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Quasi-periodic oscillations in the X-ray flux of GX 3+1 (4U 1744−26)

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Summary. GX 3+1, one of the brightest X-ray sources, was observed with *EXOSAT* in 1985 for 8.5 hr on March 24–25, and for 16 hr on September 4. During both observations the flux levels varied by about 20 per cent. The mean flux in September was about 8 per cent lower than in March.

Throughout the March 24–25 observations, low-frequency noise (LFN) was observed below roughly 10 Hz, but no quasi-periodic oscillations (QPO) were detected.

During the September 4 observations, LFN was again detected throughout, but this time QPO were also detected (with a mean frequency of about 8 Hz) during an approximately 3.3-hr period. The strength (rms variation) of the QPO was about 3 per cent The LFN strength increased from about 2 to 6 per cent for photon energies increasing from about 2 to 10 keV. Any possible energy dependence of the strength of the QPO could not be measured because of the limited photon statistics. There appears to be no correlation between the occurrence of QPO and source intensity, however, QPO were only observed (but not always) when the spectral hardness was below a certain value. QPO were not observed in the so-called 'horizontal spectral branch'.

It is possible that these QPO in GX 3+1 are similar in nature to the

intensity-independent 5.6-Hz QPO observed in Cyg X−2 which are also not observed in the horizonal branch.

1 Introduction

GX 3+1 is one of approximately 10 very bright X-ray sources in the inner part of the Galaxy (Bradt *et al.* 1968). Its X-ray flux density near 5 keV is on average about 450 μJy (this corresponds to a flux level of about 10^{-8} erg cm^{-2} s^{-1} in the range 2 to 11 keV), and it varies by about a factor of 3 (Forman *et al.* 1978; Markert *et al.* 1979; Warwick *et al.* 1981; Wood *et al.* 1984). The kT values for simple thermal bemsstrahlung fits are about 5 keV (Jones 1977; Parsignault & Grindlay 1979). Positive correlations between the hardness of the spectrum and the flux have been reported (Parsignault & Grindlay 1979; Ponman 1982; however, see Makishima *et al.* 1983). The X-ray flux was relatively low for several months in 1979 when type 1 X-ray bursts were observed (Oda 1980; Makishima *et al.* 1983; see also Inoue *et al.* 1981). This was a confirmation of earlier suggestions that burst sources and non-bursting bright galactic bulge sources are similar systems, differing mainly in their X-ray luminosities (*cf.* van Paradijs *et al.* 1979, and references therein).

Quasi-periodic oscillations (QPO) with relatively long periods (in the range of a few to 10^3 s) have been observed from half a dozen X-ray binaries (for a review see Lewin 1986a or b). QPO with a period of about 0.5 s were observed by Tawara *et al.* (1982) in two (of 63) type 2 bursts from the Rapid Burster (Hoffman, Marshall & Lewin 1978). High-frequency, flux-dependent QPO, with frequencies varying between 20 and 45 Hz, associated with low-frequency noise (LFN), were recently detected in the X-ray flux of the bright bulge source GX 5−1 (van der Klis *et al.* 1985). Subsequently, high-frequency QPO (sometimes accompanied by LFN, and sometimes not) were found in many bright 'galactic bulge' sources (for reviews, and recent observational results see Lewin & Van Paradijs 1986; Stella *et al.* 1985; Stella 1986; van der Klis 1986a, b; van der Klis *et al.* 1987a, b; Lewin 1986b, Hasinger 1986; for a comparison between models and observations, see Lewin 1986a, or b).

We have detected high-frequency QPO in the bright galactic bulge source GX 3+1, and reported some preliminary results in an IAU circular (Lewin *et al.* 1986). In this paper we describe the QPO and the characteristics of the LFN in detail. The observations are described in Section 2, and the analysis and results in Section 3. In Section 4 we discuss the results.

2 Observations

We observed GX 3+1 (4U 1744−26) from 1985, March 24.86–25.22 UT (8.5 hr), and from 1985, September 4.17–4.83 UT (16 hr) with the full array (effective area 1500 cm^2) of the medium-energy (ME) Argon detectors (Turner, Smith & Zimmermann, 1981), and the Gas Scintillation Proportional Counter (GSPC; Peacock *et al.* 1981) of *EXOSAT*.

