

## CORRELATION BETWEEN BATSE HARD X-RAY SPECTRAL AND TIMING PROPERTIES OF CYGNUS X-1

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### ABSTRACT

We have analyzed approximately 1100 days of Cygnus X-1 hard X-ray data obtained with BATSE to study its rapid variability. We find for the first time correlations between the slope of the spectrum and the hard X-ray intensity, and between the spectral slope and the amplitude of the rapid variations of the hard X-ray flux. We compare our results with expectations from current theories of accretion onto black holes.

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

### 1. INTRODUCTION

Accreting black hole candidates (BHCs) in X-ray binaries show three “source states” that are distinguished by characteristic spectral and (correlated) fast-variability properties. They are called the “low state,” “high state,” and “very high state”; the dominant parameter that determines the source state is likely to be the mass accretion rate (for recent reviews see van der Klis 1995b; Tanaka & Lewin 1995).

In the low state the X-ray spectrum is dominated by a very hard power-law component extending to several hundreds of kilo-electron volts. The source intensity shows strong fluctuations, with broadband rms amplitudes as high as 40%. At frequencies above  $\sim 1$  Hz the power density spectrum (PDS) of these variations follows a power law; at frequencies below a low-frequency cutoff the PDS is flat. In several BHCs the cutoff frequency  $\nu_c$  has been observed to vary by up to an order of magnitude while the high-frequency part of the PDS remained approximately constant (Belloni & Hasinger 1990; Miyamoto et al. 1992). As a result, the power integrated over a frequency range below  $\nu_c$  is strongly anticorrelated with that cutoff frequency.

In the high state the X-ray spectrum contains an ultrasoft thermal component, with (bremsstrahlung) temperatures of order 1 keV. In some sources (e.g., LMC X-3; see Tanaka 1989) the power-law spectral component is not detected, but in others (e.g., GS 1124–68; see Ebisawa et al. 1994) it is observed in combination with the ultrasoft component. In the 1–10 keV range the amplitude of the intensity variations is correlated with photon energy; this can be understood if the variability is connected with the power-law spectral component, which is “diluted” by the much lower variability of the ultrasoft emission (van der Klis 1994).

In the very high state the PDSs of BHCs show 3–10 Hz quasi-periodic oscillations and branch structure in an X-ray color-color diagram reminiscent of the normal-branch (NB) state of Z sources (van der Klis 1995a), i.e., accreting neutron

stars with magnetic fields of order  $10^{10}$  G. In view of the strong arguments that the accretion rate of Z sources is then close to the Eddington limit, it has been suggested that in the very high state the BHCs are likewise accreting near the Eddington limit (van der Klis 1995b).

In their low state the BHCs are remarkably similar to atoll sources, i.e., accreting neutron stars with magnetic field strengths generally believed to be below  $10^9$  G (substantially weaker than those of Z sources). At low accretion rates, i.e., in their so-called island state, atoll sources have power-law X-ray spectra (see, e.g., Barret & Vedrenne 1994). On average, these spectra appear to be not quite as hard as those of low-state BHCs (see, e.g., Gilfanov et al. 1995); however, the distribution of the spectral slopes of BHCs and atoll sources shows clear overlap (Wilson et al. 1995; Ebisawa et al. 1994; see also van Paradijs & van der Klis 1994). Also, the PDSs of island-state atoll sources are very similar to those of low-state BHCs. They follow a power law at high frequencies, and are flat below a cutoff frequency; the high-frequency part of the PDS of the atoll source 1608–522 was observed to remain approximately constant as the cutoff frequency varied, as for Cyg X-1 (Yoshida et al. 1993).

As part of our attempt to gain a better understanding of the similarities between accreting BHCs and neutron stars, we are studying the variability of bright BHCs using the almost continuous record provided by the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory*. We here report on a variability record of Cyg X-1, covering approximately 1100 days, and we show that the amplitude of its variations are strongly correlated with the slope of the hard X-ray spectrum and that correlations exist between the amplitude of the variations and the total flux.

### 2. DATA ANALYSIS

To quantify the rapid variability, we have created PDSs from the 1.024 s time resolution large-area detector (LAD) count rate data (the so-called DISCLA data) using two energy channels covering the range 20–50 and 50–100 keV. These data were filtered to eliminate bursts, Earth magnetospheric events, etc., then searched for data segments of 512 contiguous time bins (524.288 s without gaps) when the source was above the Earth’s limb. During outburst of the bright transients GRO J0422+32 and GRO J1719–24, the data from detectors that had these sources in their fields of view were eliminated from consideration. On average, we selected 40 intervals of

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these 512 bin data strings per day, amounting to a total data set of  $2.2 \times 10^7$  s.

