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OBSERVATIONS OF QUASI-PERIODIC OSCILLATIONS FROM GX 5−1 AND CYGNUS X-2 WITH THE *EINSTEIN* (*HEAO 2*) OBSERVATORY

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ABSTRACT

The bright galactic bulge X-ray source GX 5−1 was observed in 1979 April with the Monitor Proportional Counter on board the *Einstein* (*HEAO 2*) *Observatory*. Analysis of the high time resolution data from the Time Interval Processor confirms the recent *EXOSAT* discovery of quasi-periodic oscillations in the X-ray emission from GX 5−1. In addition, the summed 0.4 s power spectrum shows the low-frequency red noise component also discovered in the *EXOSAT* data. Low-frequency structure is also clearly present in data taken from the bright galactic X-ray source Cyg X-2 in 1978 December. We have calculated the expected power spectrum for quasi-periodic oscillations, including the low-frequency red noise component, using a simple shot noise model with oscillating shots. Our calculations include effects that arise from binning the data. We present the results of our calculations as well as the results of fits of this model to the *HEAO 2* average power spectra for GX 5−1 and Cyg X-2. We discuss some implications for models of quasi-periodic oscillations.

Subject headings: stars: pulsation — X-rays: binaries

I. INTRODUCTION

EXOSAT observations of the bright galactic bulge X-ray sources GX 5−1 (van der Klis *et al.* 1985*a*, *b*, *c*), Cyg X-2 (Hasinger *et al.* 1985, 1986), GX 17+2 (Stella, Parmar, and White 1985), and GX 349+2 (Lewin *et al.* 1985; Cooke, Stella, and Ponman 1985), the globular cluster X-ray burst source 4U 1820−30 (Stella, White, and Priedhorsky 1985), as well as Sco X-1 (Middleditch and Priedhorsky 1985, 1986; van der Klis *et al.* 1985*d*) and the rapid burster MXB 1730−335 (Stella *et al.* 1985), have revealed the presence of quasi-periodic oscillations (QPO) accompanied by low-frequency red noise (RN). In the cases of GX 5−1 and Cyg X-2, the central QPO frequency varies from 20 to 36 Hz and from 28 to 45 Hz, respectively, and exhibits a positive correlation with the observed X-ray intensity. This latter behavior is not exhibited by all of the QPO X-ray sources. For a brief review of QPO phenomena in these sources, see Lewin and van Paradijs (1986).

In this paper, we report the detection of QPO and RN in observations of GX 5−1 and Cyg X-2 obtained with the Monitor Proportional Counter (MPC) on board the *Einstein* (*HEAO 2*) *Observatory*. These observations confirm the *EXOSAT* discoveries. Several physical models for the QPO phenomena in these X-ray sources have been proposed (Alpar and Shaham 1985*a*, *b*; Lamb *et al.* 1985, Hameury, King, and Lasota 1985; Boyle, Fabian, and Guilbert 1985; see also the recent review by Lamb 1985). Each of these physical models can be represented mathematically by a shot noise model with oscillating shots (Lamb 1985). We analyze the power spectra obtained for these observations using a simple version of the shot noise model. This version is equivalent to the one given by Lamb *et al.* (1985), but includes effects due to the binning of data.

II. OBSERVATIONS

The MPC observed GX 5−1 and Cyg X-2 on several occasions during the lifetime of the *Einstein Observatory*. For each source, the QPO and RN phenomenon has been detected in one set of observations. These observations each spanned four consecutive orbits of the *Observatory* and are summarized in Table 1.

The data used to analyze the time variability of GX 5−1 and Cyg X-2 were obtained with the Time Interval Processor (TIP) circuitry of the MPC. The MPC and TIP are described in detail by Gaillardetz *et al.* (1978), Grindlay *et al.* (1980), Weisskopf *et al.* (1981), and Leahy *et al.* (1983). Of particular relevance to searches for QPO is the fact that the TIP data readout was telemetry limited. The TIP utilized a buffer memory in order to cope with high count rates. When the memory was full, however, no data were recorded until all the stored information was read out. For sufficiently high count rates, these features resulted in a series of short continuous integrations, whose length depended on count rate and telemetry mode.

