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CYGNUS X-1 FROM RXTE: MONITORING THE SHORT TERM VARIABILITY

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ABSTRACT

We present temporal and spectral results from monitoring Cygnus X-1 with the Rossi X-ray Timing Explorer (RXTE) in 1998 and 1999. We concentrate on the long term evolution of the hard state timing properties, comparing it to the 1996 soft state evolution. This leads to the following results: 1. the hard and soft state time lag spectra are very similar, 2. during state transitions, the lags in the 1–10 Hz range increase by more than an order of magnitude, 3. in the hard state itself, flaring events can be seen — the temporal and spectral evolution during the flare of 1998 July identifies it as a “failed state transition”. During (failed) state transitions, the time lag spectra and the power spectra change predominantly in the 1–10 Hz range. We suggest that this additional variability is produced in ejected coronal material disrupting the synchrotron radiation emitting outflows present in the hard state.

INTRODUCTION AND DATA ANALYSIS

Galactic black hole candidates (BHC) are predominantly found in two 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 ~ 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 $kT_{\text{BB}} \lesssim 1$ keV to which a steep power-law is added (Cui et al., 1997a; Gierliński et al., 1999, and references therein). The X-ray states are also known to be associated with radio states (see, e.g., Fender, 2000, for a review). The canonical BHC Cyg X-1 stays predominantly in the hard state, and only occasionally transits into the soft state for a few months (Gierliński et al., 1999; Cui et al., 1997a,b, see also Fig. 1).

In addition to spectral analysis, timing analysis can also yield insight into the radiation mechanisms in BHCs. Apart from power spectrum analysis (Belloni and Hasinger, 1990; Gilfanov et al., 1999; Churazov et al., 2000), higher order statistics like the frequency-dependent coherence function and time lags have proven to be useful in evaluating accretion models (Hua et al., 1999; Nowak et al., 1999). Although very different in their specific physical assumptions, most models for the hard and the soft state assume that the observed time lags are an indicator of some characteristic geometrical size of the Compton corona. In the case of Cyg X-1, the apparent decrease of the X-ray lags during the 1996 soft state transition of the source was considered evidence that the size of the Comptonizing corona 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 1998 we initiated a monitoring campaign of Cyg X-1 with RXTE to systematically study long term variations of the hard state properties over a period of several years. Previous results have been presented elsewhere (Pottschmidt et al., 2000). In 1998 weekly pointings of ~ 3 ks duration and in 1999 two-weekly pointings of ~ 10 ks duration were performed. In this contribution we present results of the analysis of these observations. Together with archival observations from 1996, we consider 103 observations.

We concentrate on the data from the Proportional Counter Array (PCA; Jahoda et al., 1997), and use

