THE ASTROPHYSICAL JOURNAL, 313:L19–L23, 1987 February 1

CORRELATION BETWEEN SPECTRAL STATE AND QUASI-PERIODIC OSCILLATION PARAMETERS IN GX 5 − 1

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Received 1986 October 14; accepted 1986 November 10

ABSTRACT

In a series of seven *EXOSAT* observations, the bimodal spectral behavior and the QPO/red noise properties of GX 5 − 1 show a strict correlation. In one of the two spectral states (characterized by a "horizontal branch" in the hardness-intensity diagram), strong 20–40 Hz quasi-periodic oscillations (QPO) and red noise below ~ 60 Hz were always present. In the other ("normal branch"), no QPO between 6 and 60 Hz or red noise above 1 Hz were detected, but there was an indication for weak QPO near 5 Hz. In both states "very low frequency noise" (VLFN) is detected below 0.1 Hz which has a power-law shape and which extends down to the lowest observed frequencies (10^{-4} Hz). We argue that the VLFN is probably not directly related to the QPO. The results are compared to those on Sco X-1 and Cyg X-2 and we conclude that, although all three sources show bimodal spectral and QPO/red noise behavior, there is a qualitative difference between GX 5 − 1 and Cyg X-2 on one hand and Sco X-1 on the other.

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

I. INTRODUCTION

Intensity-dependent quasi-periodic oscillations (QPO) were recently discovered with *EXOSAT* in the X-ray flux of GX 5 − 1 (van der Klis *et al.* 1985*b*), Sco X-1 (Middleditch and Priedhorsky 1986), Cyg X-2 (Hasinger *et al.* 1986*a*), and several other bright low-mass X-ray binaries (see Stella 1986, Lewin and van Paradijs 1986, and van der Klis 1986 for reviews). The oscillations have frequencies betwen 5 and 50 Hz, relative amplitudes of 2%–10%, coherence times of order one cycle, and they can persist for at least 10^5–10^6 cycles.

Sco X-1, Cyg X-2, and GX 5 − 1 are known to show bimodal spectral behavior (White *et al.* 1976; Branduardi *et al.* 1980; Shibazaki and Mitsuda 1983), with state changes occurring on time scales of days. In this *Letter* we report on data (first reported in van der Klis *et al.* 1985*a*) which show the existence of a strong correlation of QPO/red noise properties with this spectral behavior in GX 5 − 1. A similar correlation has been found in Cyg X-2 (Hasinger *et al.* 1985) and Sco X-1 (Priedhorsky *et al.* 1986; van der Klis *et al.* 1986, hereafter VDK86).

II. OBSERVATIONS AND RESULTS

GX 5 − 1 was observed seven times with ESA's X-ray observatory *EXOSAT* (Table 1). High time-resolution (0.25–8 ms) data are reported from the medium-energy (ME) 1–20 keV Ar detectors (Turner, Smith, and Zimmermann 1981). Dead-time effects involving photon losses of up to 40% have been corrected for. Simultaneous 2–35 keV spectral coverage at 8–16 s time resolution was obtained from the gas scintillation proportional counter (GSPC; Peacock *et al.* 1982).

During four observations the source was in the "horizontal branch" (HB) spectral state (Shibazaki and Mitsuda 1983); in

TABLE 1
OBSERVATIONS

	TIME RESOLUTION			L_x (10^{38} ergs s^{-1})
DATE AND TIME (UT)	ME (ms)	GSPC (s)	SOURCE STATE	(2–20 keV, 10 kpc)
1983 Sep 14; 18:22–19:33	8	8	HB	3.7
1984 Sep 18; 11:58–19:38	0.25	16	HB	2.8
1985 Apr 29–30; 20:23–6:54	2	16	HB	3.0
1985 Aug 27–28; 15:09–14:13	4	8	NB	2.4
1985 Aug 29; 10:08–16:40	4	8	NB	2.3
1985 Aug 30; 10:26–17:09	4	8	NB	2.5
1985 Sep 17; 1:08–14:18	4	8	HB	3.2