III. DATA ANALYSIS AND RESULTS

The TIP data were converted to photon arrival times at the solar system barycenter. The data were searched for QPO and RN as well as for periodic pulsations using the formalism for calculating and analyzing power spectra given by Leahy *et al.* (1983). For each search an experiment length was selected based on the average time for continuous integration. The experiment length was chosen so as to search to as low a frequency and to attain as high a frequency resolution as possible, while retaining as much data as necessary for reasonable sensitivity. The average lengths of the continuous integrations

TABLE 1

LOG OF MPC OBSERVATIONS SHOWING EVIDENCE FOR QPO PHENOMENA

Parameter	GX 5−1	Cyg X-2
Date at start of observation	1979 Apr 3.9931	1978 Dec 3.0888
Length of observation (s)	19,414	3050
Integration time (s)	3750	464
Average source rate ($c\ s^{-1}$)	856.7	393.7
Average 2–6 keV source intensity (Ufu)[a]	500 ± 17	219 ± 2

[a] In both cases, the quoted uncertainties were calculated from the RMS scatter of the values for four orbits of data about their average value. For GX 5−1, variability intrinsic to the X-ray source accounts for most of the scatter.

TABLE 2

PARAMETERS FOR POWER SPECTRUM ANALYSIS

Parameter	GX 5−1	Cyg X-2
Average length of continuous integrations (s)	0.32	0.46
Experiment length (s)	0.4	0.4
Number of bins per experiment	4096	4096
Number of experiments	3693	784
Fraction of data included in analysis (%)	39.4	67.6
Average source rate for included data ($c\ s^{-1}$)[a]	814.5	393.3
Frequency range (Hz)	2.5–4000	2.5–4000
Sensitivity (%)[b]	3.9–5.1	8.4–11.0

[a] Because of the nature of TIP operation and the chosen experiment length, for GX 5−1 this number is significantly lower than the average source rate quoted in Table 1.

[b] Frequency dependent sensitivity to pulsations at the (95%, 95%) confidence levels (see Leahy *et al.* 1983).

for these data, the experiment lengths selected, and the sensitivities to pulsations, together with other parameters of the analysis, are given in Table 2. An average power spectrum was formed from the sum of the individual power spectra for each of the experiments within an observation, and the average power spectrum was searched for significant peaks. We remark that the power spectra were corrected for frequency-dependent dead-time effects not discussed by Leahy *et al.*; these effects and the corresponding necessary corrections will be presented elsewhere.

QPO and RN were present in one observation of GX 5−1 and one observation of Cyg X-2 on the dates given in Table 1. The count rates as functions of time for these observations are shown in Figures 1 and 2. The corresponding average power spectra for these data are shown in Figure 3. QPO and RN are clearly present in the average power spectrum for the GX 5−1

