A SEARCH FOR APERIODIC MILLISECOND VARIABILITY IN CYGNUS X-1

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ABSTRACT

We have conducted a search for aperiodic millisecond variability in the integrated 1–25 keV X-ray region of Cyg X-1. We have examined HEAO A-1 archival data and Rossi X-Ray Timing Explorer (RXTE) guest observer data for evidence of excess power above the Poisson noise floor using the relative power integral power analysis and the Fourier transform method. Our results are in disagreement with the results of Meekins and coworkers. We attribute the discrepancy to an instrumental effect for which Meekins and coworkers did not apply a correction. With the correction we see no evidence for excess power above 25 Hz in the HEAO A-1 data. Our analysis of RXTE data is in agreement with previously published results of different data sets and shows no indication of excess power above 30 Hz.

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

1. INTRODUCTION

Identifying and understanding short-timescale variability in cosmic sources has repeatedly led to a better understanding of their fundamental nature and of the important physical processes present. For example, during the last decade, studies of fast time variability in low-mass X-ray binaries concentrated on quasi-periodic oscillations (QPOs) and various noise component frequencies up to 2 kHz. The study of QPOs and associated noise components led to a more qualitatively complete understanding of the accretion processes and the various omnipresent instabilities (van der Klis 1998) in the case of low-mass binaries. Similar breakthroughs for black hole candidates have yet to occur.

The dynamical and radiative timescales in the inner disks of accreting black hole candidates are predicted to be in the millisecond range. The thin disk models of Wallinder, Kato, & Abramowicz (1992), scaled to stellar mass black holes, have local thermal and acoustic timescales less than 1 ms, and quasi-periodic variability in the X-ray emission is predicted at these timescales. Bao & Østgaard (1995) have numerically modeled more realistic blob models in a geometrically thin accretion disk around a black hole, including all relativistic effects. The "blobs," or hot spots, were simulated to radiate in the accretion disk at about 10^3 Schwarzschild radii (R_s). The location of the shock defines an effective inner edge for both the disk and the halo components that can lead to abrupt changes in the PDS. Depending on the mass and angular momentum of the black hole, these effects are predicted to be in the 3–100 Hz range. In the following models, short-timescale variability arises from the special character of black hole (BH) accretion. The diskoseismology approach (Perez et al. 1997; Wagoner 1999) predicts QPOs in the 1–1000 Hz range, again depending on the mass and angular momentum of the black hole. Chaotic dynamical systems, such as the dripping handrail (Scargle et al. 1993; Young & Scargle 1996) and sandpile (Mineshige, Ouchi, & Nishimori 1994) models, lead to a picture where the QPOs and 1/f noise arise from a single physical phenomenon.

Millisecond variability in Cyg X-1 has been reported twice. Rothschild et al. (1974) reported millisecond bursts in an observation of Cyg X-1 obtained with a rocket experiment. These bursts appeared as excess counts over that expected from Poisson statistics assuming that the actual photon rate remained constant. However, the leakage of variability at lower frequencies (~10 Hz) into the higher frequencies of interest (~1000 Hz) invalidates this assumption (Press & Schechter 1974; Weisskopf & Sutherland 1978). Indeed, when the pre-1978 literature is carefully reviewed, the analysis of Cyg X-1 timing spectra from a number of experiments shows no conclusive evidence for millisecond variability (Weisskopf & Sutherland 1978). More recent results show no model-independent evidence for millisecond variability (Lochner, Swank, & Szynkowiak 1989), except in the context of the shot model (Lochner et al. 1989, 1991; Negoro et al. 1995). Lochner et al. (1991) used the phase portrait idea to determine parameters of a shot noise model. Using data from HEAO A-2 and EXOSAT, they find evidence for characteristic shot duration lasting from milliseconds to a few seconds. However, this analysis is model dependent.

Meekins et al. (1984, hereafter Me84) developed a $\chi^2$ method to untangle the effects of leakage from slower timescales and applied it to HEAO A-1 observations of Cyg X-1

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with 8 \mu s resolution. They claimed to have detected variability at timescales as low as 3–10 ms, with a cutoff below 3 ms. This result has been quoted (somewhat cautiously) as the only evidence for variability in Cyg X-1 at millisecond timescales; for example, see van der Klis (1995) and Liang (1998).

