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# Monitoring the Short-Term Variability of Cyg X-1: Spectra and Timing

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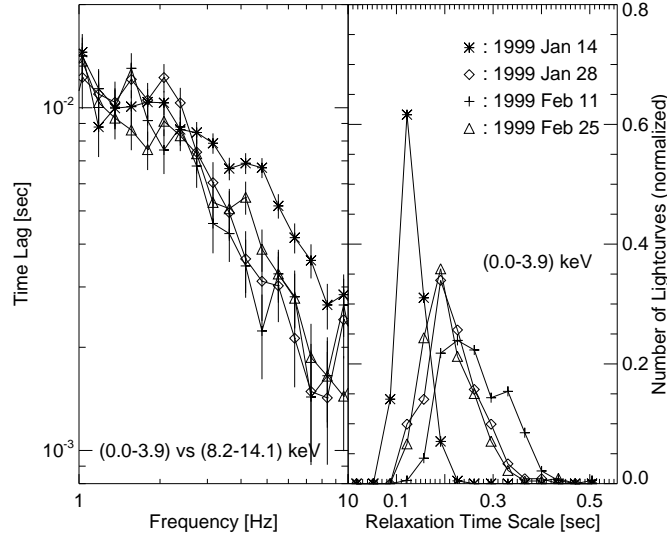
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**Abstract.** We present first results from the spectral and temporal analysis of an RXTE monitoring campaign of the black hole candidate Cygnus X-1 in 1999. The timing properties of this hard state black hole show considerable variability, even though the state does not change. This has previously been noted for the power spectral density, but is probably even more pronounced for the time lags. From an analysis of four monitoring observations of Cyg X-1, separated by 2 weeks from each other, we find that a shortening of the time lags is associated with a hardening of the X-ray spectrum, as well as with a longer characteristic “shot time scale”. We briefly discuss possible physical/geometrical reasons for this variability of the hard state properties.

## INTRODUCTION

For stellar black hole candidates, several distinct states can be identified that differ in their general spectral and temporal properties. Based mainly on spectral arguments these states have been associated with different accretion rates and different geometries of the accretion flow (e.g., Esin et al., 1998; Nowak, 1995). With broad band instruments like the Rossi X-ray Timing Explorer (RXTE) it is possible to study the states with high time resolution over a time base of several years. The focus of this work lies on parameters and functions characterizing the short-term variability ( $< 1000$  s) of the canonical black hole candidate Cyg X-1 and their stability in the hard state.

In 1996 and 1997 observations of Cyg X-1 with the pointed RXTE instruments were not performed regularly and mainly concentrated on the  $\sim 3$  month long soft state in 1996 (see, e.g., Cui et al., 1998). We initiated a monitoring campaign of the hard state in 1998 (3 ksec exposures), which we expanded to 10 ksec exposures in 1999 in order to allow the calculation of Fourier frequency dependent time lags with



**FIGURE 1.** Comparison of four consecutive RXTE observations of 1999 January and February, spaced by  $\sim 14$  d each. **Left:** Time lags as a function of Fourier frequency. The time lag in the 1 to 10 Hz band changes by a factor of three over the course of a month. Note the logarithmic  $y$ -axis! **Right:** Distribution of the relaxation time scale  $\tau$  found from short (32 s long) time segments for these observations. Observations with shorter time lags appear to have larger  $\tau$ .

sufficient accuracy (Fig. 1). Additionally, the RXTE observations are accompanied by simultaneous radio pointings. The aim of this campaign is to address fundamental questions such as the cause of the long term flux variability in the hard state, namely the 150 d periodic behavior seen in the RXTE All Sky Monitor and in the radio flux (Pooley, Fender & Brocksopp, 1999, Hjellming, priv. comm.). A precessing, interacting disk-jet system has been suggested as one possible explanation for this hard state cycle (Brocksopp et al., 1999).

We have performed spectral and/or temporal analyses on  $\sim 30\%$  of the available public data measured before 1999. In addition, we have analyzed those of our 2 weekly observations in 1999 that were scheduled before the gain change of the RXTE Proportional Counter Array (PCA) in 1999 March (for data after the gain change the calibration and background models are still uncertain). In this paper we present first results from these monitoring observations. Using the `f-tools` 4.2, we extracted PCA spectra and high (2 ms) time resolution PCA lightcurves. We computed periodograms for several energy bands, as well as the time lags, and the coherence function between these energy bands (Nowak et al., 1999a). In addition, we use the linear state space model (LSSM) to model the light curves in the time domain. This method allows one to derive a characteristic time scale,  $\tau$ , that can explain the dynamics of the lightcurve.  $\tau$  can be interpreted in terms of a shot noise relaxation time scale, but note that LSSMs only need a single time scale to provide a good fit of the lightcurve (see Pottschmidt et al., 1998, for an application of the LSSM to EXOSAT data from Cyg X-1).