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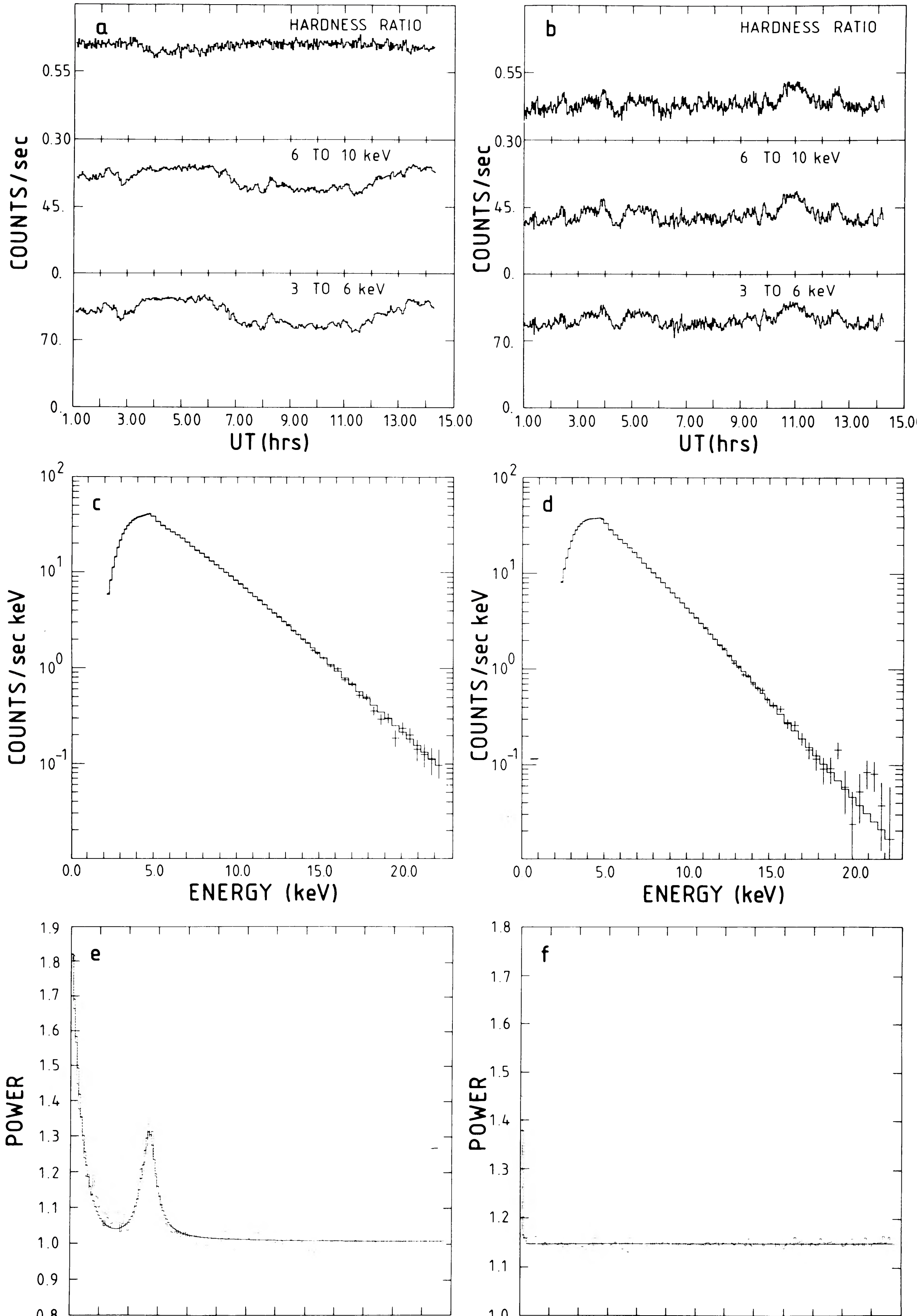

FIG. 1.—Typical X-ray intensity and (6–10/3–6) keV hardness ratio curves (a, b) and X-ray spectra (c, d) from the GSPC, and power spectra (e, f) obtained from ME Ar data in the HB (1985 September 17; *left*) and NB (1985 August 28; *right*) states.