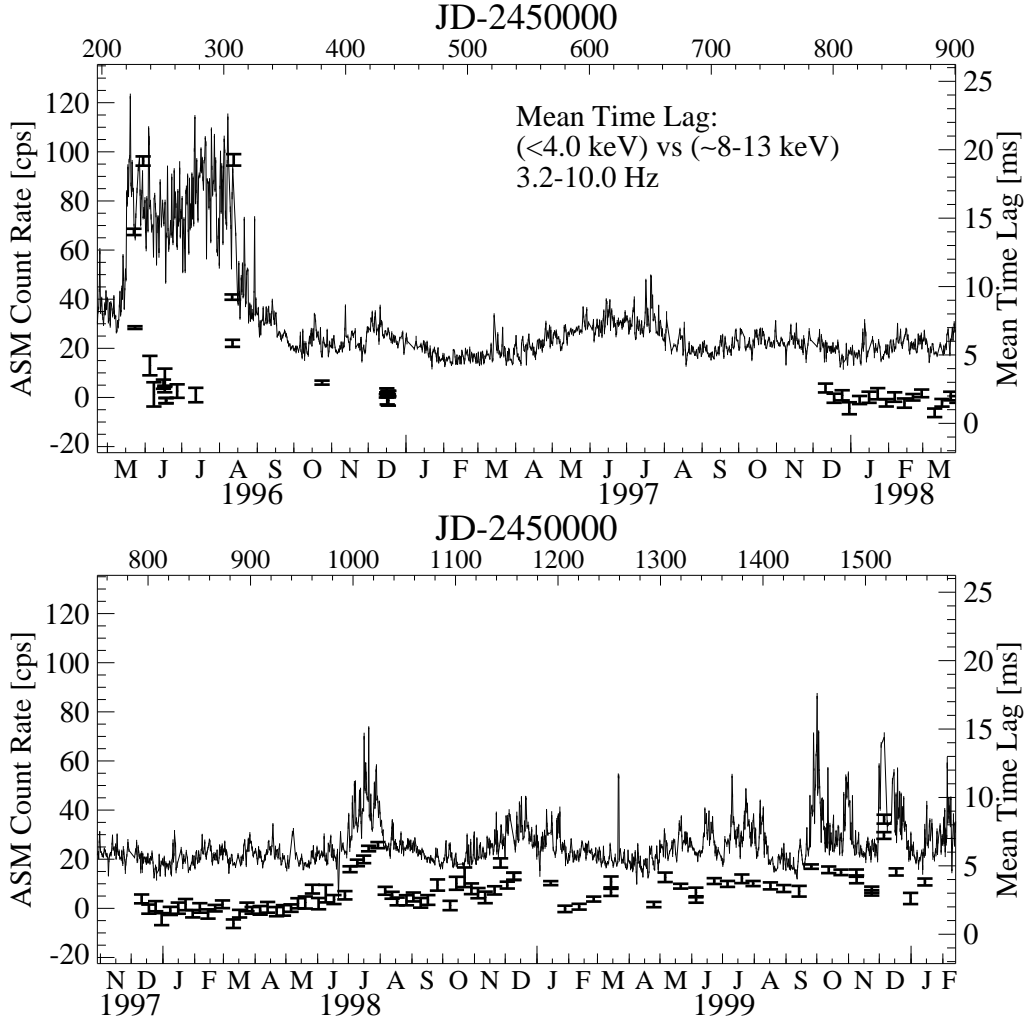


Fig. 1. RXTE ASM count rate (line) and mean time lag (symbols) between the energy band below 4 keV and the energy band from 8 to 13 keV in the frequency range from 3.2 to 10 Hz for the 1998/1999 monitoring campaign as well as for the RXTE data obtained during the 1996 soft state. During hard state phases there is a high correlation between the soft X-ray luminosity and the time lag.

the RXTE All Sky Monitor (ASM; Remillard and Levine, 1997) to place our observations in the context of Cyg X-1’s long term evolution. The data were reduced using the procedures described in detail elsewhere (Wilms et al., 1999). We mainly show results obtained from lightcurves with a resolution of 4 or 16 ms observed in two energy bands — ≤ 4 keV and ~ 8 –13 keV. The chosen energy bands are known to be well suited for time lag studies of this source (Nowak et al., 1999). The exact bands used to compare the 1996 data to the monitoring data were the closest matches possible for the available PCA modes. Furthermore, we describe the results of the spectral analysis of standard PCA spectra in the 2–20 keV range. We present the long term evolution of the averaged time lags, the frequency dependent time lag spectra and power spectra, and the spectral evolution during the flare of 1998 July. Finally, we discuss these results in the light of current accretion models.

LONG TERM EVOLUTION OF THE TIME LAGS

In Fig. 1, we display the daily averaged RXTE ASM count rate superposed on the mean time lag between the soft and the hard energy bands in the frequency band from 3.2 to 10 Hz. We have found that the X-ray time lag is most variable in this frequency band (Pottschmidt et al., 2000). In the lower panel, the 1998/1999 monitoring is displayed. It shows that in the hard state there is a clear correlation between the soft X-ray luminosity and the mean time lag (Pearson’s correlation coefficient of 0.78). This is especially true during “flaring” events (e.g., in 1998 July, see below).

