EVIDENCE FOR A TRUNCATED ACCRETION DISK

ANTICORRELATED HARD X-RAY TIME LAG IN GRS 1915+105:

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ABSTRACT

Multiwavelength observations of Galactic black hole candidate sources indicate a close connection between the accretion disk emission and the jet emission. The recent discovery of an anticorrelated time lag between the soft and hard X-rays in Cygnus X-3 (Choudhury & Rao) constrains the geometric picture of the disk-jet connection into a truncated accretion disk, the truncation radius being quite close to the black hole. Here we report the detection of similar anticorrelated time lag in the superluminal jet source GRS 1915+105. We show the existence of pivoting in the X-ray spectrum during the delayed anticorrelation, and we also find that the quasi-periodic oscillation frequency changes along with the spectral pivoting. We explore theoretical models to understand this phenomenon.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (GRS 1915+105) — X-rays: binaries

1. INTRODUCTION

In the current era, discerned by the wide-band X-ray spectral capability of the present-day X-ray satellite observatories, the nonthermal component in the hard X-ray spectrum has emerged to be the most prominent and intriguing observational feature of the Galactic black hole candidates (see Barret [2004] for a short review). Various conflicting hypotheses concerning the physical mechanism of the origin of this nonthermal emission have been offered to explain the phenomenon, ranging from synchrotron at the base of the jet (Markoff et al. 2001, 2003) to Comptonization of thermal photons by a hot corona with various geometric structures (see, e.g., Poutanen 1998)—the most favored being that of a hot quasi-spherical cloud inside a truncated disk (Zdziarski et al. 2002). In recent times, the existence of a truncated accretion disk near black holes is establishing itself as an emerging independent paradigm, with diverse theoretical formalisms, viz., advection-dominated accretion flow (ADAF; Narayan & Yi 1994) and two-component advective flow (TCAF; Chakrabarti 1996), requiring the given geometric structure. The detection of an anticorrelated delay ($\lesssim$1000 s) of the hard X-ray (20–50 keV) emission with respect to the soft X-ray (2–7 keV) emission in the X-ray hard state of the enigmatic X-ray binary Cygnus X-3 (Choudhury & Rao 2004), giving rise to the pivoting behavior in the spectrum (Choudhury et al. 2002), adds credence to this paradigm of truncated accretion disk, with the inner region consisting of (quasi-)spherical flow of highly energetic matter Comptonizing the soft seed thermal photons from the outer disk. The timescale of this delay may be attributed to the viscous timescale of flow of matter in the radiation pressure–dominated optically thick accretion disk.

GRS 1915+105 (Castro-Tirado et al. 1992) is a black hole binary system that displays the most varied types of emission states ever seen in a Galactic microquasar, with the timescale of spectral variations/transitions ranging from minutes to months. Among all the various classes of behavioral features exhibited by GRS 1915+105, in the $\chi$ state (Belloni et al. 2000) it exhibits steady X-ray emission for long durations, further characterized by a pronounced quasi-periodic oscillation (QPO) feature. McClintock & Remillard (2006) have examined the spectral classifications of black hole sources and have concluded that GRS 1915+105, in its steady states, shows characteristics closer to the thermally dominant or low/hard states. The $\chi$ state, with its band-limited power density spectrum, resembles the characteristics of the low/hard state (although the luminosity and the X-ray spectral index are slightly different from those found in other black hole sources). In this state the X-ray spectra display a pivoting behavior (for spectra obtained on different days, spanning the extent of the hard state), very similar to Cyg X-3 (Choudhury et al. 2003). In addition, the soft X-ray flux is correlated to the radio emission in this state, with the correlation spanning across 5 orders of magnitude of intrinsic luminosity for various black hole candidates (Choudhury et al. 2003), suggesting that the soft X-ray flux is driving both the hard X-ray as well as radio emission. Given the universality of the correlated behavior of these systems, and the similarity of the spectral evolution in this state of GRS 1915+105 with Cyg X-3, it was imperative that an anticorrelated delay between the hard and soft X-rays, analogous to Cyg X-3, be present in GRS 1915+105, in the $\chi$ state.