The data for each detector and each energy channel were individually fitted to a quadratic polynomial, and the fit residuals were converted to Fourier amplitudes using standard fast Fourier transform techniques. Using similar 524.288 s intervals obtained when the source was occulted by the Earth, we have determined that the quadratic detrending of the raw data yields a background (source occulted) power level that is flat between 0.01 Hz and the Nyquist frequency (0.488 Hz). The power level in these background data is very close to Poissonian; using the normalization of Leahy et al. (1983), in which Poisson noise corresponds to a power density 2.0, the background power density level equals  $2.040 \pm 0.005$ . The latter value has been subtracted from the data, so that these corrected data reflect the contribution to the PDS from Cyg X-1 only. Dead-time corrections are not important for the count rate data used here.

The Fourier transforms of each data segment were then summed coherently and converted to PDSs. We made daily averages of these PDSs over all segments selected for that day. After subtraction of the average background noise level, these were normalized to the squared fractional rms amplitude per unit frequency (van der Klis 1995b) using the daily averaged detector count rates in the 20–100 keV energy band obtained from the BATSE occultation analysis (Harmon et al. 1993). As a measure of the variability of the hard X-ray flux of Cyg X-1, we used the fractional rms amplitude,  $f$ , of the intensity fluctuations in the frequency range 0.03–0.488 Hz, obtained by integrating the power spectral density (van der Klis 1995b).

### 3. RESULTS

From their investigation of the 1–25 keV variability of Cyg X-1, Belloni & Hasinger (1990) found that the cutoff frequency  $\nu_c$  in the PDS varies between 0.01 and 0.1 Hz; since the high-frequency part of the PDS remains constant, the cutoff frequency is anticorrelated with the power level at, and below, that frequency. Crary et al. (1995a) have confirmed this result for the 20–100 keV range using the data discussed here.

We have searched for a possible correlation of the variability of Cyg X-1 with its hard X-ray intensity and spectral shape. The latter quantities were obtained from the 45–140 keV X-ray light curve of Cyg X-1, which has been monitored with BATSE since the beginning of the *CGRO* mission (Paciesas et al. 1995). The 45–140 keV flux,  $F$ , is generally between 0.07 and  $0.15 \text{ cm}^{-2} \text{ s}^{-1}$ , with no prominent long-term (>50 day) trends in the data evident through most of this period. At about Truncated Julian Day (TJD = JD - 2,440,000.5) 9250 (1993 September 20), the source flux gradually declined over a period of about 150 days to a level of  $\sim 0.01 \text{ cm}^{-2} \text{ s}^{-1}$ . After that, the flux rose within 30 days, back to a level of approximately  $0.1 \text{ cm}^{-2} \text{ s}^{-1}$ . Although it is not possible, on the basis of BATSE observations alone, to determine the source state of Cyg X-1 during these observations, the presence of a hard component in the BATSE energy range indicates that Cyg X-1 was probably in the low state during most of the BATSE observations; during the low-flux episode between TJD 9250 and TJD 9430 a temporary transition to the high state may have occurred.

In Figure 1 we show a plot of  $f$  versus  $F$ . In the following discussion we will distinguish the data from the low-flux episode (indicated by squares in Fig. 1) from the remainder of

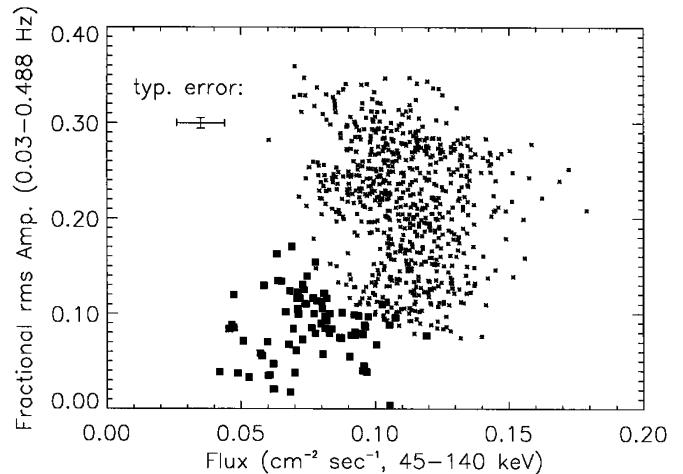


FIG. 1.—Cyg X-1 fractional rms amplitude (0.03–0.488 Hz) in the 20–100 keV band vs. 45–140 keV flux ( $\text{cm}^{-2} \text{ s}^{-1}$ ).

the data (indicated by asterisks). We have included only days when  $F$  was higher than  $0.04 \text{ cm}^{-2} \text{ s}^{-1}$ ; below this flux,  $f$  is dominated by detector noise due to unresolved sources in the uncollimated LAD field of view (Crary et al. 1995b) and the measured value of  $f$  becomes uncertain. Typical errors are shown, calculated from the variance per bin of the daily averaged power spectra propagated through the calculation of  $f$ , and from the results of the occultation analysis averaged over an entire day.

