Rapid X-ray Variability in Cygnus X-1

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Abstract. In this paper, results from temporal analysis of *RXTE* observations of the black hole binary Cygnus X-1 are reviewed. By tapping into the large amount of archival data available, a systematic study of the variability, in the form of the power spectrum, is conducted. It is clear that timing studies can give valuable information on the emission mechanisms and accretion geometry. Tying characteristic frequencies to effects predicted by general relativity directly gives information about the parameters of the compact object.

The results show that the characteristic frequencies seen in the power spectrum follow the relation predicted for the nodal and periastron precessional frequencies of relativistic precession. From this relation, the spin of the black hole is determined to $a_* = 0.48 \pm 0.01$ for a mass of $9\,M_\odot$. During times of high hardness, the hardness-flux correlation seen in the hard state of the source disappears on short timescales. Together with the variable characteristic frequencies, this is interpreted as support for the truncated disk scenario.

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INTRODUCTION

Cygnus X-1 is one of the most studied X-ray sources, and is often quoted as the prototype black hole binary system. The source exhibits two main spectral states, commonly referred to as hard and soft, with a brief intermediate state during transitions [e.g., 1–4]. Several models have been proposed to explain the observed states and transitions. The two main components of such models are usually a geometrically thin, optically thick accretion disk and a geometrically thick, optically thin hot inner flow or corona. The models vary in the geometry and properties of mainly the hot flow/corona [5–7].

Transitions between the two states are believed to be a response to a change in accretion rate. In one widely accepted model [see e.g., 3, 8–10] these changes result in a reconfiguration of the accretion flow. In the soft state (high accretion rate) the disk extends almost in to the last stable orbit, whereas in the hard state (low accretion rate) it is truncated and replaced by a hot flow at inner radii. Throughout the hard state and into the transition, the hardness of the spectrum and changing temperature of the observed disk blackbody component is believed to track the variable radius of the inner disk.

The energy spectrum of Cyg X-1 in its hard state was described by Gierliński et al. [8]. It is dominated by a component arising from thermal Comptonization in a plasma with electron temperature of ~ 100 keV and optical depth $\tau \sim 1$; only a weak blackbody component is visible, corresponding to an inner disk temperature of ~ 200 eV in a geometry with a truncated disk. An additional soft component, often modelled as an additional Comptonized component, is also required to accurately fit the spectrum.

This paper presents the results from systematic studies of the rapid variability of

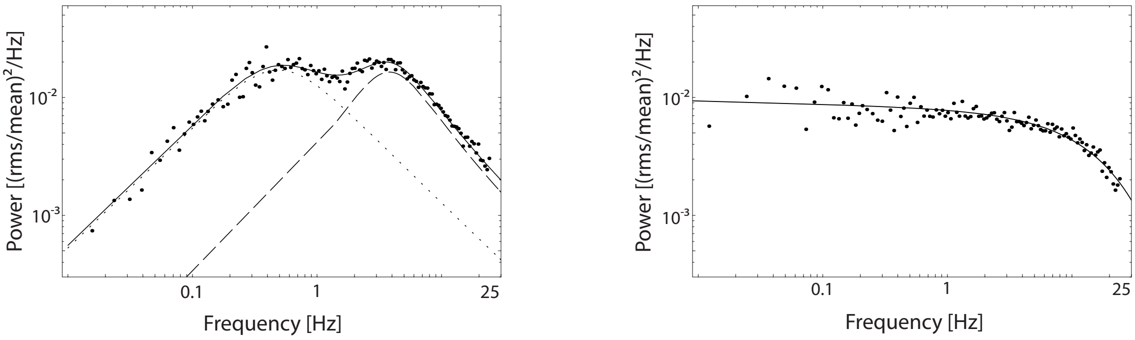

FIGURE 1. Canonical power spectra of the hard (left panel) and soft (right panel) states of Cyg X-1.

the black hole binary Cygnus X-1. The power density spectrum (PDS) is analyzed, in particular with regard to the evolution of the characteristic frequencies, or quasi-periodic oscillations (QPOs).

EVOLUTION OF THE POWER SPECTRUM

Cygnus X-1 is one of the most observed sources in the X-ray sky. As in many similar sources the PDS at higher frequencies, $> 10^{-3}$ Hz, varies greatly between the hard and soft spectral states. "Canonical" power spectra of the two states are shown in Fig. 1. In the representation used, νP_ν versus ν, the double-peaked appearance of the hard state is clear; when plotted in power versus frequency these QPO features are much less apparent. The hard state PDS was first fit in the latter representation, using a broken power-law [11–13]. As shown by Nowak [14], the hard state PDS is better fit by up to three Lorentzian components. A comprehensive study of the hard state PDS was conducted by Pottschmidt et al. [15], showing that the characteristic frequencies shift systematically with respect to spectral changes. Evidence was also found for a fourth Lorentzian component in the high end of the frequency range studied (0.002–128 Hz). The number of components in a given study depends on the frequency window and models used.