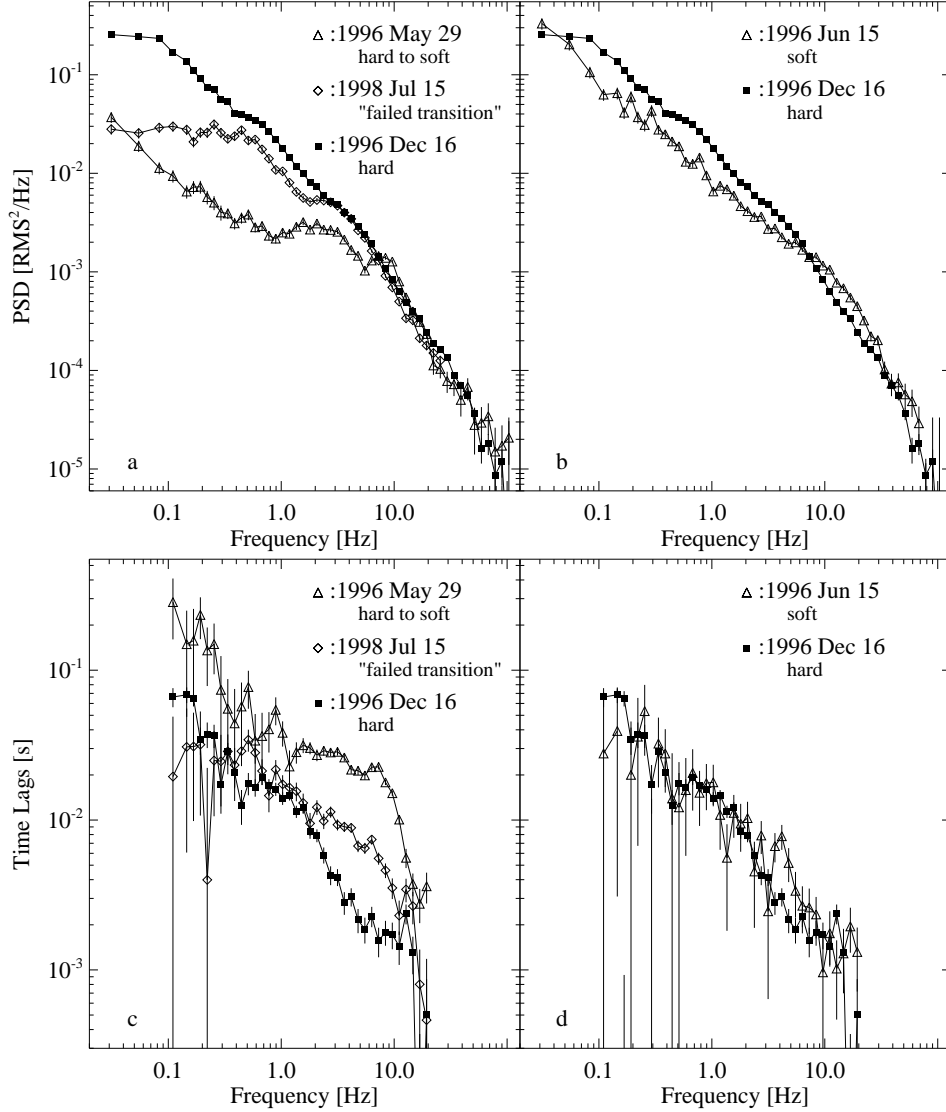


Fig. 2. Comparison between the power spectral densities (8–13 keV) and time lags for the 1996 state transition, a characteristic 1996 hard state observation, and the 1998 July failed state transition (sub figures a and c). Sub figures b and d compare the PSDs and lags between the hard and the soft state.

In the light of current accretion models, however, we would expect the lag to decrease as the source softens (with the corona becoming smaller). This was thought to happen during the 1996 full state transition, where the lag was seen to be considerably smaller in the soft state than immediately before and after (Cui et al., 1997b). Considering the hard state monitoring observations as well, however, we see a different picture (upper panel of Fig. 1): While the absolute values of the lags are comparable in the hard state and in the soft state, they are significantly longer during the transitions. In fact, the frequency dependence of the lag is very similar for the soft and hard states (Fig. 2d). It is interesting to note that for the hard energy band (8–13 keV) and the frequency range considered here, the timing behavior as characterized by the power spectral density (PSD) also looks similar (Fig. 2b). A qualitative model for explaining this PSD phenomenology in terms of transfer of variability structures through the disk/corona system has recently been presented by Churazov et al. (2000).

