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AN INTERMEDIATE STATE OF CYGNUS X-1

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ABSTRACT

We report *RXTE*/PCA observations of the black hole candidate Cygnus X-1. In 1996 February the source was in its usual "low" state. In three observations during 1996 May the source was on average brighter by a factor of 2 and showed less rapid variability and a softer energy spectrum. However, the observations indicate that Cyg X-1 did not enter a high state like the one observed in black hole transients. Flux, variability, and spectral shape suggest instead that the source was in an "intermediate" state similar to what has been observed in GS 1124−68 and GX 339−4. Perhaps also the state transitions of Cyg X-1 observed in the 1970s were not to a high state but to this intermediate state.

Subject headings: X-rays: stars — stars: individual (Cygnus X-1)

1. INTRODUCTION

Cyg X-1 has been for years the prototype of black hole candidates: its X-ray properties such as rapid variability and hard X-ray spectrum were supposed to be signatures of a black hole (see Tanaka & Lewin 1995 for a review). In its low state, the energy spectrum in the 1–200 keV band is a power law with photon index ∼1.7 (Tananbaum et al. 1972; Bałucińska-Church et al. 1996; Oda 1977). The power spectral distribution is flat below a first characteristic ("break") frequency ν_1, has a slope of 1 between ν_1 and a second frequency ν_2, then steepens to a slope of 2 (Makishima 1988; Belloni & Hasinger 1990a, hereafter BH90a). Superimposed on this power spectrum, "wiggles" are observed whose nature was never considered in detail. The total rms fractional variation of this noise component is 30%–40%. While ν_2 is always around a few Hz, ν_1 varies between 0.03 and 0.5 Hz (BH90a; Crary et al. 1996a). As the low-frequency part of the power spectrum changes, the high-frequency part stays the same (BH90a), an effect that has been observed later in other black hole candidates, as well as in neutron star systems (Miyamoto et al. 1992; Yoshida et al. 1993). Although these variations are uncorrelated with most other source parameters like 1–20 keV flux or spectral shape, Crary et al. (1996a, 1996b) found that they depend on spectral slope in the 45–140 keV band. Cyg X-1 sometimes switches to a different ("high") state, where the X-ray spectrum is much softer in the 1–10 keV band (Tananbaum et al. 1972) and the time variability is suppressed (Oda 1977). Unfortunately, no such state was reported in the last 16 years.

Recently, the number of known black hole candidates has rapidly increased, due to the discovery of a number of transient systems (see Tanaka & Lewin 1995). In black hole transient systems, three separate states have been identified (see van der Klis 1995): besides the "high" and "low" states

similar to Cyg X-1, a third state, called "very high" state, occurs at high, probably near-Eddington luminosities (Miyamoto et al. 1991; Miyamoto et al. 1993). This state is characterized by a two-component X-ray energy spectrum, consisting of an ultrasoft component dominating the flux below a few keV, and a power law extending to higher energies (Miyamoto et al. 1991; Ebisawa et al. 1994). That is considerably steeper (photon index $\Gamma \sim 2.5$) than in the low state ($\Gamma \sim 1.5$). The time variability in the very high state is characterized by the presence of a 3–10 Hz QPO peak with complex harmonic content, and by a band-limited noise or weaker power-law noise component (Miyamoto et al. 1994; Takizawa et al. 1996). This band-limited noise has a break frequency above 1 Hz, higher than ν_1 in Cyg X-1, while its total rms is considerably lower than in the low state. From the fact that in transient systems the accretion rate is supposed to usually decrease as the outburst progresses in time, it has been concluded that the three states can be ordered as a function of increasing accretion rate as: low, high, very high. Most likely this also applies to Cyg X-1, although attempts to reconstruct the bolometric luminosity indicate little change (S. N. Zhang et al., in preparation).

Interestingly, the transient GS 1124−68 on its way from high to low state (Ebisawa et al. 1994; Miyamoto et al. 1994) showed timing and spectral behavior similar to the very high state, at much lower count rates (Belloni et al. 1996a), and separated from it by a high-state episode with no detectable band-limited noise. This may be a fourth separate state, as confirmed by the discovery that *EXOSAT* observed the black hole candidate GX 339−4, the only other system besides GS 1124−68 to show all three states, in a similar state on three occasions (Méndez & van der Klis 1996). The variations of the break frequency in the low state (BH90a) can be interpreted as the source trying to reach this fourth state (van der Klis 1994), but this hypothesis could not be tested up to now.

