The Evolution of Accreting Black Holes in Outburst

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Abstract.
Black hole binaries exhibit dramatic changes in their X-ray spectral and timing properties over time, providing important clues about the physical processes that occur in these systems. Black holes and black hole candidates are prime targets for *RXTE* with observational goals including the study of extreme gravitational fields and jet formation mechanisms. The great wealth of data from *RXTE* has helped us to learn about these systems as well as raising new questions about accreting black holes. *RXTE* observations have allowed us to study a wide range of black hole science topics including the connection between the accretion disk and jets, the geometry of the inner accretion flow, and the physical changes that occur between spectral states. In this presentation, I discuss significant results on these topics that have been obtained for persistent and transient black holes over the past several years, and I present results from our program of X-ray and radio observations during the decays of black hole transient outbursts.

OBJECTIVE

The primary objective of this presentation is to describe our current understanding of the observational properties of black hole X-ray spectra. In addition to describing the phenomenology of black hole spectral states, I discuss physical implications of the observations, including how they may constrain accretion geometries and emission mechanisms. The flexible scheduling and broad bandpass of *RXTE* have been critical to these studies and especially to our group (Tomsick, Kalemci, Corbel, and Kaaret) as we have focused on frequent *RXTE* and radio observations close to state transitions. Much of the recent debate on black holes has been related to the physics of the Hard State, and, here, I provide a summary of how the predictions of the current theoretical models compare to observations. This presentation includes some discussion of black hole X-ray timing and radio emission, but these topics are dealt with in more detail by others in these proceedings (see papers by Remillard and Corbel). Finally, I discuss the instrumental capabilities that will be important in future studies of black hole spectra.

BLACK HOLE SYSTEMS OBSERVED BY *RXTE*

During the *RXTE* lifetime (1996-present), 28 accreting black hole or black hole candidate systems have been observed in outburst. Compact object mass measurements were obtained, via optical or infrared observations, for 11 of these systems, and the masses are higher than $3\,M_\odot$, the theoretical mass upper limit for neutron stars, in all of these. Eight of the 28 sources have been in outburst for the entire *RXTE* mission, and Figure 1 shows an example light curve for one of the "persistent" sources (Cyg X-1). Four of the sources have had multiple outbursts between 1996 and now, and the light curve for the most active "recurrent transient" (4U 1630–47) is shown in Figure 1. The other 16 sources have had only one outburst observed by *RXTE*, but it should be noted that several of these sources had outbursts before 1996 [1] and are known to be recurrent.

SPECTRAL STATES

Although the energy spectra of accreting black holes are complex, they are dominated by two emission components: a soft thermal component and a hard power-law or cutoff power-law component extending to hundreds of keV. The soft component is very likely blackbody emission from an accretion disk, and the disk may have properties similar to (or the same as) a Shakura and Sunyaev [2] disk. Spectral states are defined, in large part, based on the relative strength of the two components. Recently, the large number of *RXTE* observations of accreting black holes in various spectral states were used to quantitatively define the spectral states [3]. In addition to giving the most precise spectral state definitions to date, McClintock and Remillard [3] considered the fact that there are many examples (see below) for which the tradi-

