The Question of Hard-State Disk Truncation in Black Holes Binaries

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Black Hole Binaries

- Stellar-mass black holes ($\sim 5-30 M_\odot$)
- Modest variability in human timescale
- Many are transient in nature
- Bright outbursts can last several months with up to a billion fold increase in luminosity
- AU-scale persistent jets and parsec-scale ballistic jets
- X-ray QPOs (0.01–450 Hz)
- Distinct spectral states (hard/intermediate/soft)
Motivation

Dramatic spectral changes throughout the outburst!

- Study the accretion properties of Galactic Black Holes using the RXTE archive
- Detailed analysis of individual sources with physically motivated models
- Dynamically track the evolution of key parameters → inner radius

### Motivation

**Nowak**: The Microquasar Cyg X-1

![Figure 1](attachment:image.png)

Figure 1. Cyg X-1 in its two most extreme spectral emission components in the Cyg X-1 system include an accretion disk, a Comptonizing corona (with either a thermal or a power-law spectrum extending to 100 keV), and a mass of 15 M\(_{\odot}\).

**Dramatic spectral changes throughout the outburst!**

- Eddington luminosities of 2 \times 10^9 \rightarrow 2 \times 10^8 \% L\(_{\odot}\), near the so-called 'jet line'.
- The range of bolometric luminosities traversed by Cyg X-1 spans only a factor of 3–4.
- This is somewhat narrow compared to most black hole transients. Furthermore, Cyg X-1 also traverses a narrower range of colors than many black holes, never exhibiting a purely disk-dominated spectrum without a hard tail.

**Abstract**

- **Dynamically track the evolution of key parameters** → inner radius
- **Detailed analysis of individual sources with physically motivated models**
- **Study the accretion properties of Galactic Black Holes using the RXTE archive**
A Hot Corona and a Cold Disk

Figure 2.

![Diagram showing a hot corona and a cold disk. The corona is represented by a yellow cloud with an energy of kT~ 30 keV, and the disk is shown with a temperature of kT~ 0.5 keV.](Gou+11)
Spectral Components

Flux (erg/cm²/s/eV) vs. Energy (keV)

Components:
- Thermal
- Power-law
- Reflection

- Fe K Lines
- Fe K Edge
- Compton Hump

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The radius of the Inner Most Circular Orbit (ISCO) changes monotonically with the black hole spin.
Is the inner radius truncated in the hard state?

The Prototypical BHB GX 339-4

**GX 339-4 + RXTE PCA:** Vast amount of observations in a wide range of luminosities and accretion states. Data is **free of pile-up.**
Excellent constraints on fundamental parameters of the system: BH spin ($a^* = 0.95 \pm 0.04$), inclination ($i = 48 \pm 1$ deg), and Fe abundance ($A_{Fe} = 5 \pm 1$)

Fit with relxill:
- 106 observations
- 77 million total counts
- 0.1% systematic errors!

$\chi^2_{\nu} = 1.06$
For increasing luminosity, the disk’s inner edge moves inward and the corona cools down.

For a $10M_{\odot}$ black hole, these changes in inner-radius correspond to changing from $R_{\text{in}} = 75$ km to $R_{\text{in}} = 30$ km.

(García+15)
Data recalibration with the PCACORR tool (García+14) allows a ten fold increase in sensitivity to the reflection features → increased accuracy!
Location of the Inner Radius

García+15
Including the Disk Emission

* Self-consistent model including disk emission
* Parameters linked to the inner radius and the accretion rate from the soft-state data:

\[ kT_{\text{disk}} = kT_{\text{soft}} \left( \frac{\dot{M}}{\dot{M}_{\text{soft}}} \right)^{3/5} \left( \frac{R_{\text{in}}}{R_{\text{ISCO}}} \right)^{-6/5} \]

\[ N_{\text{disk}} = N_{\text{soft}} \left( \frac{\dot{M}}{\dot{M}_{\text{soft}}} \right)^{-4/5} \left( \frac{R_{\text{in}}}{R_{\text{ISCO}}} \right)^{18/5} \]

RXTE insensitive to the predicted disk emission → Need low-energy coverage from Chandra!
**NuSTAR Sensitivity to $R_{\text{in}}$**

![Graph showing the ratio of simulated NuSTAR spectra to an absorbed power-law model fitted in the 3–4 keV and 7.5–10 keV bands (for a BH with maximum spin). The change with $R_{\text{in}}$ in the reflection line profile is evident.](image)

**Figure 4:** Ratio of simulated NuSTAR spectra to an absorbed power-law model fitted in the 3–4 keV and 7.5–10 keV bands (for a BH with maximum spin). The change with $R_{\text{in}}$ in the reflection line profile is evident.

