ANTICORRELATED HARD X-RAY TIME LAGS IN GALACTIC BLACK HOLE SOURCES

K. Sriram
Department of Astronomy, Osmania University, Hyderabad-500007, India; astrosriram@yahoo.co.in

V. K. Agrawal
Tata Institute of Fundamental Research, Mumbai-400005, India

Jayant K. Pendharkar
Department of Astronomy, Osmania University, Hyderabad-500007, India

AND

A. R. Rao
Tata Institute of Fundamental Research, Mumbai-400005, India
Received 2006 June 9; accepted 2007 February 23

ABSTRACT

We investigate the accretion disk geometry in Galactic black hole sources by measuring the time delay between soft and hard X-ray emissions. Similar to the recent discoveries of anticorrelated hard X-ray time lags in Cygnus X-3 and GRS 1915+105, we find that the hard X-rays are anticorrelated with soft X-rays with a significant lag in another source, XTE J1550–564. We also find the existence of pivoting in the model-independent X-ray spectrum during these observations. We investigate time-resolved X-ray spectral parameters and find that the variation in these parameters is consistent with the idea of a truncated accretion disk. The QPO frequency, which is a measure of the size of truncated accretion disks, also changes, indicating that the geometric size of the hard X-ray emitting region changes along with the spectral pivoting and soft X-ray flux. A similar kind of delay is also noticed in 4U 1630–47.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (XTE J1550–564, 4U 1630–47) — X-rays: binaries

Online material: color figures

1. INTRODUCTION

Galactic black hole candidate sources provide a unique platform for studying the behavior of ambient accreting material in intense gravitational fields. The spectral and timing analysis of accreting black hole sources gives information about the underlying physical phenomena and dynamics of the accretion disk, which in turn helps in unfolding the nature of the central black hole. The emission properties of the accreting black holes are often classified and constrained in terms of different spectral states (Esin et al. 1997). Timing analysis also plays a key role in uncovering the geometry of the disk, especially the study of quasi-periodic oscillations (QPOs). In a recent review, McClintock & Remillard (2004) used both spectral and timing information to constrain the physics and geometry of the accretion disk. Canonically speaking, the different spectral states are different permutations of two spectral components, a thermal component (soft photons), presumably originating from an optically thick disk, and a Comptonized component (hard photons), which is thought to be the result of inverse Compton scattering of soft photons by high-energy electrons (Shapiro et al. 1976; Sunyaev & Titarchuk 1980). The coupling of a jet and the accretion disk in various spectral states of different Galactic black hole systems (Fender et al. 2005, 2006) provided a new insight into the accretion disk geometry, and there have been attempts to explain some parts of the observed X-ray spectrum as arising from jet emission (Vadawale et al. 2001; Markoff & Nowak 2004; Markoff et al. 2005).

The bulk of the X-ray emission, particularly in the very high state (or the steep power law state), however, is thought to be due to Comptonization (see Done & Kubota [2006] for a comparison of Comptonization and synchrotron models). The exact mechanism and geometry of this Comptonization process, however, are still to be revealed. There are various models that account for the presence of the hard component in the broadband spectra of Galactic black hole candidates, the most favored being a hot quasi-spherical cloud inside a truncated disk (Zdziarski et al. 2002). Among different theoretical models, advection-dominated accretion flow (ADAF; Narayan & Yi 1994) and two-component accretion flow (TCAF; Chakrabarti 1996) predict that the disk truncation radius determines the segregated spectral states in Galactic black hole sources.

Recently, two sources, Cyg X-3 and GRS 1915+105 (Choudhury & Rao 2004; Choudhury et al. 2005), provided support for the truncated accretion disk scenario on the basis of the detection of an anticorrelation between soft (2–7 keV) and hard X-ray photons (20–50 keV), delayed by a few hundred seconds. These sources also showed a pivoting behavior in the model-independent spectrum. Here the hard lag implies that hard photons are lagging the soft photons on timescales of 10 s and 100 s. The anticorrelated hard lag is defined as an opposite and delayed change in hard flux, corresponding to a change in soft flux. The anticorrelated delay (Choudhury et al. 2005) in GRS 1915+105 was discovered in the variability class C when the source was in the spectral state C (Belloni et al. 2000), which is also classified in the literature as the steep power law (SPL) state (McClintock & Remillard 2004), the very high state (VHS), or the hard intermediate state (HIMS). The wide-band X-ray spectrum shows an additional spectral component (apart from the canonical disk blackbody and a thermal Compton spectrum), which can be modeled as an additional power law (Rao et al. 2000) or as due to Comptonization from electrons having a nonthermal power-law energy distribution (Zdziarski et al. 2001). The recent discovery of a “jet line” in
the hardness-intensity diagram of black hole sources, indicating the onset of superluminal jet emission during a particular region of HIMS (Fender et al. 2004), underlines the importance of understanding the detailed accretion disk geometry in such states. From this perspective, using the hard X-ray delays and constraining the parameters of a truncated accretion disk has the potential to unravel the elusive disk-jet connection.