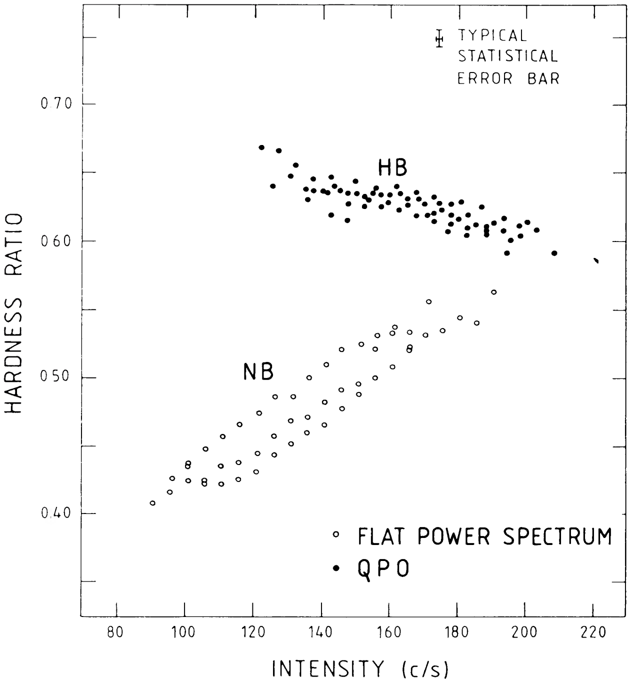

FIG. 2.—Hardness-intensity measurements from GSPC data. (*filled circles*) strong QPO (cf. Fig. 1*e*); (*open circles*) flat power spectrum (Fig. 1*f*).

the remaining three it was on the "normal branch" (NB). These three observations are close in time and may fall within one NB episode (see Table 1).

Figure 1 shows two representative data sets taken during a HB and a NB state, respectively. In the HB state the spectral hardness ratio is weakly anticorrelated to intensity, while in the NB state there is a strong positive correlation (Figs. 1*a*, 1*b*). The average X-ray spectrum is much harder in the HB than in the NB (Figs. 1*c*, 1*d*), and while in the HB strong ($\sim$ 5% rms variation) 20–40 Hz QPO and associated red noise are seen, the NB shows a nearly flat power spectrum above 0.01 Hz (Figs. 1*e*, 1*f*), with typical 2 σ upper limits to QPO between 6 and 60 Hz and to red noise between 1 and 10 Hz of $\sim$ 1% (rms). In both states, the average GSPC X-ray spectra are well fitted by the unsaturated Comptonized spectrum of White *et al.* (1986), with $\Gamma \approx 0.9$ and $kT_{\text{th}} \approx 4$ keV. An additional blackbody component is not required by the GSPC data, with typical 2 σ upper limits to its luminosity of 10%–20% of the total luminosity, nor do we detect an iron line. A preliminary analysis of the ME Ar data seems to indicate the presence of a blackbody component with a temperature of $\sim$ 1 keV and a luminosity consistent with these upper limits.

In Figure 2 the spectral hardness ratio as obtained from the GSPC is plotted versus intensity for all seven observations. The diagram shows the "horizontal" branch and the (diagonal) "normal" branch reported previously by Shibazaki and Mitsuda (1983). Small offsets between different data sets in the NB can be due to uncertainties in the GSPC gain, although we can not exclude real changes. Filled dots indicate that the simultaneous ME high time-resolution data show strong QPO; open circles imply flat power spectra such as shown in Figure 1*f*. Strong QPO were exclusively seen in the HB state; flat power spectra, in the NB state.