From Figure 1 it appears that during the low-flux episode (TJD 9250–TJD 9430), Cyg X-1 showed relatively little variability, with  $f$  generally below 12%. These low-flux data by themselves do not show a correlation between  $f$  and  $F$ ; similarly, the remaining points in Figure 1, with  $f$  usually in the range 10%–30%, do not show such correlation either. However, all points together follow a broad, upturning band in Figure 1, which indicates that there is a relation between the hard X-ray flux of Cyg X-1 and its variability.

If, during the low-flux episode, Cyg X-1 was in the high state, this result would suggest a dependence of the hard X-ray variability on source state. Although previous observations of other black hole candidates have indicated that the flux in the hard tail of the energy spectrum decreases as the source enters a high state (this, however, is very uncertain; see Gilfanov et al. 1995 and Tanaka & Lewin 1995), the hard X-ray flux alone may not be a good marker of source state. However, the lack of low-energy (1–10 keV) observations prevents us from drawing a firm conclusion on this. Note that the low value of  $f$  is not the result of dilution of the variability of a hard spectral component by a less variable soft component.

In Figure 2 we have plotted  $f$  versus the exponent,  $\alpha$ , of a power-law fit to the 45–140 keV spectrum (Paciesas et al. 1995); this figure shows that these two quantities are strongly correlated. The data obtained during the low-flux episode are offset systematically from the other data, showing both a softer spectrum (by about 0.4 in  $\alpha$ ) and smaller variability. However, the correlation between  $f$  and  $\alpha$  does not reflect this systematic offset: the same correlation is followed by each of the two groups of points separately.

The offset of the data from the low-flux episode from the other data, shown in both Figures 1 and 2, leads one to suspect that the hard X-ray flux and spectral slope of Cyg X-1 are also

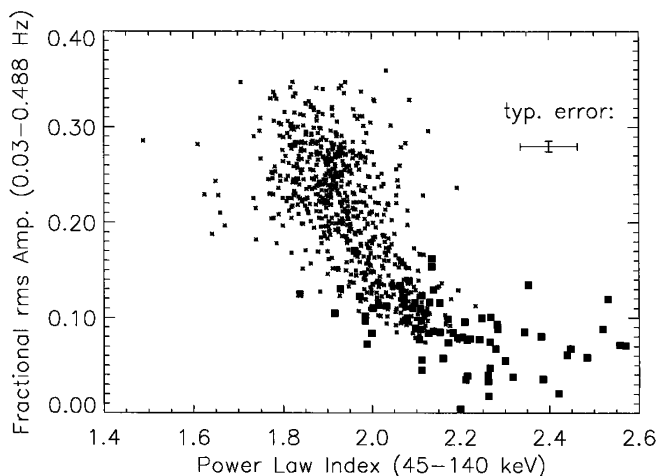


FIG. 2.—Fractional rms amplitude (0.03–0.488 Hz) in the 20–100 keV band vs. photon power-law index from a fit in the 45–140 keV range.

correlated. Figure 3, which shows a plot of  $\alpha$  versus  $F$ , confirms this suspicion. Again, the two groups of data points are clearly separated in this diagram. However, for each of the two groups of points separately the correlation is not apparent (for the “high-flux” points a correlation in the opposite sense may actually be present).

#### 4. CONCLUSIONS

We have found a strong correlation between the slope of the high-energy (20–100 keV) X-ray spectrum of Cyg X-1 and both its high-energy X-ray flux and the variability thereof. During most of our observations Cyg X-1 showed strong variability with an amplitude that varied in anticorrelation with a cutoff frequency (Crary et al. 1995a) similar to the low-state behavior in the lower energy range described by Belloni & Hasinger (1990). It is therefore likely that we encountered Cyg X-1 mainly in the low state. During a 150 day interval beginning in 1993 September both the high-energy X-ray flux and its variability were extremely low; it is possible that Cyg X-1 had then entered a high state; this remains uncertain, due to lack of low-energy coverage.

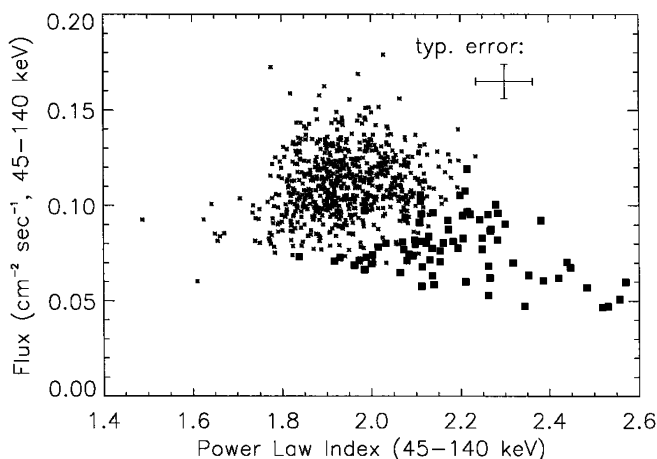


FIG. 3.—Cyg X-1 45–140 keV flux vs. photon power-law index from a fit in the 45–140 keV range.