Recently, Done & Kubota (2006) made a detailed wide-band spectral fitting to the VHS state of the source XTE J1550–564 during the 1998 outburst and obtained different geometric configurations of the thermal disk and the corona. They find that, compared to the high soft state of the source, the thermal disk has either reduced its size or changed its emission properties (or both), and the geometry of the corona is constrained to be within a truncation radius.

We have searched for anticorrelated hard X-ray delays in this source in order to confirm the robustness of the truncated accretion disk paradigm. 4U 1630–47 is another source which shows a behavior pattern similar to GRS 1915+105 and Cygnus X-3, and we have searched for delays in this source too.

XTE J1550–564 is a well-known microquasar with an identified late-type subgiant (G8 IV–K4 III) optical companion star. The mass of the black hole is 10.0 ± 1.5 M_☉, and the binary inclination is 72° ± 5° (Orosz et al. 2002). It was discovered by the All-Sky Monitor (ASM) onboard the Rossi X-ray Timing Explorer (RXTE) on 1998 September 7, just after an outburst which began on 1998 September 6 (Smith et al. 1998). A few days later (1998 September 19), a radio flare associated with a strong X-ray flare was detected, revealing a relativistic jet when the X-ray source was in the very high state (VHS; Hannikainen et al. 2001). A steady jet was discovered during the 2000 outburst, but this time the source was in the low hard state (Corbel et al. 2001). Correlation studies between quasi-periodic oscillations (QPOs) in the range of ~0.08–22 Hz and spectral parameters (multitemperature blackbody disk and power-law component) indicate that the production of QPOs is intimately tied to both disk and power-law components and is linked with the overall emission properties of the source (Sobczak et al. 2000). Detection of high-frequency QPOs (~185 and 276 Hz; Remillard et al. 1999, 2002) in XTE J1550–564 and GRS 1915+105 (~166 Hz; Belloni et al. 2006) and the relationship of 1–15 Hz QPOs with spectral parameters indicates an identical accretion disk geometry in these two sources (Markwardt et al. 1999).

Since its discovery by Uhuru in 1972, 4U 1630–47, a recurrent X-ray transient (Jones et al. 1976) located in the direction of the Galactic center, has shown all the different types of spectral states and a power density spectrum (PDS) like other black hole binaries, and hence it is considered a strong black hole candidate source (McClintock & Remillard 2004). The light curves of 4U 1630–47 show different types of high amplitude variability, classified in four different classes (Tomsick et al. 2005), but the diversity of these variabilities is less than that seen in the extremely variable source GRS 1915+105 (Belloni et al. 2000). On several occasions, a very high disk temperature (Tomsick et al. 2005), as well as polarized radio emission, were seen in 4U 1630–47 (Hjellming et al. 1999), indicating the presence of relativistic jet emission, similar to the superluminal radio emitting jets seen in GRS 1915+105.

Here we report the discovery of an anticorrelated hard X-ray delay between soft- and hard-energy photons for both these sources. Paramount importance is given to knowing the exact variation in the physical parameters, and hence unfolded spectra are compared with that from GRS 1915+105, obtained during the observation of delayed hard X-ray emission. Spectral study is also supported by a minute change in centroid frequency (~0.1 Hz) of the fundamental and the first harmonic of the QPOs in XTE J1550–564.

2. DATA REDUCTION AND ANALYSIS

We have used data from observations using the Proportional Counter Array (PCA; Jahoda et al. 2006) and the High-Energy X-ray Timing Experiment (HXTE; Rothschild et al. 1998) aboard the RXTE satellite to carry out a detailed temporal and spectral analysis. Done & Kubota (2006) have analyzed simultaneous ASCA and RXTE data on XTE J1550–564 and found evidence for an inner corona coupled energetically to the disk. We have chosen the RXTE observations used in that work to look for anticorrelated delay. There were five pointed observations on three occasions, 1998 September 12 and 1999 March 17 (MJD 51068, MJD 51079, and MJD 51254). The X-ray spectrum from the second data set shows strongly Comptonized VHS (Kubota & Done 2004). We have used Standard 2 data and have followed all the procedures for data filtering, background, and dead-time corrections (the data were obtained from all the PCUs that were “on”).

HXTE detectors switch between background and source positions. During our observations, two-sided rocking with 32 s rocking intervals was selected. We used the FTOOLS command hxtback to separate background and source data. We created source and background light curves using a bin size equal to the rocking interval (32 s) and applied the dead-time correction to both the light curves. For the timing analysis, we rebinned the light curve by a factor of 4 (128 s), thus ensuring that the source and background counts were averages of two rocking intervals. For the present work, we use data only from HXTE cluster A, which has better sensitivity than HXTE cluster B.