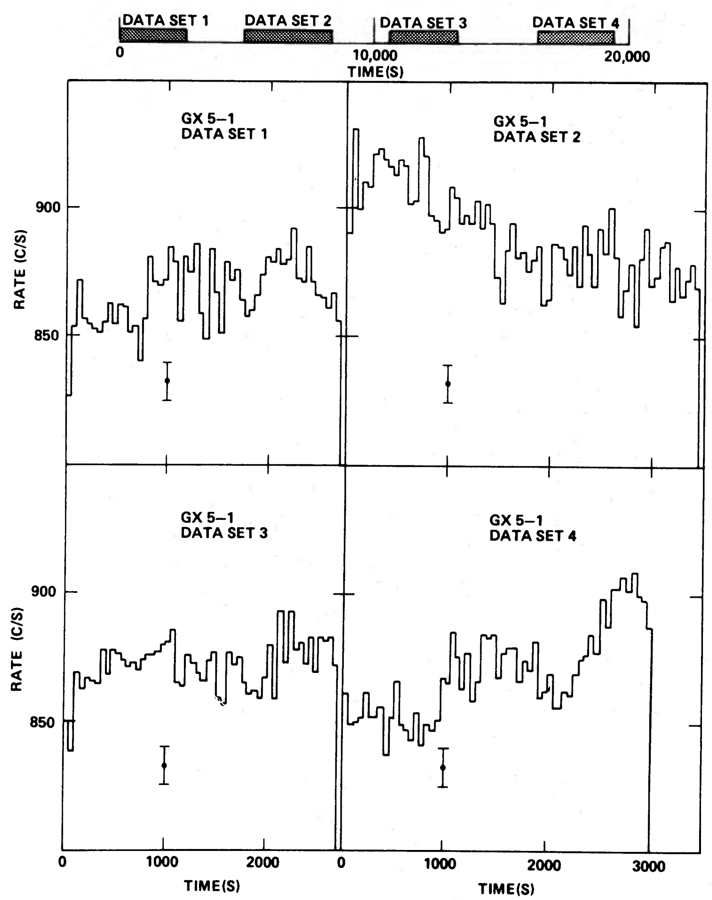

FIG. 1.—MPC/TIP count rate vs. time using 50 s bins for four orbits of data taken from GX 5−1 on 1979 April 3 and 4. The origin for the bar graph at the top of the figure corresponds to the date given in Table 1. The count rate includes background which for these data averaged 18.2 $c\ s^{-1}$. Also shown are $\pm 1\ \sigma$ error bars.

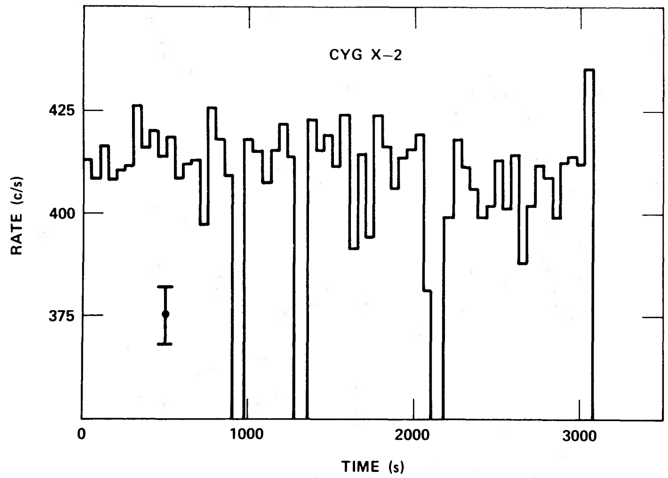

FIG. 2.—MPC/TIP count rate vs. time using 50 s bins for four orbits of data taken from Cyg X-2 on 1978 December 3. The four sets of data are plotted on one graph and the time origin corresponds to the date given in Table 1. The count rate includes background which for these data averaged 17.7 $c\ s^{-1}$. Also shown is a $\pm 1\,\sigma$ error bar.

data. Although the sensitivity is less, low-frequency structure is also clearly present in the average power spectrum of the Cyg X-2 data. The statistical quality of these data prevents us from unambiguously determining whether this structure is primarily RN or QPO, or some combination of each. For the other MPC observations of GX 5−1, the sensitivity of the search was not sufficient to detect QPO and RN at the levels shown in Figure 3 (*top*). However, several of the other observations of Cyg X-2 had sensitivities more than adequate to detect RN and QPO at the levels shown in Figure 3 (*bottom*). It is interesting to note that these other Cyg X-2 data, when plotted on a 50 s timescale, appear "noisier" than the data discussed in this paper, with significant dips and enhancements in intensity. QPO and RN from Sco X-1 are known to depend on source activity (Middleditch and Priedhorsky 1985, 1986; van der Klis *et al.* 1985*d*), with QPO best seen during quiescent periods. This aspect of the Cyg X-2 data will be examined more closely elsewhere; a spectral study of the dips using MPC data appears in Vrtilek *et al.* (1986).

An important test of the models of Alpar and Shaham (1985*a*, *b*) and Lamb *et al.* (1985) would be the detection of

