# *IVa. NEUTRON STELLAR EVOLUTION*

## *Quasi Periodic Oscillations as a Clue to Field and Spin Evolution*

*CHAIR: E. P. J. van den Heuvel*

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# QUASI-PERIODIC OSCILLATIONS IN LOW-MASS X-RAY BINARIES

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ABSTRACT. The properties of the rapid, persistent quasi-periodic oscillations (QPO) discovered with EXOSAT in the X-ray flux of at least 7 bright low-mass X-ray binaries are described. Particular attention is given to the various relations observed between QPO frequency and X-ray intensity, the link between QPO and the low-frequency noise in the X-ray intensity and the bimodal properties of in particular Sco X-1, GX 5-1 and Cyg X-2. The merits of the hypothesis that the QPO indicate the presence of a neutron star with a magnetosphere are considered.

## 1. Introduction

Observations with EXOSAT have led to the discovery of rapid quasi-periodic oscillations (QPO) in the X-ray flux of GX 5-1 (van der Klis et al. 1985a,b) and subsequently in at least 6 other low-mass X-ray binaries. The sources are listed in Table 1 in order of decreasing QPO frequency. The first seven sources listed, which show high-frequency (5-50 Hz) low-coherent ($\Delta\nu / \nu \sim 1$) strong (amplitudes typically resulting in a 5% rms flux variation) persistent ($>10^5$ cycles) QPO form the main subject of this review. They are all very luminous ($> 10^{38}$ erg/s) and classified as 'persistently bright' (Bradt and McClintock 1983). The QPO in the rapid burster (1730-33) which were discovered with the Hakucho satellite by Tawara et al. (1982) have slightly different properties: lower frequency range and a persistence of $10^3$ cycles at most (see Stella 1985). The results on Cir X-1 (Tennant 1986), which may be a massive system, and Terzan 2 (Belli et al.1986) are very recent and will not be discussed here.

Five of the seven high-frequency QPO sources are bright galactic bulge sources which notoriously lack diagnostic properties: they rarely show X-ray bursts, never periodic dips or pulsations and have no optical identifications. The QPO, which from their high frequencies probably originate from within approximately $10^2$ km from the central source, are one of the very few available probes into the structure of these systems. The remaining two sources, Sco X-1 and Cyg X-2, are low-mass X-ray binaries which are known to be accreting matter from an evolved



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Table 1 - QPO sources

| Source | $\nu_{QPO}$ (Hz) | Log $L_x$ [1)] | Persistence (log(cycles)) | Remarks [1)] | References |
|---|---|---|---|---|---|
| Cyg X-2 (2142+380) | 5,28-45 | 38.1 | 6 | PB | 1,2,3,4 |
| GX 5-1 (1758-250) | 5?,20-36 | 38.6 [2)] | 6 | PB | 5,6,7,8 |
| 4U 1820-30 (1820-303) | (0.02), 15-35 | 37.9 | (1),6 | PB,Bu,GC | 9,10,11 |
| Sco X-1 (1617-155) | 6-10-20 | 37.9 [3)] | 5 | PB | 12,13,14 15,16 |
| GX 349+2 (1702-363) | 5,11? | 38.5 [2)] | 5 | PB | 17,18,11 |
| GX 3+1 (1744-265) | 8.6 | 38.2 [2)] | 5 | PB,Bu | 19 |
| GX 17+2 (1813-140) | 7.2 | 38.4 [2)] | 5 | PB,Bu? | 20,11 |
| Rap. Burs-ter (1730-333) | 1-5 | 37.0 | 3 | Bu,GC | 21,22,11 |
| Cir X-1 (1516-569) | 1.4 | 38.9 | ? | Bu?,Tr,RV | 23 |
| Terzan 2 (1724-307) | 0.092? | 36.7 | 3 | Bu,GC | 24,25 |

1) Bradt and McClintock (1983)
PB = persistent bright   Tr = transient
Bu = X-ray burst source   RV = rapidly variable
GC = in globular cluster
2) at 10 kpc
3) at 1.2 kpc (White, Peacock and Taylor 1985)
4) ref. 27