To take care of the calibration uncertainties, 0.5% systematic errors are added to the PCA spectrum. We have obtained the PDS for both the sources from generic bin mode and single bit mode covering 2–20 keV and 20–50 keV energy band with a 1 ms bin size. Tomsick et al. (2005) have presented a detailed analysis of RXTE data during 2 years of X-ray activity of 4U 1630–47. We have chosen 34 observation from MJD 52790–52849, when 4U 1630–47 was in the outburst state and the data were not contaminated by nearby sources. Generally, it was found that during these observations, PCU 2 was “on” for a maximum duration, and hence we have used PCU 2 for obtaining the light curves and the spectra. The data reduction and analysis were done using HEASOFT.
Fig. 1.—Light curves and corresponding cross correlation between the soft and hard X-ray flux in 4U 1630–47 and XTE J1550–564.

Fig. 2.—Pivoting of the X-ray spectrum during the observations of anticorrelated hard X-ray delays in XTE J1550–564 on two occasions. The left panel (ObsID 30191-01-09-00) shows a clear pivoting pattern around ~8–11 keV. The right panel (ObsID 30191-01-09-01) shows change in the normalization around ~10 keV and merging of individual spectra at higher energies. [See the electronic edition of the Journal for a color version of this figure.]
3. HARD X-RAY DELAY

During these observations, XTE J1550–564 was in an outburst state and spectrally in the very high state or steep power law state (VHS or SPL). After obtaining the background-subtracted light curves, we started with cross-correlating the soft X-ray light curves (2–5 keV) and hard X-ray light curves (20–50 keV) using the crosscor program. The crosscor program performs cross-correlation on two simultaneous time series by using a fast Fourier transform algorithm, and the output is given as the cross-correlation value as a function of time delay. The cross covariances are obtained by normalizing the cross-correlations by dividing by the square root of the product of the number of good new bins of the pertinent light curves. To calculate the observed delays and their uncertainties, we have fitted an inverted Gaussian function to the anticorrelated hard delay part of the cross-correlation. Out of five observations, two clearly show anticorrelated hard X-ray delays of the order of a few hundred seconds (see Table 1). Similarly, 4U 1630–47 was also in an outburst state and spectrally mostly in the SPL (steep power law) state and IS (intermediate state), spending the least amount of time in the TD (thermal dominated) state. Performing a similar procedure of timing analysis, we found that the majority of them show a sharp positive correlation with no measurable delay, except for a few ObsIds which show some anticorrelated hard delay. For one observation (ObsID 80117-01-01-01, which shows a minute but considerable signature of delay), we obtained the background-subtracted light curves in different energy bands (2–5 keV, 5–10 keV, . . . , 25–30 keV) and found an anticorrelated hard delay (~360 s) between the 2–5 keV and 25–30 keV energy bands, and this particular observed delay was further supported by HEXTE analysis. The cross-correlation values, as a function of delay, are shown in Figure 1, along with the relevant light curves. To emphasize the reality of the delay seen in 4U 1630–47, analysis results from HEXTE observations are shown. The observed delays are given in Table 1, along with the 90% confidence errors (obtained by the criterion of $\Delta \chi^2 = 2.7$ for an inverted Gaussian fit to the data).

4. SPECTRAL EVOLUTION

Since the anticorrelated hard X-ray delay could cause a pivoting pattern in the spectrum in a single observation, as observed in Cyg X-3 and GRS 1915+105 (Choudhury & Rao 2004; Choudhury et al. 2005), we divided the first (ObsID 30191-01-09-00) and second (ObsID 30191-01-09-01) observations of XTE J1550–564 into two parts and extracted the spectra covering the 2–50 keV energy band. The observed spectra are shown in Figure 2. Inspection of the model-independent spectra for the first observation (Fig. 2, left panel) reveals a sharp pivoting around 8–11 keV. In the case of the second observation, a marginal pivoting around 20 keV is observed. It is also noted that for the second observation, the spectra merge above 20 keV, similar to that observed in GRS 1915+105 during MJD 50,729 (Choudhury et al. 2005; see Fig. 3). We argue that the pivoting/marginal pivoting in the spectrum is due to hard lags in the truncated accretion disk scenario. Koerding & Falcke (2004) showed that the lag patterns in Cyg X-1 can be reproduced with a simple pivoting power law.

