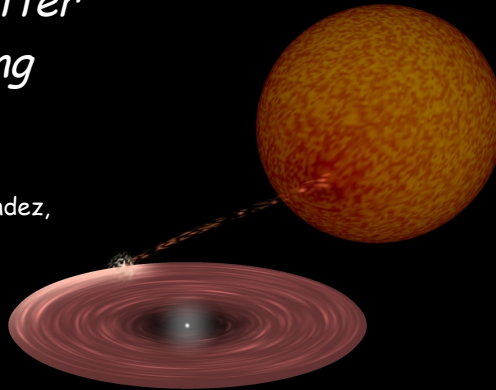


Millisecond timing X-ray binaries

- *Strong field gravity*
- *High density matter*
- *Pulsar recycling*

- First of several more talks:
Altamirano, Patruno, Mendez, Belloni, Done, Misra ...
- History
- Methods
- Themes
- Current status
- News
- Prospects



R. Hynes 2002

Predictions of millisecond variability

- Random luminosity variations expected 10^{-5} - 10^{-2} s (Svartzman 1971)
- Millisecond wavetrains due to clumps near ISCO (Sunyaev 1973)
- Detect neutron star spin during X-ray bursts (Livio & Bath 1982)
- Millisecond accreting pulsars (Alpar et al. 1982, Radhakrishnan & Srinivasan 1982, Cheng 1984)

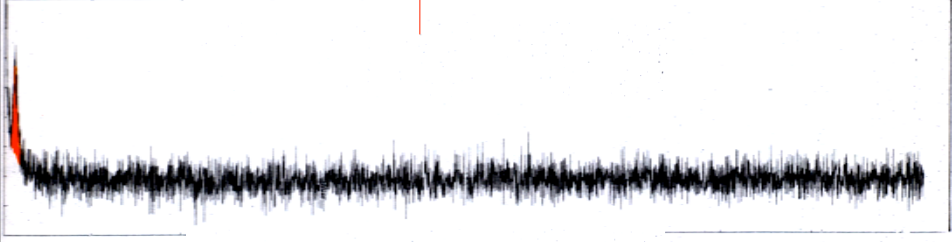
**SEARCH FOR MILLISECOND ROTATION PERIODS
AMONG GALACTIC-BULGE SOURCES**

Principal Investigator: J. van Paradijs
 Co-Investigators: J. Trümper, M. Sztajno, N. van der Klis, W. Lewin, H. U. Zimmerman
 Proposing Organisation: Astronomical Institute, University of Amsterdam, Postbus 15, 1018 WB Amsterdam, the Netherlands

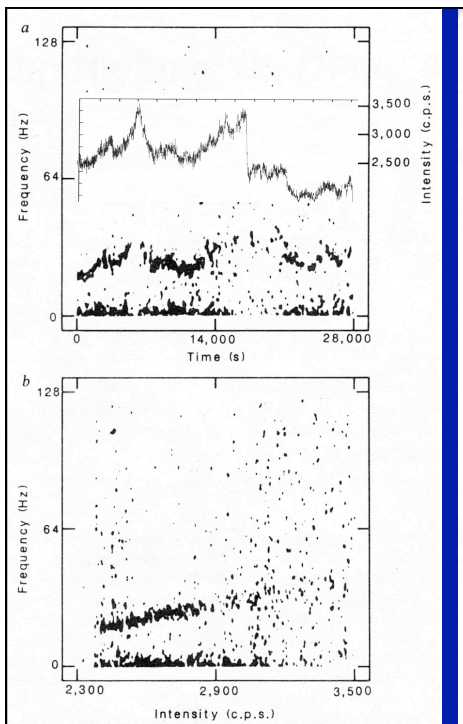
Abstract:
 We attempt to search for millisecond periodicities in the persistent X-ray emission from the Galactic bulge. The A-1 experiment on HEAO-1 has collected only a total of ~2 hours of data with a time resolution of 5 milliseconds, which could be used for a search for millisecond periodicities, and only a small fraction of these two hours were spent on strong sources (T. A. Chubb, private communication). The High Speed Event Monitor on board SAS-3 did not always function properly and to date only 7 results using SAS-3 have been reported in this time domain. Thus, the millisecond time domain has hardly been explored. The discovery of millisecond periodicity in the intensity of bright LMXBs would be of fundamental importance. It would give support to and a quantitative basis for present ideas on the evolution and accretion history of low-mass X-ray binaries, and - of course - open the exciting possibility of making orbital studies of these systems, comparable to the by now classical studies of massive X-ray binaries.