References to Table

1. Hasinger et al. 1985a; 2. Hasinger et al. 1986a; 3. Norris and Wood 1985; 4. Hasinger et al. 1985b; 5. Van der Klis et al. 1985a; 6. Van der Klis et al. 1985b; 7. Van der Klis et al. 1985c; 8. Van der Klis, these proc.; 9. Stella et al. 1985c; 10. Stella 1985; 11. Stella et al. 1984; 12. Middleditch and Priedhorsky 1985a; 13. Van der Klis et al. 1985d; 14. Middleditch and Priedhorsky 1985b; 15. Van der Klis et al. 1986a; 16. Priedhorsky et al. 1986; 17. Lewin et al. 1985; 18. Cooke et al. 1985; 19. Lewin et al. 1986; 20. Stella et al. 1985a; 21. Tawara et al. 1982; 22. Stella et al. 1985b; 23. Tennant 1986; 24. Belli et al. 1986; 25. Morini, priv. comm. 1986.

low-mass companion. Except for their position relative to us and the galactic center, they may be very similar to bright galactic bulge sources.

A typical QPO power spectrum is shown in Figure 1. Apart from the part dominated by the broad QPO peak, there is a section that gradually rises towards lower frequencies below the QPO peak. This is due to 'low-frequency noise' (LFN), a common phenomenon of noisy time series. It consists of stochastic variations (here occuring in addition to the QPO) of which the slowest have the largest amplitudes.

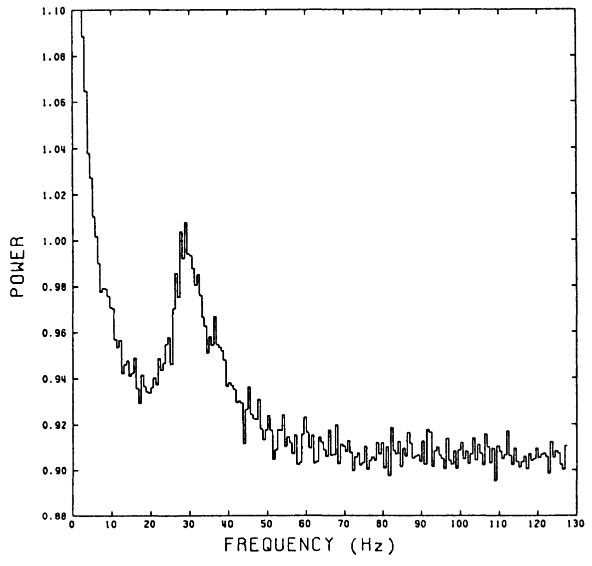


Figure 1. A power spectrum of GX 5-1.

The following description of the observational data of the QPO in these sources concentrates on three main subjects:

1) the relations between X-ray intensity and QPO frequency,
2) the connection between QPO and LFN, and
3) the correlated bimodal X-ray spectral and QPO/LFN behaviour observed in some sources.

This paper will follow a roughly historical line, first discussing the QPO/LFN properties of GX 5-1 and Cyg X-2 in their 'horizontal branch' spectral state, then moving on to the bimodal properties of Sco X-1 and finally comparing this to the bimodal behaviour of GX 5-1 and Cyg X-2. I shall be indicating at some points what is the significance of the discussed observational data for QPO models; for a full review of QPO models see Lewin (these proceedings). We shall be mainly concerned with the three best-studied QPO sources: GX 5-1, Sco X-1 and Cyg X-2.

## 2. GX 5-1 and Cyg X-2 on the 'horizontal branch'

### a) Frequency-intensity relations

Both GX 5-1 and Cyg X-2 show, in their horizontal branch spectral state (see Section 4) a strong positive correlation between X-ray intensity and QPO frequency (van der Klis et al. 1985b, Hasinger et al. 1986a). In both cases the intensity-frequency relation is consistent with a straight line (Figure 2).