In the soft state, the PDS does not display any strong QPO frequencies, and is instead well fit by a power-law ([2]; however, this depends on the definition used for the soft state, cf. [16]). The index is close to -1, matching the PDS appearance at low frequencies in both spectral states. This led Reig et al. [17] to suggest that the same power-law extends throughout the whole frequency range. Around 20 Hz, the power-law steepens. No variability has been detected at frequencies greatly above 100 Hz in either state.

There is a wealth of data on Cyg X-1in the *RXTE* data archive, and Axelsson et al. [16] analyzed all publicly available data in this archive – more than 750 observations. It was discovered that the power spectrum changed on short timescales, within the timescale of a typical PCA observation ($\sim$ 1 hour). In order to fully model the complete range of the power spectrum, from hard to soft state, a model with three components was used: two Lorentzians (as in the hard state) and an exponentially cut off power-law (matching

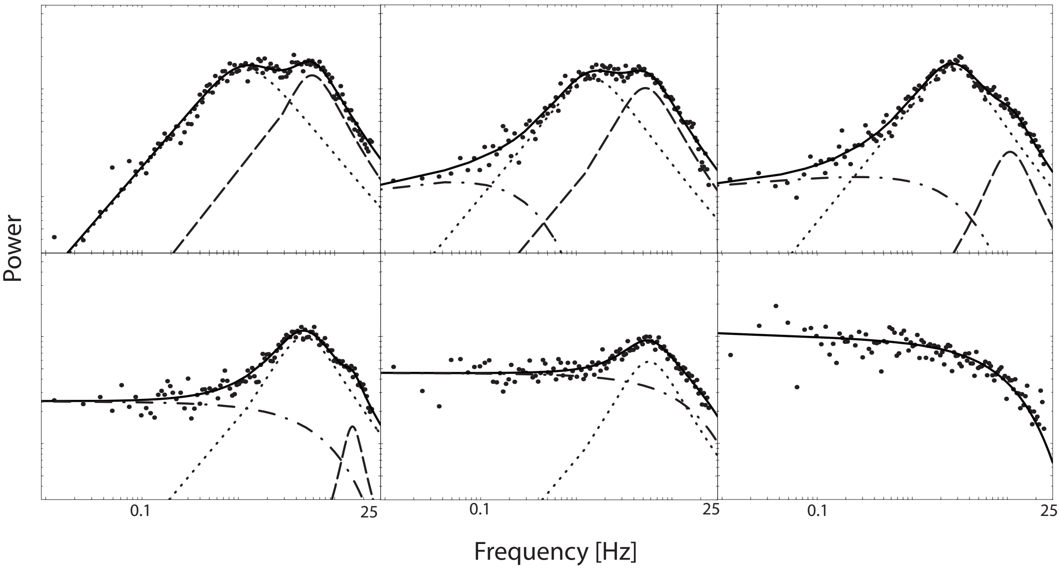

FIGURE 2. The full power spectral evolution of Cyg X-1, from hard state (top left panel) to soft state (bottom right panel). The data are from Axelsson et al. [16].

the soft state appearance). This model proved sufficient to fit nearly all of the power spectra, allowing Axelsson et al. [16] to accurately follow the complete evolution of the power spectrum between the states, for the first time. The complete evolution is shown in Fig. 2.

The components of the power spectrum

When the same model components are used throughout the evolution, it is possible to study the behavior of the individual components, as in Axelsson et al. [18]. In Cyg X-1, the combined fractional variability of the two Lorentzian components is constant throughout the PDS evolution [15, 18]. This supports a common origin; the two components could for example be sharing the same constant energy – if one variability amplitude grows the other must weaken. In contrast, the analysis of Axelsson et al. [18] showed that the variability behind the power-law component is most likely not related to the same process as the Lorentzian components. These results thus indicate at least two separate emission components from Cyg X-1, where one dominates in the hard state and the other in the soft state.