We propose to use only the ME detector in a timing mode (HTR3) with 0.375 millisecond time resolution (WSP2-6). In this way we will be able to look for periods down to 0.75 ms, the first harmonic of the theoretical break-up limit for a neutron star. Below we estimate the feasibility of the proposed observation. This estimate is based on the assumption that the noise has a Poissonian distribution. If stochastic behaviour in the millisecond domain is present, the estimate will be adversely affected. However such behaviour would by itself be extremely interesting.

Feasibility of the proposed observations
 During the observations, the orbital motion of the satellite, of



ed chi-squared distribution for ν degrees of freedom, and the confidence level required for a period detection. In this expression, we take into account the effects on the sensitivity of the binning of the data and of the discrete character of an FFT in the way described by Leahy et al. (8). For $S=1000$ c/s, it follows that a pulsation of 22



Intensity-dependent quasi-periodic oscillations in the X-ray flux of GX-1

M. van der Klis¹, F. Jansen², J. van Paradijs¹, W. H. G. Lewin³, E. P. J. van den Heuvel⁴, J. E. Trümper⁵ & M. Sztajno⁶

¹Space Science Department of ESA, European Space Research and Technology Centre, Postbus 299, 2200 AG Noordwijk, The Netherlands
²Laboratory for Space Research Leiden, Postbus 9502, 2300 RA Leiden, The Netherlands
³Astronomical Institute of the University of Amsterdam, Postbus 15, 1018 WB Amsterdam, The Netherlands
⁴Massachusetts Institute of Technology, Center for Space Research and Department of Physics, Room 35-827, Cambridge, Massachusetts 02139, USA
⁵Max-Planck Institute for Extraterrestrial Physics, 8060 Garching (b. Munich), FRG

The X-ray flux of the bright galactic bulge source GX-1 shows intensity-dependent quasi-periodic oscillations between ~20 and ~40 Hz, appearing as a broad peak in the power spectrum whose centroid frequency, width and integrated excess power strongly depend on the source intensity. The strength and steepness of low-frequency noise present in the power spectra below 15 Hz also depend on the source intensity. No evidence is found for coherent X-ray pulsations between 0.5 and 2,000 Hz. We discuss possible mechanisms to explain these new phenomena.

NEUTRON stars in low-mass X-ray binaries have long been suspected to have been spun up to periods in the millisecond range. Several searches for such short rotation periods in low-mass X-ray binaries have been made but none has been successful (refs 1-4 and J. Fleischman, S. Rappaport, D. Stralov and W. Lewin, personal communication). We have renewed the search using the medium energy detector of the X-ray observatory EXOSAT. One of the first sources we observed was the bright bulge source GX-1, in which we found no periodic pulsations but, unexpectedly, we discovered quasi-periodic oscillations. These oscillations are the subject of this report; some preliminary results have already been reported⁵.

Observations
 We observed GX-1 (4U 1758-25) with the medium-energy detector (ME) and the gas scintillation proportional counter (EXOSAT). The observations started on 18 September 1984 11:50 UT and lasted for ~1.8 h. We shall discuss 1-16 keV data obtained with the Ar/CO₂-filled proportional counters of the medium-energy detector; the counters were co-aligned with a total effective area of 150 cm². The data were obtained in 2-s blocks, each containing 8,192 samples (time resolution ~0.25 ms). Within each of the 1,023 blocks, the data are continuous with a negligible 'dead time' of ~1% and between two consecutive data blocks there is a gap of 1 s. The data contain no spectral information.

Figure 1 shows the counting rate as a function of time. The data include an approximately constant background of ~30 c/s. The sharp drop seen at 17:00 is caused by a change ('trim') in the satellite pointing direction. The reason for this trim was the high counting rate, at which detector damage was feared. Before the trim, the collimator efficiency was 93%, whereas afterwards it was ~70%.

For the average spectral shape, as measured with the gas scintillation proportional counter, 1 c.p.s. from the ME (pre-trim collimator efficiency) corresponds to ~2.2 × 10¹¹ erg cm⁻² s⁻¹ (1-18 keV), or ~0.5 μJy (2-18 keV). The source flux (~700-1,100 μJy) and its variability on a timescale of hours are similar to those encountered previously^{6,7}. All count rates described here have been reduced to the pre-trim collimator efficiency.