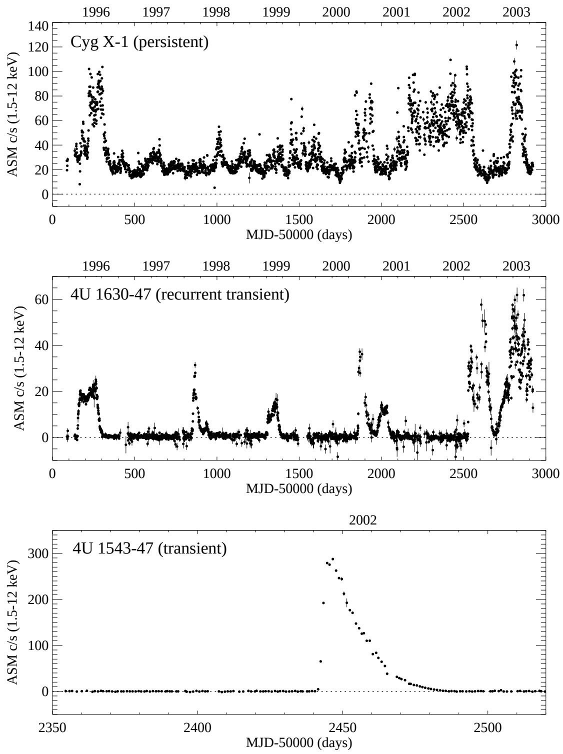

FIGURE 1. X-ray light curves for accreting black holes from the *RXTE* All-Sky Monitor. The energy band is 1.5-12 keV, and each point represents the average count rate over 1 day. The top two panels show the light curves for a persistent source (Cyg X-1) and a recurrent transient (4U 1630–47) over the entire *RXTE* mission to date. The bottom panel shows a single outburst from a transient source (4U 1543–47).

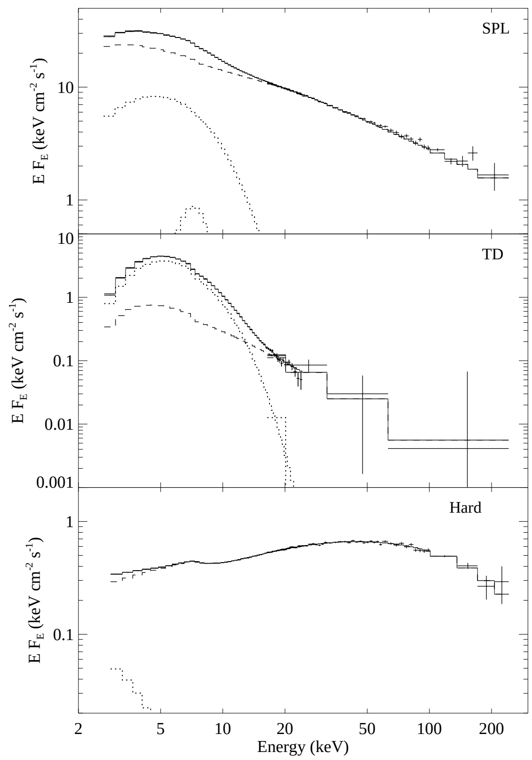

FIGURE 2. Examples of *RXTE* (PCA+HEXTE) energy spectra of black hole systems in the Steep Power-Law, Thermal Dominant, and Hard states. In each panel, the soft disk component (dotted line), power-law or cutoff power-law component (dashed line), and the total model spectrum (solid line) are shown. The SPL spectrum is from a 1996 observation of GRO J1655–40. Note that an iron Kα line is also included in the model (see the paper by Rothschild et al. in these proceedings). The TD spectrum is from a 1996 observation of 4U 1630–47. The Hard spectrum is from a 2001 observation of XTE J1650–500.

tional luminosity-based state names are not appropriate and re-named the spectral states. A listing of the three outburst states and their general properties follow [see 3, for the complete quantitative definitions of the states]. Figure 2 shows examples of spectra for sources in these three states.

- The **Steep Power-Law (SPL)** state was formerly known as the Very High state. Both disk and power-law components are usually present in this state, and a source is said to be in the SPL state if either the power-law accounts for more than 50% of the 2-20 keV flux or if quasi-periodic oscillations (QPOs) are present and the power-law accounts for more than 20% of the 2-20 keV flux. In this state, the power-law component has a photon index of $\Gamma > 2.4$.
- The **Thermal-Dominant (TD)** state was formerly known as the High-Soft state. The disk component dominates the X-ray spectrum, accounting for more than 75% of the 2-20 keV flux. The level of timing noise in this state is usually very low.
- The **Hard** state was formerly known as Low-Hard state[1]. The power-law, with $1.5 < \Gamma < 2.1$, dominates in this state, accounting for more than 80% of the 2-20 keV flux. There is a high level of timing noise, and radio emission, likely from a compact jet, is typical of this state [4].

