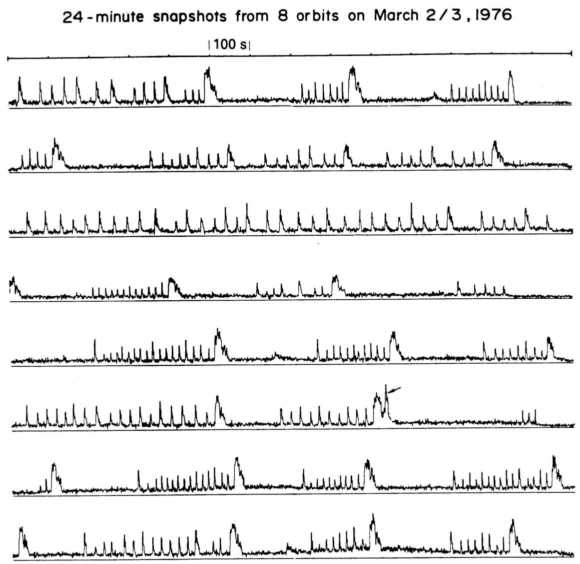
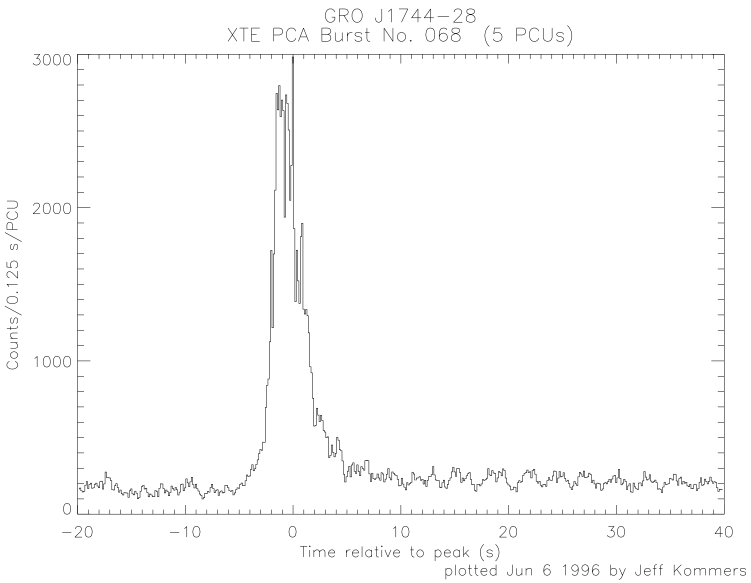


(Joss & Rappaport, 1984, Fig. 18)

Bursting of the “Rapid Burster” MXB1730−335: Type I and Type II bursts.

Type II bursts: **magnetospheric gate model**: B-field blocks accretion until $P_{\text{gas}} > P_{\text{mag}} \Longrightarrow$ BOOM.

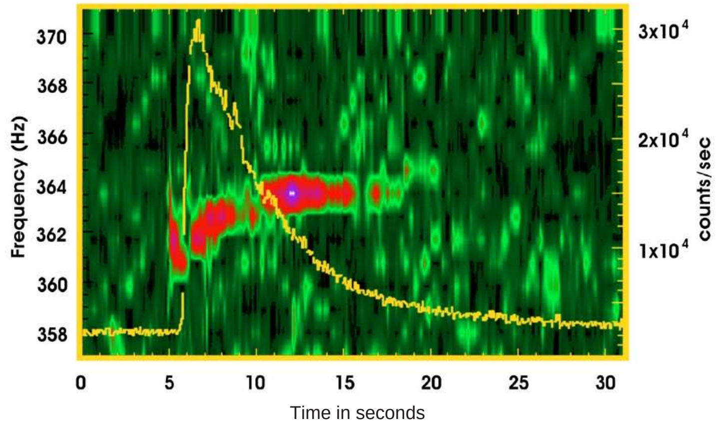


(Bursting Pulsar; Kommers, 1996, priv. comm.)

Before 1995 December 2: X-ray bursts and pulsations **cannot** occur in the same object.

Then: **GRO J1744−28** the **bursting pulsar**. Pulsations with 2 Hz *and* type II bursts. *Burst rate:* $\sim 20\,\text{h}^{-1}$, then decreasing to $1\,\text{h}^{-1}$. Orbit ~ 2 d. Source temporarily brightest X-ray source in the sky (several Crab).