Here we report the presence of such an anticorrelated time lag of the hard X-ray (20–50 keV) emission to that of the soft X-ray...
(2–7 keV) emission observed in six pointed observations by the Rossi X-Ray Timing Explorer Proportional Counter Array (RXTE PCA) during the $\chi$ state of GRS 1915+105. During these particular pointings, the “in situ” pivoting feature in the spectra is similar to that reported for Cyg X-3 (Choudhury & Rao 2004). More importantly, we also report a corresponding change in the QPO parameters ubiquitously present in the low/hard state of this source, most notably being the shift in the centroid frequency.

2. DATA AND ANALYSIS

The pointed observations of the narrow field-of-view instrument PCA on board RXTE are used for the timing as well as the spectral analysis. The light curves for the cross-correlation tests as well as the spectra (obtained from the PCA) use the Standard2 form of data (all Proportional Counter Units added), with all the procedures of data filtering, background, and dead-time corrections strictly adhered to. The light curve for the QPO analysis was obtained from the single-bit mode data, covering the 2–7 keV band. The data reduction and analysis was carried out using HEASOFT (ver. 5.2), which consists of (chiefly) FTOOLS (ver. 5.2), XRONOS (ver. 5.19), and XSPEC (ver. 11.2).

2.1. Data Selection

This source is extremely variable in nature, and the behavioral patterns have been categorized into several variability classes (Belloni et al. 2000). Based on the RXTE pointed observations carried out in 1996–1997, Belloni et al. (2000) have identified long-duration steady hard states (the “C” state in their nomenclature) as the $\chi$ class. As discussed by McClintock & Remillard (2006; see also Rao et al. 2000b and Vadawale et al. 2001), this is the closest analog to the canonical low/hard states of Galactic black hole sources, and it is in this state that the source seems to spend most of its time. This $\chi$ state is further subdivided into four subclasses, $\chi^1$–$\chi^4$. The subclasses $\chi^1$–$\chi^3$ are the long uninterrupted steady states, whereas the $\chi^4$ class is a collection of isolated individual pointed observations with properties similar to $\chi^1$–$\chi^3$ classes. Since a portion of other variability classes (like the $\iota$ class) can look like the $\chi$ class, we have only taken the $\chi^1$–$\chi^3$ classes for the present study. The Belloni et al. (2000) classification covers a total of 49 pointed observations from RXTE PCA covering the early years of its operation with the source in the $\chi$ state; of these, the $\chi^1$–$\chi^3$ states consist of 30 observations (with some long observations separated into more than one observation ID in the RXTE data archives). All observations pertaining to the $\chi^1$–$\chi^3$ states, as per the classification covered by Belloni et al. (2000), were inspected for the presence of the anticorrelated lag between the hard (20–50 keV) and soft (2–7 keV) emission, following the analogous results obtained for Cyg X-3 (Choudhury & Rao 2004). Considering the fact that the mechanism causing the change in the soft X-ray spectrum (the accretion rate being one of the most likely candidates), with the corresponding delayed opposite change in the hard X-ray emission, is very unlikely to be a continuous process, a large number of long pointed observations are needed to serendipitously capture the occasional individual events that may have occurred during the pointings. The 30 observations (pertaining to the $\chi^1$–$\chi^3$ states) are classified according to the variability exhibited by the source during each particular pointed observation. To check for the variability, we obtain the variance from a constant fit to the light curve (binned to 128 s), normalized to the number of time bins ($W_N$). The histogram giving the number of observations as a function $W_N$ is plotted in Figure 1, where it is clearly seen that for values of $W_N > 250$ there are four observations (occurring on MJD 50,441–50,442; 50,477; 50,480; and 50,729) corresponding to the high-variability cases, within the class of observations considered by us. It is interesting to note that the lagged anticorrelation of the hard X-rays (20–50 keV) with respect to the soft X-ray (2–7 keV) is seen in all four cases. In Figure 1 only one observation corresponds to the variability measure ($W_N$) in the range 200–250; we use this band to demarcate the boundary of high and low variability, and this observation gives a marginal detection of the anticorrelated delay. Of the 25 observations corresponding to the low-variability cases (Fig. 1), the lagged anticorrelation is seen only in one; in no other case is there any detection of the delay in the correlation results. The presumption behind the classification with respect to the variability was that the observations during which significant variability is seen will be the ones where noticeable features of the lagged anticorrelation can be obtained. Of course, this precludes the fact that the variability should be nonmonotonic in nature, because first the continuous monotonic evolution will result in state transition, and second, more importantly from the observational purview, a nonmonotonic evolution with a point of maxima/minima is the best feature to measure the delay in the anticorrelation.