An "Intermediate State" has also been defined as one of the canonical black hole spectral states [5]; however, the only property that clearly separates this state from the SPL state is that the Intermediate State has traditionally been used to describe black holes at lower luminosity. Thus, the argument that the states are not strictly dependent on luminosity makes this state, as canonically defined, unnecessary. However, there are times, especially during state transitions, where the source properties do

[1] Even McClintock & Remillard (2003) continued to use the old terminology for this state, but several examples indicate that the "Low-" should be dropped.

not fit into the SPL, TD, or Hard states, and I agree with the suggestion of McClintock and Remillard [3] that the states that show various combinations of SPL, TD, and Hard state properties be referred to as intermediate states.

There is a final state that is simply defined by (low) luminosity called the "quiescent" state. For black hole systems, a source is typically said to be in quiescence if its X-ray luminosity is in the 10^{30-33} erg s^{-1} range [6, 7, 8]. However, due to the relatively poor statistical quality of the low luminosity observations, it is difficult to determine if there are other source properties that distinguish quiescent properties from Hard state properties, and, below, I discuss this issue further.

EXAMPLES OF LUMINOSITY INDEPENDENCE OF STATES

Here, I provide some examples of sources that exhibit X-ray properties that fit in well with the standard spectral state definitions outlined above, but do not show the luminosity dependence that is considered to be typical. This is not meant to be an exhaustive list, but I simply discuss some of the clearest examples. It has long been known that some sources exhibit "Hard state outbursts" where they reach high luminosities, but remain in the Hard state. The most dramatic example of this behavior is seen from V404 Cyg (= GS 2023+338), which remained in the Hard state while reaching a luminosity of $\sim 2 \times 10^{39}$ erg s^{-1}, assuming a distance of 3.5 kpc [9]. A more recent example is the behavior of XTE J1650–500 as this source began its outburst in the Hard state and remained in the hard state for two weeks (see Figure 3), during which time the 3-20 keV luminosity peaked. The source eventually made a transition to the SPL and TD states [10], and, later in the outburst, the source showed a transition back to the Hard state [11, 10]. *Chandra* observations occurred near the end of the outburst, showing that the source exhibited Hard state properties at a luminosity of 9×10^{34} erg s^{-1} [12]. Overall, XTE J1650–500 exhibited Hard state properties over a range of three orders of magnitude in X-ray luminosity. Another excellent example of luminosity independence comes from a study of a full outburst from XTE J1550–564 [13]. The hardness-intensity diagram for XTE J1550–564 indicates that this source can enter the Hard state, the SPL state, or various intermediate states over a large intensity range. Other examples include GRS 1758–258 and 1E 1740.7–2942, which show transitions from Hard to TD states as the source luminosity drops [14, 15]. Also, Cygnus X-1 [16] and SAX J1711.6–3808 [17] illustrate the luminosity independence of spectral states.

In addition to being important for determining the most meaningful classification of spectral states, this

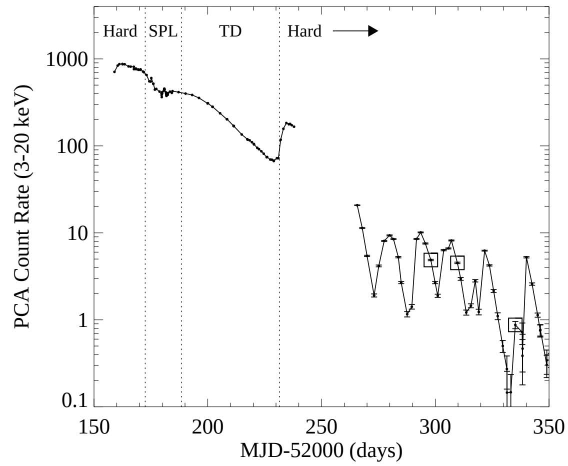

FIGURE 3. The 3-20 keV light curve for XTE J1650–500 during its 2001-2002 outburst. Each point shows the Proportional Counter Array (PCA) count rate from a pointed *RXTE* observation. The gap in coverage centered at MJD 52,250 is due to a sun angle constraint. More details about the 14 day oscillations that occurred after the sun gap are presented in Tomsick et al. [18]. The three squares during this part of the outburst mark the times of *Chandra* observations. XTE J1650–500 exhibited Hard state properties at luminosities ranging over three orders of magnitude.

luminosity independence implies that the states are not simply set by the mass accretion rate. As discussed by Homan et al. [13] and others, this indicates that another physical parameter that is not directly tied to the mass accretion rate must be important in setting the emission properties. Although there have been suggestions for what this second parameter might be, such as the inner radius of the optically thick accretion disk (R_{in}), the size of the corona, or the jet power, it is currently unclear which of these parameters cause significant changes in the X-ray emission properties.