Burst oscillations



(after Galloway et al., 2006, Fig. 3; colors: power spectrum)

Burst oscillation: strong, coherent oscillation in decay of burst with long term stability. Asymptotic frequency ∼agrees with pulsar rotational frequency

Timing

To describe the variability of an evenly spaced time series $x_k = x(t_k = k\Delta t)$ we use the **Discrete Fourier Transform** $X_j = X(f_j = j/N\Delta t)$

$$X_j = \sum_{k=0}^{N-1} x_k \exp(2\pi i jk/N) \quad \text{, for } j = 1 \ldots N/2 \qquad (6.11)$$

Remember: $\exp(i\phi) = \cos\phi + i\sin\phi$

The amount of variability at a frequency f_j is then characterized by the **Power Spectral Density**,

$$\text{PSD}_j = A\, X_j^* X_j \qquad (6.12)$$

where A is a normalization constant.

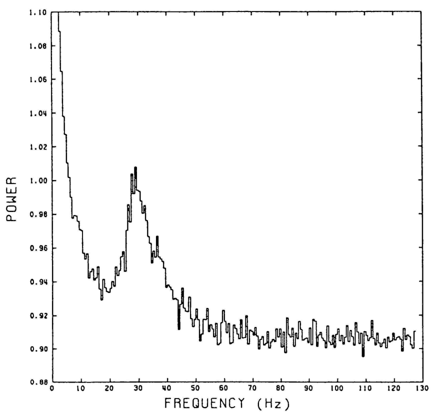
To reduce scatter, one often averages the power spectra of several data segments.

The PSD describes the **contribution of a given frequency to the total variance** of the lightcurve (power).

One often uses the **Miyamoto normalization** where

$$A_{\text{Miyamoto}} \Longleftrightarrow (\text{rms}/\langle\text{rate}\rangle)^2\,\text{Hz}^{-1} \qquad (6.13)$$

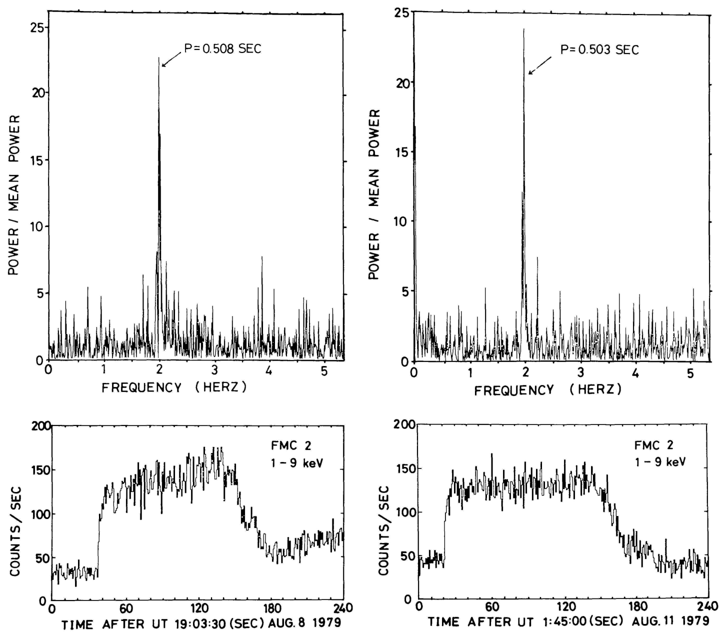
EXOSAT: The QPO Era, I



1985, IAUC 4043:
"EXOSAT observations of the bright galactic-bulge source GX 5−1 made during 1984 Sept. 18.46−18.83 UT with a time resolution of 0.25 ms show the presence of quasiperiodic oscillations of the 1–10 keV flux with a typical period between 25 and 50 ms [20–40 Hz]."
"Since this is the discovery of a new phenomenon, we urge observers to search for similar X-ray behavior in other sources . . . "

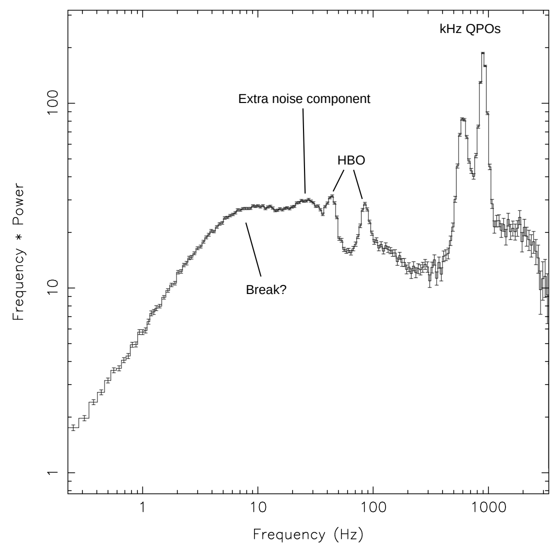
van der Klis, Jansen, van Paradijs, Lewin, van den Heuvel, Trümper, Sztajno