This paper presents a reanalysis of the same HEAO A-1 data and an analysis of new Rossi X-Ray Timing Explorer (RXTE) data that contradicts the apparent detection of millisecond power from Cyg X-1 by Me84. These results lead to the conclusion that the millisecond power reported in Me84 was due to either the known HEAO A-1 reset problem (Wood et al. 1984) or a previously unknown instrumental effect. After considerable archaeological work, we were unable to reconstruct the actual cause of this instrumental effect (Wen 1997).

2. ANALYSIS

We have analyzed archival observations of Cyg X-1 and the supernova remnant Cas A from the High Energy Astronomical Observatory A-1 experiment (HEAO A-1). We have also analyzed new observations of Cyg X-1 made by RXTE.

2.1. Observations

The HEAO A-1 observations were made on 1978 May 7 while Cyg X-1 was in the hard (low) state. Cas A was observed on 1978 August 2. Data from this presumably constant source were used to model the response of the detector and to search for instrumental effects. Both sets of A-1 data were recorded using the high bit rate mode described below. The RXTE observations occurred on 1996 June 8, June 17, June 27, and July 12 and were part of our Guest Investigator program. Cyg X-1 was in its soft (high) state at the time of the RXTE observations (see Fig. 9 below). Table 1 shows the observation dates and times for all of the data used in our analyses. Similar observations have been previously published (Cui et al. 1997; Belloni et al. 1996; Nowak et al. 1999; Timmer et al. 2000).

We have used two techniques to analyze the HEAO A-1 data: the relative integral power method of Me84 and the standard fast Fourier transform (FFT) power spectrum method. The RXTE observations were analyzed using the latter method only. For the HEAO A-1 analyses, we have derived new methods to correct the data for both dead time and instrumental effects. For the RXTE analysis we use the standard RXTE dead time correction (Zhang et al. 1995).

2.2. Analysis of the HEAO A-1 Data of Cas A and Cyg X-1

The HEAO A-1 data were recorded in the high bit rate (HBR) mode and consisted of a series of zeros and ones. A zero indicated no photons in the previous 8 \mu s, and a one indicated that at least 1 photon was detected in the 8 \mu s interval. There was no energy information in this mode. The energy range covered by these observations is about 1–25 keV. At the time of the data analysis presented in Me84, only part of the Cyg X-1 data were available. The rest of the Cyg X-1 data and the Cas A data used in this analysis were not available for use in the Me84 analysis.

The data for Cas A were Fourier transformed to search for deviations from the spectrum expected for a constant source. For a nonvariable source measured by a detector with no dead time, the expected spectrum is flat with a value 2, using the Leahy normalization (Leahy et al. 1983). Introducing dead time into the system slightly reduces the normalization value, but the shape remains relatively flat in the region in which we are interested. The observed Fourier power for Cas A was not flat but instead showed a broad "knee," as shown in Figure 1. The distribution of the intervals between arrival times of successive photons (\Delta t_i) showed a kink relative to the expected offset exponential distribution. This effect was modeled under the assumption that it was a previously uncorrected instrumental problem. The effect may have been unique to the HBR data or general to the HEAO A-1 data, but it would have been difficult to observe in the well-studied 5 and 320 ms binned data modes. In the HBR PDS it was apparent only at frequencies above about 100 Hz, which is the Nyquist frequency for the 5 ms data. It was not possible to determine

![Figure 1](image_url)

FIG. 1.—HEAO A-1 Leahy-normalized power density spectrum (PDS) for Cas A. The solid line represents the best-fit PDS assuming the underlying difference in photon arrival times (\Delta t_i) distribution is given by eq. (1).

| Instrument | Source | Date       | Obs. Time (UT) | Time Resolution (\mu s) | Time (s) |
|------------|--------|------------|----------------|------------------------|----------|
| HEAO A-1   | Cyg X-1| 1978 May 07| N/A            | 8                      | 510      |
| HEAO A-1   | Cyg X-1| 1978 Aug 02| N/A            | 8                      | 540      |
| RXTE PCA   | Cyg X-1| 1996 Jun 08| 03:14–03:36    | 4                      | 1362     |
| RXTE PCA   | Cyg X-1| 1996 Jun 17| 03:19–04:03    | 4                      | 876      |
| RXTE PCA   | Cyg X-1| 1996 Jun 27| 05:14–05:47    | 4                      | 858      |
| RXTE PCA   | Cyg X-1| 1996 Jul 12| 12:31–12:59    | 4                      | 726      |