IDENTIFICATION OF FREQUENCIES

There is as yet no widely accepted model explaining the characteristic frequencies seen in Cyg X-1, or X-ray binaries in general. The fact that the frequencies change over an order of magnitude rules out models invoking relativistic resonance or most diskoseismic models as these predict constant frequencies. In Fig. 3, the frequencies

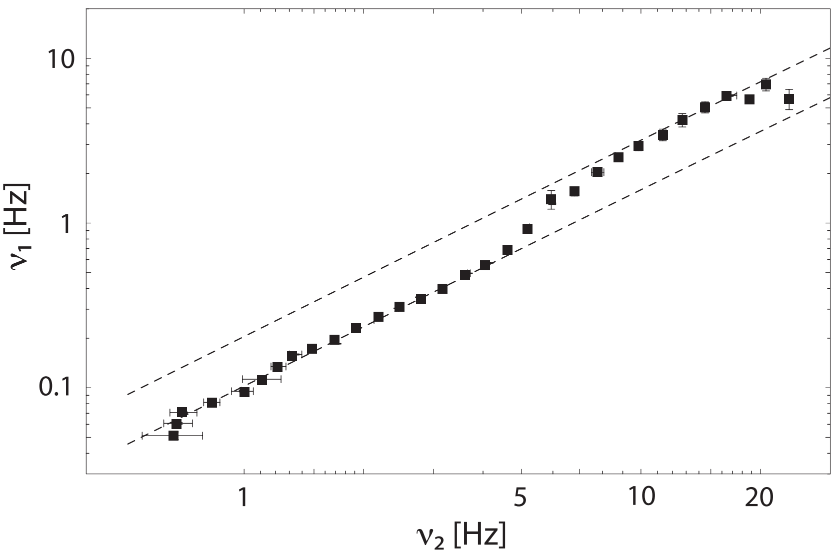

FIGURE 3. The frequency relation between the peak frequencies of the two Lorentzian components. The data (black squares) have been binned – over 2000 data points create the relation. A power-law fit to the data points below 5 Hz gives an index of 1.20 ± 0.01 (lower dashed line). The upper dashed line is a power-law of the same index, shifted by a factor of 2. The data are from [18].

of the two Lorentzian components are plotted against each other (the data, taken from [16, 18], are binned). As can be seen in the figure, there is a clear correlation. Such frequency correlations have been reported before, both in Cyg X-1 [14, 15] and other sources [19]. However, the amount of data analyzed in Axelsson et al. [16, 18] led to the relation being better constrained. The correlation was there shown to be well described by a power-law, with index 1.20 ± 0.01. This relation is the one predicted by the relativistic precession model, if the two QPOs are identified with the nodal and periastron precessional frequencies.

The relation of the frequencies appears to change as Cyg X-1 transits from hard to soft state ($\nu_2 \sim 5$ Hz in Fig. 3). The results of Axelsson et al. [18] points to the change being related to the transition, with the hard state index being recovered in the correlation once the soft state had been reached. It was also noted that the shift of the power-law was consistent with a doubling of the lower QPO frequency.

The signal-to-noise ratio of the observations do not allow an additional component to be inferred from the data. While increasing the data used for each PDS would increase the sensitivity, the Lorentzian components shift in frequency on very short timescales, so it is not clear that this would alleviate the problem. Axelsson et al. [18] instead adopted an approach using simulations. Artificial PDS were created, mimicking the observed parameter behaviors, and a harmonic to ν_1 was introduced. When the resulting PDS were fit with the two-Lorentzian model, the frequency correlation was well reproduced. The results are thus consistent with the QPOs connected to relativistic precession, assuming the lower frequency QPO is replaced by its first harmonic during the transition into the soft state.

In some of the observations, the QPOs shift to such low frequencies that a third component, previously observed at higher frequencies [14, 15] enters the studied frequency window (0.01 – 25 Hz). These observations correspond to the lowest flux and highest hardness levels. This third frequency does not have any immediate interpretation in the relativistic precession model; in this framework it scales as the square root of the Keplerian frequency [20].

The spin of the black hole

The relativistic precessional frequencies are not only determined by the mass of the black hole, but also by its spin. Interpreting the observed QPOs in this framework gives the possibility to determine the spin parameter a_* directly from the frequency correlation. In the weak field limit, Stella et al. [25] derived the relation

$$\nu_{\rm nod} \propto a_* M^{1/5} \nu_{\rm per}^{6/5} \ , \tag{1}$$

for a slowly rotating black hole. From the frequency relation shown in Fig. 3, the spin parameter for the black hole in Cyg X-1 is determined to be $a_* = 0.48 \pm 0.01$ for a mass of 9 $M_\odot$.

TRUNCATED DISK?