EXOSAT ME: 1–20 keV, $A_{\text{eff}} = 1600\,\text{cm}^2$, $\Delta t \sim 0.25\,\text{ms}$



(QPOs during type II bursts of the rapid burster; Lewin, van Paradijs & van der Klis, 1988, Fig. 1.3)

RXTE: The Kilohertz QPO Era, I

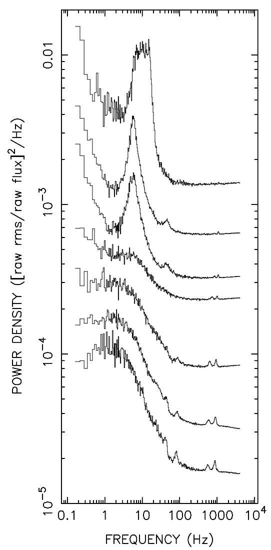


"The kHz QPO are the most important scientific result to date of RXTE".
(`http://heasarc.gsfc.nasa.gov/docs/xte/Greate`

RXTE PCA: 2–25 keV, $A_{\text{eff}} = 5000\,\text{cm}^2$, $\Delta t = 1\,\mu\text{s}$

Sco X-1; van der Klis et al., 1996, IAUC 6319, Wijnands & van der Klis (1999)

RXTE: The Kilohertz QPO Era, II

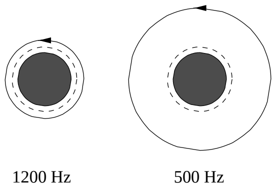


- always have 3 characteristic frequencies:
  - "Low Frequency QPOs" (ν_{LF}): 0.1–100 Hz, many types
  - "kHz Twin Peaks" (ν_1, ν_2): 200–1400 Hz
- "real" kHz QPOs only for neutron star binaries, mostly persistent LMXBs, $\gtrsim$ 20 kHz QPO sources are known, mostly showing double peaks

The kHz QPO strength is flux dependent.

(Wijnands & van der Klis, 1999)

Origin of QPOs



kHZ QPOs occur are on timescales close to the innermost stable circular orbit:
The Keplerian orbit frequency: is

$$\nu_{\text{orb}} = \left(\frac{GM}{4\pi^2 R_{\text{orb}}^3}\right)^{1/2} \approx 1200\,\text{Hz} \left(\frac{R_{\text{orb}}}{15\,\text{km}}\right)^{-3/2} m_{1.4}^{1/2} \tag{6.14}$$

The edge of the accretion disk is at the innermost stable circular orbit (ISCO), Schwarzschild geometry:

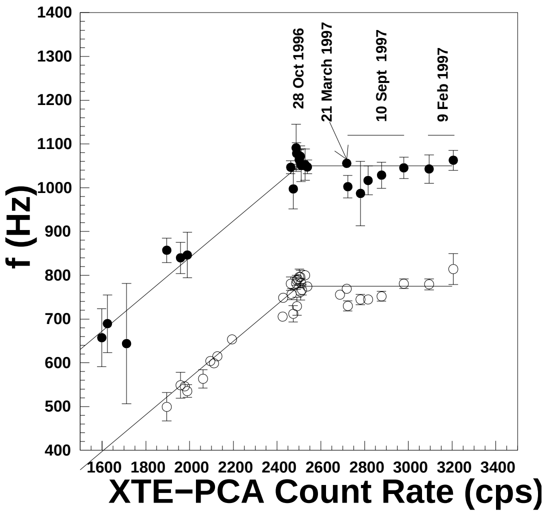
$$R_{\text{ISCO}} = \frac{6GM}{c^2} \sim 12.5 M_{1.4}\,\text{km} \tag{6.15}$$

and therefore the maximum stable frequency in an accretion disk is

$$\nu_{\text{ISCO}} \sim \frac{1580\,\text{Hz}}{M_{1.4}} \tag{6.16}$$

Corrections due to the spin of the central object can amount to several 10%

Origin of QPOs



The frequencies of kHz QPOs usually increase with X-ray flux ("parallel-lines phenomenon"), and can saturate at a maximum frequency.

$\Longrightarrow$ Models need to explain ν_{LF}, ν_1, and ν_2.