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 associated with transition or flaring intervals, and not with the state of the source itself.*

FLARING & HARD STATE STABILITY

Of special interest are the episodes of enhanced ASM count rates in the hard state, which, as we have seen, also show larger mean time lags than the “canonical” hard state. Figs. 2a and c display the PSD and the time lag spectrum for an observation performed during the 1998 July flare and compares them to a typical hard state observation as well as to the transition phase of the 1996 state transition.

Compared to the typical hard state lag spectrum the appearance of an additional component in the 1 to 10 Hz range can be seen during the 1998 July flare. This component becomes more prominent and “flattens” during the hard to soft transition in 1996 May, with the lag being longer by almost a factor of 10 at 6 Hz as compared to 1996 December. As has been reported by Cui et al. (1997b), the PSDs of the state transition show an additional steep component at lower frequencies, a shift of the break frequency to higher frequencies, and additional “QPO-like” features. The PSD of the 1998 flare is intermediate between the hard state and the state transition, i.e., the break frequency has moved from ~ 0.1 Hz to ~ 0.5 Hz. Furthermore, a quasi-periodic oscillation appears at ~ 2 Hz, i.e., in the frequency range that exhibits the enhanced lag (the QPO might also be present in the hard state PSD at ~ 0.4 Hz). Since the flaring episode displays all the features of the real state transition, presumably at the onset of their appearance, we identify it as a “failed state transition”.

This interpretation as a failed state transition is confirmed by the spectral analysis: Outside of the “flaring episode” the hard state X-ray spectrum as seen by the PCA can be described by the canonical power-law (photon index $\Gamma = 1.80 \pm 0.01$)¹, reflected off neutral material with a covering angle of $\Omega/2\pi = 0.44 \pm 0.04$ (the inclination has been fixed at 35°). An additional broad ($\sigma = 0.8$ keV) Fe line at 6.4 keV with an equivalent width of 150 eV is required ($\chi^2/\text{dof} = 19.6/42$; note that the $\sim 1\%$ systematics of Wilms et al. 1999 have been applied). During the flare the spectrum softens to $\Gamma = 2.13 \pm 0.02$ and the covering factor increases to $\Omega/2\pi = 0.93 \pm 0.07$. At low energies an additional soft spectral component appears (modeling this component as a multi-temperature disk black body results in $kT_{\text{in}} = 0.45 \pm 0.05$ keV. The soft component contributes $\sim 7\%$ of the flux at 3 keV. Thus, although the power law component still dominates the higher energy spectrum, there is clear evidence for a strong soft component, such that the 1998 July event should be associated with a failed state transition.

Although the flaring episodes introduce considerable long term variability into the hard state properties, the timing characteristics can be reproduced to great detail in observations separated by more than a year (Fig. 3): the time lag spectra and the PSDs of the 1996 December and the 1998 February observation are identical. This includes the “shelves” in the lags and the “wiggles” in the PSDs that might indicate that multiple processes are responsible for the observed timing behavior (see also Nowak, 2000).

DISCUSSION

Since Comptonization models generally give a satisfactory explanation for the X-ray spectrum, most models for the generation of the X-ray time lags assume that the lags are at least partially produced by scattering of seed photons (which might have an intrinsic time lag) in a Compton corona (Poutanen, 1998, and references therein). Comptonization cannot be the only cause for the time lags, however, as the magnitude of the lag implies very large Compton coronae ($\gtrsim 300$ gravitational radii Nowak et al., 1999), in conflict with the assumption of most Comptonization models. Furthermore, the energy dependence of the lags is also in disagreement with Comptonization (Nowak et al., 1999).

We note, however, that the coherence function in the frequency regime considered here is not equal to unity, but slightly smaller. This might be an indication that (part of) the time lag is produced by non-linear processes in the accretion disk, and not by the time delay due to the Compton scatterings in the corona (Churazov, 2000, priv. comm.).