Analysis and results
 To investigate the variability of GX-1 on timescales between 0.5 ms and 2 s, we estimated the power spectrum by calculating (via a fast Fourier transform (FFT) algorithm) the Fourier amplitudes of the average-subtracted signal in each 2-s block

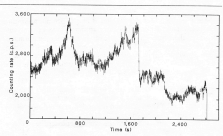


Fig. 1 Average counting rate in c.p.s. versus time in seconds. The rate is around 30 c.p.s. with a sharp drop at approximately 17:00. The plot is labeled 'Fig. 1'.

separately. The power spectra of single data blocks are too noisy to allow meaningful study. However, the average of these power spectra clearly shows three components: (1) low-frequency noise below 15 Hz (the power increases towards lower frequencies); (2) a strong broad peak with a centroid frequency near 30 Hz; and (3) a flat spectrum above 100 Hz, consistent with Poisson noise.

No evidence was found for coherent pulsations in the X-ray flux. The 99% confidence upper limit to the pulsed fraction of coherent pulsations in the 40-400-Hz range is 0.3%; in the 400-2,000-Hz range it varies between 0.6 and 2.5%, depending on frequency. In calculating these values, we followed the procedure described by Leahy et al.⁸ and took into account possible Doppler shifts resulting from orbital motion of the source and of the satellite.

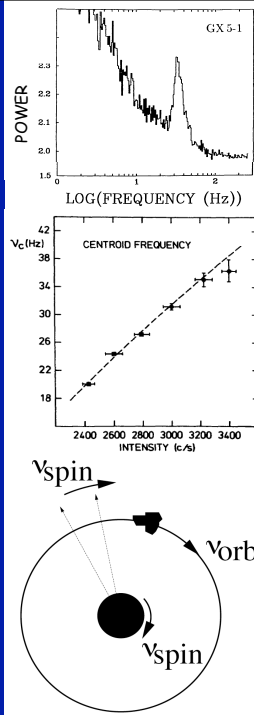
Power density estimates, using conventional FFT techniques, may be in error because of low-frequency 'leakage' (if a steep low-frequency 'red' noise component is present).⁹ The power-law slope of the red noise in our data is considerably below the critical value of 2, above which problems may occur. Low-frequency leakage is therefore not expected to affect our analysis. This was confirmed by tests on artificial red-noise data and by repeating the analysis of the 2-s blocks after 'detrending' each of them by subtracting a low-order polynomial.

The properties of the broad peak in the power spectrum (centroid frequency, width and integrated excess power) and the low-frequency noise (slope, and integrated excess power) strongly depend on source intensity. In Fig. 2, we show the

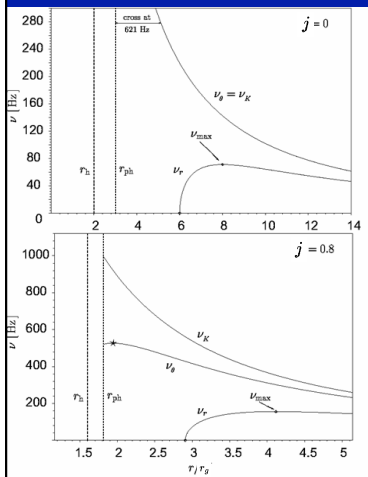
Reprinted from Nature, Vol. 316, No. 6025, pp. 225-230, 18 July 1985
 © Macmillan Journals Ltd. 1985

Horizontal-branch QPOs in GX 5-1

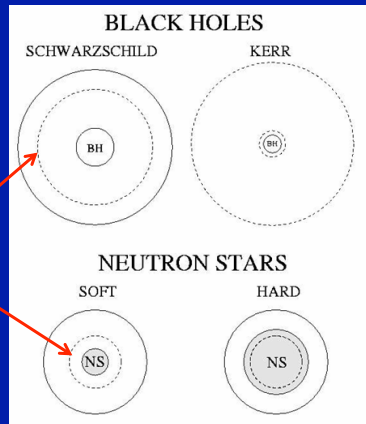
- Intensity dependent 20-40 Hz QPO
- → 15-60 Hz; 16 milliseconds
- QPO frequency depends on X-ray count rate
- Alpar & Shaham (1985): beat frequency model: $\nu_{QPO} = \nu_{orb} - \nu_{spin}$