The global correlations we have found between flux, variability, and spectral hardness suggest to us that all three are determined by a basic system parameter; the mass accretion rate is the obvious candidate. A variety of models have been calculated for the structure of the accretion disks around black holes, to explain the two-component character of their X-ray spectra and the suspected relation of these spectral components with accretion rate (Liang & Nolan 1984 and references therein; see also Haardt et al. 1993; Chakrabarti & Titarchuk 1995).

Most of these models invoke a very hot medium, e.g., a corona around the inner disk regions that produces the hard power-law component through upscattering of low-energy photons, and a standard Shakura-Sunyaev disk that provides the latter. Most of these models do not address source variability.

The fast variability of Cyg X-1 and other black holes has often been described in terms of shot-noise models; the break frequency in the PDS reflects the decay time of the shots (Sutherland, Weisskopf, & Kahn 1978; Miyamoto & Kitamoto 1989; Belloni & Hasinger 1990). However, the X-ray spectral properties are usually not considered in these models.

Mineshige, Takeuchi, & Nishimori (1994) and Mineshige, Kusunose, & Matsumoto (1995) proposed that accretion disks around black holes are in a self-organized critical state. Their qualitative arguments, aimed at an understanding of the low and high states, indicate that relatively hard X-ray spectra go with strong variability, and relatively soft X-ray spectra with weak variability.

Chakrabarti & Titarchuk (1995) recently argued that accretion disks around black holes contain a shock, at several tens of Schwarzschild radii. In the low state, the postshock region is quite hot, and the emergent spectrum is very hard ( $\alpha < 2.5$ ). In this model,  $\alpha$  increases with disk accretion rate in the low state. Also in this context, Molteni, Sponholz, & Chakrabarti (1996) found that over a range in mass accretion rates the cooling time of the flow inside the shock is comparable to the infall timescale. Under these conditions the location of the shock, and the X-ray luminosity, undergo quasi-periodic oscillations. The centroid frequency of these oscillations increases with the mass accretion rate, with typical values around 5 Hz for a  $5 M_{\odot}$  black hole.

This result may be related to the anticorrelation between  $\alpha$  and  $f$  for Cyg X-1, by using the recent results of van der Hoof et al. (1996) on the PDS of the black hole transient GRO J1719–24. They found that the detailed shape of the PDS remained invariant under a frequency shift marked by the variation of a strong quasi-periodic oscillation (QPO) peak (between  $\sim 40$  and  $\sim 300$  mHz), while also the power in a given (stretched and squeezed) “rest frequency” interval remained constant.

This would suggest that the QPO frequency is proportional to a break frequency in the PDS of this source, and that the latter may be used as a frequency scaler as well. If we are allowed to generalize this result for GRO J1719–24 to Cyg X-1, at least the direction of the correlation between  $\alpha$  and  $f$  found by us for Cyg X-1 would be accounted for by the model described by Chakrabarti & Titarchuk (1995) and Molteni et al. (1996).

At super-Eddington disk accretion rates the model of Chakrabarti & Titarchuk (1995) predicts that the flow inside the shock is cooled by Comptonization of low-energy photons from the disk, and the postshock flow becomes predominantly

radial (and converging). Comptonization in this region can still occur due to bulk motions, producing a hard tail with  $\alpha \sim 2.5$ . The value of  $\alpha$  increases weakly with the accretion rate; note, however, that in this model the X-ray luminosity may not be a good measure of the accretion rate, as part of the internal energy in the disk is advected into the black hole (see also Narayan, McClintock, & Yi 1996). In this regime the flux variability is determined by the variability of the illumination geometry of the converging inflow and not by the change in the size of the postshock region, as it is in the low state. The amplitude variation of the hard flux is expected to be smaller in this case (corresponding to the high state, since the increase in disk accretion rate leads to an increase in soft emission) than in the low state. It appears, then, that these theoretical results are in qualitative agreement with the data from the low-flux episode that we have observed in Cyg X-1.

The correlations we have found for Cyg X-1 would easily have escaped attention had it not been for the 1100 days of continuous coverage provided by the BATSE all-sky monitor-

ing capabilities. We are looking forward to an improved understanding of our results in terms of the source state framework for black holes (van der Klis 1994) by combining the BATSE hard X-ray monitoring with that provided in the near future at low energies by the X-Ray Timing Explorer (XTE).

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