Astro2020 Science White Paper

Accretion Physics with Fast X-ray Spectral Timing

Thematic Areas:
□ Planetary Systems  □ Star and Planet Formation
✓ Formation and Evolution of Compact Objects  □ Cosmology and Fundamental Physics
□ Stars and Stellar Evolution □ Resolved Stellar Populations and their Environments
□ Galaxy Evolution □ Multi-Messenger Astronomy and Astrophysics

James F. Steiner
Institution: MIT
Email: jsteiner@mit.edu
Phone: (617) 324-1194

Co-authors:
Joseph Neilsen (Villanova),
Edward Cackett (Wayne State),
Nathalie D. Degenaar (Amsterdam),
Javier A. Garcia (Caltech),
Jeroen Homan (Eureka Scientific),
Dipankar Maitra (Wheaton College),
Thomas Maccarone (Texas Tech),
Sara Motta (Oxford),
Dheeraj Pasham (MIT),
Abigail Stevens (Michigan State),
John Tomsick (UC Berkeley SSL)
Overview

Accreting compact objects produce the brightest sources in the high-energy sky. In particular, actively accreting neutron star and black-hole systems peak in the X-ray band, and can even outshine the bright Crab nebula several-fold. In addition to prominent X-ray emission, accreting compact objects and their supermassive counterparts in active galactic nuclei (AGN) generate powerful mechanical outflows in the forms of winds and jets. The stellar-mass systems exhibit wide-ranging evolution over human timescales, with a full transient X-ray binary outburst cycle lasting for characteristically months to years from onset to quiescence.

At shorter second and subsecond timescales, Fourier products such as power-density spectra reveal periodic and quasi-periodic behavior, which are related to the accretion process. For instance, subsets of the quasi-periodic oscillation (QPO) features are dynamic and exhibit evolution closely tied to both the spectral state and brightness changes.

Present efforts to investigate these short timescales and QPOs are count limited. Current cutting-edge endeavors push towards unraveling the fastest kHz variations in these brightest X-ray sources to probe the fundamentals of accretion in the innermost reaches for which the effects of extreme gravity are manifest. In this White Paper, we demonstrate the enormous progress in our understanding of accretion onto compact objects that can be readily achieved by a next generational large-area X-ray timing instrument, for which our touchstone is the probe concept mission STROBE-X (Ray et al. 2018, 2019).

Transient Detection

At present, the only reliable means of identifying new X-ray transients, and capturing the onset of an outburst is through rapid detection and community alert from a sensitive wide-field X-ray monitor. A prompt response to new X-ray binary outbursts, i.e., within hours, is important as the earliest stages of outburst are presently among the most hotly contested regarding the accretion flow (for instance, the hotly debated topic of disk-truncation radius; e.g., see García et al. 2015; De Marco et al. 2015; Basak & Zdziarski 2016; Wang-Ji et al. 2018).

Each year, \(\gtrsim 10\) Galactic X-ray transient outbursts occur, with \(\sim 1/3\) from previously unknown systems (Tetarenko et al. 2016). Additionally, there are dozens of persistently bright Galactic X-ray binary systems (e.g., Cyg X-1), often wind fed, and always detected in the X-ray sky. Over sixteen years of operation, the Rossi X-ray Timing Explorer’s All-Sky Monitor (ASM) set the gold standard for monitoring the transient X-ray sky. For a next-generation sky monitor with an order of magnitude gain in sensitivity that offers daily coverage of the full sky, the ability to detect and rapidly respond to a new transient as faint as several mCrab with pointed instruments is critical to enable ready monitoring for the crucial early phase of outburst onset\(^1\). In addition to improving sensitivity, a key improvement over ASM offered by a facility like STROBE-X’s Wide Field Monitor, is extended hard X-ray coverage (e.g., across the range of Swift’s Burst Alert Telescope; Barthelmy et al. 2005). This coverage greatly enhances sensitivity to the earliest, rising phase of a new outburst, in which the emission is quite hard in comparison to later outburst phases.

Moreover, daily coverage offers an essential diagnostic product in providing a continuously updated “roadmap” of the outburst, following the gradual Q-shaped track of hardness versus intensity

\(^1\)New systems rise across 7 orders of magnitude in brightness from quiescence to peak as rapidly as in days (e.g., XTE J1859+226; Brocksopp et al. 2002), or as slowly as over months (e.g., XTE J1752-223; Brocksopp et al. 2013).
evolution across the outburst cycle (e.g., Fender et al. 2004; McClintock & Remillard 2006). Such monitoring, while not our focus, is fundamentally critical for enabling the science at hand; namely the synoptic study of accretion. Sky monitors provide rapid source detection in outburst, ready diagnostic capabilities through monitoring, and enable triggered response to initiate pointed observations at periods of particular interest which are indicated in the hardness-intensity landscape. These are essential capabilities which underpin detailed (pointed) spectral-timing monitoring for X-ray studies of accretion.

