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Letter to the Editor

Temporal evolution of X-ray lags in Cygnus X-1

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Abstract. We present the long term evolution of the frequency-dependent X-ray time lags of the black hole candidate Cygnus X-1 as measured in 1996 and 1998 with the Rossi X-ray Timing Explorer (RXTE). Lag spectra measured during the 1996 June soft state are very similar to those seen during 1996 December and most of 1998 while Cyg X-1 was in its hard state. During state transitions, however, the shape and magnitude of the X-ray lag is highly variable and tends to be much larger than outside of the state transitions. This behavior is most obvious in the 1–10 Hz band. The increase of the X-ray lag during the state transitions might be related to the formation and destruction of the synchrotron radiation emitting outflows present during the hard state.

Key words: stars: individual: Cyg X-1 – stars: binaries: close – X-rays: stars

1. Introduction

Galactic black hole candidates (BHC) are predominantly found in two generic states: the hard state, in which the X-ray spectrum is a Comptonization spectrum emerging from a hot electron cloud with a typical electron temperature of $\sim$150 keV (Dove et al. 1997; Poutanen 1998), and the soft state, in which the X-ray spectrum is thermal with a characteristic temperature of $kT_{\rm BB} \lesssim 1$ keV to which a steep power-law is added (Cui et al. 1997a; Gierliński et al. 1999, and references therein). Transitions between these states have been seen in all persistent galactic BHC, with the exception of LMC X-1. Optically thick radio emission is observed during the hard state, during transitions between the hard and the soft states the radio emission tends to be optically thin and more highly variable. Finally, during the soft state, galactic black hole candidates tend to be radio quiet (see, e.g., Fender 2000, for a review). Although the phenomenology of the states is rather well understood, the accretion geometry in these sources is still a matter of debate. Most current models for the hard state posit an accretion disk corona with a large covering factor that Comptonizes most of the accretion disk radiation (Poutanen 1998, and references therein). Its physical size is also assumed to be rather large. On the other hand, the corona is assumed to have almost vanished during the soft state, where the X-ray luminosity is dominated by thermal radiation (Gierliński et al. 1999).

In recent years, several attempts have been made to use X-ray timing methods to constrain these models. In addition to the power spectrum analysis (Belloni & Hasinger 1990; Gilfanov et al. 1999), higher order statistics like the frequency-dependent coherence function and time lags have proven to be useful in evaluating physical accretion models (Hua et al. 1999; Nowak et al. 1999a) by providing combined spectral and temporal information. For example, the maximum expected time delay between hard and soft photons is roughly the size of the Comptonizing medium divided by the slowest propagation speed of a disturbance, while the minimum time lag is roughly the photon diffusion time through the corona (Nowak et al. 1999b).

The canonical BHC, Cygnus X-1, stays predominantly in the hard state, but occasionally transits into the soft state for a few months (Gierliński et al. 1999; Cui et al. 1997a,b, see also Fig. 3). The apparent decrease of the X-ray lags during the 1996 state transitions was considered evidence that the size of the accretion region during the soft state is smaller than during the hard state (Cui et al. 1997b). First comparisons of transition and soft state lags to hard state lags, however, indicated that the physical interpretation has to be more complex (Cui 1999).

In addition to the state transitions, quasi-regular variations on a $\sim$150 d timescale are observed in the X-ray spectral shape and soft X-ray flux as well as in other wavelength bands (Pooley et al. 1999; Brocksopp et al. 1999). In 1998 we initiated a monitoring campaign with the Rossi X-ray Timing Explorer (RXTE) to systematically study the multi-wavelength long term variation of Cyg X-1 over a period of several years. During 1998, weekly pointings of $\sim$3 ks duration were performed. In later years, longer exposure times (but larger sampling intervals) were used (Pottschmidt et al. 2000). In this Let-

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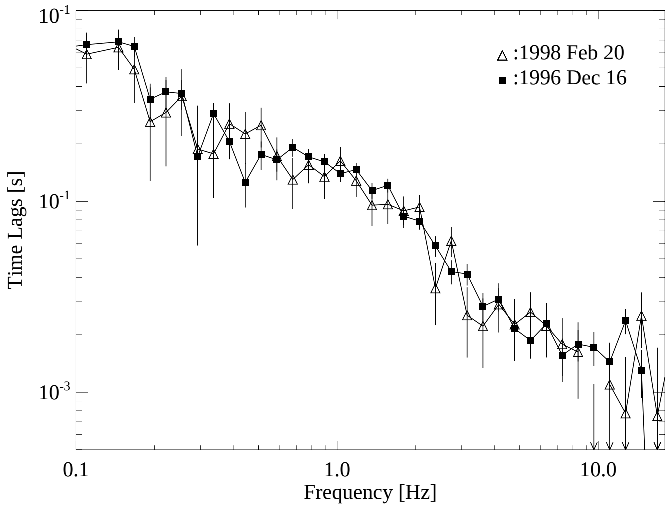

Fig. 1. Comparison of the X-ray lag spectrum for one of the 3 ks monitoring observations of 1998 with that obtained for ∼30 ks of the RXTE observation of 1996 December 16. The lags have been measured between $\lesssim$4 keV and ∼8–13 keV. Both examples are typical hard state observations.