X-RAY PROPERTIES AND PHYSICAL IMPLICATIONS

In this section, I describe the specific observational properties of different phases of the evolution of accreting black holes and discuss the physical implications of the observations. The different evolutionary phases include: states that typically exhibit a significant or dominant soft component (SPL and TD); transitions to the Hard state; and the Hard state.

Steep Power-Law and Thermal-Dominant States

The SPL and TD state spectra both typically include a significant contribution from an optically thick disk, but, with the stronger power-law component in the SPL, a third "reflection" component arises due to the hard flux illuminating the accretion disk [19]. The two main features of the reflection component are an iron Kα emission line near 6.4 keV and a "reflection bump" between 10 and 100 keV, and, for many broadband black hole spectra, these features are present [e.g., 20]. Recent observations by *Chandra* and *XMM-Newton* [e.g., 21] indicate that many black hole systems have an intrinsically broad iron line, and the broadening is interpreted as being caused by a redshift due to the black hole's gravitational field. The inner radii inferred from spectral modeling of the broad lines provides sone of the strongest evidence that the inner radius of the disk reaches the Innermost Stable Circular Orbit (ISCO). Other evidence that the disk extends close to the black hole comes from the detection of high frequency quasi-periodic oscillations (QPOs), which are only seen in the SPL state (see the paper by Remillard in these proceedings), and also from modeling the soft spectral component using a Shakura and Sunyaev [2] model (although it has been shown that, in some cases, the inner radii inferred from such fits give unphysically small values).

While there is a relatively good understanding of the origin of the soft component and of the geometry of the optically thick portion of the accretion flow, the origin of the power-law component is currently unclear. However, the fact that the power-law in the SPL state can extend up to energies approaching at least 1 MeV [e.g., 22] indicates that a non-thermal electron energy distribution is required. Understanding the production of this component in detail is an important, unsolved problem (see the paper by Coppi in these proceedings for more on this issue).

Transitions to the Hard State

A main focus of our group has been to measure the properties of accreting black holes in X-rays with *RXTE* and in the radio band close to state transitions. Frequent (e.g., daily) monitoring is critical for this study because it is known that state transitions can occur on time scales of days [23]. The most accessible and reliable state transition is the transition from the TD or SPL state to the Hard state at the ends of transient outbursts, and performing radio observations close to such a transition is especially interesting for understanding the compact jet turn-on.

Using our observations as well as observations from the *RXTE* archive, Kalemci [24] analyzed data from observations of 16 outbursts from 11 different sources, and, in eight cases, good *RXTE* coverage was obtained close to the state transition. The data are shown in the paper by Kalemci et al. in these proceedings, and I summarize some of the basic results here. The sharpest changes were seen in the timing properties, with sources typically showing a change from a very low, undetectable, level of timing noise to an RMS level of tens of % in less than a day. It is clear that the timing noise can turn on very rapidly in these systems. While the timing changes are very sharp, gradual changes are seen in the spectral parameters, including the power-law photon index, Γ, and the temperature at the inner edge of the accretion disk, $kT_{\rm in}$. Finally, a very large drop in the 3-25 keV flux of the soft component is apparent, and, typically, this component becomes undetectable after the transition.

The sharp timing transition that is seen provides a clearly defined transition time, and Figure 4 shows radio measurements that were made close to this time for four systems. For 4U 1543–47, XTE J1550–564, and XTE J1650–500, we obtained radio detections after the state transition. For 4U 1630–47, we obtained an upper limit very close to the time of the state transition. The most interesting case is 4U 1543–47 because, when our data are combined with the measurements reported by Park et al. [25], very good radio coverage was obtained. For this source, the radio emission increased, but not until 8-12 days after the state transition (see also the paper by Buxton et al. in these proceedings for information on the behavior of 4U 1543-47 during this time in the infrared). Our analysis of the *RXTE* data for 4U 1543–47 indicates that the first radio detection occurred about the time that the source reached the true Hard state as indicated by Γ reaching its hardest value of about 1.6 (Kalemci et al., in preparation). This suggests that the processes that lead to an increase in timing noise do not automatically result in jet production, and re-enforces the connection between jets and the hardness of the X-ray spectrum [e.g., 26].