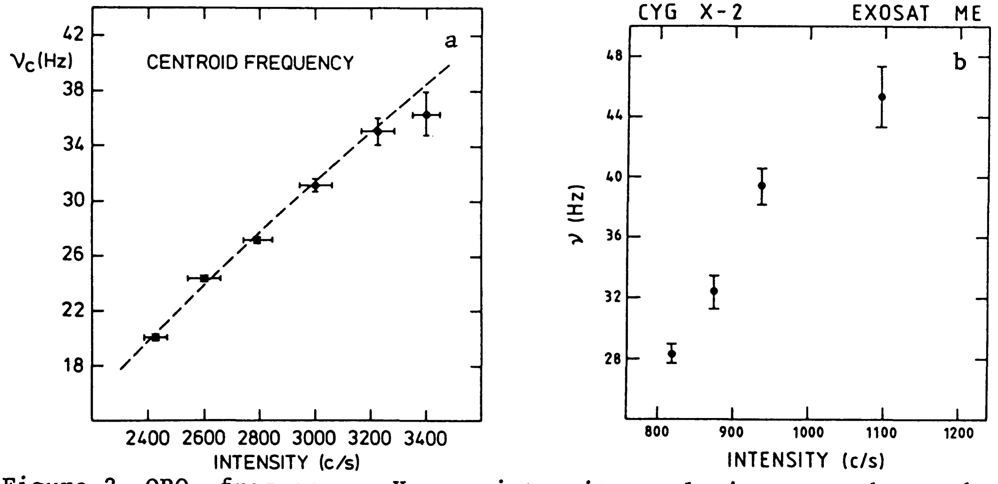


Figure 2. QPO frequency - X-ray intensity relation as observed in GX 5-1 (a, van der Klis et al. 1985b) and Cyg X-2 (b, after Hasinger 1985b) on the horizontal branch.

From the beginning this positive correlation suggested that the QPO frequency might be related to the Keplerian rotation frequency of matter in an accretion disk just outside a magnetosphere. Alpar and Shaham (1985a,b) proposed that the QPO might arise as a beat between the Keplerian rotation of matter in the accretion disk and the spin of a magnetised neutron star. The derived spin frequency would then be of the order of 10 ms and the neutron star surface field $10^9$-$10^{10}$ Gauss.

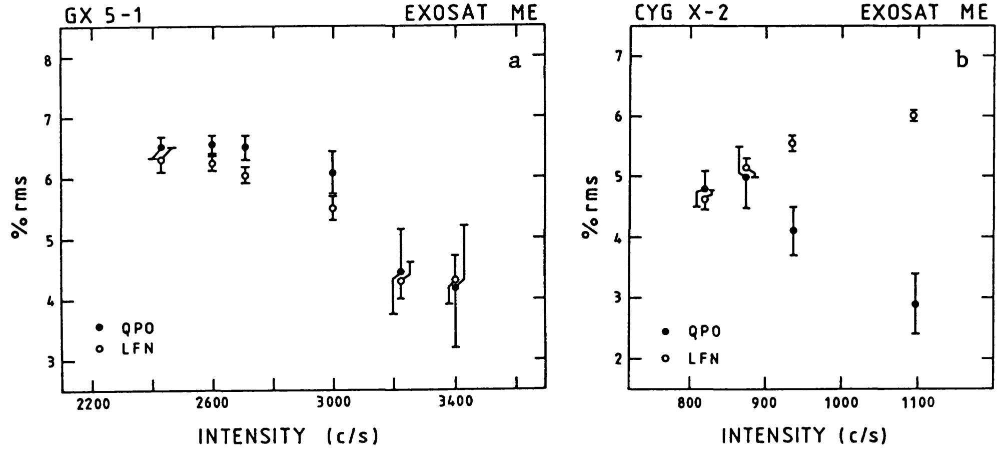


Figure 3. QPO (dots) and LFN (circles) strength as a function of X-ray intensity as observed in GX 5-1 (a, after van der Klis et al. 1985b) and Cyg X-2 (b, after Hasinger et al. 1985b).

b) Low-frequency noise (LFN)

Both sources show LFN of similar strength as the QPO (see Figure 3 for their intensity dependence). This fact prompted the development of a version of the beat-frequency model in which the accreting matter contains random clumps and the
X-ray signal consists of oscillating shots (each shot is the accretion of one clump, the oscillation is due to a magnetic gating mechanism operating at the beat frequency; Lamb et al. 1985). A prediction of this model is that, somewhat dependent on the assumed QPO wave form, the power in the LFN is at least about equal to the power in the QPO.

## 3. Sco X-1

a) Bimodal behaviour

The QPO in Sco X-1 were first discovered in its 'quiescent' state (Middleditch and Priedhorsky 1985a,b). Later QPO were also found in 10-30 min. intensity dips in between flaring episodes (van der Klis et. al. 1985d, 1986a; Priedhorsky et al. 1986). Figure 4a shows both types of QPO in a time vs. frequency diagram where the power in the intensity variations at any given time and frequency is gray-scale coded (darker for higher power). In the active state the QPO centroid frequency varies between 10 and 20 Hz; in quiescence it remains near 6 Hz. A gradual transition between the two states is visible.