2.1 1985 MARCH 24–25 OBSERVATIONS

During the March 24–25 observations, the data from the Medium-Energy detectors were recorded in only *one energy channel* (1–16 keV). During the first 2.2 hr, the time resolution was 2 ms. During the remaining 6.3 hr, the time resolution was 0.25 ms (the deadtime was negligible). During this period, data were obtained continuously in 2-s time intervals (during which the deadtime was less than 1 per cent), but each such 2-s interval was followed by a period usually of 15 s during which no data were transmitted to Earth.

Spectral information is available from the GSPC data (effectively in the 2–11 keV range), but

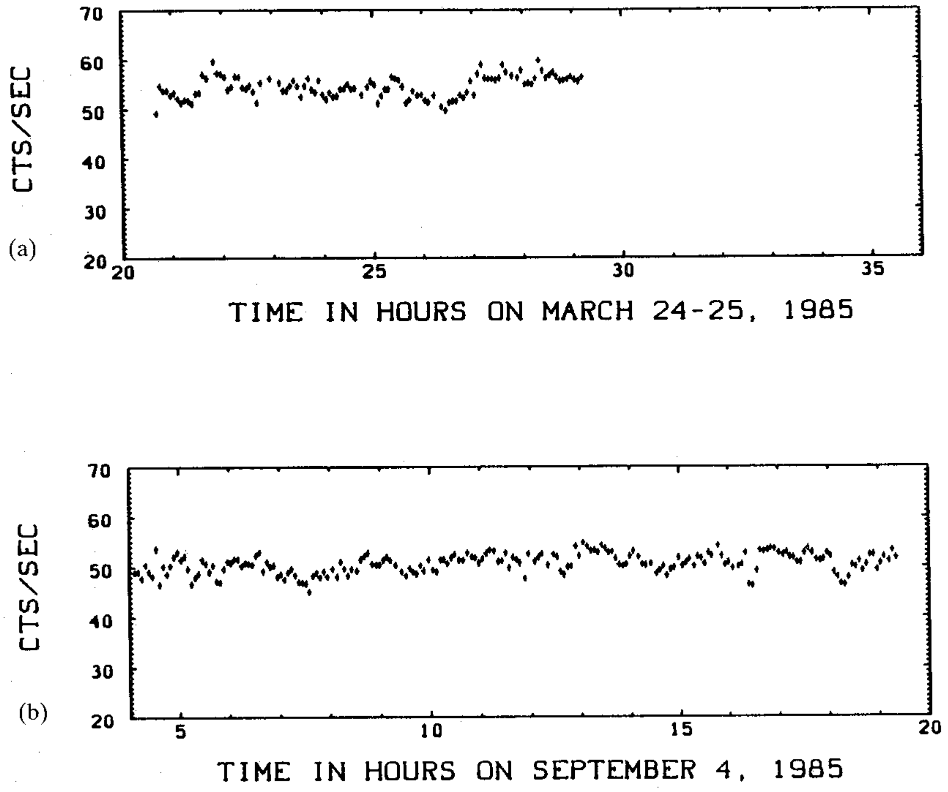

Figure 1. Counting rates from the GSPC (2–11 keV; corrected for background and deadtime). (a) 1985 March 24–25 observations; (b) 1985 September 4 observations. The statistical errors are much smaller than the size of the data points.

with a time resolution of only 8 s. The counting rates from the latter (2–11 keV) are shown in Fig. 1(a) (the background is subtracted, and deadtime corrections were made).

2.2 1985 SEPTEMBER 4 OBSERVATIONS

On September 4, the observations with the ME detectors were made with a time resolution of 4 ms in *four energy channels*; the deadtime was about 16 per cent. During the first 6.5 hr, the channel boundaries were 0.9, 3.1, 5.8, 7.0 and 16 keV; during the remaining 9.5 hr the 5.8 keV boundary was changed to 5.0 keV.

More detailed spectral information is available from the GSPC data but with a time resolution of only 16 s. The counting rates from the latter (2–11 keV) are shown in Fig. 1(b).

For the observed average spectral shape, 1 count s^{-1} of the GSPC (2–11 keV) corresponds to approximately 1.25×10^{-10} erg cm^{-2} s^{-1}. Thus, the mean flux levels (2–11 keV) during the March and the September observations were about 6.8×10^{-9} and about 6.4×10^{-9} erg cm^{-2} s^{-1}, respectively.