Hard State

A current topic of debate concerns the questions of what is the X-ray emission mechanism and what is the source geometry in the Hard state. The standard picture is that the cutoff power-law is produced by inverse Comptonization from a thermal distribution of coronal electrons where the coronal temperature is close to the cutoff energy. While the energy spectrum is well-described by thermal Comptonization, the discovery that a compact jet is present in the Hard state has led to the question of whether at least some of the X-ray emission could be produced in the jet, and jet-based synchrotron [28] and

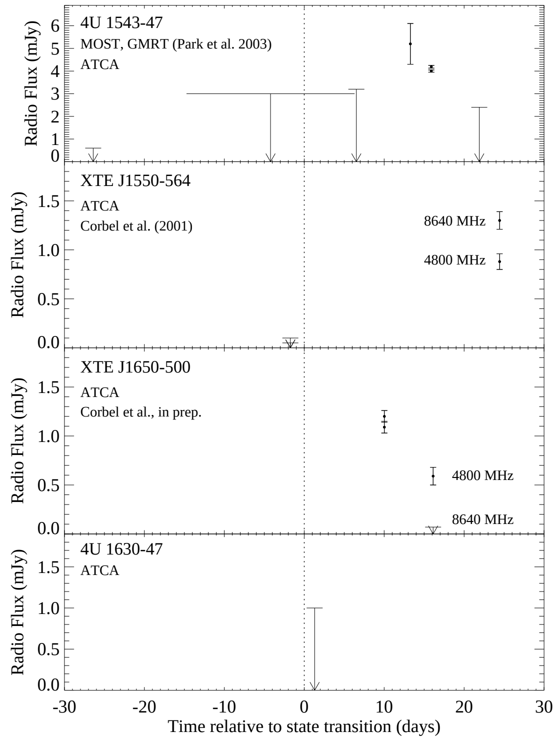

FIGURE 4. Radio observations of black hole transients made close to the times of transitions to the Hard state during outburst decay. For each source, the dotted line marks the sharp change in the level of the RMS timing noise (see the paper by Kalemci in these proceedings). 4U 1543–47 has the best coverage when our radio data is combined with data from Park et al. [25]. The radio flux does not increase until 8-12 days after the increase in the RMS noise. The XTE J1550–564 points were previously published in Corbel et al. [27].

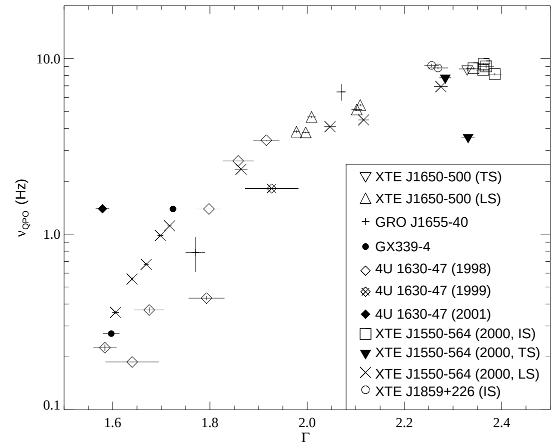

FIGURE 5. The QPO frequency vs. the power-law photon index (Γ) for six different black hole transients during outburst decay [from 24]. This illustrates the gradual drop in the QPO frequency as the sources enter the Hard state, and shows that these sources all lie on approximately the same correlation.

Compton [29] models have been investigated.