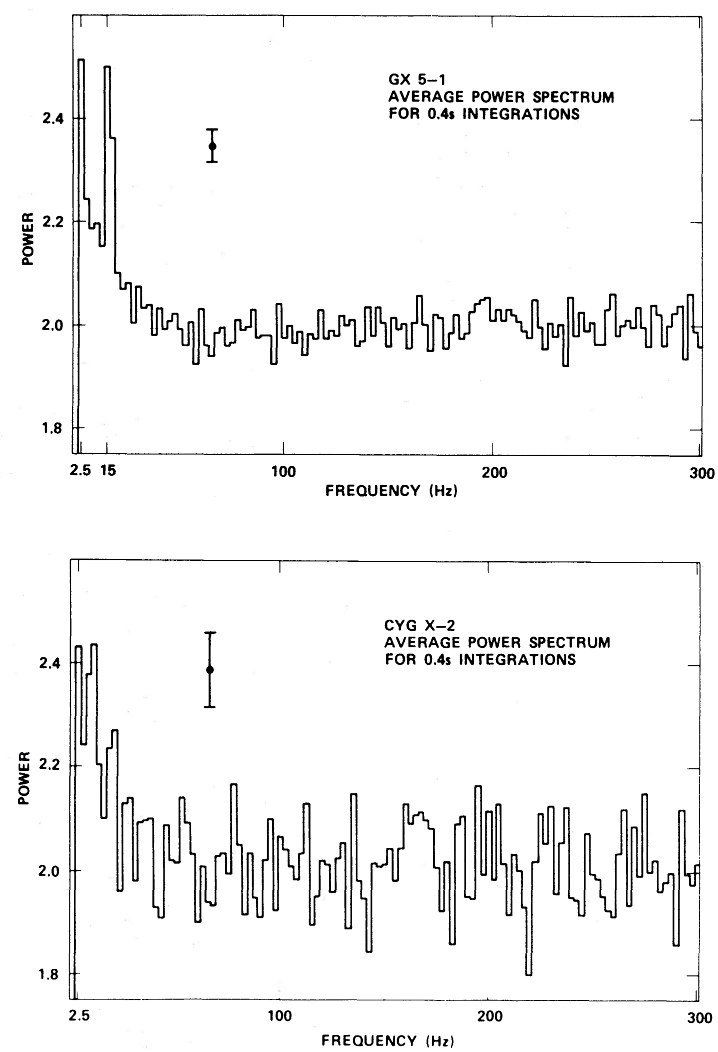

FIG. 3.—Average power spectra for 0.4 s continuous integrations for the MPC/TIP observations of GX 5−1 (*top*) and Cyg X-2 (*bottom*) summarized in Table 1. The QPO peak rising above the shoulder of the RN is especially clear for GX 5−1. Both power spectra are flat at frequencies (300–4000 Hz) above those shown in the figure. Also shown are $\pm 1\,\sigma$ error bars. For both cases, stastically independent frequencies are separated by 2.5 Hz.

periodic pulsations in the range 1–100 ms. No short-period pulsations were detected in any TIP data from either GX 5−1 or Cyg X-2. Upper limits to the amplitude of pulsations for the observations described here appear in Table 2.

IV. SHOT NOISE MODELS

Various physical models for QPO phenomena (Alpar and Shaham 1985*a*, *b*; Lamb *et al.* 1985; Hameury, King, and Lasota 1985; Boyle, Fabian, and Guilbert 1985; see also the review by Lamb 1985) correspond mathematically to shot noise with oscillating shots. The resulting form expected for the power spectrum, in the continuous limit and under specific assumptions, is given by Lamb *et al.* (1985) and Lamb (1985).

Using tools developed for studies of Cygnus X-1 (Weisskopf, Kahn, and Sutherland 1975; Weisskopf and Sutherland 1978; Sutherland, Weisskopf, and Kahn 1978), we have recalculated the expected QPO power spectrum in terms of the shot parameters and have included effects due to binning of data. Following Lamb *et al.* (1985), we assume that the X-ray intensity (in $c\ s^{-1}$) is given by

$$R(t) = C + \sum_i F(t - t_i;\ \phi_i)\ , \qquad (1)$$

where

$$F(t;\ \phi_i) = \theta(t) h e^{-t/\tau}[1 + b \cos(2\pi f_0 t + \phi_i)]\ . \qquad (2)$$