The power spectra of the ME high time-resolution data (Fig. 3) in both states show a break between 0.03 and 0.3 Hz, below which the spectrum is dominated by power-law red noise with a slope of 1.7. As suggested by Figures 1*a* and 1*b*,

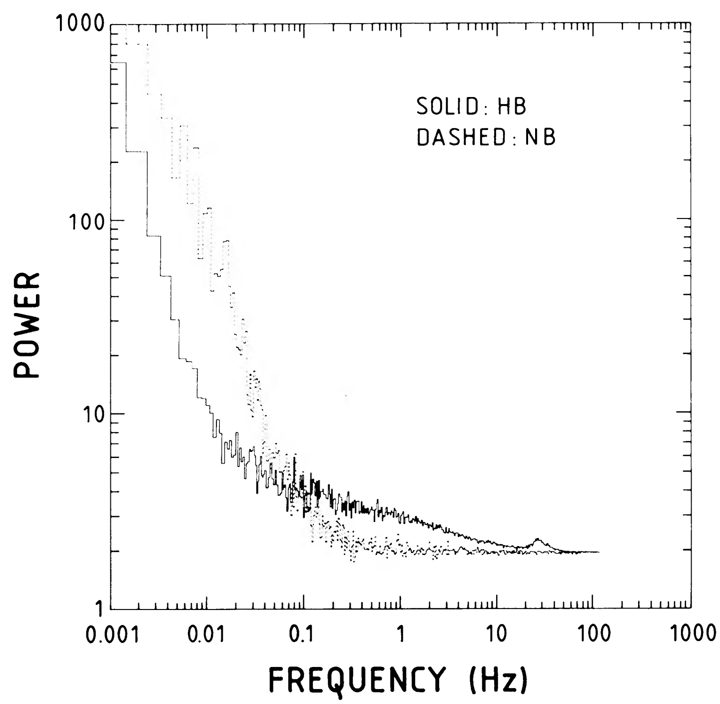

FIG. 3.—Typical HB (*drawn*) and NB (*dashed*) state power spectra. Note the presence of the VLFN in both states.

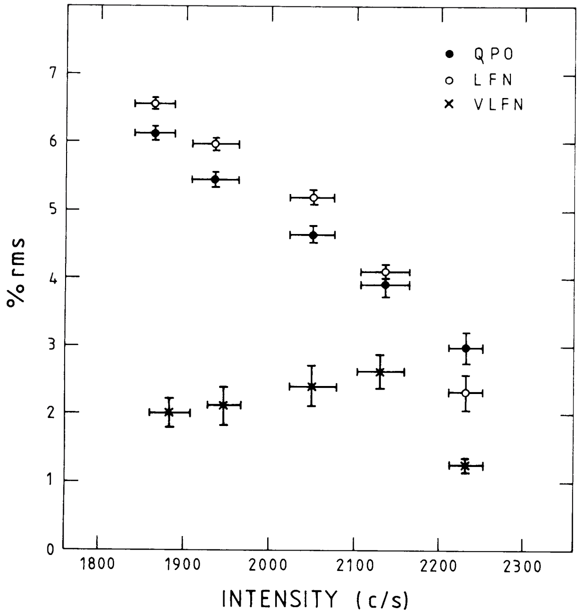

FIG. 4.—Strength of QPO, LFN, and VLFN as a function of ME Ar source intensity in HB state. Intensity scale is uncorrected for dead time.

the power of this very low frequency noise (VLFN) is higher in the NB than in the HB (typically by a factor of 6).

In Figure 4 the dependence on source intensity of the strength of the VLFN as observed in the HB state is compared to that of QPO and associated red noise. In accordance with previous usage, we will refer to this component of the red noise (above the break) as "LFN." QPO and LFN decrease in strength when the source brightens, while the VLFN (also in the NB state) remains roughly constant.

Following the report of 5.6 Hz QPO in Cyg X-2 in its NB state (Hasinger *et al.* 1985) we searched for a similar effect in GX $5-1$ by summing together the power spectra of all high time-resolution *EXOSAT* data of GX $5-1$ in the NB state, including also data obtained with the 5–35 keV Xe detectors. The summed power spectrum shows a bump with a centroid frequency of 5.0 ± 0.3 Hz, a FWHM of $2 \pm_1^2$ Hz, and a strength of $0.7\% \pm 0.3\%$ with a formal *single trial* significance of $\sim 10^{-4}$, which is too low for the feature to have been detected independently of the Cyg X-2 result. Further observations are required to confirm this probable detection of ~ 5 Hz QPO in GX $5-1$ in its NB state.