3 Analysis and results

We estimated the power spectra by calculating (via an FFT algorithm) the Fourier amplitudes of the average-subtracted signal. For the first 2.2-hr period on March 24–25, power spectra were calculated for individual 64-s data intervals, and then averaged (see below). For the remaining 6.3 hr, power spectra were calculated for the individual 2-s data blocks (0.25 ms time resolution).

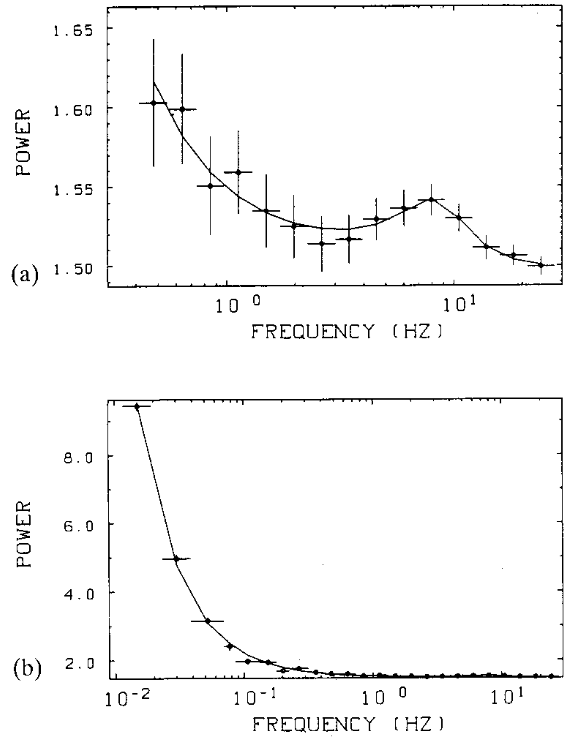

Figure 2. Average power density spectra. The solid lines represent the best fit (see text). (a) The 3.3-hr interval (period 2 in Fig. 3), between September 4.34 and 4.46 UT during which QPO were observed; (b) same as (a), but with different scales to highlight the low-frequency noise in the region below a few Hz.

During this 6.3-hr period, observations were made for only 2 s of every 17 s (see above). Therefore, the effective observing time is only about 45 min. For the September 4 data, power spectra were calculated of individual 64-s data blocks, and then averaged.

Time-resolved power spectra were made by consecutively averaging several minutes of data and displaying them in a 'time image' which allows one to follow the QPO (and/or LFN) behaviour in time (see, e.g. van der Klis *et al.* 1985).

No evidence for either coherent pulsations (with frequencies less than 2000 Hz), or QPO was found in the March 24–25 data, but LFN (below approximately 10 Hz) was detected throughout the 8.5-hr observations The September 4 data showed no evidence for coherent pulsations (below 256 Hz) either; LFN was again observed during the whole 16-hr observing period, and QPO was observed, but only during an approximately 3.3-hr period (from September 4.34–4.47 UT). The average power spectrum for this interval is shown in Fig. 2. Average power spectra were also made independently for three approximately 4-hr periods (one preceding, and two following the above 3.3-hr period; see below). Apart from the fact that QPO is not present, they are very similar to the spectrum shown in Fig. 2(b).

In order to describe the power spectra quantitatively, we performed least-squares fits to the average power spectra. Following van der Klis *et al.* (1985), we used fitting functions in which the LFN is described by either an exponential or a power law, and the QPO by a Lorentz profile.

3.1 MARCH 24–25 DATA

The time-resolved spectra showed that LFN was present throughout the March 24–25 observations. The LFN could not be adequately fit to an exponential. However, a power-law dependence on the frequency, f, where the excess power, $P(f)$, is proportional to f^{γ}, with $\gamma=1.22\pm0.04$ fit the data very well. The best fit to the average power spectrum has a reduced chi-squared value of 1.2. The excess LFN power (above the constant level due to Poissonian noise, independently obtained from the fits) in terms of the rms variations in the flux, is 2.32±0.04 per cent (0.01–32 Hz; 1–16 keV).

We have calculated upper limits to the strength of the QPO using the average power density spectrum of the first 2.2 hr. A 2σ upper limit to the percentage rms flux variation for QPO with similar characteristics (i.e., centroid frequency, and peak width) as observed on September 4 (see below), is 2.7 per cent. Two-sigma upper limits for QPO with centroid frequencies anywhere between 2 and 50 Hz, and a peak width anywhere between 10 and 50 per cent, are less than 10 per cent.