In 1996 May, *RXTE*'s ASM showed a brightening and hour timescale flaring in Cyg X-1 in the 2–12 keV band (Cui 1996), while BATSE detected a decreased 20–200 keV flux (Zhang et al. 1996a), with a softening of the energy spectrum and a decreased variability. These are all characteristics that had been associated to the high state of Cyg X-1 (1–10 keV brightening, spectral softening, low variability). However, *ASCA* determined the spectral distribution to be a $\Gamma = 2.4$ power law plus a 0.34 keV blackbody (Dotani et al. 1996). The

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Date	UT Start	UT End	PCA Rate (ch. 0–35)	PCA Rate (ch. 36–249)
96 Feb 12	02:00	09:34	5040	2380
96 May 22....	17:45	19:49	9620	970
96 May 23....	14:14	18:08	9220	1280
96 May 30....	07:47	08:45	7260	710

presence of a strong power law and the moderate flux increase suggest that this state is not the high state observed in GS 1124−68 (Ebisawa et al. 1994), but instead similar to the intermediate state observed both in GS 1124−68 and GX 339−4 (Ebisawa et al. 1994; Miyamoto et al. 1994; Méndez & van der Klis 1996). Reports of subsequent *XTE* observations (Cui, Focke, & Swank 1996) show that the source might have reached the high state in 1996 June, although the evidence is still not conclusive.

2. DATA ANALYSIS

We analyzed four *RXTE*/PCA observations of Cyg X-1, one in 1996 February in a "standard" low state and three in the bright, softer state of 1996 May–June (Cui 1996); see Table 1.

We produced power spectra in the PCA channel bands 0–35 and 36–249. Due to the 30% change in PCA gain

between 1996 February and May, this corresponds to 2.0–9.5 and 9.5–70.4 keV for February, and 2.0–11.1 and 11.1–83.9 keV for May. Poisson noise, including the VLE contribution, has been calculated following Zhang et al. (1995) and Zhang (1995), and subtracted. The spectra are normalized to squared fractional rms per Hz (the same normalization as used by Belloni & Hasinger 1990b). No spectral windowing has been applied to the data.

In all observations we calculated the power spectra out to frequencies as high as 4096 Hz. We can exclude the presence of high-frequency QPO peaks of similar strength as observed in neutron stars (van der Klis et al. 1996; Strohmayer et al. 1996; Berger et al. 1996; Zhang et al. 1996b). Above 100 Hz our power spectra might be affected by remaining uncertainties in Poisson noise.

2–60 keV energy spectra were obtained simultaneously using PCA Standard mode 2. Background spectra were obtained from slew data to and from the source (excluding contaminating sources) and from observations taken during Earth occultations.

3. RESULTS

3.1. *Power Spectra*

The power spectra in the two energy bands are shown in Figure 1. The right-hand panels contain the same spectra as
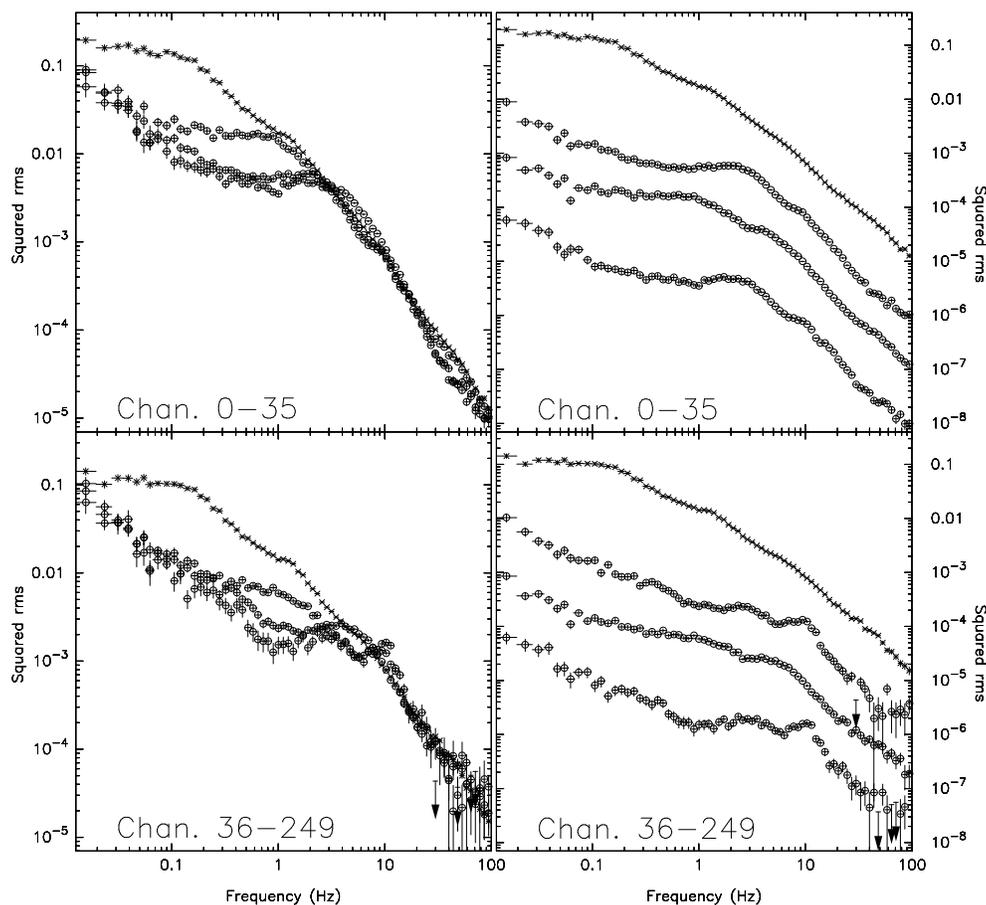