To discover the change in the spectral parameters during these observations, we extracted the spectrum at two different parts of the observation (initial and final 300 s of the light curve). We used a multicomponent model that includes a disk blackbody (Makishima et al. 1986) plus a thermal Comptonization model (Zdziarski et al. 1996; thcomp) plus a power law to take care of...
high-energy nonthermal photons (diskbb+thcomp+powlaw) and a smeared edge to mimic the reflection component (Ebisawa et al. 1994), along with a narrow Gaussian line. Since the spectral resolution of PCA is not good enough to constrain all the parameters, we have closely followed the spectral model derived from the superior ASCA+RXTE simultaneous data (Done & Kubota 2006). Furthermore, the value of the absorption column density, power-law index, and Gaussian line energy were frozen (\(N_H = 0.70 \times 10^{22} \text{ cm}^{-2}\), \(\Gamma_{PL} = 2.2\), and \(E = 6.5 \text{ keV}\)). The source was in a strongly Comptonized very high state during these observations, typically showing a disk temperature \(~80 \text{ keV}\), \(\Gamma_{th} \sim 2.32\)–\(2.41\), and \(kT_e \sim 10.50 \text{ keV}\). The unfolded spectra are shown in Figure 4, and the derived parameters are given in Table 2. We confirmed that in leaving the power-law index and absorption column density free, the values of the other parameters are not changed (but less constrained).

For 4U 1630−47, we extracted the spectra in the energy band 2.0–50.0 keV at two different parts of the light curve, corresponding to the observation 80117-01-01-01. The model-independent spectra show marginal pivoting around \(~10 \text{ keV}\) (see Fig. 3). We fitted the spectra of these two parts with a model that includes a disk blackbody plus a thermal Comptonization model and found that this model gives unacceptable fits. Hence, we unfolded the spectra using diskbb+powlaw, which gave reliable values, as shown in Table 3. The change in disk temperature is quite low and may not be high enough to describe the marginal pivoting pattern in the spectrum. The spectral parameters indicate that the source is in TD (thermal dominated state), in which the disk extends close to the last stable orbit. We speculate that the delay may be attributed to a marginal change in the power-law index.

We also analyzed one of the observations (MJD 50,480) of GRS 1915+105, which shows a delay of the order of \(~1000 \text{ s}\). To unfold the spectrum, we used the same multicomponent model that was used for XTE J1550−564 (see Fig. 5). Three parameters are frozen, \(N_H = 6.00 \times 10^{22} \text{ cm}^{-2}\) (Belloni et al. 2000), power-law index \(\Gamma_{PL} = 2.0\), and Gaussian line energy \(=6.5 \text{ keV}\). It can be seen from Table 4 that both the electron temperature and thcomp normalization have changed between the two parts of the observation, causing a sharp pivoting point at \(~7 \text{ keV}\) (Choudhury et al. 2005; see Fig. 3).

We have calculated the unabsorbed disk flux (soft X-ray flux) and unabsorbed thermal Comptonization flux (hard flux) for both the XTE J1550−564 and GRS 1915+105 observations (Table 7). In all the observations, the soft X-ray flux is changing, reflecting the degree of variability of the accretion disk. It can be seen from the derived spectral parameters that the quality of the data is not sufficient to discern the changes in all the parameters. To investigate the most dominant change in spectral parameters, we have investigated the minimum set of parameters that definitely show a change, as demanded by the data. For this purpose, we fitted the part A (first part of the respective observation) and part B (second part of the respective observation) spectra simultaneously, keeping all the parameters tied to the spectral parameters obtained by fitting only the part A spectrum. This resulted in a very high reduced \(\chi^2\) value (e.g., \(\chi^2/\text{dof} = 436/185\) for ObsID 30191-01-09-00; see Table 5), suggesting a spectral change between the two parts of the observation. Then the thcomp normalization \((N_{th})\) of these two parts was allowed to vary independently. The \(F\)-test values given in Table 5 suggest that the fit improved drastically. We then allowed two other parameters to vary, diskbb normalization \((N_{diskbb})\) and \(kT_{in}\), one by one. The fit again improved significantly in this way. When we continued this method for all the spectral parameters, no considerable improvement in the fit was observed. Hence, the \(F\)-test analysis suggests that normalization and disk parameters vary between the two parts (A and B) of a single observation.

5. QUASI-PERIODIC OSCILLATIONS

XTE J1550−564 and 4U 1630−47 show prominent QPOs in their PDSs (Remillard et al. 1999; Tomsick et al. 2005). To unveil the hidden physical phenomenon behind the anticorrelated hard X-ray delay, we have obtained the PDS of the same individual observation at two ends (300 s each; part A and B) of the corresponding light curve, binned at 1 ms in the energy range 2–20 keV (B..500us_..4A_..0..49_H) and 20–50 keV (SB..125us_..50..249_1s) and normalized the output to squared fractional rms (with the white noise subtracted). The spectral study of 4U 1630−47 shows that the source is in the TD state, which is further supported.
by the absence of a QPO feature in the PDS, whereas XTE J1550–564 shows a strong QPO signature with one harmonic when the source is in the strong VHS state. To quantify the nature of the QPO parameters, we fitted a power law to the continuum and two Lorentzian functions to the QPO profile (see Table 6). In the PDS of the energy band 2–20 keV, we found a harmonic that is not present in the PDS of 20–50 keV.