3.2 SEPTEMBER 4 DATA

The 'time images' showed that LFN was again present throughout the September 4 observations. During a period of very roughly 3.3 hr, QPO were also detected. Fits to the average power density spectrum of this 3.3-hr period, covering the frequency range 0.015–32 Hz, are shown in Fig. 2. Exponential functions could not adequately represent the LFN, but power laws could. The best-fit values (1–16 keV) are: $\gamma=1.29\pm0.03$, the centroid QPO frequency is 8±1 Hz, the peak width, FWHM, is 8±4 Hz. The reduced chi-squared value is 0.88 (18 degrees of freedom). The rms modulation in the QPO (above the LFN and the Poissonian noise, independently obtained from the fits), is 3.5±0.9 per cent. The rms modulation in the LFN (0.01–32 Hz) is 3.1±0.03 per cent. These values are corrected for background, and deadtime (of about 16 per cent), including channel cross-talk. The deadtime suppresses the white noise (Poissonian) level from about 2.0 (see van der Klis *et al.* 1985) to about 1.5 (see Fig. 2a).

All errors are 1σ single parameter errors which take into account the correlations between the parameters and the non-linearities in the dependence of the deviations from the fitting function on variations in its parameters (Avni 1976). The above uncertainty in the strength of the QPO does not reflect the significance of the existence of the QPO. *This significance is given by the probability that its strength is zero or less.*

3.3 SIGNIFICANCE OF THE QPO DETECTION

F-tests were performed to evaluate the significance of the QPO detection. We first calculated the probability that the data, shown in Fig. 2(b), are consistent with no QPO peak; this is 2.5×10^{-6}. We then took into account the fact that the QPO were only observed during about one-fifth of the time, and that the broad QPO peak could have been found at other frequencies. The above probability was therefore multiplied by 20 (representing an equivalent number of independent trials). This leads to a probability (chance coincidence); of 5×10^{-5} which indicates that the QPO detection has an approximately 4-σ-level of confidence.

We realize that this method is not at all precise. However, we believe that there is no 'proper' way to express the significance of this detection. A better way would be to simulate about 10^5 power density spectra (Monte Carlo calculations) from data in which no QPO are present, and to ask the question how often do we observe a 'bump' in these spectra with excess power larger than we have observed. But this rather time-consuming method is not without problems either since one would again have to specify an 'acceptable' range of frequencies and an 'acceptable' range of peak widths (Dr Daniel Kleitman, private communication).

3.4 QPO DEPENDENCE ON ENERGY

The September observations were made in four energy channels (see above). We can, however, not say anything useful about the energy dependence of the QPO, as the QPO signal is too weak. However, the LFN showed a clear dependence on energy.

3.5 LFN DEPENDENCE ON ENERGY

We have divided out 16-hr observation into four periods; they are indicated in Fig. 3. Period 1, of about 4 hr, precedes the 3.3-hr period (period 2) during which QPO were observed. Periods 3 and 4, during which no QPO were observed, are each about 4.2 hr. Averaged over the entire energy range (0.9–16 keV), the LFN strength in the range 0.01–32 Hz (corrected for background, and deadtime), was approximately the same (3.1±0.02 per cent) during all four periods. For all periods combined, the strength was 2.02±0.03, 3.35±0.02 and 5.94±0.13 per cent in the energy intervals 0.9–3, 3–7 and 7–16 keV, respectively. During period 1 alone, and independently during period 3 alone, the values were the same within the uncertainty of the measurements. This is also the case for periods 2 and 4 with the exception, however, for the energy channel 3–7 keV where the differences were statistically significant; the strengths were 3.11±0.06 (period 2) and 3.57±0.05 per cent (period 4).

For all periods combined, the γ-values for the three energy channels above are 1.85±0.06, 1.28±0.07 and 1.38±0.05, respectively. During all four individual periods, the γ-values, for a given energy channel, were the same within the uncertainty of the measurements.