2.2. Hard X-Ray Delay and Pivoting in the Spectrum

Of the observations listed by Belloni et al. (2000) belonging to the $\chi^1$–$\chi^3$ states, on four occasions (Fig. 2), corresponding to
Fig. 2.—Cross-correlation between the soft (2–7 keV) and hard (20–50 keV) X-ray flux in the $\chi^2$ (MJD 50,441–50,442, 50,477, and 50,480) and $\chi^3$ (MJD 50,729) states for which the lagged anticorrelation is observed. These four observations correspond to the high-variability cases of Fig. 1.
the high-variability cases (Fig. 1), the cross-correlation results show the hard X-rays to be anticorrelated and lagging with respect to the soft X-ray emission (the details are given in Table 1). The cross-correlation is initially obtained using the XRONOS program crosscor, which uses the fast Fourier transform (FFT) algorithm to compute the coefficient, which is normalized by the square root of the product of number of good newbins of the concerned light curves; effectively, this coefficient is the cross-covariance of the two light curves. On MJD 50,441–50,442; 50,477; and 50,480, the source was in the $\chi^2$ state (also known as the radio-quiet $\chi$ state; Vadawale et al. 2001), and on MJD 50,729 the source was in the $\chi^3$ state (the radio-loud $\chi$ state). We further substantiate the correlation results by performing the Pearson’s test as well as the Spearman’s rank correlation test after correcting for the delay of the hard X-ray flux for each corresponding observation; the coefficients thus obtained are given in Table 1. In obtaining these coefficients, we have used data corresponding to only those time stamps for which both the fluxes are present after shifting the hard X-ray light curve to correct for the delay. In these cases if the hard X-ray light curve is not compensated for the delay, the correlation coefficients obtained are as follows: MJD 50,441–50,442 (Pearson’s = 0.09 and Spearman’s = 0.12); MJD 50,477 (Pearson’s = –0.03 and Spearman’s = 0.02); MJD 50,480 (Pearson’s = –0.04 and Spearman’s = –0.06); and MJD 50,729 (Pearson’s = –0.28 and Spearman’s = –0.26). Comparing these values with the coefficients obtained for the delay compensated hard X-ray light curves (Table 1) establishes that the four observations pertaining to the high-variability cases, within the $\chi^1$–$\chi^3$ classes, do indeed exhibit this physical phenomenon of the hard X-ray emission being delayed as well as anticorrelated to the soft X-ray emission process. The relative closeness of the Pearson’s and Spearman’s rank (anti-)correlation values in the two cases (with and without the compensation for the delay in the hard X-rays) on MJD 50,729 is easily attributed to the fact that the lag measured in this occasion is only 128 s.

On all four days, the X-ray spectral evolution displays a pivoting pattern, during the individual pointings. The timescale of the delay in the cross-correlation gives the timescale for the spectral evolution from the cross-correlation results, from observations within the span of one pointed observation.