The PDS of XTE J1550–564 for ObsID 30191-01-09-00 (parts A and B) is shown in Figure 6, separately for 2–20 keV (Fig. 6a) and 20–50 keV (Fig. 6b). For clarity, the part B data are shifted down by a factor of 2. The best-fit models are shown as continuous lines, and the respective residuals (as a ratio of data to model) are shown in the two bottom panels of each figure for parts A and B. The fitted centroid frequencies are shown as vertical lines. Similarly, the PDS for the same source for ObsID 30191-01-09-01 is shown in Figure 7. Clear shifts are seen in the centroid, as well as the peak frequencies, particularly in the data for the second ObsID.

In both the observations, clear and consistent changes in the centroid frequency of the fundamental and the first harmonic of the QPOs are recognized. The PDS of the 20–50 keV energy band reveals that in one case, the fundamental centroid frequency shows no significant shift, and in another case, a significant amount of change is quite observable. In a single pointed observation, the centroid frequency is increasing in both the fundamental and harmonic QPOs, clearly suggesting that the inherent source size (Compton cloud) is decreasing, giving rise to a geometrically and physically larger disk (Chakrabarti & Manickam 2000). The firm and undeniable change in fundamental and harmonic centroid frequencies demonstrates that there is a small but effective degree of variation in the physical scenario of the accretion disk, favoring a truncated accretion disk.

### TABLE 4
**Spectral Parameters of GRS 1915+105 in an Individual Observation**
(ObsID 20402-01-14-00)

| Part of Observation | $kT_{\text{in}}^a$ (keV) | $kT_{\text{e}}^b$ (keV) | $N_{\text{th}}^d$ | $\chi^2$/dof |
|---------------------|--------------------------|------------------------|-----------------|-------------|
| A                   | 0.84$^{+0.03}_{-0.02}$   | 2.55$^{+0.04}_{-0.03}$ | 127$^{+42}_{-36}$ | 1.34$^{+0.36}_{-0.40}$ | 80.64/83 |
| B                   | 0.82$^{+0.02}_{-0.02}$   | 2.22$^{+0.02}_{-0.02}$ | 19.00$^{+8.05}_{-7.80}$ | 3.48$^{+0.89}_{-1.40}$ | 78.48/83 |

**Notes.**—Results of simultaneous fitting of the different parts of a single observation for the sources XTE J1550–564 and GRS 1915+105. “None” denotes that all the parameters were tied to the spectral parameters obtained from the first part of the observation. “All” denotes that all the spectral parameters were allowed to vary independently.

### TABLE 5
**Simultaneous Fitting Results**

| Parameters Varied | $\chi^2$ | dof | F-Test Probability |
|-------------------|---------|-----|--------------------|
| (XTE J1550–564)   |         |     |                    |
| None              | 436     | 185 | $9.13 \times 10^{-17}$ |
| $N_{\text{th}}^a$ | 285     | 182 | $1.74 \times 10^{-7}$  |
| $N_{\text{th}}^a$+$N_{\text{diskbb}}^b$ | 245 | 181 | $3.79 \times 10^{-8}$  |
| $N_{\text{th}}^a$+$N_{\text{diskbb}}^b$+$kT_{\text{in}}^c$ | 207 | 180 | $3.18 \times 10^{-2}$  |
| All               | 195     | 176 |                    |

| (XTE J1550–564)   |         |     |                    |
| None              | 316     | 183 |                    |
| $N_{\text{th}}^a$ | 220     | 182 | $5.17 \times 10^{-16}$ |
| $N_{\text{th}}^a$+$N_{\text{diskbb}}^b$ | 219 | 181 | $0.364$ |
| $N_{\text{th}}^a$+$N_{\text{diskbb}}^b$+$kT_{\text{in}}^c$ | 207 | 180 | $1.47 \times 10^{-3}$ |
| All               | 205     | 176 | $0.787$ |

| (GRS 1915+105)    |         |     |                    |
| None              | 976     | 151 | $3.04 \times 10^{-7}$ |
| $N_{\text{th}}^a$ | 819     | 150 | $5.60 \times 10^{-4}$ |
| $N_{\text{th}}^a$+$N_{\text{diskbb}}^b$ | 216 | 149 | $1.84 \times 10^{-10}$ |
| $N_{\text{th}}^a$+$N_{\text{diskbb}}^b$+$kT_{\text{in}}^c$ | 164 | 148 | $1.15 \times 10^{-2}$ |
| All               | 150     | 144 | $5.20 \times 10^{-2}$ |

**Notes.**—Results of simultaneous fitting of the different parts of a single observation for the sources XTE J1550–564 and GRS 1915+105. “None” denotes that all the parameters were tied to the spectral parameters obtained from the first part of the observation. “All” denotes that all the spectral parameters were allowed to vary independently.