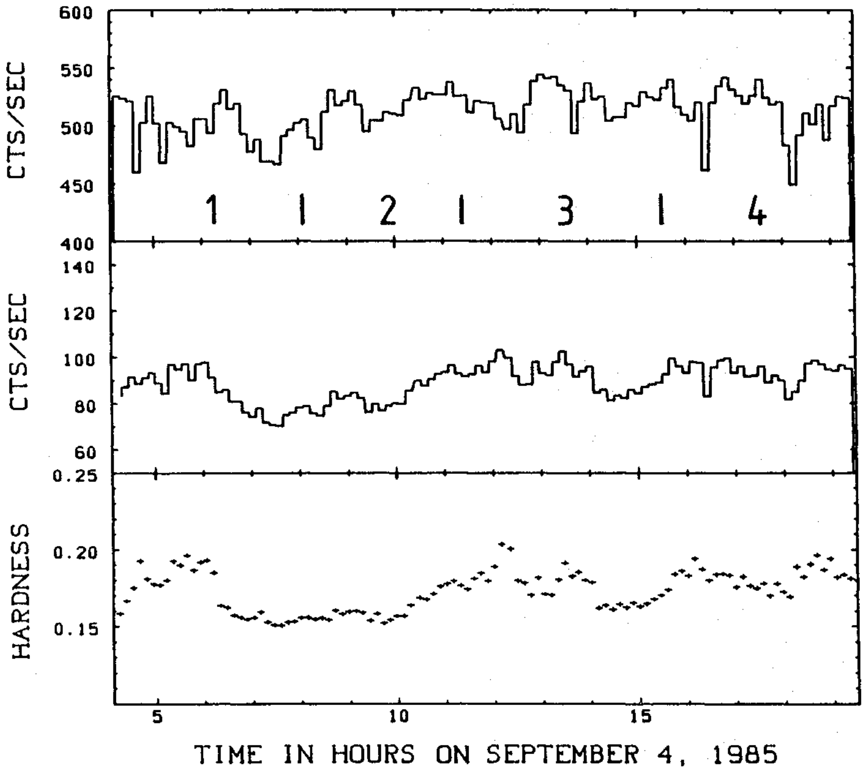

Figure 3. Counting rates (corrected for background, and deadtime) from the medium-energy detectors during 1985 September 4 in the 3–7 (upper panel), and 7–16 keV (middle panel) energy channels. The (hardness) ratio between them is shown in the bottom panel. The four periods (see text) are indicated in the upper panel. QPO were observed during period 2.

3.6 SPECTRAL HARDNESS VERSUS THE OCCURRENCE OF QPO

In Fig. 3 we show the counting rates (corrected for background, and deadtime) of the medium-energy detectors during the September 4 observations in the 3–7 and 7–16 keV energy channels (upper panels); we also show the hardness ratio between them (bottom panel). The four periods (see above) are indicated. QPO were only detected at a significant level during period 2.

3.7 SPECTRAL HARDNESS VERSUS SOURCE INTENSITY

In Fig. 4 we show the same hardness ratios as a function of source intensity (1–16 keV) for the September 4 observations. The data points cluster along two branches which we tentatively identify as the 'horizontal spectral branch' (upper branch), and the 'normal branch' (lower) (Shibazaki & Mitsuda 1984). In our data (Fig. 4), QPO are only observed (but not always) in the 'normal branch' (the filled dots are data from the 3.3-hr period during which QPO were detected).

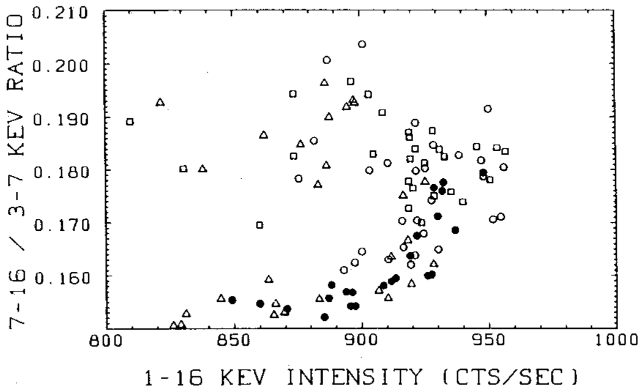

Figure 4. Ratios of the counting rates in the 7–16 and 3–7 keV energy channels, versus the total counting rate in the 0.9–16 keV range (ME data). The triangles are data for period 1, the filled circles for period 2 during which QPO was observed, the open circles are for period 3, and the squares for period 4 (see Fig. 3). The 'horizontal branch', and the 'normal branch' are clearly visible (see text). QPO were only observed (but not always) in the 'normal branch' (see filled circles).