Here f_0 is the QPO frequency, b is the amplitude of modulation for the oscillating shots, t_i is the time of onset of the ith shot, h is the shot amplitude, τ is the shot width, and $\theta(t)$ is the step function. The constant C represents the steady component of the X-ray emission. The shot strength $Q = h\tau$, while the fraction of flux in shots (or shot fraction) $\alpha = \lambda Q/(\lambda Q + C)$, where λ is the rate at which shots occur. As in Lamb *et al.* (1985), we assume that ϕ_i is uniformly distributed over the interval 0–2π and uncorrelated with t_i. Assuming an exponential distribution for the time intervals between the onset of shots, the expected average power spectrum for the binned mean subtracted data is then given by

$$P(f_j) = 2 + 2\alpha Q\left[\frac{\sin(\pi j/N)}{(\pi j/N)}\right]^2 \times \left\{g(f_j) + \left(\frac{b^2}{4}\right)[g(f_j - f_0) + g(f_j + f_0)]\right\}\ , \qquad (3)$$

where for the exponential envelope given in equation (2)

$$g(f) = 1/[1 + (2\pi f\tau)^2]\ . \qquad (4)$$

The form of equation (4) changes if a different form for the shot envelope is adopted. Here $f_j = j/T_e$, $j = 1$ to $N/2$, is the jth frequency in the discrete power spectrum, T_e is the experiment length, and N is the number of bins per experiment. In equation (3), the factor containing N arises from the binning of the data and applies in this simple form only if $N \gg 1$. Except for this factor, equation (3) is equivalent to that given by Lamb *et al.* (1985) for the continuous limit. Additional complications arise when the condition $N \gg 1$ is not satisfied.

The power spectra shown in Figure 3 were fitted to equations (3) and (4); the results of these fits are given in Table 3. The errors quoted in Table 3 are the extreme values on two-dimensional orthogonal projections of the four-dimensional contour for $\chi^2 = \chi^2_{min} + 4.7$ (Lampton, Margon, and Bowyer 1976). Since none of the parameters of a shot noise model for QPO can be considered uninteresting in the sense required by the work of Avni (1976), use of $\chi^2 = \chi^2_{min} + 1$ contours to determine errors is not correct. The value for f_0 appearing in Table 3 for GX 5−1 lies below the range of values (20–36 Hz) found by van der Klis *et al.* (1985*c*). The difficulties involved in comparing count rates from different satellite instruments prevent a meaningful extension of the *EXOSAT* relationship between frequency and intensity.

TABLE 3

RESULTS OF FITS OF AVERAGE POWER SPECTRA TO SIMPLE QPO SHOT NOISE MODEL

Parameter	GX 5−1	Cyg *X*-2
Frequency range (Hz)	2.5–75	2.5–50
Number of degrees of freedom	26	16
χ^2_{min}	33.93	29.28
Prob$[\chi^2 \geq \chi^2_{min}]$	0.14	0.07
αQ[a, b]	0.59 ± 0.13	0.085
b[a, b]	$1.32^{+0.19}_{-0.15}$	2.3
f_0 (Hz)[a]	15.8 ± 0.4	$9.2^{+3.6}_{-4.2}$
τ(s)[a]	0.070 ± 0.015	$0.020^{+0.037}_{-0.011}$

[a] Errors on best-fit parameters were determined from extreme values on two-dimensional orthogonal projections of the $\chi^2 = \chi^2_{min} + 4.7$ error contours.

[b] For Cyg X-2, the low-frequency structure is not unambiguously either RN or QPO. As a result, there is a strong anticorrelation between b and αQ. Therefore, we have not assigned errors to b and αQ on this case.

If the simple model assumptions apply, then fits of average power spectra obtained from the data to the power spectrum determine f_0, τ, b, and the product αQ. Measurement of the mean determines the quantity $(\lambda Q + C)$. The expression for the *third moment* contains terms proportional to αQ^2 (Sutherland, Weisskopf, and Kahn 1978). Sufficiently precise measurements of the first and third moments combined with the results of fits to model power spectra therefore allow the determination of *all* the shot noise model parameters. Unfortunately, in practice it is difficult to deduce αQ^2 from the third moment. The third moment is inherently noisier than the first and second moments and therefore more difficult to measure accurately. In addition, important bias terms arise if a small number of bins is required in order to raise the shot noise contribution above the counting statistics contribution. Our data do not allow a precise determination of αQ^2; our work on third moment constraints on QPO models will be presented alsewhere.