**Outflows**

Mechanical outflows are a defining feature of the accretion evolution of an X-ray transient in outburst: at various stages, X-ray transients exhibit powerful ballistic jet ejections, weaker steady jets, and highly ionized winds. These outflow modes can coexist, and may actively quench or regulate each other (Miller et al. 2008; Neilsen & Lee 2009; Homan et al. 2016).

**Winds**

Blueshifted X-ray absorbers are ubiquitous in soft(er) states of high-inclination X-ray transients (e.g., Ponti et al. 2012; Díaz Trigo & Boirin 2013), and are interpreted as signatures of equatorial accretion disk winds. The significance of these highly ionized outflows is twofold: first, they may remove a considerable fraction of the inflowing gas mass (Neilsen et al. 2011; Tetarenko et al. 2018) and angular momentum (Miller et al. 2015), and are thus critical for understanding accretion disk evolution. Second, because their observable properties (line strengths and ratios) couple to the local radiation field, they offer a unique diagnostic of accretion-ejection physics.

The precise details of these connections depends sensitively on the wind launching mechanism, which may include a combination of radiative, thermal, and magnetic driving (see Miller et al. 2006; Neilsen 2013, and references therein). These driving mechanisms generally operate in different regimes of ionization, density, and distance from the black hole, so that measuring these quantities unlocks not only the physics underlying accretion disk winds but also illuminates their role in the accretion process.

Historically, efforts have focused on the application of photoionization models (e.g., Kallman & Bautista 2001) to measure these parameters, but a large-area spectral-timing instrument opens the door for another technique: temporal variability. For a variable source, the ionization response time depends on density, with recombination time \( t_{\text{rec}} \sim 1 \text{s} \left( \frac{n}{10^{11} \text{ cm}^{-3}} \right)^{-1} \), meaning that fast time-resolved spectroscopy can pinpoint the density and test models of time-dependent photoionization (e.g., García et al. 2013). Sensitivity is crucial, and particularly near \( \sim 6 \text{–} 8 \text{ keV} \), where strong absorption lines (Fe XXV, Fe XXVI) are prominent, making a mission like STROBE-X a powerhouse for wind physics (Figure 1). At Crab-level fluxes, it will be possible to make direct estimates of densities below \( \sim 10^9 \text{ cm}^{-3} \) and \( \gtrsim 10^{12} \text{ cm}^{-3} \) with Fourier methods, effectively revealing the links between radiation and outflows on the viscous timescale of the inner accretion flow.

**Disk-jet connection**

Jets are found in X-ray binaries at different stages of evolution, but are principally associated with hard spectral states (e.g, Fender et al. 2004). X-ray reflection and reverberation modeling each
directly probe the size-scales of the corona-disk separation, which may be linked to changes in the base of the jet (e.g., Wilkins & Gallo 2015; Dauser et al. 2014).

The connection of variability in the accretion disk behavior and that in the jet is best revealed through multiwavelength campaigns with X-ray behavior acting as tracer of the disk and lower-energy wavelengths revealing the jet emission, especially radio (e.g., Gallo et al. 2003) and optical / infrared (e.g., Eikenberry et al. 1998).

A next-generation high-throughput and large-area X-ray timing mission would launch in an era of unprecedented large-area ground-based capabilities, from the Square Kilometer Array to giant optical telescopes (GMT, ELT, and TMT). Such facilities will mutually probe the fastest and closest-in variations in jet activity, and offer the ultimate complement to X-ray’s unrivaled time-domain capability for discerning the inner-reaches at which jets are produced.

**Disk Variability at Critical Timescales**

There are several critical timescales present in accretion flows around compact objects. The shortest of these is simply the dynamical timescale: $t_{\text{dyn}} \approx 1/\sqrt{G\rho}$. The longest is typically the viscous timescale: $t_{\text{visc}} \approx \alpha^{-1} (\frac{H}{R})^{-2} \Omega^{-1}$. For thin disks around stellar-mass black holes, the innermost disk (within a radius $\sim 10 R_g$), the viscous timescale is of order 1s. The corresponding dynamical timescale is thousands of times shorter, of order 1 ms.

Earlier missions have been incapable of constraining the detailed thermal accretion disk spectrum. CCD X-ray imagers are confounded by pileup when observing bright black hole sources. RXTE was virtually immune to pileup, but insensitive to the disk spectrum below the thermal peak. At the same time, precise knowledge of the thermal disk shape is essential for modeling disk structure, and determining the transition between the “thin-disk” models pioneered by Shakura & Sunyaev (1973) and Novikov & Thorne (1973) and the onset of “slim-disk” effects (e.g., Steiner et al. 2010; Sądowski et al. 2011).
Figure 2: (left): A simulated model for neutron star QPOs based on Barret et al. (2005) and Cackett et al. (2008). As the kHz QPO moves around, so too does the inner disk radius. The upper QPO frequency is set by the orbital frequency of the inner disk radius, which is measured via reflection modeling. (right): Joint spectral-timing monitoring constrains frequency and radius at once, resulting in independent measurements of the neutron star mass for each time segment.