General relativistic orbital motion



Abramowicz 2004



$$r_g \equiv GM/c^2 \quad j \equiv Jc/GM^2$$

$$\nu_\phi = \sqrt{GM/r^3}/2\pi(1 + j(r_g/r)^{3/2})$$

$$\nu_r^2 = \nu_\phi^2(1 - 6(r_g/r) + 8j(r_g/r)^{3/2} - 3j^2(r_g/r)^2)$$

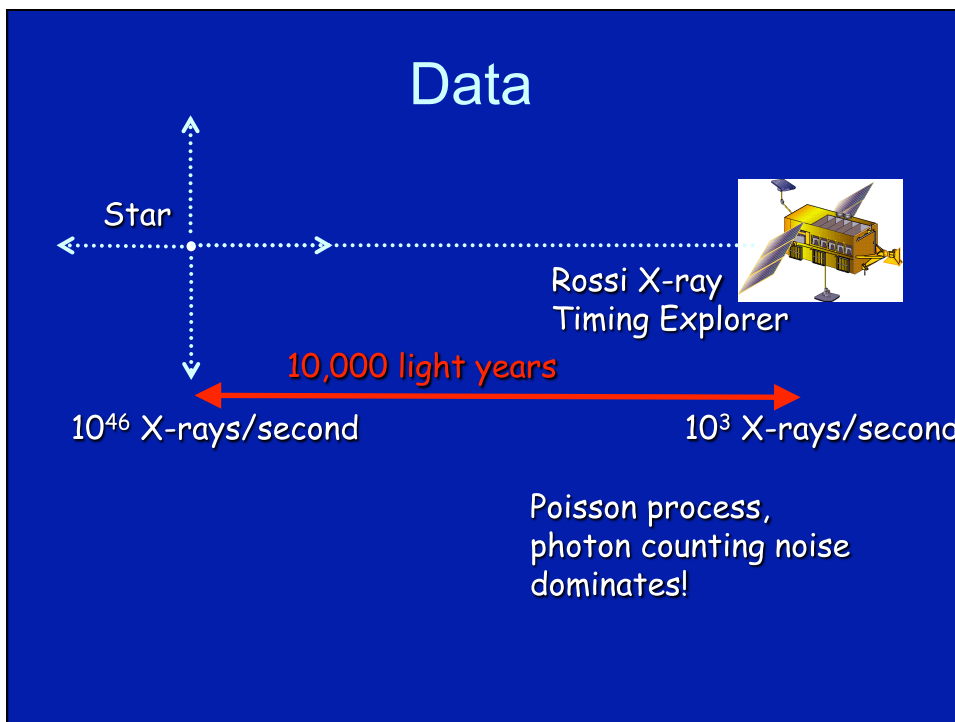
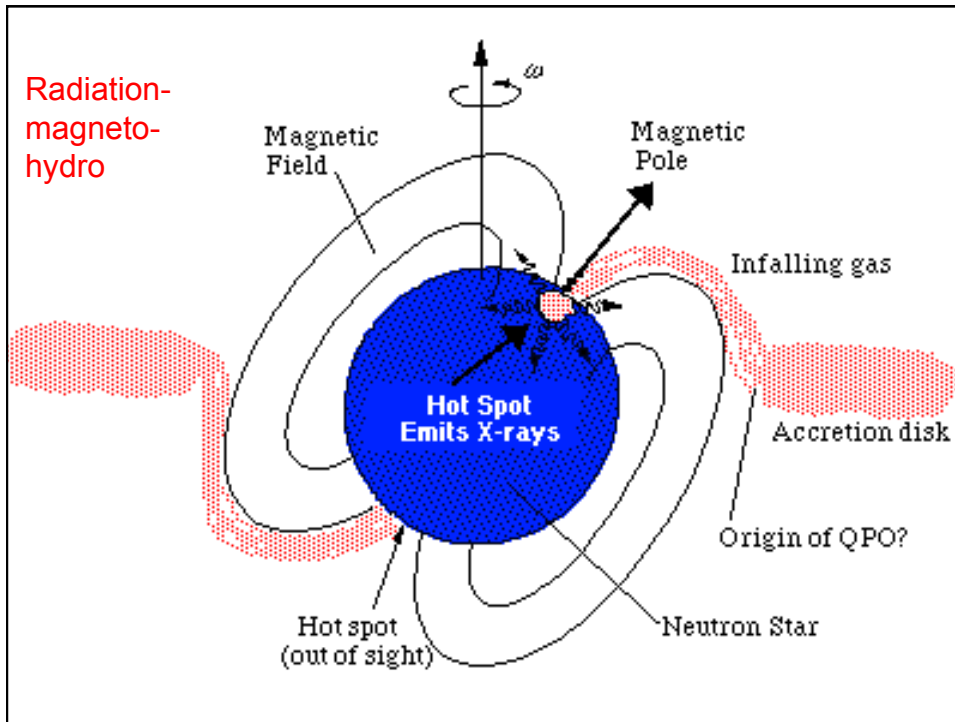
$$\nu_\theta^2 = \nu_\phi^2(1 - 4j(r_g/r)^{3/2} + 3j^2(r_g/r)^2)$$