2.3. X-Ray Spectral Fitting

We have used the model prescribed by Vadawale et al. (2003) to unfold the count spectrum. The value of the parameters and the error bars are similar to the other $\chi$-state spectra mentioned in Vadawale et al. (2003). Detailed spectral analysis is out of the scope of this paper and is not needed, as the given results are model independent, for the purpose of the spectral fit was to mimic the shape of the count spectrum in order to unfold it and not to provide any physical interpretation from the fitted parameters.

2.4. Quasi-periodic Oscillation

QPO is a ubiquitous feature of this source in the low state. To characterize the nature of the physical phenomenon giving rise to the lagged anticorrelation, we have done a detailed study of the QPO characteristics, corresponding to the comparative softer and harder regions of the light curve. The power density spectra (PDS) was obtained from the single-bit mode of data in the 2–7 keV band, with a bin size of 10 ms, using the XRONOS program powspec. In this program the PDS was computed by a FFT algorithm, and the errors were obtained by propagating the theoretical error bars of the spectra from individual intervals (from the relevant $\chi^2$ distribution), while the normalization was such that the integral of the spectra gives the squared rms fractional variability (with the white noise subtracted). The QPO parameters were obtained by fitting a power law to model the continuum of the PDS and a Lorentzian to fit the QPO profile (Fig. 4), the details of which are given in Table 2. The centroid frequency of the QPO evolves consistently with the minute change in the X-ray emissions during the individual pointed observations. The frequency always has a higher value at the softer region of the X-ray emission. Furthermore, the rms variability of the QPO is always more in the harder region of the light curve. This small but indisputable and consistent change in the QPO parameters provides further validation of the small but definitely perceptible

### TABLE 1

| MJD      | Observation ID | Delay (Error) (s) | FFT (Error) | Pearson (Null Prob.) | Spearman (Null Prob.) |
|----------|----------------|-------------------|-------------|----------------------|-----------------------|
| 50,441–50,442 | X-08-00, X-08-01 | ~220–1000±87 | ~0.38±10^{-5} | ~0.07×10^{-5} | ~0.38×10^{-5} |
| 50,477    | X-13-00        | ~960±50          | ~0.40±10^{-5} | ~0.08×10^{-5} | ~0.52×10^{-5} |
| 50,480    | X-14-00        | ~704±35          | ~0.44±10^{-5} | ~0.08×10^{-5} | ~0.54×10^{-5} |
| 50,477    | X-14-00        | ~128±30          | ~0.36±10^{-5} | ~0.07×10^{-5} | ~0.37×10^{-5} |
| 50,436    | X-07-00        | ~1600±200        | ~0.28±10^{-5} | ~0.17×10^{-5} | ~0.24×10^{-5} |
| 50,455    | X-10-00        | ~1050            | ~0.35±10^{-5} | ~0.13×10^{-5} | ~0.18×10^{-5} |

Notes.—The details of the pointed observations for which the lagged anticorrelation of the hard X-rays (20–50 keV, PCA) with respect to the soft X-rays (2–7 keV, PCA) is observed. (Here X corresponds to 20402-1.)

a Marginal case.
b Anomalous case.
Fig. 3.—Broadband X-ray spectra of the source on the days for which the lagged anticorrelation is observed (Fig. 2), for the soft and the hard regions of the light curve, resulting in comparative softer and harder spectral distribution, displaying the in situ pivoting in the $\chi^2$ and $\chi^3$ states.
Fig. 4.—Power density spectra of the source on the days for which the lagged anticorrelation is observed, for the soft (*top panels*) and the hard (*bottom panels*) regions of the light curve, depicting the shift of the QPO frequencies corresponding to the soft and hard regions.
change in the accretion state in the system during these episodes of soft X-ray emission impelling the hard X-ray emission, in the steady low states. Trudolyubov et al. (1999) and Trudolyubov (2001) have obtained the centroid frequencies of the QPO during the four \( C_3 \) states reported here, averaged over the entire individual observations, the values of which indeed lie between the two values obtained by us corresponding to the softer and harder regions of the light curve (except for the observation on MJD 50,477, when the averaged value coincides with the centroid frequency in the softest region of the light curve; see Table 1).