(4U 1820−30; Zhang et al., 1998)

Beat Frequency Model, I

"beat": resonance between some preferred Keplerian orbit & spin frequency

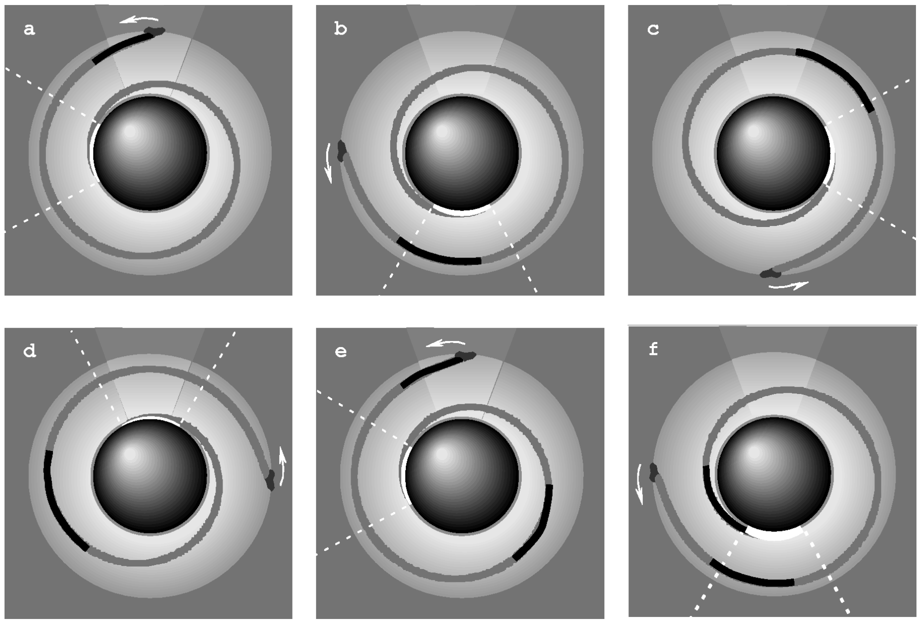
Magnetospheric BFM:

- preferred radius = Alfvén radius
- orbiting clump ($\nu_{\text{Alfvén}}$) modulated by B-field (ν_{spin})

$\Longrightarrow$ can explain LF QPOs, 5–50 Hz

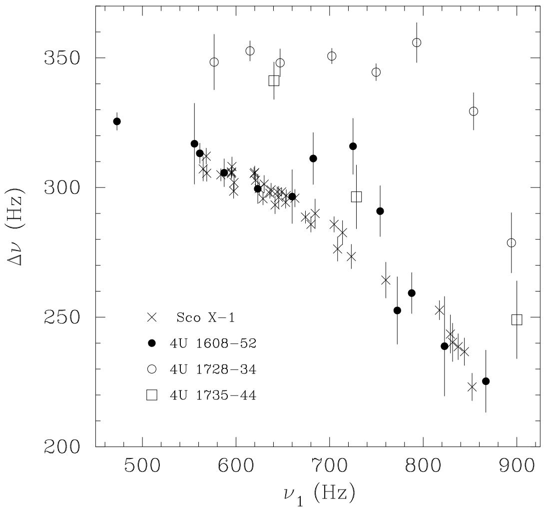
Sonic Point BFM:

- preferred radius = where radial inflow velocity becomes supersonic, near ISCO
- orbiting clump ($\nu_{\text{sonic}} > \nu_{\text{spin}}$) causes bright footpoint near surface, footpoint: upper kHz QPO, $\nu_2 = \nu_{\text{sonic}}$
- clumps are irradiated with ν_{spin} $\Longrightarrow$ footpoint emission is modulated with beat between ν_{sonic} and ν_{spin}, footpoint modulation: lower kHz QPO, $\nu_1 = \nu_{\text{beat}}$



(Miller, Lamb & Psaltis, 1998)

Beat Frequency Model, III

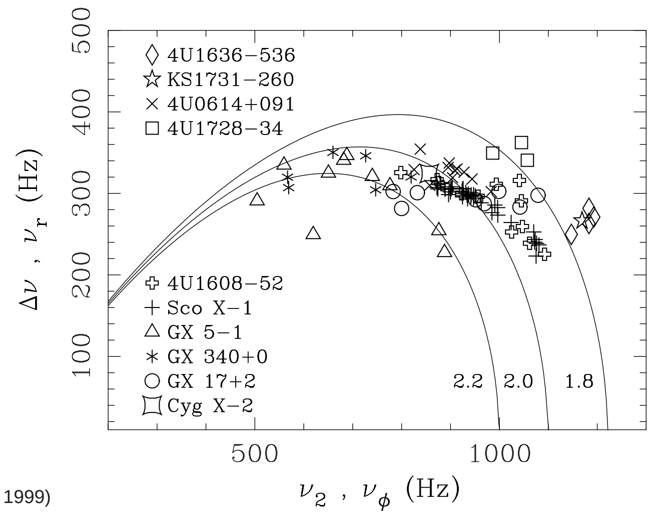


There is a varying frequency separation between the kHz QPOs of different sources

$\Longrightarrow$ problem for the beat frequency model?