One specific issue concerning the source geometry is whether the inner radius of the optically thick accretion disk increases in the Hard state. One might think that the drop in flux and temperature of the soft component during and after the transition to the Hard state described above demonstrates that $R_{\rm in}$ increases; however, other possibilities have been suggested such as the idea that the inner disk remains intact, but, in the Hard state, the viscosity mechanism in the inner disk turns off and the accretion energy goes into producing the jet or heating the corona rather than being radiated away in the inner disk [30]. Still, even if the inner disk does not radiate efficiently, one might expect to see a reflection component if the inner disk remains at the ISCO. Studies of the strength of the reflection component have been carried out, showing a large decrease in the strength of the reflection component as Γ becomes harder when the source passes through intermediate states on its way to the hard state [31, 32]. While the trend in the strength of the reflection component is consistent with an increase in $R_{\rm in}$, other possible explanations for the trend include ionization of the inner part of the disk [33], but also see [34], or beaming of emission away from the disk [35].

While the evolution of the soft component and the reflection component do not provide a definitive answer to the question of how $R_{\rm in}$ evolves, it is notable that changes in both of these components are well-explained by an increasing $R_{\rm in}$. Furthermore, an increasing $R_{\rm in}$ can provide a rather natural explanation for observed changes in timing properties. As shown in Figure 5, the black hole sources appear to show a uniform drop in QPO frequency as Γ hardens [24], and similar trends have been reported for either QPO frequencies or break frequencies in the power spectrum in other work [36, 37, 38, 39]. An increasing $R_{\rm in}$ may help to explain these trends as it provides an increasing dynamical time scale in the system.

Recently, we used *RXTE* and *Chandra* observations of XTE J1650–500 to show that the trend of characteristic frequencies dropping with luminosity extends to very low luminosities near 1×10^{34} erg s^{-1} as shown in Figure 6 [12]. We detect a change in the break frequency by a factor of $\sim$1200 between the transition to the Hard state and the lowest luminosity we sampled, and if this is set by a dynamical time scale that is determined by the inner radius of the disk, the implication is that $R_{\rm in}$ increases by a factor of $\sim$110. The power spectra we measure for XTE J1650–500 at low luminosities are consistent with the standard broken power-law or zero-centered Lorentzian models that are typically used to fit Hard state power spectra [12], and it is interesting that optical observations

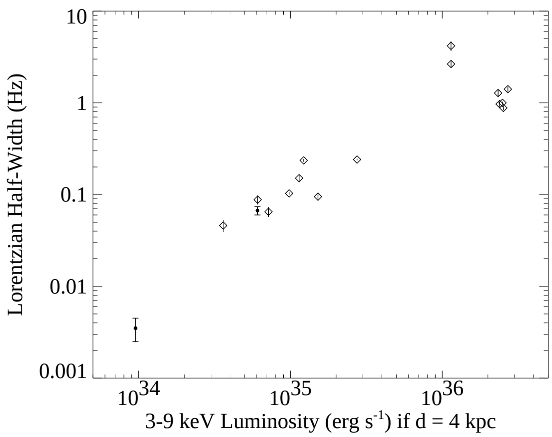

FIGURE 6. The Lorentzian Half-Width (approximately the "break frequency" described in the text) for the continuum component in the power spectrum vs. the source luminosity for the black hole candidate XTE J1650–500 in the Hard state [see 12]. Observations come from *RXTE* (diamonds) and *Chandra*.

of other black hole systems in quiescence show similar power spectra but with even lower break frequencies [see 40, and the paper by Shahbaz et al. in these proceedings]. Although we are comparing optical and X-ray properties, the similar timing properties suggest that black hole transients have the same overall structure and that the same physical processes are operating in the Hard state and in quiescence [12]. Furthermore, the fact that the quiescent energy spectra of black holes exhibit a component at optical and UV energies that may be caused by thermal emission from a truncated disk [41] underscores the idea that physical properties change gradually as the source luminosity drops in the Hard state and quiescence but that the overall structure does not undergo a major transition.

THEORETICAL MODELS FOR THE HARD STATE

Table 1 compares the predictions of three different theoretical pictures for the Hard State to observational properties. In the "Sphere+Disk" model, the accretion disk is truncated at some value of R_{in} and a spherical corona is present for radii closer to the black hole [42, 43]. The "Slab" model is typically envisioned as an optically thick disk extending close to the ISCO with active regions above the disk acting as the corona to produce the hard X-ray emission [44]. While the emission mechanism for these first two models is inverse Componization, the third, which is the X-ray jet model, produces emission via a synchrotron mechanism [28].