Spectral data as shown in Fig. 4 are not available for March 24–25. However, we do have spectral data from the GSPC for the March, and the September observations. They are of much lower quality, however, than the spectral data from the ME detectors (September 4) since the GSPC has a much smaller area. Since the GSPC data are the only means to make a spectral comparison, we show in Fig. 5 hardness ratio-intensity plots for the two observations.

4 Discussion

Our September 4 observations are another example of bimodal spectral behaviour similar to that observed in Cyg X-2 (Branduardi *et al.* 1980; Hasinger 1986), and in GX 5−1 (Shibazaki & Mitsuda 1984; van der Klis *et al.* 1987a) where the 'break' in the branches occurs at high intensities (see Fig. 4). This is different from the bimodal behaviour observed in Sco X-1 where the branches break at low intensities (Priedhorsky *et al.* 1986).

To date, there is no conclusive explanation for either one of these bimodal behaviours. *It is very interesting, however, that the QPO behaviour seems to be bimodal as well, and correlated with the*

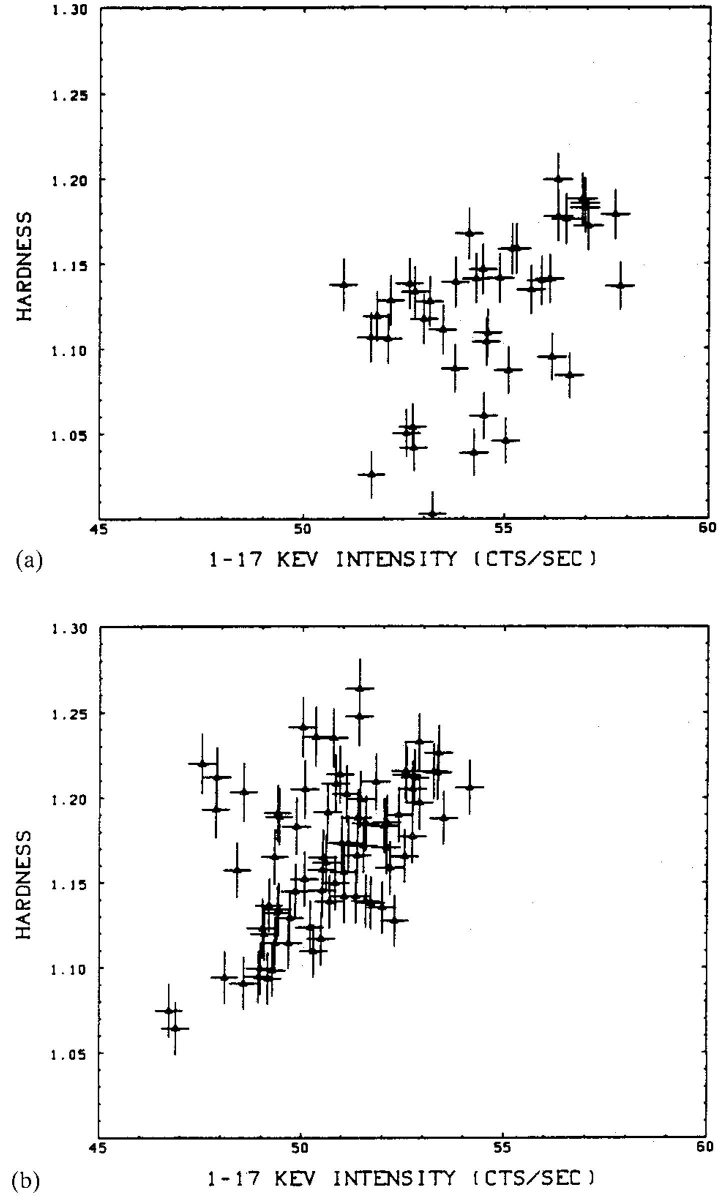

Figure 5. Hardness ratios (6–11/2–6 keV) versus intensity (2–11 keV) obtained from the GSPC data. (a) March 24–25 observations; (b) September 4 observations. These data are of much lower statistical quality than those shown in Fig. 4. However, they are the only available spectral data that allow for a comparison between the March 24–25, and the September 4 observations. The 'horizonal branch', and the 'normal banch' (see text) can be easily seen in (b).

bimodal spectral behaviour. The intensity-dependent QPO in GX 5−1 and Cyg X-2 (in the frequency range of about 20–50 Hz), are only observed in the 'horizontal branch' (van der Klis *et al.* 1987a; Hasinger 1986). However, intensity-independent QPO (i.e. where the frequencies of the QPO are independent of the source intensity) have been observed at a frequency of about 5.6 Hz in Cyg X-2 (Hasinger 1986), and possibly near 5 Hz in GX 5−1 (van der Klis *et al.* 1987a).