Broadband spectral data is required to jointly constrain thermal and nonthermal effects, and sufficient counts to resolve critical timescales which may impact disk structure. For the first time, NICER (Gendreau et al. 2012) is resolving the disk spectrum at the viscous timescale for bright black holes (e.g., MAXI J1820+070, which reached several Crab intensity; Kara et al. 2019). A next-generation instrument with several square meters of effective area offers the incredible capability of reaching the dynamical timescale (count rates of \( \gtrsim 10^6 \text{ s}^{-1} \)) for bright black holes.

**Origin of QPOs**

Quasi-periodic oscillations have been identified in the X-ray light curves of accreting black holes and neutron stars dating back more than 30 years (van der Klis et al. 1985), and yet the physical processes governing them (and even the precise location of those processes) are still a mystery. Low-frequency QPOs (0.1-30 Hz in black holes, 1-200 Hz in neutron stars) and high-frequency QPOs (\( \gtrsim 50 \text{ Hz} \) in black holes, \( \sim 400-1200 \text{ Hz} \) in neutron stars) are hard features - with spectra peaking above 30 keV - but have only been studied below 20 keV thus far due to instrumental constraints.

Low-frequency QPOs in black hole systems are typically strong features (several percent rms amplitude) and are useful probes of accretion; e.g., several models of type-C QPOs relate QPO frequency as tracer of the inner-disk radius (for instance, Rodriguez et al. 2002). But for neutron stars, low-frequency QPO are often drowned in broadband noise. By contrast, high-frequency QPOs are prominent and commonplace in neutron stars, but quite rare (almost certainly owing to
deficient signal-to-noise) for black holes. The best avenue towards improving our understanding of QPO origin is through gains in signal-to-noise, requiring larger effective area, and high throughput.

Studying QPO and broadband noise variability with energy-dependent time lags with a high-throughput large area X-ray timing mission provides a tomographic depiction of variability across different size scales that maps out the disk-jet-corona interrelation. At the extreme end of this, sufficient signal in line signatures from the inner disk near the horizon can reveal dynamic variability which offers the tantalizing capability of opening tests to probe the strong gravity of the Kerr metric directly for X-ray binaries, e.g., via methods like in Jiang et al. (2015).

Spectral-timing techniques such as lag-energy, covariance, and phase-resolved spectroscopy have shown that QPO variability exhibits significant energy dependence (e.g., Morgan et al. 1997). With sufficient gain in signal, established spectral-timing techniques (e.g., the energy-dependent bispectrum; for instance, see Maccarone et al. 2011), which have been out of reach, will be attainable and provide new insight into familiar phenomena.

High frequency QPOs from accreting black holes (above 100 Hz) potentially can provide the cleanest measurements of black hole spins. In several cases, oscillations are seen at frequencies that require a spinning black hole (e.g., Strohmayer 2001). Their frequencies can be measured more precisely, with better understood systematics, than spectral modeling either of fluorescence spectra or disk continua can achieve. At the present time, the spin inferred is highly dependent on which model for interpreting the QPO is used; with certain models, high and low-frequency QPOs can be modeled in concert to jointly constrain both mass and spin (Motta et al., 2014a,b). With a more sensitive timing instrument, additional modes should be detectable, and it should be possible to study the nonlinear interactions between these modes and break model degeneracies (Maccarone & Schnittman, 2005), allowing the most precise timing measurements of the spin to be used. This in turn will allow better calibration of the modeling and detector calibration uncertainties that affect spectral methods which can be applied to a much larger number of sources.

Present boundary-pushing analyses only possible with cutting-edge data can test models of the origins of the QPO signal using phase-resolved line variations, e.g., Miller & Homan (2005); Ingram & van der Klis (2015); Stevens & Uttley (2016), but only at sub-Hz frequencies. It will be game-changing when such analyses become routine, through being applied broadly across wide ranges in brightness and at shorter timescales (smallest length scales) corresponding to the highest QPO frequencies. With gains in collecting area, spectral and timing domains are able to couple together to uniquely probe strong-gravity around black holes and neutron stars. One such novel example is highlighted in Figure 2.

**Summary & Recommendations**

The present and past X-ray instruments have revealed a rich library of spectral and time evolution from the bright and abundant X-ray binary systems in our Galaxy. However, no single mission has offered the optimal combinations of large effective area, high-throughput, precise (µs) time resolution, fine (∼ 100 eV) energy resolution; and broadband – soft and hard – X-ray coverage. All these attributes are important for maximizing the science return of spectral-timing data. At the same time, the dynamic and bright inner-reaches of compact X-ray sources are our richest resource for investigating dynamic accretion, and for testing physics in strong gravity. Our best effort to understand these bright Galactic neighbors demands the deployment of a next-generation large-area spectral-timing mission.
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