Assuming the frequencies are those of relativistic precession, a preferred radius is required. In the hard state the disk is likely replaced with a hot inner flow at small radii, and a possibility is then the scenario of Psaltis & Norman [21], where the transition between the two acts as a filter picking out the relativistic precession frequencies. Changes in the QPO frequencies would then be a direct result of variations in the inner disk radius, and measuring the QPO frequencies provides a way to determine this parameter. The results point to an inner disk radius varying between $50\,R_{\rm g}$ in the hard state and $20\,R_{\rm g}$ at the start of the transition to the soft state. If the origin of the QPO frequencies is associated with the truncation radius, a natural explanation for the lack of kHz features in Cyg X-1 is provided: this frequency range is far above the Keplerian frequency at the truncation radius.

Further support for the QPO frequencies tracking the inner radius of a thin accretion disk can be found when studying the hard state observations with low flux and high hardness. The hardness-flux correlation in Cyg X-1 is known to be negative in the hard state (see for example [10, 22, 23]). However, Axelsson et al. [20] showed that this correlation disappears on short timesales ($\sim$ 30 min) as the source reaches its highest hardness levels. Figure 4 shows the correlation index between flux and hardness as a function of flux; as the flux decreases (signifying increasing hardness) the correlation weakens. From the frequency analysis, the truncation radius is in these cases determined to be $> 50\,R_{\rm g}$. On longer timescales, *between* observations, the normal hard state anticorrelation is recovered.

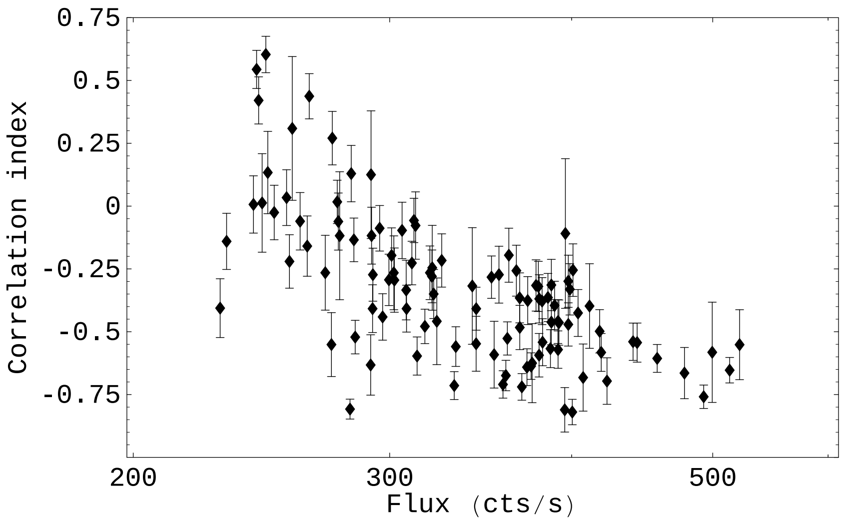

FIGURE 4. Spearman rank correlation index between hardness and flux as a function of flux. Low flux corresponds to high hardness. Each point corresponds to one observation of ~30 minutes. The hardness is calculated for the 9–20 keV over 2–4 keV bands, and the flux is the sum of these two bands. For the lowest flux levels, the hardness-flux correlation disappears on short timescales. Data from [20].

A possible interpretation of this behavior can be found by connecting the mechanism behind the hardness-flux correlation to the viscous timescale at the disk truncation radius. For a standard Shakura-Sunyaev disk, this timescale is given by [24]:

$$t_{\rm visc} \sim \alpha^{-1} \left(\frac{H}{R}\right)^{-2} t_{\rm dyn}\,, \tag{2}$$

where H/R is the ratio between disk scaleheight and radius, and $t_{\rm dyn}$ the dynamical timescale, usually taken to be Keplerian. As argued in Axelsson et al. [20], if the disk is sufficiently far away ($> 50\,R_{\rm g}$), the viscous timescale does not allow the truncation radius to adjust to a changing accretion rate within the time of a single *RXTE* observation. The effect can be compared to the hysteresis observed in transient sources, albeit at much smaller scale.

CONCLUSIONS

Cygnus X-1 shows strong variability over a large range of timescales. Temporal analysis of the rapid variability has the potential to give valuable information about the geometry of the region closest to the black hole. In this paper, results are presented from systematic analysis of the 0.01–25 Hz PDS. The pattern seen in the shifting characteristic frequencies can be explained within the framework of relativistic precession, with the two components identified with nodal and periastron precession. Adopting this identification furthermore allows determination of the black hole spin parameter.

The changes seen in the hardness-flux correlation are interpreted as indications of the inner disk being truncated at a large radius, $> 50\ R_{\rm in}$. The timescale for the observed short term pivoting behaviour is related with the viscous timescale for variations of the inner radius of the accretion disk of a few R_g. The results support the commonly adopted scenario where the hard state is explained by a truncated inner disk.

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