The detection of 8-Hz QPO in the bright bulge source GX 3+1 does not come as a surprise. About eight other bright bulge sources have shown this phenomenon (for reviews, and recent observational results see Lewin & van Paradijs 1986; Stella *et al.* 1985; Stella 1986; van der Klis 1986a, b; van der Klis *et al.* 1987a, b; Lewin 1986b; Hasinger 1986).

In GX 3+1 QPO were only observed (but not always) when the spectral hardness was below a certain value; it was not observed when the source was in the 'horizontal spectral branch' (see Fig.

4). These characteristics appear to be similar to the normal branch QPO in Cyg X-2 and GX 5−1 (see above).

QPO were not detected in GX 3+1 during our 8.5-hr observation on 1985 March 24–25, however, we did detect them (but only for roughly 3.3 hr) during a 16-hr observation on September 4. There could be various reasons why they were not seen on March 24–25. The mean flux was then about 8 per cent higher than during our September 4 observations (see Figs 1 and 5); that may have been the reason. On the other hand, if the strength of the QPO on March 24–25 had been only slightly below that of September 4 (when it was about 3 per cent during period 2, see Fig. 3), we would not have been able to detect it since the total effective observation on March 24–25 was only about 3 hr, because of the special recording mode (see above).

The strength of the LFN in GX 3+1 is strongly energy-dependent (the higher the X-ray energies, the higher is its strength). This would be expected if the LFN is associated with the same type of spectral variability (but on a much shorter time-scale) that one can see in Fig. 3. There, the spectral hardness changes (on time-scales of hours) are largely due to the changes in the high-energy channel. (Notice that the middle panel, and the lower panel of Fig. 3 look very similar.) The observed energy dependence may mean that the variations are produced in the inner (hotter) regions near the neutron star. If, however, Comptonization plays a role, a variation in optical depth of the scattering medium could produce the observed behaviour as well.

There is a wide variety in the behaviour of the QPO (and the LFN); not only between sources but also for one source. In spite of many interesting suggestions (see e.g. Alpar & Shaham 1985; Lamb *et al.* 1985; Hameury, King & Lasota 1985; Boyle, Fabian & Guilbert 1986; Morfill & Trümper 1986; Lamb 1986; van der Kils *et al.* 1987b), we do not know yet what causes the QPO (for a comparison between models and observations see Lewin 1986a or b). Recent results have been interpreted as indicating that QPO observed in Cyg X-2 may have a magnetospheric origin, and that the frequency is the Keplerian frequency of accreting matter near the magnetopause (Hasinger 1986; see also Bath 1973). However, it is too early to tell. It is quite possible that there are different 'kinds' of QPO and that more than one mechanism is at work (see e.g. Lewin 1986a or b; see also Note added).

Models in which QPO have a magnetospheric origin (see e.g. Alpar & Shaham 1985; Lamb *et al.* 1985; Berman & Stollman 1985; Morfill & Trümper 1986) have so far received a lot of attention. An attractive feature of these models is that the magnetic dipole field strengths, inferred from the observed QPO frequencies, are of the same order as the fields determined for binary millisecond radio pulsars in wide orbits (see e.g. van den Heuvel 1986). These fast-rotating pulsars are believed to be the final stages of the evolution of bright low-mass X-ray binaries (Joss & Rappapport 1983; Paczynski 1983; Savonije 1983). However, when confronted with the observations, these QPO models face some serious problems (for a review of magnetospheric, and other models, see e.g. Lewin 1986a or b).