With the additional free parameter, R_{in}, the Sphere+Disk (SD) model provides a natural explanation for the reflection strength vs. Γ and characteristic frequency vs. Γ correlations described above. In addition, the luminosity independence of states argues for the addition of a parameter that may not be directly tied to mass accretion rate. However, while there is observational evidence that jets are present in the Hard state[2], jets have not been incorporated into SD models such as the Advection-Dominated Accretion Flow (ADAF) model. It has previously been suggested that accretion energy in the Hard state might be used to power a jet [45, 46], but it is not clear if, e.g., the Advection-Dominated Inflow-Outflow Solution (ADIOS) can explain the Hard state radio emission.

For the Slab model, it has been demonstrated in more detail that a magnetic corona can drive a jet [49]. However, in this model, explanations for the reflection and frequency vs. Γ correlations are unclear. Perhaps the size of the corona changes, but more work is necessary to determine if the correlations can be reproduced within this model. A significant point in favor of the X-ray jet model is that it can explain, in detail, the reported correlations between X-ray and radio flux [see 50, and the paper by Corbel in these proceedings]; however, similar X-ray/radio flux correlations may arise in more general situations with non-X-ray-emitting jets [51]. More work is necessary to determine if a synchrotron X-ray jet is viable. As shown in Zdziarski et al. [32], a synchrotron cutoff is expected to be more gradual than the exponential cutoffs that are typically observed in black hole spectra. Also, as discussed in Tomsick et al. [12], it is not clear if the X-ray jet model can reproduce a change in the characteristic frequencies of the system by a factor of 1200 since this would seem to imply a very large change in the location of the shock that produces the high energy electrons that give rise to X-ray emission.

BEYOND *RXTE*

Studies of black hole X-ray spectra require a broad bandpass as well as flexible scheduling due to the rapid evolution that these sources can exhibit. With the combination of an all-sky monitor, instrumentation (PCA and HEXTE) covering the 3-200 keV energy range, and a dedicated Project Scientist and scheduling team, *RXTE* has been an excellent tool for research on black hole spectra.

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[2] Steady, compact radio jets have been resolved in the Hard state for GRS 1915+105 and Cyg X-1 [47, 48]. The radio emission from other Hard state systems is likely also from unresolved jets.

TABLE 1. Comparison between Models and Observational Properties

Model	Spectral Continuum (2-20 keV)	Spectral Continuum (20-200 keV)	Correlations (Reflection and Frequency)	Jet	Radio/X-Ray Correlation
Sphere+Disk (e.g., ADAF) Dove et al. [42] Esin et al. [43]	Yes	Yes	Yes	No (ADIOS?)	?
Slab (e.g., Magnetic Corona) Galeev et al. [44] Merloni and Fabian [49]	Yes	Yes	?	Yes	Yes?
X-Ray Emitting Jet Markoff et al. [28]	Yes	?	No?	Yes	Yes

An instrument with an even larger effective area, as has been discussed at this meeting, would be useful for spectral studies. Black hole systems are highly variable, and a larger area would allow for high quality spectra to be obtained over a shorter period of time. For example, it may be possible to study spectral evolution on sub-second time scales when QPOs are present. Also, a larger effective area above ∼50 keV would allow for detailed studies of the evolution of the high energy component. Although I have not discussed measurements of time lags and coherence, our group's observations of sources during state transitions indicate that these parameters provide useful information on the physics of the system [11], and a larger area would be very beneficial to such measurements.

The spectra shown in Figure 2 show that the *RXTE* bandpass captures the two primary spectral components, but it should be noted that important information would be lost with a reduced bandpass. Background is another consideration as the transition to the Hard state during outburst decay can occur at 3-25 keV flux levels below 1×10^{-9} erg cm^{-2} s^{-1} even for relatively nearby systems with distances of a few kpc. A significantly higher background level could limit black hole studies to the brightest portions of the outburst. Finally, as most X-ray binaries are in the Galactic plane, source confusion is a concern for studying fainter sources, and this can be problematic for *RXTE*, given the 1° radius (FWZI) field of view. A smaller field of view could be beneficial for studies of fainter sources in the Galactic plane.

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