FIG. 1.—Power spectra for the four *RXTE*/PCA observations of Cyg X-1. The right panels show the same spectra as in the corresponding left panels, but shifted in the *Y* coordinate by factors of 10. In the right panels the order of the spectra, from top to bottom, is February 12, May 22, May 23, and May 30. Upper frames refer to PCA channels 0–35, lower frames refer to PCA channels 36–249.

TABLE 2
TOTAL RMS, INTEGRATED IN THE 0.01–100 Hz
FREQUENCY RANGE

Date	rms (ch. 0–35)	rms (ch. 36–249)
96 Feb 12......	30.57 ± 0.10	28.66 ± 0.09
96 May 22	19.49 ± 0.07	17.76 ± 0.14
96 May 23	24.19 ± 0.08	20.08 ± 0.09
96 May 30	18.21 ± 0.08	17.68 ± 0.26

the left-hand ones, but shifted by factors of 10 to better show details in the shapes.

In both bands, the low-state spectra have the usual shape: flat below a break frequency ν_1 (here ∼0.2 Hz), slope ∼1 between ν_1 and ν_2 ∼10 Hz, slope 2 above ν_2. A feature near 1 Hz is visible in both energy bands, but more pronounced at higher energy. This had already been detected with *Ginga* (Berger & van der Klis 1996; Belloni et al. 1996b).

The three spectra from 1996 May are considerably different. In particular below 1–10 Hz the power is much smaller than in the low state. Below 0.1–1 Hz there is an additional power-law component, which is the same between the three observations. Ignoring this power-law component, a flat top is seen that extends to a break frequency ν_1 much higher (1–3 Hz) than in the low state (0.2 Hz). Above ν_1, the power spectra roughly coincide with that of the low state.

Two broad peaks are visible in the low-energy data. One is located approximately at ν_1 and therefore seems to be associated to the break frequency, the other one is at a frequency that varies between a few and 10 Hz. In the high-energy data, this second feature is much more pronounced, and assumes a narrower, peaked shape (Fig. 1). In the high-energy band the total rms of this peak is as high as 10%. Its central frequency is different in different observations. There is a positive correlation between the break frequency and the frequency of the peak.

The total fractional rms variation is reported in Table 2. The reduction in total rms in the May observations is due to the relative lack of power below the break frequency. For all observations the total rms is lower at high energy, although only marginally for the May 30 observation.

3.2. *Energy Spectra*

The low-state energy spectra fitted a power law with a photon index of 1.60 ± 0.02 and a total 1–30 keV flux of 2.72×10^{-8} erg cm^{-2} s^{-1}, with the addition of an iron line plus absorption edge ($\chi^2 = 1.18$ at 103 d.o.f.). Significant residuals were still present at low energies, but we could not improve the fit by adding a soft component (blackbody, thermal bremsstrahlung, or multicolor blackbody).

The three energy spectra from 1996 May could not be fitted by means of a single power-law component: a soft component was required. We used a multicolor disk blackbody (e.g., Makishima et al. 1986) plus a power law. The three spectra were fitted to the same model, allowing for changes in normalization. The best fit was obtained for a temperature of 0.36 ± 0.01 keV at the inner radius of the disk (consistent with the 0.34 keV blackbody fitted to the *ASCA* observation of May 30, Dotani et al. 1996) and a photon index of 2.15 ± 0.02 for the power law ($\chi^2 = 1.43$ at 317 d.o.f.). The slope of the power law was not sensitive to the choice of the model for the soft component. The total 1–30 keV fluxes were 1.1×10^{-7}, 1.0×10^{-7} and 9.4×10^{-8} erg cm^{-2} s^{-1} on May 22, 23, and 30,

respectively. A line was also added in this case to further improve the fit, but as in the low-state spectra some low-energy features remained unfitted.