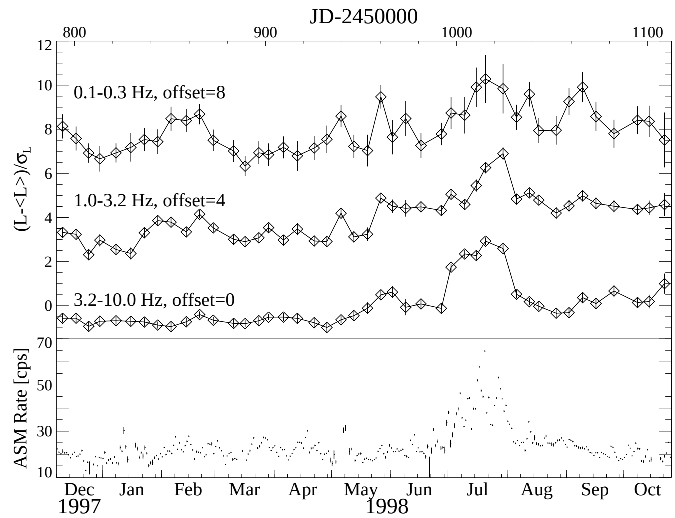

Fig. 2. Diamonds: Temporal evolution of the average lag between $\lesssim$4 keV and 18.3–72.9 keV for the indicated frequency intervals. The deviation of the lag from its mean value as determined from all observations of 1998 for the respective frequency band, in units of its standard deviation is shown. Dashes: RXTE ASM 2–10 keV count rate binned to a resolution of 1 d.

ter we present results of the first year of the campaign, focusing on the X-ray time lags. We describe our data analysis methods (Sect. 2) and compare the temporal behavior of Cyg X-1 during 1998 with that seen during 1996 (Sect. 3). Specifically, we show that large X-ray lags appear to be associated with *transitions* between the soft and hard state, but *not* with the state itself. In Sect. 4 we discuss implications for the accretion models in galactic black hole candidates.

2. Observations and data analysis

The RXTE data presented here were obtained with the Proportional Counter Array (PCA; Jahoda et al. 1997) and with the All Sky Monitor (ASM; Remillard & Levine 1997). We used the standard RXTE data analysis software, ftools 4.2. A log of the observations is presented in Table 1 which is available in electronic form only from the Centre de Donées Stellaires (CDS). The data were reduced using the procedures described in detail in our analysis of the RXTE observations of GX 339−4 (Wilms et al. 1999). Intervals with large background flux were removed after visually inspecting the "electron ratio". As a result of the data screening, ∼2 ks of usable data were left for each of the 3 ks monitoring observations. We then extracted lightcurves with a resolution of 16 ms for three energy bands ($\lesssim$4 keV, ∼8–13 keV, and 18.3–72.9 keV)[1]. The computation of the time lags for these energy bands follows Nowak & Vaughan (1996) and Nowak et al. (1999a).

[1] Since the PCA data modes used to obtain the 1996 data differ from those used in 1998, it was impossible to use identical energy bands for all observations. The bands used to compare the 1996 data to the 1998 data were the closest matches possible (the highest energy band is unavailable for some of the 1996 soft state data). The detailed bands are given in Table 1 available from the CDS.

According to our previous experience, the methods used to compute the uncertainty of the time lag spectrum are applicable over a large range of source fluxes and exposure times. Since most of the 1998 observations were quite short, however, we independently verified the determination of the lag in these cases by comparing them to much longer observations. As an example, Fig. 1 displays the time lag spectra for two RXTE observations spaced by 1.25 years. Taking the much larger uncertainty from the short observation into account, the overall agreement is excellent. To further increase the signal to noise ratio in the lag determination we rebinned the X-ray lag spectrum into five frequency bands.

3. Temporal evolution of the lag

In Fig. 2 we display the evolution of the average time lag for three representative frequency bands and the RXTE ASM count rate. The Figure shows that a clear long term variability of the lags is present during 1998. For frequencies above ∼1 Hz, the mean lag is significantly *larger* during the interval in 1998 July that is characterized by a larger ASM count rate. At lower frequencies the fractional change of the lag decreases (Fig. 2). This tendency is a consequence of the temporal evolution of the shape of the lag spectrum as characterized by its rough $f^{-\alpha}$ proportionality: During 1998 July, $\alpha \sim 0.6$, compared to its usual value of $\alpha \gtrsim 0.7$ (Nowak et al. 1999a).