---

6. DISCUSSION

Detection of anticorrelated hard delays in Cyg X-3 and GRS 1915+105 (Choudhury & Rao 2004; Choudhury et al. 2005) suggested dynamical evidence of a truncated accretion disk. We anticipated the same physical scenario in two other sources, XTE J1550–564 and 4U 1630–47. The aim of this paper is to quantify the variation in the spectral parameters responsible for the hard X-ray delay, which in turn constrains the geometry of the accretion disk. Proper inspection of the model-independent spectrum indicates that even a marginal pivoting can account for the hard X-ray delay.
During our observations, the sources XTE J1550−564 and GRS 1915+105 were in the VHS. Spectral analysis of these two sources suggests that the soft and hard spectral components varied significantly, along with a strong indication of a change in the inner disk temperature. We noticed a nominal change in the thermal Comptonization parameters in both these sources. These changes are indirectly connected to the hot electrons in the corona. In the case of GRS 1915+105, the increase in the electron temperature is very significant.

We have also calculated the unabsorbed bolometric flux for both the disk (soft flux) and thermal Comptonization components (hard flux) (shown in Table 7). For both the observations of XTE J1550−564, we found that whenever the soft flux changed during the pivoting of the spectra, an opposite change in the hard flux occurred. Similarly, we noticed that in GRS 1915+105, the soft flux increased during the pivoting and an opposite change in the hard flux was observed. This indirectly implies that there is a change in either the geometry or physical properties of the accretion disk and the corona. The timescales of the delays observed in these two sources suggest that disk and corona properties change on viscous timescales. The observed delay is the readjustment timescale of

![Fig. 6.—Power density spectrum (PDS) for XTE J1550−564 (ObsID 30191-01-09-00) shown separately for the two energy channels (a) 2−20 keV and (b) 20−50 keV. In each figure, two parts of the same observations (part A and B; see text) are shown, with the part B data shifted down by a factor of 2 for clarity. Best-fit models (power law and Lorentzians for QPOs) are shown as continuous lines, and the residuals are shown as a ratio of data to model in the bottom panels (for part A and B, separately). The centroid frequencies of the QPOs are indicated as vertical lines.](image1)

![Fig. 7.—Same as Fig. 6, but for ObsID 30191-01-09-01.](image2)

| ObsID          | Energy          | Centroid Frequency $(f)$ (Hz) | FWHM (Hz) | rms (%) |
|----------------|-----------------|-------------------------------|-----------|---------|
|                |                 | Fundamental | Harmonic | Fundamental | Harmonic | Fundamental | Harmonic |
| 30191-01-09-00 | Soft (2−20 keV) | 4.32 ± 0.02* | 8.37 ± 0.08 | 0.52 | 1.14 | 1.64 | 0.18 |
|                |                 | 4.38 ± 0.02* | 8.57 ± 0.05 | 0.41 | 0.89 | 1.36 | 0.18 |
| 30191-01-09-00 | Hard (20−50 keV) | 4.34 ± 0.02 | Absent | 0.48 | Absent | 2.73 | Absent |
|                |                 | 4.35 ± 0.02 | Absent | 0.38 | Absent | 2.81 | Absent |
| 30191-01-09-01 | Soft (2−20 keV) | 3.87 ± 0.01 | 7.64 ± 0.04 | 0.29 | 0.51 | 1.41 | 0.10 |
|                |                 | 4.07 ± 0.01 | 7.95 ± 0.03 | 0.36 | 0.53 | 1.30 | 0.10 |
| 30191-01-09-01 | Hard (20−50 keV) | 3.90 ± 0.01 | Absent | 0.30 | Absent | 2.42 | Absent |
|                |                 | 4.05 ± 0.05 | Absent | 0.45 | Absent | 2.87 | Absent |

* Represents different regions of a single pointed observation.
SRIRAM ET AL.