III. DISCUSSION

GX $5-1$, Cyg X-2, and Sco X-1 all show bimodal spectral and correlated QPO behavior. Relatively rapid QPO (between 10 and 50 Hz) whose frequency is strongly correlated to intensity occur in one spectral state, and slower (5–6 Hz) QPO whose frequency is not or weakly correlated to intensity in the other.

In Cyg X-2 the hardness-intensity diagrams and the QPO and red noise behavior are very similar to what is observed in GX $5-1$. In both sources there is a jump in QPO frequency when the source changes state. In Sco X-1, on the other hand, the hardness-intensity diagrams are different, and there is no change in QPO frequency when the source changes state (Priedhorsky *et al.* 1986; VDK86). Sco X-1 therefore does not fit the scheme defined by Cyg X-2 and GX $5-1$ even though superficially it seems to.

The properties of the red noise of GX $5-1$ and Cyg X-2 on one hand and Sco X-1 on the other also differ. The LFN of GX $5-1$ and Cyg X-2 in the HB state is best fit by an exponential shape and is of similar strength as the QPO (van der Klis *et al.* 1985*b*; Hasinger *et al.* 1986*a*; if the LFN is described with a power law, its index is very low: 0.1–0.3); in Sco X-1 the red noise is always much weaker than the QPO when they are present, but it becomes stronger when the QPO disappear and has a power-law shape with a slope of 1.4–2 (VDK86). These properties are very similar to those of the above-described VLFN; in both cases the noise is present irrespective of whether QPO are detected or not, suggesting that there is no direct connection with the QPO. The different dependences of the VLFN in GX $5-1$ on intensity (Fig. 4) and photon energy (F. Jansen *et al.*, in preparation) as compared to those of the QPO/LFN further support this. This increases the challenge which Sco X-1 presents to the accretion-modulated beat-frequency model (Alpar and Shaham 1985; Lamb *et al.* 1985) which in its simplest form predicts the occurrence of LFN of similar strength as the QPO, as observed in GX $5-1$ and Cyg X-2 (but see Shibazaki and Lamb 1986; Shaham 1986).

None of the originally proposed models for the QPO (see Lewin 1986 for a review) predict bimodal behavior. Recently proposed explanations for the bimodality of the spectral (Priedhorsky 1986) and of the correlated spectral and QPO/red noise (VDK86) behavior of Sco X-1 can not directly be carried over to GX $5-1$ and Cyg X-2 because of the jump in QPO frequency that occurs in these sources between spectral states. The explanation for the bimodal behavior of GX $5-1$ proposed by Berman and Stollman (1986) implies an absence of QPO in the NB contrary to what is observed. It may be necessary to face the possibility that the 5 Hz QPO observed in Cyg X-2 (whose frequency may be intensity-independent; Hasinger *et al.* 1986*b*) and probably also in GX $5-1$ in the NB state are caused by a different mechanism than the intensity-dependent QPO seen otherwise in these sources. If QPO are caused by obscuration by an oscillating accretion disk, which seems attractive from the point of view of explaining the widely different red noise properties (VDK86), then we may be observing the effects of more than one of the different physical mechanisms proposed (see Pringle 1981 and references therein) to produce geometrically thick regions in the inner accretion disk.

M. v.d.K. acknowledges an ESA research fellowship. The Laboratory for Space Research Leiden is supported financially by the Netherlands Organization for the Advancement of Pure Research ZWO. W. H. G. L. acknowledges a generous award from the Alexander von Humboldt Stiftung and support from the United States National Aeronautics and Space Administration (grant NAG8-571), the John Simon Guggenheim Memorial Foundation, and the Max-Planck Gesellschaft.

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