TABLE 1
HEAO A-1 AND RXTE OBSERVATIONS
the times between individual events for the 5 and 320 ms modes since the data were binned; therefore the \( \Delta t_c \) distribution is not likely to be observable. We searched the 5 ms data for this effect and did not find any indications of it. Eadie et al. (1971) note that the hyperexponential function is applicable in situations where there is a mixture of exponential processes. An offset hyperexponential function is a good representation of the \( \text{HEAO A-1 HBR} \) \( \Delta t_c \) distribution:

\[
f_h(t) = U(t - \tau)[\rho_1 e^{-\rho_1(t-\tau)} + (1 - \rho_1)\rho_2 e^{-\rho_2(t-\tau)}],
\]

where \( U(t - \tau) \) is the Heavyside step function, \( \tau \) is the dead time, \( \rho_1 \) and \( \rho_2 \) are the count rates for two Poisson processes, and \( \rho_1 \) is the probability of generating a \( \Delta t_c \) from the first Poisson process. The model was fitted to the Cas A data, and the results are shown in Figure 2.

### 2.3. Power Spectrum Analysis of \( \text{HEAO A-1 Data} \)

A newly computed Fourier transform power spectrum of the \( \text{HEAO Cyg X-1 high bit rate data} \) is similar to that of Cas A. We again interpret this as a manifestation of either the instrument reset problem or of a previously unreported instrumental effect. We determined the effective Poisson noise floor in the presence of the instrumental effect for a variable (and therefore non-Poisson) source, Cyg X-1. Using the following procedure we fit equation (1) to the Cyg X-1 \( \Delta t_c \) distribution. Random \( \Delta t_c \) were drawn from equation (1) as defined by the above fit parameters and accumulated to generate absolute times. This Monte Carlo time series was Fourier transformed in the same manner as the data were. The \( \chi^2 \) of the Monte Carlo PDS to the data PDS was calculated for frequencies above 100 Hz. This procedure was repeated for a grid of parameter values whose origin was defined by the initial fit to the \( \Delta t_c \) distribution. The resulting best-fit PDS defined the effective Poisson noise floor. The resultant noise-corrected PDS for the \( \text{HEAO data} \) is shown in Figure 3. Figure 4 shows the region of the PDS above 10 Hz to better examine the power at high frequencies. No statistically significant power above the noise floor is observed above 25 Hz. This is consistent

![Figure 2](image1.png)

**Fig. 2.—** \( \text{HEAO A-1} \) difference in photon arrival times \((\Delta t_c)\) distribution for Cas A. The solid line represents the best fit of eq. (1) to the distribution. The dashed line represents the best fit of a simple offset exponential to the distribution.

![Figure 3](image2.png)

**Fig. 3.—** \( \text{HEAO A-1} \) Leahy-normalized noise-subtracted PDS for Cyg X-1, using eq. (1) as the underlying difference in photon arrival times \((\Delta t_c)\) distribution. The solid line represents the 95\% confidence level upper limit for detecting excess power above the Poisson noise floor.

![Figure 4](image3.png)

**Fig. 4.—** \( \text{HEAO A-1} \) Leahy-normalized noise-subtracted PDS for Cyg X-1, using eq. (1) for the underlying difference in photon arrival times \((\Delta t_c)\) distribution and expanded to show the high-frequency region. The upper solid line represents the 95\% confidence level upper limit for detecting excess power above the Poisson noise floor and is consistent with zero excess power for frequencies greater than 40 Hz. The lower solid line represents the zero excess power line.
with our assumption that power above 100 Hz is attributable to Poisson noise.

2.4. Relative Integral Power Analysis

Me84 derived a statistic, which they called the relative integral power, to quantify aperiodic variability. The details of their approach are described in Section III of their paper.

The new statistic, \( P_{rel} \), of Me84 is defined as the total discrete Fourier transform power of the mean subtracted time series divided by the square of the total number of X-ray counts, \( N^2 \), in the time series of length \( T \) divided into \( m \) equal length bins.

\[
P_{rel} \equiv \frac{1}{N^2} \sum_{j=-m/2}^{m/2-1} (|a_j|^2 - a_0^2) = \frac{\chi^2}{N},
\]

where the \( a_j \) are the standard Fourier coefficients

\[
a_j = \frac{1}{N} \sum_{k=0}^{N-1} x_k e^{2\pi jk/m},
\]

\( x_k \) is the number of events in the \( k \)th time bin, and \( a_j \) is the Fourier coefficient at frequency \( f_j = j/T \).

