HIGH TIME RESOLUTION GAMMA-RAY STUDIES OF CYGNUS X-1

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ABSTRACT

We report results of our studies of high-time-resolution data on Cygnus X-1 collected by the OSSE instrument in several observations from June, 1991 to June, 1993. Rate samples were collected in several energy bands with a time resolution of 4 milliseconds. Using Fast Fourier Transforms and auto-correlation functions, we have searched these OSSE data on various timescales for evidence of flares and other time structures, both periodicities and overlapping shots. We describe these searches, present the results, and compare them with previous observations at lower energies.

INTRODUCTION

Cygnus X1 is an X and γ-ray source which varies on timescales from milliseconds to months (Rothschild et al. 1977; Sutherland, Wasserman & Kahn 1978; Friedlander, Terrell & Holt 1983; Friend & Castinelli 1986; Ling, Mahoney & Wheaton 1990). The millisecond variability combined with mass estimates provide compelling arguments that the power source for this object is an accretion disk surrounding a stellar mass black hole. The OSSE instrument has monitored Cygnus X1 using its high time resolution mode on several occasions. For some observations, the detectors were operated in their regular 'chopping' mode, switching between source and background pointings every two minutes. For other observations, one or more detectors were set to stare at the source the entire time it was above the horizon. Table I summarizes these observations on which we have completed preliminary analyses.

DATA ANALYSIS

For this report, the data are collected in batches of 131.072 seconds with 4 millisecond time resolution. Each batch is then detrended by subtracting a best-fit second-order polynomial to remove effects of the South Atlantic Anomaly (SAA) and the slowly varying background rate due to geomagnetic rigidity. A Hanning filter is applied to reduce the rippling effects of data truncation and enhance the appearance of line features in the spectrum. We perform the Fast Fourier Transform (FFT) and compute the power density spectrum (PDS) from the square

of the absolute value. The data-set size and resolution translates to a frequency space range of zero to 125 Hz and a resolution of $125/16384 = 0.0763$ Hz. The PSDs of each batch are then added together (called incoherent summing since the phase information from the FFT is lost) in the hope that features due to random noise will tend to cancel out while real features due to the source variability will be enhanced. Some results of this process are illustrated in Figure 1.

Table I OSSE Viewing periods with RATE data for Cygnus X-1

Detector-hours On-Target	Low Energy Window	Average cts/sec[a]	High Energy Window	Average cts/sec[a]	Average Flux[b]	Comments
VP 002: 91/157 - 91/166 (June 6-15, 1991)						
8.49 hr	40-190 keV	299.5	190-780 keV	170.9	8.68×10^{-2}	VP 002a
22.58 hr	33-132 keV	259.4	132-630 keV	121.1	7.92×10^{-2}	
14.81 hr	33-132 keV	245.4	132-630 keV	118.5		staring
VP 203: 92/343 - 92/344 (December 8-9, 1992)						
14.47 hr	88-140 keV	105.5	140-414 keV	137.6	6.42×10^{-2}	staring
VP 223: 93/151 - 93/154 (May 31-June 3, 1993)						
18.44 hr	40-70 keV	83.7	70-169 keV	65.7	6.19×10^{-2}	

[a] Includes background flux

[b] Flux in 45-140 keV band, photons/cm^2/s

The detrending process creates the low power near zero Hz. The error bars represent the standard deviation of the mean. We see no significant features like the quasi-periodic oscillations (QPO) reported by some observers at energies below 70 keV (Vikhlinin et al. 1992; Angelini et al. 1992; Kouveliotou et al. 1992, 1993). Even the small features in the summed spectra are generally not consistent among the multiple detectors, a good example being the 'feature' at ≈ 0.07 Hz in VP 203, which is clear in only two of the four detectors used for the observation. In addition, the appearance of features varies with the batch size chosen for the FFT lending additional support to the notion that they are the result of random fluctuations. However, the general appearance of the spectra themselves varies considerably from one viewing period to the next and may be related to the variability in total flux from Cygnus X1.

The auto-correlation function (ACF) is calculated in 6.144 second batches and then summed. The functional form for the chosen auto-correlation function is

$$C_{yy}(u) = \frac{1}{N-u} \sum_{i=0}^{N-u-1} (y_i - \bar{y})(y_{i+u} - \bar{y})$$

(Enochson & Otnes 1968) which generates good results for finite-sized data sets. The ACFs, if they show any structure at all, reveal approximately exponentially declining profiles. Like the PSDs, they vary considerably from one viewing period to the next.