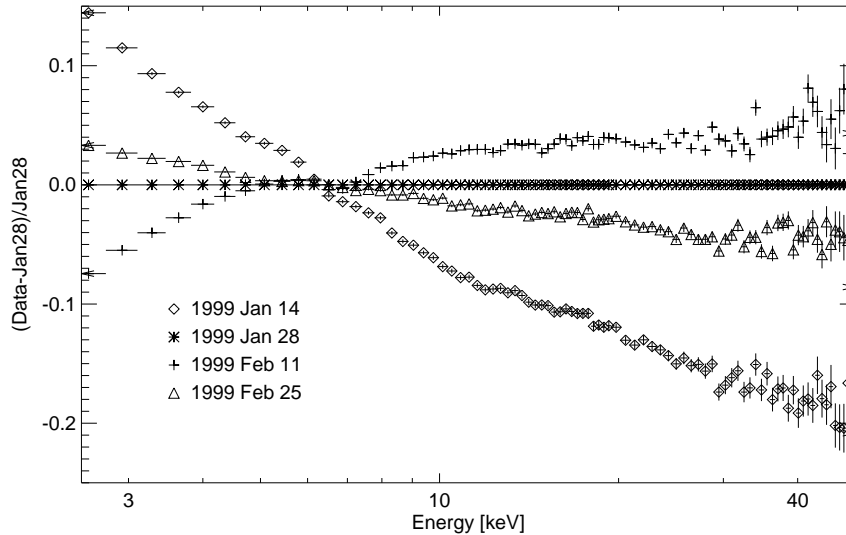
# VARIABILITY OF SPECTRAL AND TEMPORAL PROPERTIES

Fourier frequency dependent time lags of up to  $\sim 0.1$  sec are known to exist between different energy bands in Cyg X-1. While the lags increase with energy, they cannot be explained by the diffusion time scale of photons in a Compton corona alone (Miyamoto & Kitamoto, 1989; Nowak et al., 1999a). Nevertheless, the characteristic time lag “shelves” allow to roughly constrain coronal parameters (Nowak et al., 1999c). We find that over the course of weeks, the typical time lag in the hard state can vary by at least a factor three (Fig. 1, left panel). The first three observations show a gradual decrease in the time lags, while the fourth observation has intermediate values. This systematic development is mirrored by the shot relaxation time scale  $\tau$ , which gets larger for observations with smaller time lag (Fig. 1, right panel).

At the same time, the X-ray spectrum also changes systematically (Fig. 2). Spectral fitting of black hole candidate spectra with the PCA is severely affected by the uncertainty of the PCA response matrix. Although the data exhibit a clear and varying hardening above  $\sim 10$  keV, it is difficult to associate these changes with physically interpretable spectral parameters. For example, both, a broken power-law and a power law reflected from cold matter result in acceptable fits. This behavior is similar to GX 339–4 (Wilms et al., 1999). In order to characterize the spectral variability of Cyg X-1 independently of any spectral model, therefore, we directly compared the data in detector space. Fig. 2 displays the relative deviation of the four observations with respect to the observation of 1999 Jan 28. Cyg X-1 is clearly spectrally variable on a time basis of 14 d (note that part of the variation could be due to orbital modulation).

Comparison of Figs. 1 and 2 shows that a spectral hardening of the source correlates with a decrease of the time lags and with an increase of the relaxation time  $\tau$ . Recently, Gilfanov, Churazov & Revnivtsev (1999) also analyzed several of the public RXTE observations of Cyg X-1. They found a variability of the spectral hardness of the same order as presented here and an increase of the PSD break frequency with the reflection fraction. They also confirmed for Cyg X-1 a correlation between the intrinsic spectral slope and the reflection fraction (Zdziarski, Lubinski & Smith, 1999), as well as a relationship between two temporal parameters, namely the PSD “break frequency” and the PSD “hump frequency” (Wijnands & van der Klis, 1999; Psaltis, Belloni & van der Klis, 1999).

Due to the long time basis of the available RXTE data it is also possible to compare observations that are widely spaced in time, e.g., the 1999 monitoring observations with an observation made more than two years earlier, in 1996 Oct 23. The latter has previously been published in a series of papers (Dove et al., 1998; Nowak et al., 1999a,c). It was performed shortly after the soft state of 1996, and we cautioned, therefore, that the observation might still have been “contaminated” by soft state peculiarities. But, the comparison with the observation of 1999 Feb



**FIGURE 2.** Relative deviation of the shape of the RXTE PCA count rate spectra from the observation of 1999 Jan 28.

25 shows almost identical PSDs and time lags. So, we see that the source really was in its hard state and that the hard state timing properties can be reproduced with great accuracy on the time scale of years.

## DISCUSSION

We have presented first results from our systematic analysis of RXTE data of Cyg X-1 in the hard state. Apparently, during the canonical hard state this source can vary by up to a factor of  $\sim 2$  in 2–50 keV flux and by up to a factor of three in the associated time lags within a few weeks. On the other hand, we were also able to identify data with almost identical spectral and temporal behavior spaced by more than two years.

As we noted in the previous section, there is possible evidence for a correlation of the changes in the spectral and temporal behavior of the source. Harder spectra appear to be associated with shorter time lags, similar to the hard state of GX 339–4 (Nowak et al., 1999b). A possible interpretation would be that the accretion disk penetrates to smaller disk radii at times of harder flux, thereby increasing the reflection fraction of the Comptonized radiation (see also Gilfanov, Churazov & Revnivtsev, 1999), i.e., hardening the spectrum, and shortening the time-delay of the harder photons (with the smaller system geometry corresponding to shorter lags). Alternatively, the harder spectra might be due to changes in the coronal parameters: our results might indicate that coronae with larger optical depth and/or temperature are physically smaller. This is also consistent with the development of the shot time scale in the sense that more scattering events lead to longer relaxation times.

## Acknowledgments

We thank all participants in the 1999 broad band campaign for their continued effort to obtain simultaneous radio through X-ray observations of Cygnus X-1. This work has been partially financed by DFG grant Sta 173/22 and a travel grant by the Deutsche Forschungsgemeinschaft to JW.

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