The distribution of power variability over all possible frequencies forms the Fourier power spectrum. With the Leahy normalization, this power spectrum is given by Leahy et al. (1983):

\[
P_j = \frac{2|a_j|^2}{N}, \quad j = 1, \ldots, m/2 - 1,
\]

where \( N \) is the total number of X-ray counts observed in the time interval \( 0 \rightarrow T \).

The Me84 analysis did not include corrections for dead time or instrumental effects. We have derived an approximation to the relative integral power that allows for simple corrections to equation (1) of Me84 for these effects. Define \( \chi^2 \) as

\[
\chi^2 = \sum_{j=1}^{m/2-1} P_j + \frac{1}{2} P_{m/2},
\]

where \( m \) is the number of time bins in the data segment under consideration. As in Me84, the 9 minutes of HEAO A-1 data is divided into \( L \) contiguous data segments of width \( \Delta t_{seg} \), each containing \( m (=10) \) time bins, and various quantities were calculated. This is repeated with \( T \equiv \Delta t_{seg} = 0.3, 1, 3, 10, 30, \) and 100 ms.

The average of the \( \chi^2 \) in equation (5) over the entire ensemble of 10 bin data segments for a given \( \Delta t_{seg} \) can be approximated by

\[
\langle \chi^2 \rangle \approx \frac{m-1}{2} \langle P \rangle,
\]

where \( \langle P \rangle \) is the average Leahy-normalized power over the entire ensemble of 10 bin data segments (\( L \approx 9 \) minutes/\( \Delta t_{seg} \)) and the set of frequencies \( f_j = 1/\Delta t_{seg}, 2/\Delta t_{seg}, \ldots, m/2\Delta t_{seg} \). Using equation (6) for the average \( \chi^2 \) in equation (1) of Me84 yields

\[
\langle P_{rel} \rangle \approx \frac{\langle m-1/2 \rangle \langle P \rangle - \langle P \rangle_{\text{noise}}}{\langle N \rangle - 1}
\]

for each \( \Delta t_{seg} \). The expected noise floor for Poisson statistics is easily computed from the total photon count (Scargle et al. 1993).

The Me84 analysis of the HEAO A-1 HBR observation of Cyg X-1 found an excess of variability at timescales as low as 3–10 ms with a sharp cutoff below 3 ms. We have reanalyzed the same observation using their method without dead time and instrumental corrections and have found excellent consistency with their results. There are some minor discrepancies that can be attributed to differences in the bin offsets and the use of a different digitization of the original analog tape. The comparison of our analysis with that of Me84 is shown in Figure 5.

By ignoring instrumental effects, Me84 chose a value of 2 for the noise floor, where 2 is the value at all frequencies of the Fourier transform of a Poisson source in the Leahy normalization. Using equation (1) as the probability distribution for the noise floor, we have calculated the expected noise floor in equation (7). We binned the data in a different manner than the original Me84 analysis. The uncorrected results with the new binning are shown in Figure 6. The shape and normalization are in good agreement with those of the original Me84 work, shown in Figure 5. Figure 7 shows the results of correcting for standard Poisson dead time. Note that the normalization is increased and that the peak is broader, enhancing the effect observed by Me84. The results of our analysis, which has been corrected for dead time and instrumental effects, of the HEAO A-1 observation of Cyg X-1 are shown in Figure 8. There is no evidence for the previously reported rise in the relative integral power, once the corrections for the previously uncorrected instrumental effects or the manifestation of the known reset problem are applied.

2.5. Power Spectrum Analysis of RXTE Data

We have analyzed four RXTE/PCA observations of Cyg X-1 (see Table 1). The RXTE data were recorded with 4 \( \mu \)s
time resolution. During all four observations the source was in the high (soft) state. Figure 9 shows the RXTE All Sky Monitor (ASM) light curve for Cyg X-1 around the time of our observations.