Compared to the hard state, intervals like 1998 July show an increased disk contribution to the X-ray spectrum (Zdziarski et al. 1999; Gilfanov et al. 1999) and have often been associated with "failed state transitions". One would expect the lag behavior to show the same tendency as during a successful state transition. At first glance, the 1996 data presented by Cui et al. (1997b) suggest that we should expect the

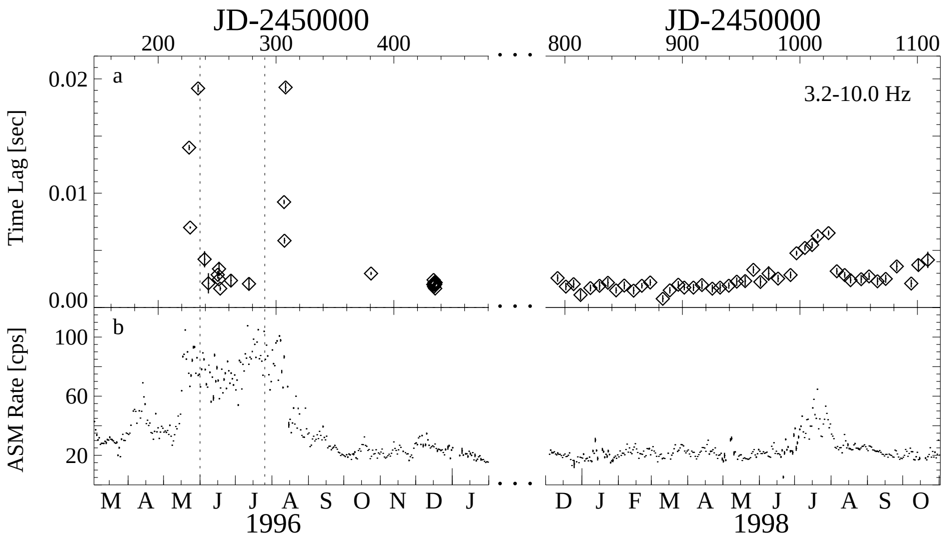

Fig. 3. a Temporal evolution of the absolute value of the average lag between ≲4 keV and ∼8–13 keV in the 3.2 to 10 Hz band and **b** ASM count rate for 1996 and 1998. The dotted lines denote the 1996 soft state.

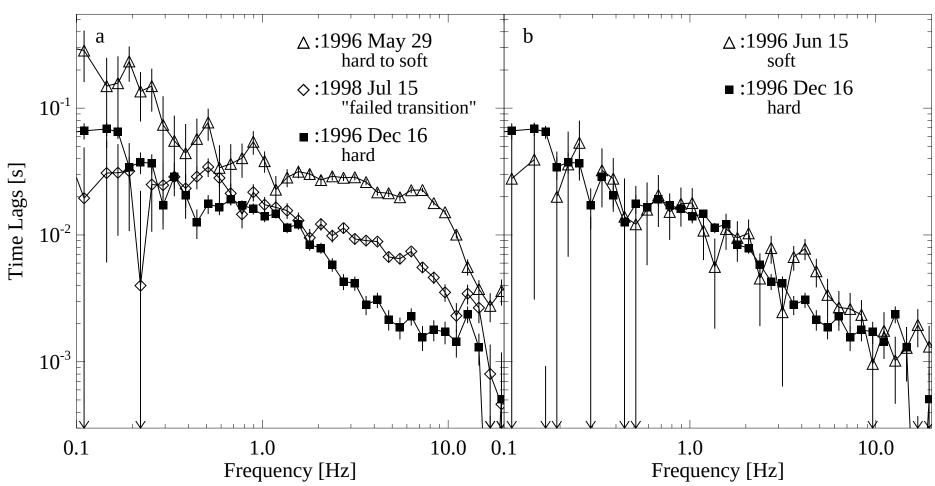

Fig. 4. X-ray lag spectra between ≲4 keV and ∼8–13 keV. **a** Comparison of the hard to soft state transition, the 1998 July transitional state, and the typical hard state. **b** Comparison of the 1996 soft state and the hard state.