THE SIMPLE EXPONENTIAL SHOT MODEL

One of the popular models for the time variability of Cygnus X1 is the shot noise model which assumes the signal is composed of 'shots' which turn-on suddenly, then slowly decay

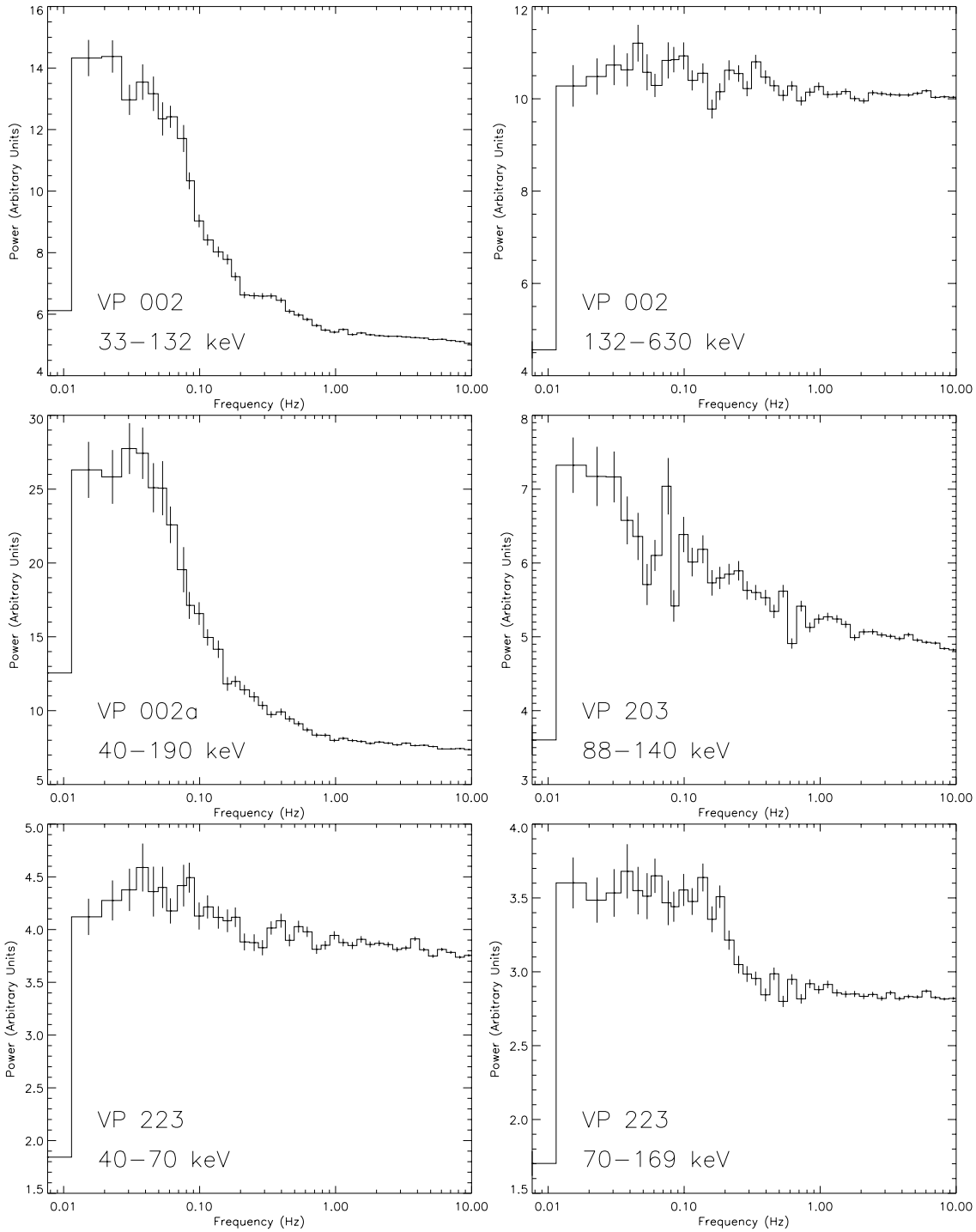

Figure 1: *Some of the averaged Power Density Spectra for Viewing Periods described in Table I. The results are averaged over the detectors and rebinned on a logarithmic scale. Note that the y-axis minimum is not zero. The spectra vary considerably from one viewing period to the next.*

(Sutherland et al. 1978; Meekins et al. 1984; Lochner 1989). A common shot model is the simple exponential shot which has the functional form

$$f(t) = \begin{cases} 0, & t < 0 \\ e^{-t/\tau}, & t \geq 0 \end{cases}$$

where τ is a characteristic decay time for the shot.