Nevertheless, although all of these arguments point against Comptonization as the sole cause for the X-ray lags, one is tempted to assume that the magnitude of the lag is at least somehow proportional to the characteristic size of the X-ray emitting region. Accepting this paradigm, however, implies that the size of the X-ray emitting corona during the soft and hard states is the same as the lags during these states are identical. This is puzzling, given that the luminosity of the corona, and thus the release mechanism for the potential energy of the accreted material, is so different between the hard and the soft state.

¹All uncertainties are at the 90% level.

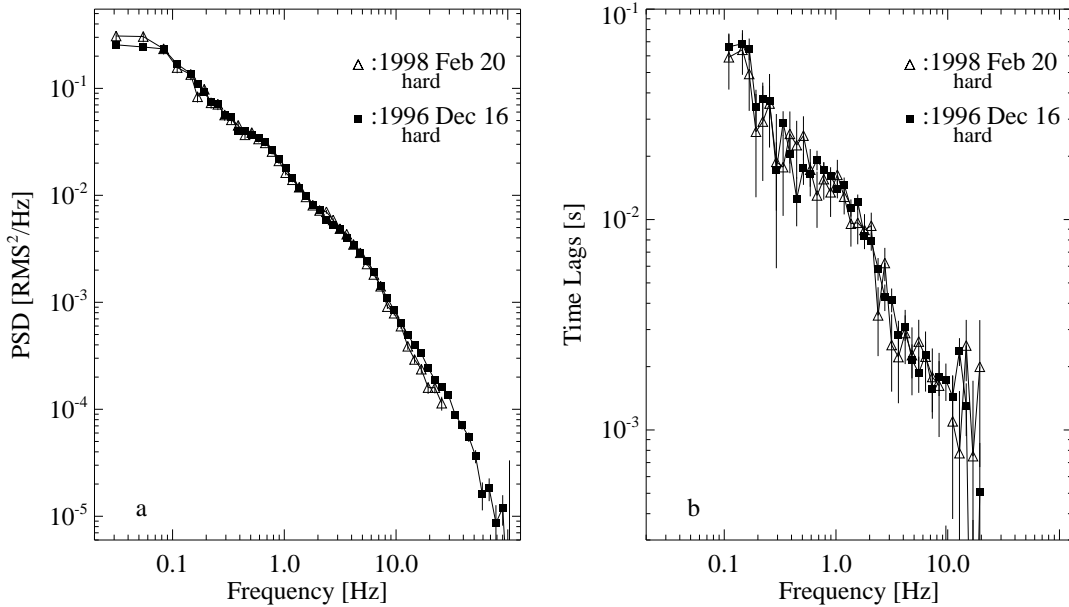


Fig. 3. Comparison of the PSDs and time lags for two hard state observations separated by 14 months. Both indicators for the temporal variability are virtually indistinguishable.

During state transitions, larger X-ray lags are observed in the 1–10 Hz band. These larger lags might be related to the radio outbursts seen during the transitions (Pottschmidt et al., 2000). Galactic BHCs in the hard state emit optically thick radio emission, while the soft state is radio quiet. During transitions, the radio emission tends to be optically thin and highly variable (e.g., GX 339–4, Corbel et al. 2000, but also Cyg X-1 itself; see Fender 2000 for a review). For Cyg X-1, there exists a good correlation between the radio and the soft X-ray flux (Brocksopp et al., 1999), and state transitions are correlated to radio outbursts (Zhang et al., 1997, see also Tananbaum et al. 1972). Such outburst are usually associated with the ejection of synchrotron radiation emitting outflows (see Fender et al., 1999; Corbel et al., 2000, for the case of GX 339–4). We suggest that the radio outflows and the larger lags might be related (Pottschmidt et al., 2000). One possible source for the electrons seen in the radio outflow might be the accretion disk corona. During state transitions, when the accretion disk is thought to reconfigure, the corona might be ejected and then observed as the radio outflow. In this picture, soft X-rays from the accretion disk might get Compton upscattered in the base of this outflow. As the base is much larger than the common accretion disk corona, one would expect larger X-ray lags. We note that such a picture, where part of the observed lags is due to the presence of a jet, has been previously suggested by van Paradijs (1999, priv. comm., see also Fender et al. 1999).

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