1998 July lags to *decrease* during this interval. This contradicts our results (Fig. 2). We therefore went back to the 1996 soft state data and applied the same analysis as for the 1998 data. We also computed X-ray lags for two observations performed after the 1996 soft state, one in 1996 October (Dove et al. 1998; Nowak et al. 1999a), as well as the one in 1996 December (Focke 1998). Fig. 3 shows the absolute values of the average lag between ≲4 keV and ∼8–13 keV for 1996 and 1998. The lags are indeed longer during the state transitions than they are in the soft state, however, during the soft state itself, the absolute value of the X-ray lag equals that of the hard state. In fact, the frequency dependence of the lag is very similar for the soft and hard state (Fig. 4b). Previous analyses of two hard state observations already suggested that the soft and hard state lags might not be so different as previously thought (Cui 1999). Our numerous hard state monitoring observations now clearly indicate that *the X-ray lag spectrum of Cyg X-1 is rather independent of the spectral state*. The *enhanced lags are then associated with transition or failed transition intervals*, and not with the state of the source itself.

4. Discussion and conclusions

In Fig. 4a we display examples for the whole range of lag spectra present in this analysis. Taking the shape of the typical hard state lag spectrum as a baseline, the lag is significantly longer during the 1998 July failed state transition. The frequency range from 1 to 10 Hz exhibits these changes most prominently. During the hard to soft transition in 1996 May, the lag is longer by almost a factor 10 at 6 Hz. As already shown in Sect. 3, these results indicate that the magnitude and shape of the X-ray lag spectrum in Cyg X-1 is related to the state transitions.

Previous models for the generation of the X-ray lags assumed more or less static media to produce the X-ray lag by scattering of seed photons in a Comptonizing medium. The size of the region required to produce the observed lags in such a model is large (≳300 gravitational radii; Nowak et al. 1999b). Such a large size simplifies models in which the soft state Compton corona is much smaller than the hard state corona, as had been initially inferred from the 1996 soft state lags and spectral shape. Indirect evidence for the change of the size of the X-ray emitting corona has also been presented by Zdziarski et al. (1999), Gilfanov et al. (1999), and commented on by di Matteo & Psaltis (1999), with the latter authors suggesting an upper limit for the hard state coronal radius of $\sim$30 gravitational radii. Zdziarski et al. (1998) suggested that in the hard state of GX 339$-$4 there is a correlation between the X-ray power law photon index and the fraction of this power law that is reflected by cold material. Specifically, they suggested that softer power laws implied greater reflection, which implies smaller coronae in certain models. Within the hard state, softer power laws are associated with higher luminosities, implying again that the corona is shrinking as the source goes from the hard to the soft state. Our data clearly show that the soft and hard state lag spectra are very similar. This makes the geometrical interpretation of the lags in terms of Comptonization models alone difficult. We therefore need to look for other models to explain the observed lags. In the following we present a qualitative picture, based on recent observational results. Note, however, that a detailed theoretical model is beyond the scope of this Letter.

In recent years, evidence has emerged that the state transitions are not solely an X-ray phenomenon. Studies of Cyg X-1 and GX 339$-$4 have revealed that in the hard state the X-ray and radio behavior is correlated (Brocksopp et al. 1999; Corbel et al. 2000). In GX 339$-$4, there is strong evidence that the source is radio quiet during the soft state (Fender et al. 1999). At least in one case, optically thin radio flares accompanied the state transition. In Cyg X-1, no radio data are available for the soft state. The end of the 1996 soft state as well as the 1998 July "failed state transition", however, coincided with radio flares (Zhang et al. 1997; Brocksopp et al. 1999). Such flaring events are typically associated with the ejection of a synchrotron emitting cloud from the central, X-ray emitting region (Corbel et al. 2000; Fender et al. 1999).

We suggest that the scattering of primary X-rays in ejected material may be responsible for the enhanced transition X-ray time lags in Cyg X-1: In the hard state, a stable, presumably partially collimated, radio emitting outflow ("jet") exists, while the soft state shows no outflow (Brocksopp et al. 1999). During the formation and (failed) destruction of the jet, when radio flaring is observed, outflows that are uncollimated and much larger than those of the hard state might be present. Assuming that the hard state lag spectrum is produced in the accretion disk (which still poses a problem for most models; Nowak et al. 1999b) and that the rather weak hard state jet does not significantly affect these intrinsic lags, the prolonged lags during the transitions could be produced in these large ejected outflows. Additional scattering might also be responsible for the reduced X-ray coherence that was reported by Cui et al. (1997b) for the 1996 state transitions. Such a model wherein a fraction of the observed lags is created near the base of a radio emitting jet or wind has been previously suggested in analogy to blazar jet emission models (van Paradijs 1999, priv. comm., see also Fender et al. 1999). The state change following the flaring/ejection could then lead to a new accretion disk configuration with different X-ray spectral emission characteristics, different power spectra, but similar inherent lag spectrum.

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