4. DISCUSSION

The 1996 May power spectra with low-frequency power-law noise, band-limited noise and energy-dependent QPO have some similarity to the very high-state spectra observed in GS 1124−68 and GX 339−4 (Miyamoto et al. 1993; Belloni et al. 1996a). The energy spectra are also similar, although the power law was somewhat flatter in Cyg X-1 (Γ∼2.2) than in the very high state of GX 339−4 and GS 1124−68 (∼2.5; Miyamoto et al. 1991; Miyamoto et al. 1994). However, it is very unlikely that Cyg X-1 was in the very high state in May, since the increase in 2–60 keV luminosity is only a factor of ∼5 compared to the low state, much less than in GS 1124−68 (50–100: Ebisawa et al. 1994) and GX 339−4 (50: Iga, Miyamoto, & Kitamoto 1992; Miyamoto et al. 1991). A high state such as the one known from the above mentioned sources seems to be ruled out both by the energy spectrum and the power spectrum (see Ebisawa et al. 1994; Miyamoto et al. 1994).

In fact, the 1996 May properties are similar to the "intermediate" state observed both in GS 1124−68 and in GX 339−4 (Belloni et al. 1996a; Méndez & van der Klis 1996). We can speculate that the increase in accretion rate was not sufficient to move Cyg X-1 into a high state, but that it managed to reach the "intermediate" state.

In this intermediate state the power spectrum of the source extends the correlation between break frequency and flat-top level discovered in the low state by BH90a, out to a few Hz. The same was found earlier for the very high state in GX 339−4 and GS 1124−68 (van der Klis 1994) and the intermediate state of GX 339−4 (Méndez & van der Klis 1996; van der Klis 1995). The ν_1 flat-top level values found in the 1996 May data lie approximately on the extrapolation of the BH90a relation (see Méndez & van der Klis 1996). Just as in the low state, in the intermediate state the break frequency can assume different values in different observations, with no obvious dependence on the 2–60 keV count rate (see Table 1).

As in GX 339−4 (Méndez & van der Klis 1996), this state might not be so rare in Cyg X-1: Crary et al. (1996a, 1996b) observed a softening of the energy spectrum in 20–200 keV BATSE data, corresponding to a decrease of the flat level of the band-limited noise and an increase of ν_1 to 0.5 Hz. In earlier observations Cyg X-1 may have been encountered in this intermediate state as well (Canizares & Oda 1977), and it is possible that the earlier reports of state transitions (Oda 1977; Liang & Nolan 1984) also involved such an intermediate state.

As suggested by BH90a (see also Meekins et al. 1984), the shape of the power spectrum of Cyg X-1 in the low state can be qualitatively interpreted with a light curve consisting of a superposition of randomly distributed shots with a range of lifetimes, an extension of the standard "shot-noise" model (Terrell 1972, Sutherland, Weisskopf, & Kahn 1978). The higher frequency cutoff at higher count rates (which we interpret as an increase in accretion rate) indicates that in the 1996 May data the longer living shots disappear and only the fastest ones survive. The steep slope of ∼2 above the break frequency suggests that only shots of a much more limited range of lifetimes contribute to the light curve. So, in the low

state shots with different timescales are observed, while only short living shots are seen in the intermediate state. Any shot-based theoretical model for the timing variability of black hole candidates must be able to explain this disappearance of slow shots from the light curve when the source enters a brighter and softer (at 2–60 keV) state. The low and high states might be the extremes of a continuum distribution of "states," characterized by smooth variations in both energy and timing behavior.

5. CONCLUSIONS

Our analysis shows that in 1996 May Cyg X-1 did not enter a typical high state, but rather an "intermediate" state, similar to those already observed in GS 1124−68 and GX 339−4. This state is characterized by variability and spectral distribution similar to those observed in the very high state, but at a considerably lower luminosity. From the observations of GS 1124−68, it is natural to associate this state to a moderate increase in accretion rate, not sufficient to enter a high state. This indicates that the transition from low to high state may be more gradual than previously thought.

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Note added in proof.—After submission of this Letter, we became aware of another Letter based on independent work on the same data by Cui et al. The state that we have identified as intermediate state is described in their work as a high state.