With our setup established, we present a set of simulated observations in Table 1 and Figure 5. These simulations illustrate two representative and bracketing cases for GX 339–4: catching the peak of its bright hard state, and an observation just over the trigger threshold. In both instances, the simulations are derived using fits to RXTE spectra from García et al. (2015), where different temperature disks result from changing the reflection inner radius. The data are first simulated using the full detector response and then binned to 3-times oversample the detector resolution. The Chandra data are given a 5% systematic uncertainty as described above. We establish the detection significance of the thermal disk by fitting both the self-consistent model which includes the thermal disk emission, and also fitting a standard reflection model which ignores this component. All typical fit parameters are kept free for both fits (i.e., $N_{\text{H}}$, a detector cross-normalization, relxill, and xillver normalizations, the temperature and optical depth of the corona, the reflection fraction, the spectral index, ionization parameter, and Fe abundance.). Both models contain the same number of free parameters, and so the goodness-of-fit comparison is straightforward. We equate a 4 result to a difference in fit $\chi^2$ of 16 or greater. The brightest data, for small $R_{\text{in}}$ achieve a 14 detection of the thermal disk component.

**5 Request Summary**

We request a total of 60 ks of joint Chandra and NuSTAR time, to be divided into a trio of observations during a bright outburst. Each pointing will obtain several million counts in Chandra and $>10^6$ counts in NuSTAR. Based on a recent study of all archival X-ray data for Galactic black hole binaries (Tetarenko et al. 2015), one can expect 2–3 outburst per year. However, since we require the flux to be at least over 100 mCrab, and in the visibility window, we expect a $\sim 40\%$ chance of triggering in a year. Our team will follow new X-ray binary outbursts with X-ray monitors including Swift/BAT and MAXI (and possibly Astrosat’s SSM), and we will activate a trigger upon detecting a rising BH transient crossing 100 mCrab in the hard state. An observing schedule will be coordinated with Chandra and NuSTAR to take place over the ensuing month. We will actively monitor and cancel any exposures if the source declines below threshold or transitions to a soft state (the transition being outside the objective of this proposal).

Our study will achieve one of two outcomes: either (1) we will confirm the presence of the thermal disk and establish that the bright hard state reaches the ISCO (or very near to it) or else (2) we will conclusively rule out a the presence of the thermal disk at radii within tens of $R_g$, and have identified a fundamental problem with reflection modeling. Achieving this firm test requires both Chandra’s low-energy sensitivity and high-throughput CC-mode, in conjunction with the pileup-independent hard X-ray detectors aboard NuSTAR.

**NuSTAR:** Higher spectral resolution than RXTE makes it more sensitive to small changes in the inner radius.
NuSTAR’s bandpass similar to RXTE (also insensitive to the disk emission), whereas Chandra data is highly sensitive to its presence.

Chandra will open a new window into the thermal disk emission in the bright hard state!
Combined RXTE data with 0.1% systematics provide unprecedented precision to measure X-ray reflection from accretion disks.

In the case of GX 339-4 in the hard-state, clear signatures of reflection are observed over a wide range of luminosities (factor of $\sim 20$). The variations in $L/L_{Edd}$ are well correlated with changes in ionization $\xi$.

These fits present evidence of $R_{in}$ moving inwards with increasing luminosity, and possible disk truncation of just a few $R_{ISCO}$ for low $L/L_{Edd}$.

While NuSTAR is currently the best instrument for reflection spectroscopy, only simultaneous Chandra observations will provide a definitive test of the truncation paradigm for the bright hard state.
Backup Slides
Modeling Relativistic Reflection: RELXILL

**RELXILL:** Relativistic reflection model that combines detailed reflection spectra from *xillver* (García & Kallman 2010), with the *relline* relativistic blurring code (Dauser et al. 2010).

![Diagram]

**Model Parameters**
- $a$: Black hole spin
- $R_{in}$: Disk’s inner edge
- $i$: Inclination
- $\epsilon$: Emissivity index
- $R_f$: Reflection fraction
- $\Gamma$: Power-law index
- $E_{cut}$: High-energy cutoff
- $A_{Fe}$: Fe abundance

(García+14b)
Comparing XMM-Newton TM and RXTE PCA

![Graph showing data/model ratio vs. energy (keV).]