TABLE 7
SIMULTANEOUS SPECTRUM FITTING VALUES

| SPECTRAL PARAMETER | 30191-01-09-00 | 30191-01-09-01 | 20402-01-14-00 |
|--------------------|---------------|---------------|---------------|
| $N_{\text{in}}$    | 4.59 ± 0.65   | 4.46 ± 0.72   | 3.33 ± 0.62   | 3.91 ± 0.66   | 3.16 ± 1.45   | 3.02 ± 1.35   |
| $N_{\text{diskbb}}$ | 2253 ± 652    | 1600 ± 476    | 3580 ± 626    | 2557 ± 882    | 614 ± 34     | 824 ± 92     |
| $kT_{\text{in}}$ (keV) | 0.80 ± 0.02  | 0.87 ± 0.04   | 0.73 ± 0.01   | 0.78 ± 0.02   | 0.88 ± 0.01  | 0.79 ± 0.02  |
| Disk flux ($10^{-9}$ ergs cm$^{-2}$ s$^{-1}$) | 20.9          | 21.9          | 17.7          | 23.5          | 8.50         | 6.61         |
| Thermal Comptonization flux ($10^{-9}$ ergs cm$^{-2}$ s$^{-1}$) | 52.5          | 46.5          | 52.6          | 42.3          | 11.40        | 22.0         |
| Delay (s)          | 132 ± 9      | ...           | 375 ± 13      | ...           | 704 ± 35     | ...           |
| $(\Delta f/f)^{l}$ (%) | 1.39         | ...           | 5.16          | ...           | -10.03       | ...           |
| $(\Delta kT_{\text{in}}/kT_{\text{in}})$ (%) | 8.75          | ...           | 6.85          | ...           | -10.23       | ...           |
| $(\Delta N_{\text{diskbb}}/N_{\text{diskbb}})$ (%) | 4.78          | ...           | 32.76         | ...           | -22.2        | ...           |
| $(\Delta N_{\text{in}}/N_{\text{in}})$ (%) | -11.43        | ...           | -19.6         | ...           | 92.98        | ...           |

Notes.—The values obtained from the simultaneous spectrum fitting for the respective sources. The three parameters (shown in the table) were allowed to vary because of F-test results. The fluxes reported here are bolometric fluxes. For all the parameters, 90% confidence errors are given.

- Normalization of the $kT_{\text{in}}$ model.
- Normalization of the $N_{\text{diskbb}}$ model.
- Inner disk temperature using $kT_{\text{in}}$ model.
- $f$ corresponds to the centroid frequency of the respective QPO.

The thermal disk, as well as the inner Comptonizing cloud. A truncated accretion disk is required to convert soft X-ray photons to hard X-ray photons via the Comptonization process, and hence the extent of the truncation radius decides the fate of the pivot point or the change in the respective flux.

The power density spectra of the source XTE J1550−564 clearly shows a minute change in the centroid frequency of the fundamental and harmonic QPOs. This small change in the centroid frequency of the QPOs observed in XTE J1550−564 indicates the physical aberration of the corona on a timescale of ~1000 s. There are various models (Titarchuk & Fiorito 2004; Chakrabarti & Manickam 2000) that explain the production of QPOs, and these models seem to converge to the fact that the origin of QPOs is inherent to the compact corona region close to the black hole. In both observations of the source XTE J1550−564, the change in the centroid frequency is strongly correlated with the change in the soft and hard fluxes. In both observations, the centroid frequency is increasing with increasing soft flux and decreasing hard flux (see Table 7). In the case of GRS 1915+105, the hard flux is increasing with decreasing soft flux, showing a corresponding change in the QPO frequency. The proportional change in the QPO centroid frequency with hard and soft fluxes strengthens the idea that during these hard lag observations there is an inward/outward movement of the Compton cloud.

The second observation of XTE J1550−564 (ObsID 30191-01-09-01) shows the most well-determined delay (375 ± 13 s) and the most significant shift in the QPO frequency. Let us assume that the truncation radius, $R_c$, is at 10 Schwarzschild radii ($R_S$), consistent with the ~300 km derived for the disk-corona coupling radius (Done & Kubota 2006). The observed 5% increase in the QPO frequency, $f$, corresponds to a 15% decrease in the truncation radius, assuming a Lense-Thirring precession model for QPO generation (Done & Kubota 2006; Stella et al. 1999), which predicts $f \sim R_c^{-1/3}$. This decrease of 15% in $R_c$ is possibly due to an increase in the disk accretion rate by ~20% if $R_c$ varies as an inverse power $\beta$ of the mass accretion rate through the disk, with $\beta \sim 0.65 - 0.85$, as suggested by McHardy et al. (2006). The increase in the disk luminosity would be about 35% (scaling directly as the accretion rate and inversely as $R_c$, as would be the case for a standard thin disk), which is very close to the observed variation of 33% (see Table 7). A corresponding decrease in the Compton flux will occur after a delay corresponding to the Compton cooling timescale for the plasma confined within $R_c$. By assuming similar properties of accretion disks as seen in GRS 1915+105 during the inner-disk evaporation, a Compton cooling timescale of several hundred seconds (Chakrabarti & Manickam 2000) can be derived, similar to the observed delay of 375 s.

On the other extreme, 4U 1630−47 shows significant anticorrelated hard delay in the thermal dominated state. We find that the index of the power-law component increases during the pivoting and as the soft flux decreases. Hence, we suggest that pivoting is primarily due to a decrease in the soft disk flux and a hardening of the power-law component. Since during the observation a QPO was not observed, we cannot reach any concrete conclusions about the physical changes in the accretion disk and the corona.