(van der Klis, 2000)

Beat Frequency Model, IV



(Stella & Vietri, 1999)

The frequency separation of the QPOs varies differently in different sources.

Beat Frequency Model, V

Properties & problems of the sonic point beat frequency model:

- needs surface
  $\Longrightarrow$ not valid for BHC sources
- Keplerian motion inside $r_{\text{Alfén}}$
- r_{sonic} depends on $\dot{M}$
  $\Longrightarrow$ varying ν_2 can be explained
- $\Delta\nu = \nu_2 - \nu_1$, constant, can be $< \nu_{\text{spin}}$
  $\Longrightarrow$ varying $\Delta\nu$ cannot easily be explained
- predicts additional frequencies (differing from precession model)

Relativistic Precession Model, I

General Relativity: free-particle orbits show characteristic frequencies

Idea of the model:

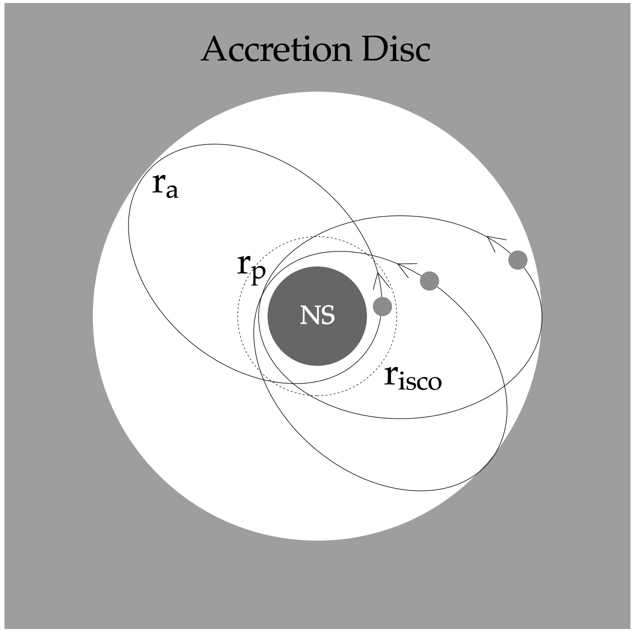
- disk is disrupted near ISCO, forming blobs
- blob orbits are inclined and eccentric

Characteristic frequencies:

- orbit frequency: upper kHz QPO, ν_2
- periastron precession: lower kHz QPO, ν_1
- relativistic frame dragging $\longrightarrow$ "wobble of the orbital plane":
  nodal precession (Lense-Thirring)
  $\nu_{\text{LF}} = 2 \times \nu_{\text{nod}}$

$\nu_{\text{nod}} = 8\pi^2 I\ \nu_2^2 \nu_{\text{spin}} / c^2 M$, where I: moment of inertia

see, e.g., Stella & Vietri (1998)



(Marković & Lamb, 1998, see also Marković & Lamb, 2000, astro-ph/0009169)

Relativistic Precession Model, III

Properties & problems of the RPM:

- does not need surface
  $\Longrightarrow$ also valid for BHC sources
- can explain $\Delta\nu$ (more or less)
- how to disrupt the disk?
  how to create compact clumps?
  how to maintain tilted orbits?
- how to create the flux modulations?
- other frequencies could be more important

Model Summary

Promises:

- constrain M and R (via kHz QPOs)
  $\Longrightarrow$ constrain Equation of State for neutron stars
- constrain spin
  (“holy grail”, LMXB/ms radio pulsar evolution?!)
- constrain B-field (via LF QPOs)
- observe GR effects

Difficulties:

- observations (varying $\Delta\nu_{\text{kHz}}$, ν-correlations)
  triggered evolution of many different models ($>$ 12)
- no individual model does address all issues
  (i.e, generation of flux modulation, ...)
- models predict different ν_{spin} and M, e.g.,
  BFM: $\nu_{\text{spin}} =$ 250–350 Hz
  RPM: $\nu_{\text{spin}} =$ 300–900 Hz
- what about “surface models”? $\Longleftrightarrow$ big question: do BHCs show the same behavior as neutron star XRBs?

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