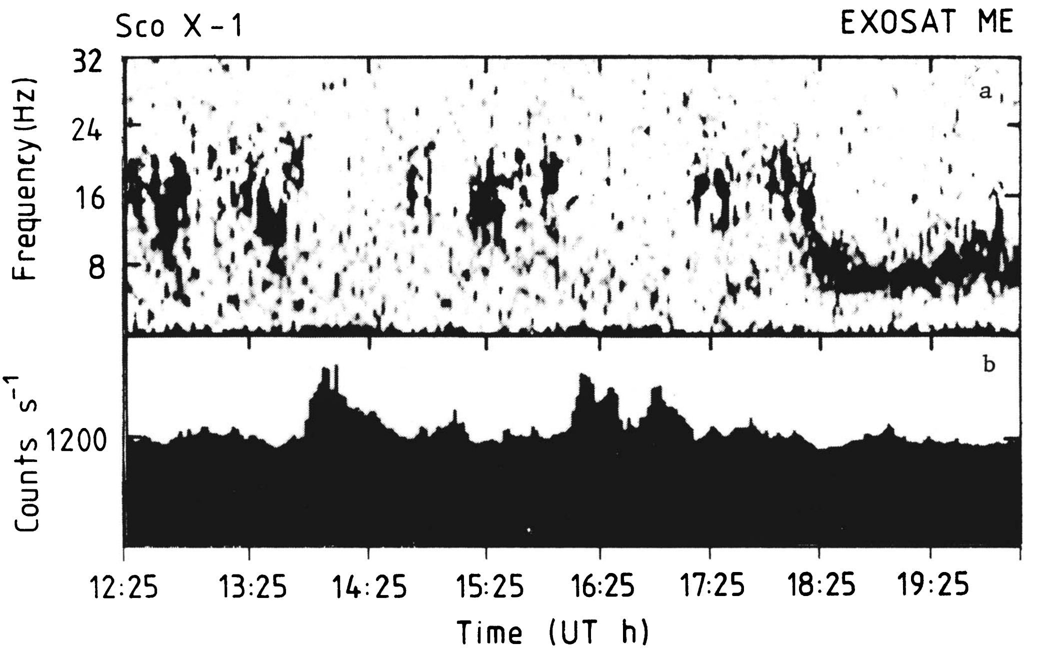


Figure 4. Dynamic power spectrum (a) and X-ray light curve (b) of Sco X-1 (Priedhorsky et al. 1986).

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In the dips in the active state a strong positive correlation is observed between frequency and intensity (van der Klis et al. 1985d), in quiescence a weak anti-correlation (Middleditch and Priedhorsky 1985b). QPO which show rapid intensity-uncorrelated variations in frequency have been seen on several occasions ('intermediate' state, van der Klis et al. 1986a; Pollock et al. 1986). The time history of the QPO in the intensity- frequency diagram can in these cases be loop-like (both clock- and counter-clock-wise loops have been seen). Figure 5 shows a sample of the frequency-intensity relations observed in active, 'intermediate' and quiescent states.