2.5. Marginal and Anomalous Cases

In Figure 1 the low-variability and high-variability cases are demarcated by the histogram bin corresponding to \( W_N \) values of 200–250, which has only one observation (MJD 50,436), and indeed there is a detection of lagged anticorrelation with a comparative smaller value of coefficient, and we classify this as the marginal case of detection of lagged anticorrelation. The light curve and the cross-correlation results are shown in Figure 5 (bottom panels). As is the normal case with the other observations without the lagged anticorrelation, at zero delay it shows a fairly strong positive correlation (but not so strong as the normal lower variability cases), but it shows a definite, albeit comparatively weaker, anticorrelation at a delay of 1600 s. The spectra show a weak pivoting at \( \sim 20 \) keV (Fig. 6), and also the QPO parameters vary according to the pattern established thus far (Fig. 7), with the centroid frequency shifting by 0.1 Hz, whereas for the other high-variability cases the shift is of the order of \( \sim 0.5 \) Hz (Table 2). This particular observation does indicate a gradual progression of the physical properties and phenomena that may be classified by the empirical measure of variability quantified in Figure 1.

Of the 25 cases of the low-variability observations, the presence of the lagged anticorrelation is seen in only one (on MJD 50,455). Since this marks an exception to the general behavior,
we classify this particular observation as an anomalous case. The cross-correlation, depicted in Figure 5 (top panels), shows anticorrelation of the hard X-rays (20–50 keV) with respect to soft X-rays (2–7 keV), with a delay that is fairly widely spread, albeit with as strong and significant cross-correlation coefficient as the high-variability cases, but the Pearson’s and Spearman’s rank coefficient (after compensating the for a delay of 1000 s in the hard X-ray emission) are significantly weaker.

3. DISCUSSION

In Choudhury et al. (2003) it was shown that the characteristics of X-ray emission in the hard state of the Galactic black

Fig. 6.—Broadband X-ray spectra of the source on the days for the marginal (MJD 50,436) and anomalous (MJD 50,455) cases for which the lagged anticorrelation is observed, for the soft and the hard regions of the light curve, resulting in comparative softer and harder spectral distribution, displaying the in situ pivoting in the $\chi^2$ state.

Fig. 7.—Power density spectra of the source on the days for the marginal (MJD 50,436) and anomalous (MJD 50,455) cases for which the lagged anticorrelation is observed, for the soft (top) and the hard (bottom) regions of the light curve, depicting the shift of the QPO frequencies corresponding to the soft and hard regions.
hole binary systems seem to possess universal features, leading to the picture of a truncated accretion disk system. Diverse sources, viz., Cyg X-3, GRS 1915+105, Cyg X-1, and GX 339-4 showed similar pivoting in X-ray spectrum, with the pivot point varying for the different sources. This pivot point was considered to be dependent on the extent of the truncation radius. In this geometric structure, the Compton-scattered X-rays originate from a region close to the compact object inside the truncated disk, giving rise to the nonthermal component in the hard X-ray regime. The extent of the accretion disk determines the amount of seed photons available for the Comptonizing component. With any change in the extent of the truncation radius (probably due to change in accretion rate) there is an opposite change in the flux of the Comptonizing component in the spectrum, leading to the anticorrelation between the hard and soft X-rays. This physical picture is applicable for all the models that require a truncated disk, viz., ADAF (Narayan & Yi 1994) or TCAF (Chakrabarti 1996).