The five distinct properties, viz., anticorrelated hard delay, change in QPO centroid frequency, model-independent spectrum, systematic variation in thermal Comptonization parameters, and disciplined change in the QPO frequency with fluxes, swing the pendulum toward the idea of a truncated accretion disk and remove the possibility of nontruncated models.

We thank the anonymous referee for constructive and critical comments. This research has made use of data obtained through the HEASARC Online Service, provided by the NASA/GSFC, in support of NASA High Energy Astrophysics Programs.

REFERENCES
Belloni, T., Soleri, P., Casella, P., Mendez, M., & Migliari, S. 2006, MNRAS, 369, 305
Belloni, T., et al. 2000, A&A, 355, 271
Chakrabarti, S. K. 1996, Phys. Rep., 266, 229
Chakrabarti, S. K., & Manickam, S. G. 2000, ApJ, 531, L41
Choudhury, M., & Rao, A. R. 2004, ApJ, 616, L143
Choudhury, M., Rao, A. R., Dasgupta, S., Pendharkar, J., Sriram, K., & Agrawal, V. K. 2005, ApJ, 631, 1072
Corbel, S., et al. 2001, ApJ, 554, 43
Done, C., & Kubota, A. 2006, MNRAS, 371, 1216
Ebisawa, K., et al. 1994, PASJ, 46, 375
Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865
Fender, R., Belloni, T., & Gallo, E. 2004, MNRAS, 355, 1105
———. 2005, Ap&SS, 300, 1
Fender, R., Stirling, A. M., Spencer, R. E., Brown, I., Pooley, G. G., Muxlow, T. W. B., & Miller-Jones, J. C. A. 2006, MNRAS, 369, 603
Hannikainen, D., Campbell-Wilson, D., Hunstead, R., McIntyre, V., Lovell, J., Reynolds, J., Tzioumis, T., & Wu, K. 2001, Ap&SS Suppl., 276, 45
Hjellming, R. M., et al. 1999, ApJ, 514, 383
Jahoda, K., et al. 2006, ApJS, 163, 401
Jones, C., Forman, W., Tananbaum, H., & Turner, M. I. L. 1976, ApJ, 210, L9
Koerding, E., & Falcke, H. 2004, A&A, 414, 795
Kubota, A., & Done, C. 2004, MNRAS, 353, 980
Makishima, K., et al. 1986, ApJ, 308, 635
Markoff, S., & Nowak, M. A. 2004, ApJ, 609, 972
Markoff, S., Nowak, M. A., & Wilms, J. 2005, ApJ, 635, 1203
Markwardt, C. B., Swank, J. H., & Taam, R. E. 1999, ApJ, 513, L37
McClintock, J. E., & Remillard, R. A. 2004, in Compact Stellar X-ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 157
McHardy, I. M., Koerding, E., Knigge, C., Uttley, P., & Fender, R. P. 2006, Nature, 444, 730
Narayan, R., & Yi, I. 1994, ApJ, 428, L13
Orosz, J., et al. 2002, ApJ, 568, 845
Rao, A. R., Naik, S., Vadawale, S. V., & Chakrabarti, S. K. 2000, A&A, 360, L25
Remillard, R. A., McClintock, J. E., Sobczak, G. J., Bailyn, C. D., Orosz, J. A., Morgan, E. H., & Levine, A. M. 1999, ApJ, 517, L127
Remillard, R. A., Munu, M. P., McClintock, J. E., & Orosz, J. 2002, ApJ, 580, 1030
Rothschild, R. E., et al. 1998, ApJ, 496, 538
Shapiro, S. L., Lightman, A. P., & Eardley, D. N. 1976, ApJ, 204, 187
Smith, D. A., et al. 1998, IAU Circ. 7008
Sobczak, G. J., et al. 2000, ApJ, 531, 537
Stella, L., Mario, V., & Morsink, S. M. 1999, ApJ, 524, L63
Sunyaev, R. A., & Titarchuk, L. G. 1980, A&A, 86, 121
Titarchuk, L., & Fioroti, R. 2004, ApJ, 612, 988
Tomsick, J., Corbel, S., Goldwurm, A., & Kaaret, P. 2005, ApJ, 630, 413
Vadawale, S. V., Rao, A. R., & Chakrabarti, S. K. 2001, A&A, 372, 793
Zdziarski, A. A., Grove, E., Poutanen, J., Rao, A. R., & Vadawale, S. V. 2001, ApJ, 554, L45
Zdziarski, A. A., Johnson, W. N., & Magdziarski, P. 1996, MNRAS, 283, 193
Zdziarski, A. A., et al. 2002, ApJ, 578, 357