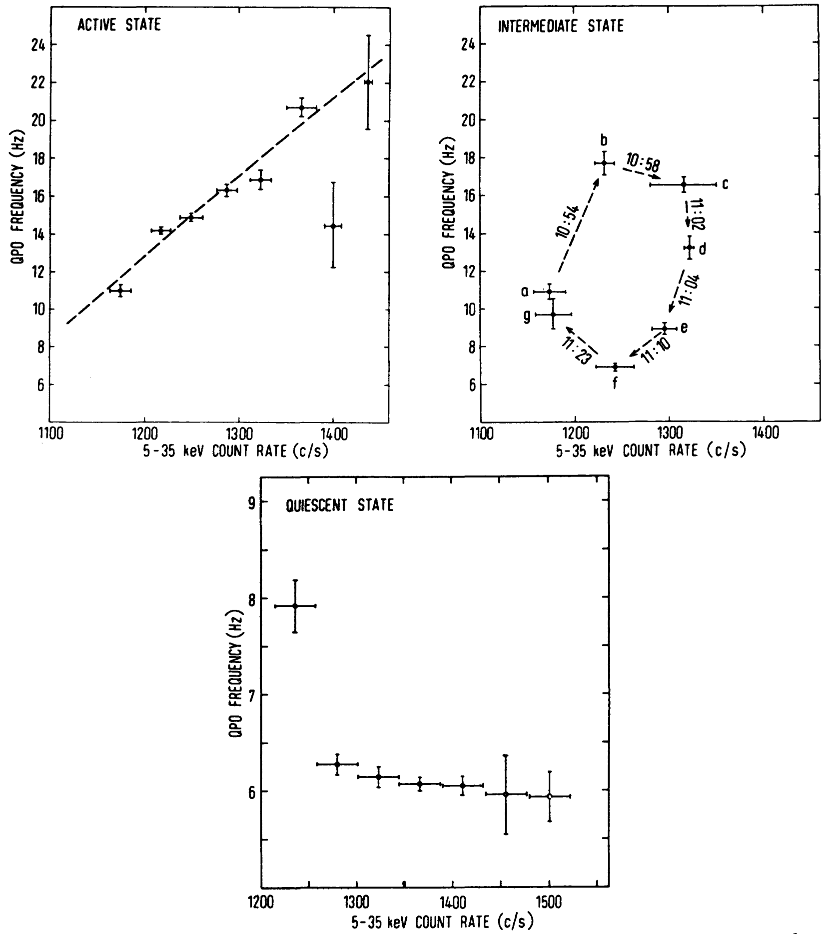


Figure 5. QPO frequency - X-ray intensity relations as observed in Sco X-1 (van der Klis et al. 1986a).

When the source switches from one intensity state to the other, its X-ray spectral characteristics change. There is a gradual change in QPO frequency as the source evolves from one spectral state to the other.

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Decomposition of the X-ray spectrum into a blackbody component and an unsaturized comptonization component shows that the flaring is dominated by increases in the blackbody component (White et al. 1985; but see also Mitsuda et al. 1985). Contrary to the case of the relations between QPO frequency and total source intensity (Figure 5), there seems to be one simple relation between frequency and blackbody luminosity (van der Klis et al. 1986a; Figure 6).

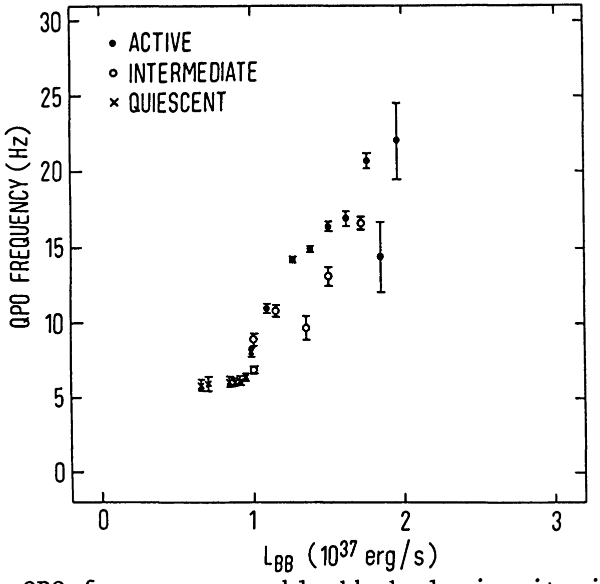


Figure 6. QPO frequency vs. blackbody luminosity in Sco X-1. These are the same data as in Figure 7 (van der Klis et al. 1986a).

The fact that different intensity-frequency relations apply in Sco X-1 makes the magnetospheric hypothesis less compelling.
The basic prediction of magnetospheric QPO models is a correlation between accretion rate and QPO frequency. To explain the complexity of the observed intensity-frequency relations in Sco X-1 within this framework, an additional hypothesis is required about the relation between accretion rate and X-ray intensity (and -spectrum), and this additional hypothesis could be chosen in such a way that other than magnetospheric models can be accommodated.

b) Low-frequency noise

The prediction of the 'random clump accretion beat-frequency model' that QPO and LFN should have approximately the same power is strongly violated by Sco X-1 (van der Klis et al. 1985d; and even more strongly by the rapid burster, Stella 1985). The power in the LFN (down to 1/64 Hz) is usually less than 10% of that of the QPO (van der Klis et al. 1986a). Figure 7 shows how the relative strength of LFN and QPO depend on source intensity: when the source becomes brighter, the QPO disappear but the LFN gets stronger.

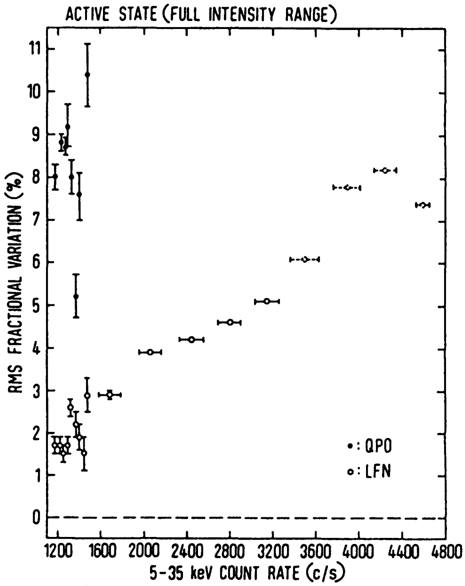


Figure 7. QPO (dots) and LFN (circles) strength as a function of X-ray intensity as observed in Sco X-1 in the active state. The QPO disappears when the source flares (van der Klis et al. 1986a).