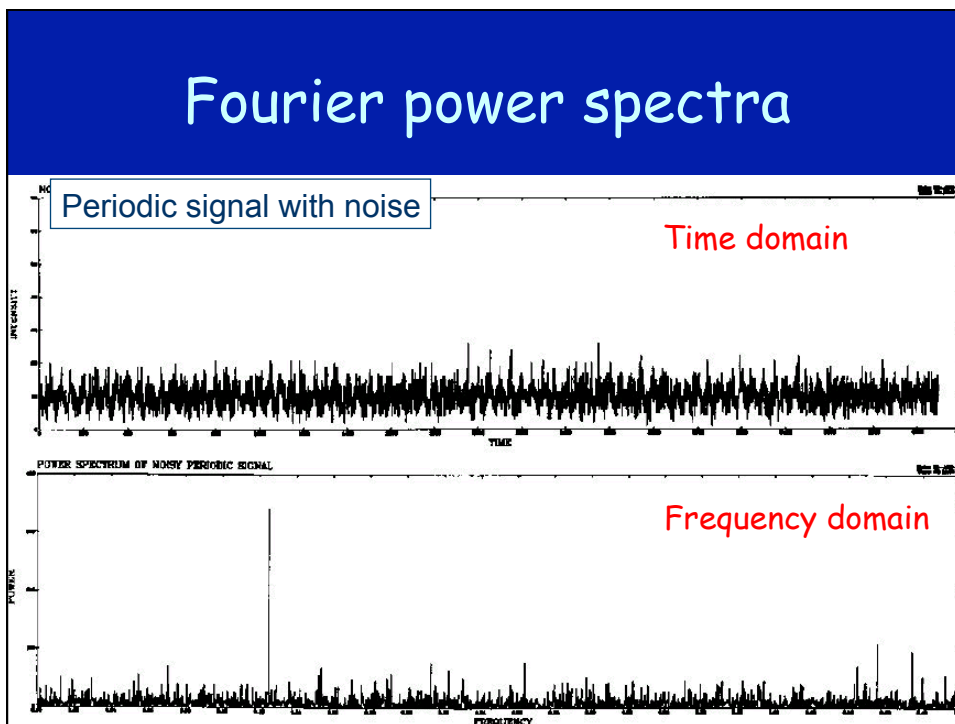
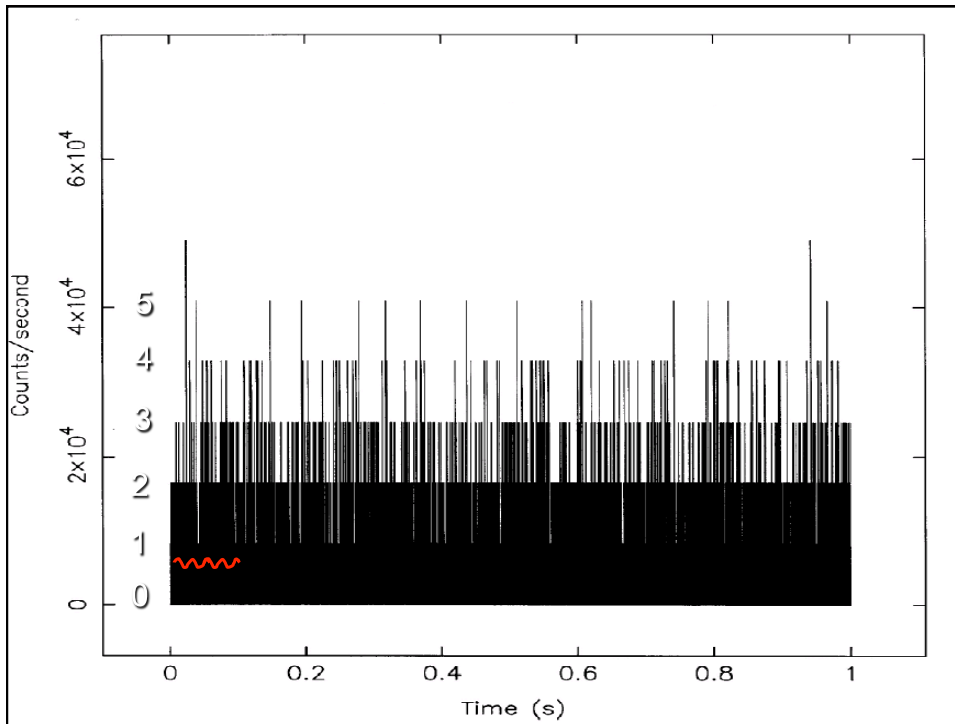
Schwarzschild:

$$\nu_\phi = \sqrt{GM/r^3}/2\pi \approx 1200 \text{ Hz} \left(\frac{r}{15 \text{ km}}\right)^{-3/2} m_{1.4}^{1/2}$$

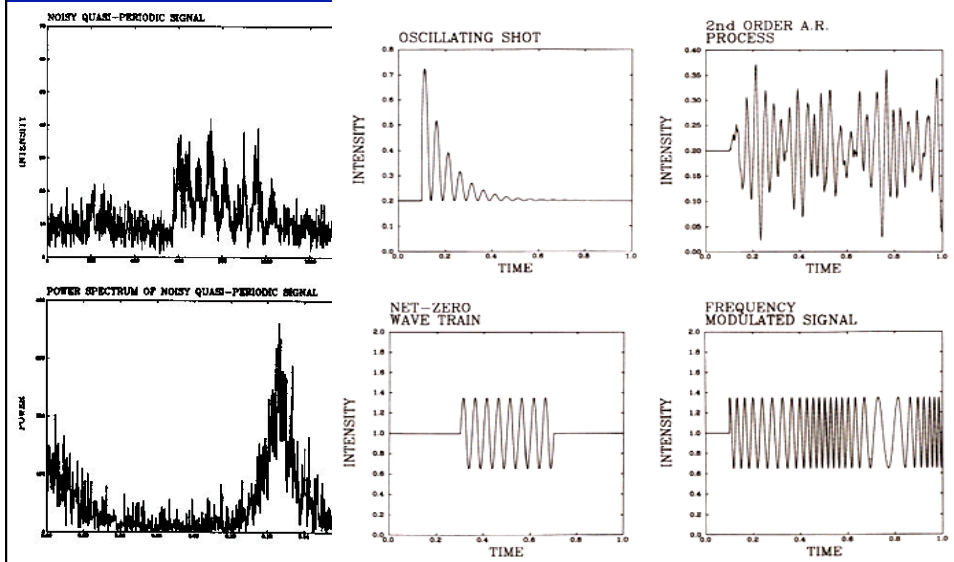
$$r_{ISCO} = 6r_g = 6GM/c^2 \approx 12.5 m_{1.4} \text{ km}$$

$$\nu_{ISCO} = (6^{3/2}/2\pi)(c^3/GM) \approx (1580/m_{1.4}) \text{ Hz}$$





Quasi-periodic oscillation



Lorentzians

$$\text{Lorentzian : } P(\nu) = \frac{r^2 \Delta}{\pi} \frac{1}{\Delta^2 + (\nu - \nu_0)^2}$$

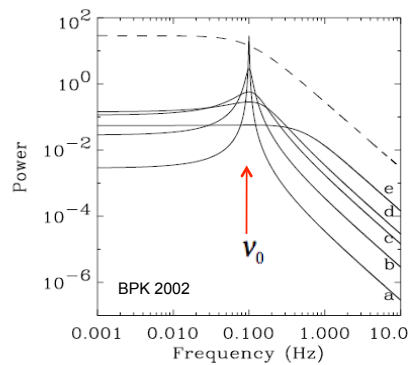
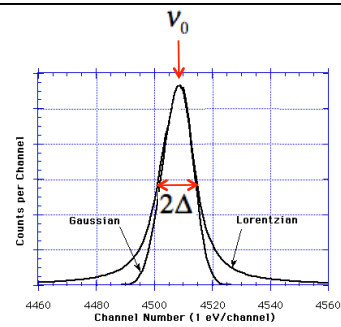
Centroid frequency : ν_0 Half - width : Δ

