BH transients as they move from state-to-state over periods of months (e.g., [16]). Independently of X-ray observations, we are expecting two major improvements to these studies over the next several years. One of these is the great increase in radio capabilities expected with facilities that provide all-sky monitoring like the Low Frequency Array (LOFAR) and the Murchison Widefield Array (MWA). With such capabilities, we will obtain radio data while interesting BH behavior is occurring rather than observing after such behavior has occurred. Secondly, there have been advances in theoretical modeling of the emission from jets (e.g., [20]), allowing us to connect measurements to physical jet properties. However, to take advantage of these improvements requires that we also keep up our ability to monitor these sources in the X-ray band.

5 Observational Requirements for X-ray Timing

The state of the art in X-ray timing is the *Rossi X-ray Timing Explorer (RXTE)* mission. *RXTE* has an all-sky monitor that has been essential in tracking the behavior of accreting X-ray sources, but provides little detailed timing information, and a narrow-field/large-area detector array, the Proportional Counter Array (PCA), that produced most of the scientific advances described above. The only mission currently scheduled for launch that will build on *RXTE*'s timing capabilities is the Indian *ASTROSAT* mission. *ASTROSAT* will contain an X-ray detector array comparable to the PCA, but will not offer any significant advance beyond the PCA in sensitivity or energy resolution.

The scientific goals described above require new instrumentation. The key observational goals are increased sensitivity (both detection of weaker QPOs and detection of known QPOs on shorter time scales), improved energy resolution, and a capability for monitoring (since the BH sources are highly variable and certain signals, such as HFQPOs, only occur in certain spectral states). For bright sources, defined as sources for which the source counting rate is much larger than the background counting rate, the time for detection of a QPO signal varies as $T \propto 1/A^2$, where A is the effective area [15]. An increase by a factor of 10 in A will lead to a decrease of two orders of magnitude in the time required for the detection of QPO signals. This would enable a new X-ray timing mission to achieve a qualitative advance in the measurement of QPOs by permitting the detection of kHz QPOs within their coherence time (see Figure 3).

Non-focusing detector arrays are effective timing instruments for the brightest sources. Next

generation detector arrays are likely to be based on solid state rather than gas detectors that offer improved response at high energies and improved energy resolution relative to the PCA [14, 6]. For weaker sources, sheer area is not the only concern, and the background counting rate must also be considered. A disadvantage of large, non-focusing detector arrays is their high background counting rates. This limits the effectiveness of such arrays for weak sources for which focusing telescopes are strongly preferable. Options include the use of a single detector at the focus of a large telescope [2, 7] or an array of small telescopes each with a compact detector [13]. Focusing telescopes can achieve very large areas at low energies, below $\sim$10 keV. The small detector sizes for focusing telescopes also permit much improved energy resolution relative to non-focusing detector arrays.

6 Summary and Conclusions

Accreting black hole systems provide us with a unique probe of strong gravity, allowing us to address several important questions. Are the properties of the inner regions of the accretion disk consistent with the predictions of GR? What is the radius of the ISCO? What are the spin rates of BHs, and does precession of the inner disk around a rapidly rotating BH occur? In addition, BH studies address questions of the properties and production of relativistic jets. To date, the work that has been done by X-ray timing has set the stage for producing reliable measurements of BH spin and testing GR in the next decade. Here, we have especially emphasized the opportunity presented by the studies of HFQPOs. These weak signals are close to the *RXTE* detection limit, and larger effective area missions are required to use HFQPOs as tools to study fundamental physics.

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