Any physical shot profile must always remain positive in order to avoid a finite probability of negative flux. For the simple QPO shot noise model presented earlier, this physical constraint requires $b < 1$ (Lamb *et al.* 1985). However, the best-fit value for b given in Table 3 for GX 5−1 is >1. We have also fitted the observed average power spectrum to that expected for a square shot envelope. In this case we find a best value for $b > 1$, suggesting that this conclusion does not depend sensitively on the shape of the shot envelope. Van der Klis *et al.* (1985*c*) fitted the power spectra obtained by *EXOSAT* for GX 5−1 to an empirical formula given by

$$P(f) = A + Be^{-\gamma f} + C[(f - f_0)^2 + (\Delta/2)^2]^{-1}\ . \qquad (5)$$

TABLE 4

RESULTS OF FITS OF *EXOSAT* MODEL POWER SPECTRA TO A SIMPLE QPO SHOT NOISE MODEL

EXOSAT Rate	αQ[a]	b	f_0	τ
2427	1.21	1.35	20.3	0.066
2603	0.87	1.29	24.2	0.046
2790	0.73	1.29	26.8	0.038
3001	0.64	1.12	30.9	0.033
3225	0.37	1.02	37.5	0.027
3403	0.43	0.95	42.0	0.029

[a] The parameters Q, R, C, and h depend on detector characteristics, such as area and efficiency, as well as on properties of the source. Therefore, the values for αQ given here for the *EXOSAT* data should not be directly compared to the GX $5-1$ value given in Table 3 for the MPC/TIP data.

After introducing statistical fluctuations based on the observing parameters given by van der Klis *et al.* (1985*c*), we fit the *EXOSAT* QPO model power spectra to the QPO shot noise model given by equations (3) and (4). The results are given in Table 4. We did not assign errors, since we fitted one model to another. However, in view of the high statistical quality of the *EXOSAT* data, we expect that the errors would be smaller than those we have assigned to the results obtained from our data (Table 3). Note that the parameters vary with *EXOSAT* count rate but that $b > 1$ for most cases. Thus the assumptions underlying equation (3) break down for the case of GX $5-1$.

V. CONCLUDING REMARKS

Shot noise models with oscillating shots (Lamb *et al.* 1985; Lamb 1985) mathematically describe a number of physical models for QPO phenomena. Fits of the power spectra obtained for GX $5-1$ to the simple QPO shot noise model yield an amplitude of modulation $b > 1$. This result is not physical so the simple model assumptions must be violated in some way. A strength of shot noise models is that QPO and RN arise naturally from a single process. However, it is possible, if unlikely, that they are unrelated in that they may arise from separate causes. If so, $b > 1$ is not required. On the other hand, the shot noise model is flexible and can be made more complicated. Possible alternatives to the simple version discussed in this paper include: (1) different and more complicated shot shapes, including different forms for the oscillating and envelope terms; (2) different distributions for ϕ_i or even t_i; (3) various correlations between ϕ_i and t_i (or other physical variables); and (4) oscillations that are coherent on time scales longer than the duration of a single shot. Some of the consequences of generalizing the simple model have already been mentioned by Lamb *et al.* (1985), Lamb (1985), and Alpar (1985). Finally, sufficiently accurate measurements of the third moment would allow the specification of all the shot noise model parameters. This would greatly enhance the usefulness of the shot noise model as a probe of the physical processes in QPO X-ray sources.

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Note added in proof.—We wish to emphasize that our results show only that the power spectra obtained from GX $5-1$ are not consistent with the model assumptions leading to equations (3) and (4); our results do *not* rule out shot noise models in general. For the *EXOSAT* observations of GX $5-1$, Lamb *et al.* (1985) previously noted that the total power in the QPO peak, P_{QPO}, and that in the red noise, P_{RN}, were comparable, thus violating the condition $P_{QPO} \leq 0{\cdot}5 P_{RN}$ required by the simplest model assumptions. This condition is equivalent to our requirement $b \leq 1$. However, Lamb *et al.* also showed with specific examples that power spectra derived assuming either a generalized waveform or a distribution of shot lifetimes were consistent with the power spectra obtained for GX 5−1. The introduction of correlations between ϕ_i and t_i can also lead to power spectra consistent with observation (Lamb *et al.* 1985; Lamb and Shibazaki 1986, private communication; Elsner, Weisskopf, and Sutherland 1986, in preparation).

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