Since magnetic dipole fields of young neutron stars appear to decay on a time-scale of about 10^7 yr (see e.g. Lyne, Manchester & Taylor 1985) it was expected that, if magnetospheric QPO models are correct, the neutron stars in QPO sources are relatively young ($\lesssim 5\times10^7$ yr) (van der Klis *et al.* 1985; *cf.* Lewin & van Paradijs 1986). Based on evolutionary considerations it is considered likely that neutron stars in low-mass X-ray binaries (LMXB) have been formed by the accretion-induced collapse of an accreting white dwarf, during the same stage of mass transfer which now gives rise to the bright X-ray source (see e.g. van den Heuvel & Taam 1984). The mass transfer phase of a LMXB with an evolved companion (which is expected to have a high mass transfer rate during most of its lifetime, see Webbink, Rappaport & Savonije 1983; Taam 1983) lasts only about 10^8 yr. Thus, neutron stars in such systems could be young. The mass transfer phase of a LMXB with an unevolved companion can last up to about 10^9 yr (Rappaport, Verbunt & Joss 1983), and the probability of finding a young neutron star in such systems is small.

Thus it was concluded that if QPO are a magnetospheric phenomenon, QPO are expected to be observed preferentially in LMXB with an evolved companion (van der Klis *et al.* 1985; Lewin & van Paradijs 1985, 1986; van Paradijs & Lewin 1986).

However, there is now evidence that the decay of neutron star magnetic dipole fields (which has been established over the range 10^{13}–10^{11} G) does not continue indefinitely, but stops (or proceeds on a much longer time-scale of $\gtrsim 10^9$ yr) when the field has reached a value of order 10^9 G (Kulkarni 1986; van den Heuvel, van Paradijs & Taam 1986; Bhattacharya & Srinivasan 1986). As a consequence, old (about 10^9 yr) neutron stars, which are expected in LMXB with *unevolved* companions, may well have magnetic fields in the range inferred from the magnetospheric interpretations of QPO (van der Klis *et al.* 1985, 1987b; Hasinger *et al.* 1986). Thus, if QPO have a magnetospheric origin, the preferential occurrence of QPO in LMXB with an evolved companion is no longer to be expected, and the necessity of neutron star formation through the accretion-induced collapse, is no longer required by magnetospheric models of QPO (there may, of course, be other arguments in favour of the accretion-induced collapse, see, e.g. van den Heuvel & Taam 1984).

Two of the QPO sources (Sco X-1 and Cyg X-2) have an 'evolved' companion (we mean by this that the donor is *moving up the giant branch*), and no QPO have, as yet, been observed from a system of which the companion star is known to be unevolved (i.e. a main-sequence star with an orbital period between about 1 and 8 hr). Thus, in spite of the above disclaimer, observations so far made are still consistent with the idea that QPO occurs preferentially in LMXB with an evolved companion.

Since LMXB with an evolved companion, in general, have substantially larger mass transfer rates than systems with an unevolved companion (see Webbink *et al.* 1983; Taam 1983; Rappaport *et al.* 1983) the preferential occurrence of QPO in these systems could be the result of a selection effect. The detection of QPO in bright sources is much easier than in faint ones, as the time required to detect QPO (with the same assumed characteristics) at the same level of significance scales inversely with the square of the observed source flux. It should, in addition, be noted that in view of the observed (sometimes rapid) variability of the QPO strength and frequency, the detection limit for QPO may not be set by the length of an observation, but by the time interval during which QPO properties do not change; this makes the selection effect even worse.

Another possible interpretation, consistent with the present observations, is that QPO is preferentially observed in luminous sources (i.e. that they are dictated by the magnitude of the accretion rate). To test this possibility one should study the QPO behaviour of X-ray sources which show a large range in X-ray luminosity. Prime candidates for such studies are soft X-ray transients, whose luminosities vary between about 10^{32} (van Paradijs *et al.* 1986) and about 10^{38} erg s^{-1}. Unfortunately, no bright soft X-ray transients were detected during *EXOSAT*'s lifetime, after the possibility of such a test occurred to us. We will have to wait for *ASTRO-C* to make these observations.

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Note added

After completion of this manuscript, we learned about the discovery of 686-s *coherent* oscillations in the X-ray flux of the burst- and QPO source 4U/MXB 1820−30 (located in the globular cluster NGC 6624) by Priedhorsky, Stella & White (private communication). They interpret this as an orbital period. If their interpretation is correct, it would demonstrate that QPO can be produced by sources with a companion that is neither a main-sequence star nor a star moving up the giant branch.

Note added in proof

A more detailed analysis of timelags in the X-ray flux of Cyg X-2 and GX 5-1 is discussed in van der Klis *et al.* (1987c).