After binning in 50 μs bins, the light curves were divided into equal segments of 26 s. An FFT was performed on each data segment. The results were averaged over all segments and over equal logarithmic frequency intervals and used the Leahy normalization. The dead time-corrected Poisson noise power was then subtracted from the PDS obtained to yield the remaining signal above the noise. To determine the Poisson noise floor, we calculated the Poisson power spectrum, correcting for nonparalyzable dead time using equation (44) in Zhang et al. (1995) with a dead time of 10 μs (W. Zhang & K. Jahoda 2000, in preparation). Corrections were not made for the energy-dependent dead time or for very large events. However, below 30 Hz, these corrections are not significant and can be ignored (Cui et al. 1997). Figure 10 shows the Poisson noise-subtracted PDS.
for these observations. Figure 11 shows the 10–30 Hz region on a linear scale to show the behavior of the PDS as it approaches the limit imposed by the corrections.

Figure 12 shows the PDSs for both RXTE and HEAO A-1 on the same axes. Because of the similarity between the two power spectra, we did not apply the Me84 $\chi^2$ analysis to the RXTE data.

3. RESULTS

3.1. HEAO A-1

As reported above, we have discovered either an unknown instrumental effect or a manifestation of the known reset problem in the HEAO A-1 high bit rate data. This effect could not have been discovered using the binned 5 and 320 ms timing resolution modes of HEAO A-1 because their Nyquist frequencies are too low. The effect is observable only with the higher 8 $\mu$s time resolution of the HBR data, or it is a mode-dependent problem that only occurs in the HBR data mode. Once this effect is taken into account, there is no evidence for either the millisecond excess or the sharp cutoff in the relative integral power for Cyg X-1 reported by Me84.

We observe excess power with a 95% confidence level at frequencies below 25 Hz in the noise-subtracted PDS from Cyg X-1 in its hard state. Above 30–40 Hz, the noise-subtracted PDS is consistent with the null hypothesis. In the region where excess power is significant, we find that the spectral shape can be described by a power-law spectrum with a break in the spectrum at 3 Hz. From 0.1 to 3 Hz the spectral index is $1.20 \pm 0.08$, and above 3 Hz the spectrum steepens to $1.7 \pm 0.2$.

3.2. RXTE

Our results are consistent with previously published results (Cui et al. 1997; Belloni et al. 1996). Below 30 Hz we find that the spectral shape can be described by a broken power law with the break occurring at about 10 Hz. Below 10 Hz the spectral index is $1.05 \pm 0.01$, and between 10 and 30 Hz the spectral index steepens to $1.75 \pm 0.03$.

The lack of corrections for very large events and energy-dependent dead time in the standard RXTE corrections make it impossible to extend the search for excess power beyond about 30 Hz in this paper. There is adequate data in the sample to extend the search to higher frequencies once these additional corrections are developed. Additional work on these corrections is necessary to exploit the full timing capabilities of RXTE to search for excess power using this method.

We have checked for deleterious instrumental effects by analyzing RXTE/PCA data on a constant Poisson source, the Crab Nebula (after removing the pulsar signal). The power spectrum was within errors completely white to over 100 Hz. See Wen (1997) for details.

4. CONCLUSIONS

In light of our discovery of either a new instrumental effect or a correction for the known reset problem that accounts for the observed relative integral power of Me84, there is no longer any evidence for model-independent aperiodic variability on millisecond timescales from Cyg X-1. This lack of observed variability does not rule out its existence. RXTE should have the capability to make measurements of excess power at millisecond timescales once the appropriate corrections are available.

Our results for the Cyg X-1 PDSs are consistent with previous measurements in the hard and soft states. Previous measurements of Cyg X-1 often show a flat PDS below about 0.1 Hz, although the location of the maximum frequency varies from about 0.04 to 0.4 Hz. The minimum frequency studied here is only 0.1 Hz, and we see no indication of a flat PDS in our data. Our RXTE spectral shape determination is consistent with other RXTE observations (Cui et al. 1997; Belloni et al. 1996) made around the same time. In both sets of observations the spectral shape is similar to that observed for most black hole candidates in the same state (van der Klis 1995).

In order to extend the range of the types of searches into the regime where they can start to impact the models discussed above, we must make several improvements to the data and the techniques. At present, the limiting factor on the RXTE data is the lack of adequate background subtraction at high frequencies. This is being worked on...
Cross-checks on Poisson sources, as presented here using Cas A, are invaluable in searching for uncorrected dead time and instrument difficulties. To maximize the utility of the cross-checks, the cross-checking observations are best done in the same data-taking modes and at around the same times as the observations of the source under study. Unfortunately, the current available instrument data sets do not have these properties.

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