To explain the lack of LFN within the beat-frequency model it is necessary to postulate ad-hoc mechanisms to 'line-up' some of the accreting clumps, so that the phase of the QPO can be kept from one oscillating shot to the next (Lamb et al. 1985) or to produce an 'ever-lasting' clump in the Keplerian flow (Shaham 1987). By contrast, in an 'obscuration' model for the QPO (see van der Klis et al. 1986a) it depends on the details of the obscuration geometry (such as inclination) whether or not QPO-related LFN is produced.

## 4. Bimodal behaviour of GX 5-1 and Cyg X-2

Cyg X-2 (Branduardi et al. 1980) and GX 5-1 (Shibazaki and Mitsuda 1983) show both very similar two-branched spectral behaviour. In both cases, the strong 20-50 Hz intensity-dependent QPO and associated LFN described in Section 2 are only seen in the so called 'horizontal branch' (van der Klis et al. 1985d, Hasinger et al. 1985b). In Cyg X-2, 5.6 Hz QPO whose frequency does not depend perceptibly on intensity are seen in parts of the so called 'normal branch' (Hasinger et al. 1986) and there is an indication that ~5 Hz QPO may also occur in GX 5-1 on the normal branch (van der Klis et al. 1986b).
So, also in these sources QPO with different frequency-intensity relations occur in different spectral states.

## 5. Conclusion

Strong, persistent, high-frequency QPO have been discovered with EXOSAT in seven luminous, persistently bright low-mass X-ray binaries. The

detailed properties of these QPO, in particular their dependence on source intensity, are diverse. In the three best-studied sources, GX 5-1, Sco X-1 and Cyg X-2 the known bimodal X-ray spectral behaviour is found to be strictly correlated to bimodal QPO behaviour.
A large variety is observed in the relations between source intensity and QPO frequency. If QPO frequency is simply related to accretion rate, as is the prediction of most proposed QPO models, in particular the magnetospheric ones, then a matching large variety of relations between accretion rate and X-ray intensity will be required - a strong departure from the traditionally assumed strict proportionality.
QPO-related LFN is only detected in part of the QPO sources. This presents problems for oscillating-shot models such as the (magnetospheric) random clump accretion beat-frequency model, and could be more easily accounted for in an obscuration model.

In conclusion, from the point of view of the QPO data, the case for the presence of a magnetic field in the low-mass X-ray binaries is as yet undecided.

Acknowledgements

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## DISCUSSION

**F. Frontera:** Have you studied the power behavior vs. frequency of the LFN after subtraction of the Poisson component and after correction for effects of dead time, averaging and samplings?

**M. van der Klis:** Yes. In Sco X-1, the LFN is weak; it is only detected below ~ 1 Hz and it has a power-law shape with index between -1 and -2. In GX5-1 and Cyg X-2 the QPO-related LFN is stronger (about as strong as the QPO) and it is not fit by a power law. An exponential provides a better fit. In GX5-1 we recently found an additional "very low-frequency" component to the LFN. This "VLFN" is much weaker than the QPO, it is present irrespective of whether QPO are present or absent, it is only detected below ~ 0.1 - 1 Hz and it has a power law shape with index ~ 1.7. It is therefore very similar to the LFN in Sco X-1.

**S. Colgate:** The signature of a magnetic field is a cyclotron line and limited luminosity from a polar cap at high-Eddington limit temperature ~ 2 KeV. What is the correlation of either of these with the observed QPO.

**M. van der Klis:** There is no correlation I know of.

**J. Shaham:** The BF model does not necessarily require LFN, only the blob-BF does! Details in my talk.

**M. van der Klis:** The "slightly modulated Keplerian flow" you are invoking to explain QPO without LFN is essentially a big blob which lives forever. You claim that this big blob is created by interaction of the plasma with the magnetic field at the corotation radius, but I do not understand why the big blob is not destroyed on its way down from the corotation radius to the magnetospheric radius, as it will encounter ever higher field strengths. I note that you now need two types of flow ("slightly modulated Keplerian flow" and "chaotic blobs") to explain QPO without and QPO with associated LFN, respectively.

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