Choudhury & Rao (2004) discovered a lagged anticorrelation between the hard and soft X-rays in Cyg X-3, roughly the origins of which can be ordained to be from the inner Comptonizing cloud and the thermal disk, respectively. This delay may be attributed to the viscous timescale of matter in the truncated thermal disk, which is the readjustment timescale of the disk as well as the inner Comptonizing cloud. In this scenario, the soft X-ray flux changes due to any inherent accretion process (viz., the accretion rate), and after a lag of the observed timescale the disk readjusts its geometric size, effecting an opposite change in the Comptonizing cloud in the inner regions, and thence the nonthermal component of the spectra changes, resulting in the pivoting phenomenon.

Due to the similarity of the features of the X-ray emissions of GRS 1915+105 with that of Cyg X-3 in the hard state, we were prompted to search for analogous lagged anticorrelation of the hard X-ray emission (20–50 keV) with respect to the soft X-ray emission (2–7 keV), resulting in the pivoting in the spectrum. Inspection of all the observations compiled by Belloni et al. (2000) yielded four occasions when the pointed RXTE PCA observations were able to catch the serendipitous events leading to the restructuring of the accretion system. The difference in the pivot point in the spectra for \(\chi^2\) and \(\chi'^2\) states suggest that the intrinsic accretion system GRS 1915+105 is more complex than that of Cyg X-3 with the broad scenario of the accretion system in the two \(\chi\) (sub-)states being not exactly the same. But the short timescale evolution of the accretion system in the X-ray hard state, resulting in the readjustment in the disk structure and size, is similar for both the (sub-)states.

The presence of low-frequency QPOs in GRS 1915+105 (Muno et al. 1999) is an inherent feature of the X-ray hard state (Rao 2001). Various prescriptions exist without any general consensus as to the precise nature of this temporal character.

istic. These low-frequency QPOs are found to be correlated to observed phase lag in the Fourier cross-spectrum for two different channels (Reig et al. 2000), which may arise from the Compton spectrum in the inner regions of the disk (Nobili et al. 2000). Furthermore, the centroid frequency is shown to be correlated to the spectral index (of the spectral energy distribution) in the hard \(\chi\) state (Vignarca et al. 2003). Rao et al. (2000a) found the low-frequency QPOs in the \(\chi^2\) state to originate in the region of the Comptonizing cloud, while Chakrabarti & Manickam (2000) interpret the QPOs as due to oscillation of the region responsible for the hard X-ray emission. Arguing on a similar vein, Titarchuk & Fiorotti (2004) provide a two-component model with a truncated thermal accretion disk with a quasi-spherical “transition layer” (TL model) inside giving rise to the hard X-ray emission as well as the QPOs. The general consensus seems to converge toward the idea that a physical model for the compact corona must naturally produce oscillations on timescales of hours to days (Remillard 2004). Models not conforming directly to this geometric structures, viz., magnetic flood scenario (Tagger & Pellat 1999) leading to “accretion ejection instability” (Tagger et al. 2004), also invoke advection as a necessary element of the theoretical formalism, and the QPOs are supposed to originate at inner regions of the accretion. The consistent increase in the centroid frequency of the QPOs with the softening of the X-ray emission, in the small scale reported here, provides additional support as well as constraint on the physical scenario favoring a truncated disk and high-energy inflow inside. This increase in frequency may indicate the decrease in truncation radius, resulting in a physically and geometrically bigger accretion disk (rendering the increased softness of the spectrum). In addition, the decrease in the rms variability of the QPO with increasing softness may indicate the decrease in volume of the Comptonizing cloud, under the assumption that the physical origin of the QPO phenomenon lies in this highly energetic matter.

The discovery of the hard X-ray delay (anticorrelated) in the hard state of this source (second after Cyg X-3) represses the accretion models without a truncated disk. In addition to the pivoting in the spectra, the consistent increase in the QPO centroid frequency puts the observational feature on very firm footing. Further searches for such features in sources such as Cyg X-1 and GX 339-4, where the pivot point is at higher energy, 50–80 and >300 keV, respectively, are needed to get a complete picture of the X-ray emission in the hard state.

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