RESULTS

The single shot model assumes the signal is generated by a random superposition of shots of constant amplitude and time constant plus a constant noise level. The double shot model assumes the signal is composed of noise and two uncorrelated shots, each with its own amplitude and time constant. Tables II and III show the results of fitting these models for observations with some time structure.

Table II Model Fits: Single Shot Model

Viewing Period	Energy (keV)	ACF			HFT		
		τ (ms)	χ^2/dof	dof	τ (ms)	χ^2/dof	dof
002a	40-190	$957.7^{+45.2}_{-52.7}$	1.1288	1497	$1461^{+68.7}_{-69.5}$	1.0662	297
203	80-140	$30.2^{+2.2}_{-2.3}$	1.0228	247	$596.3^{+80.3}_{-71.4}$	1.98776	297
203	140-414	$107.8^{+21.6}_{-17.5}$	1.08341	247	$769.8^{+84.1}_{-74.7}$	1.8022	297

Table III Model Fits: Double Shot Model

Viewing Period	Energy (keV)	ACF		HFT	
		τ_1 (ms)	χ^2/dof	τ_1 (ms)	χ^2/dof
		τ_2 (ms)	dof	τ_2 (ms)	dof
002a	40-190	$1380.6^{+58.5}_{-62.3}$	0.7243	$2138.7^{+170.1}_{-178.0}$	0.8786
		$25.8^{+3.4}_{-2.5}$	1495	$311.5^{+66.7}_{-64.0}$	295
203	80-140	$137.9^{+46.9}_{-45.1}$	0.9121	$7616.2^{+3982.5}_{-2476.6}$	1.93488
		$18.1^{+3.4}_{-3.3}$	245	$421.5^{+75.8}_{-59.6}$	295
203	140-414	$152.5^{+113.8}_{-55.6}$	0.9659	$7563.9^{+\infty}_{-4997.8}$	1.8061
		$2.5^{+1.4}_{-1.3}$	245	$695.9^{+86.2}_{-93.6}$	295

The agreement of the time constants for the ACFs and HFTs is poor, but it does seem that the values for the HFTs are consistently greater than those for the ACFs. We see three possible explanations for this difference: 1) There are additional time structures in the Cygnus X1 output which appear in the HFT but not in the ACF, 2) The shots do not have a simple exponential profile, 3) The shot model paradigm is not applicable at all.

There is also considerable difference between the time constants for the single and double shot models. In fact, the prime motivation for investigating the double shot model was the appearance in many of the ACFs of an apparent steep exponential drop at short lag times which merged into a much gentler exponential-like decline at longer lags. This is very apparent in the relative sizes of the two time constants for the ACFs. It's also worth noting that while good fits are obtained with both the ACFs and HFTs in VP 002a, the HFTs have much poorer fits in VP 203. The shot times for VP 203 are also quite different from Lochner (1989) who

obtained slot times from 0.82 to 1.46 seconds at energies below 60 keV, and Sutherland, et al. (1978) with times from 0.35 to 0.67 seconds between 1.8 and 8.6 keV.

The HPGS and ACS at energies below $\approx$ 140 keV shows some time structure, but the higher energies look like random noise. Since we know that Cygnus X1 generates photons in this higher energy range, one wonders if the region generating them has any detectable time structure. Alternatively, these photons might be Compton upscattered from the lower energies over such large distances that the oscillations are washed out. To wash out say 0.10 Hz oscillations the scattering path length would have to be on the order of 10^9 meters. If we assume the X-ray source is a 10 solar mass black hole, this distance corresponds to $\approx$ 50,000 Schwarzschild radii, which is far larger than the high temperature ($T_e > 100$ keV) region in our current black hole accretion disk models. The model of Melia & Misra (1993) for Cygnus X1 indicate that the innermost region of the accretion disk should be optically thick. This region could therefore act as a direct source for these photons and provide sufficient scattering to remove any temporal signatures from the lower energy photons. Additionally, their model exhibits considerable structural changes for the inner disk with changes in the disk viscosity and accretion rate. These structural changes or the structures themselves may be the source of the radical variations in the temporal signatures displayed in separate viewing periods.

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