$$\text{Characteristic frequency : } \nu_{\max} = \sqrt{\nu_0^2 + \Delta^2}$$

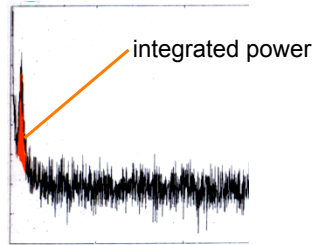
For narrow QPOs: $\nu_{\max} \approx \nu_0$

For broad noise components: $\nu_{\max} \approx \Delta$

$$Q \equiv \nu_0 / 2\Delta$$

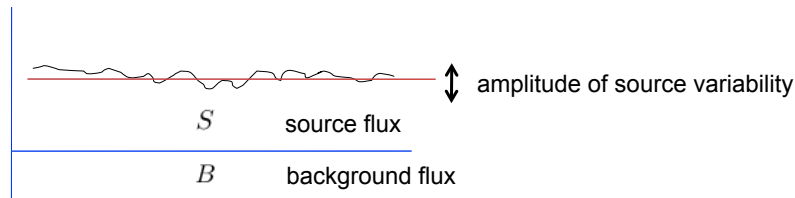


Fractional rms amplitude

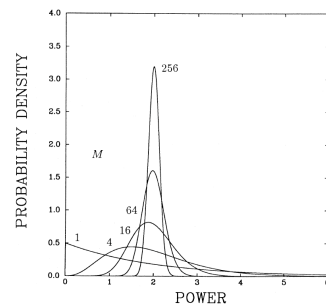
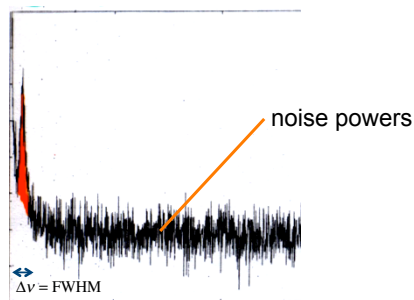


$$\text{rms} = \sqrt{\text{Variance}} = \sqrt{\int \text{power}}$$

$$r = \text{source fractional rms} = \text{rms} / S$$



Poisson noise power spectral statistics



Noise powers: white noise, distributed as chi-squared

with 2 dof (χ_2^2 = exponential distribution)

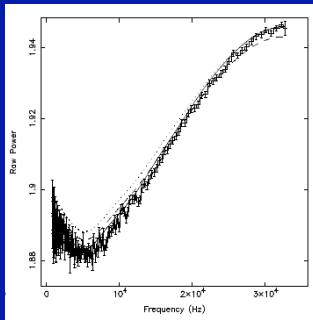
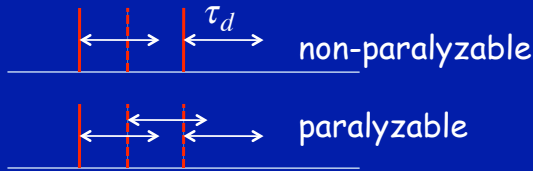
M times averaged noise powers distributed as χ_{2M}^2

Distribution tends to normal as $M \rightarrow \infty$

$$\text{Signal to noise: } n_\sigma = \frac{1}{2} r^2 \sqrt{\frac{T}{\Delta\nu}} \frac{S^2}{(B+S)}$$

Instrumental deadtime

"not the fraction but the process"



Deadtime-modified Poisson noise power spectrum is not white

$$\langle P_j \rangle = 2 - 2r_o t_b \times \left\{ 1 - \left(\frac{N-m}{N} \right) \left(m + 1 - \frac{t_d}{t_b} \right)^2 \cos \left(\frac{m 2\pi j}{N} \right) + \left(\frac{N-m-1}{N} \right) \left(m - \frac{t_d}{t_b} \right)^2 \cos \left[(m+1) \frac{2\pi j}{N} \right] + 2 \cos \left(\frac{m+1}{2} \frac{2\pi j}{N} \right) \sin \left(\frac{m}{2} \frac{2\pi j}{N} \right) \sin \left(\frac{\pi j}{N} \right) - [(m+1)/N] \left[\sin \left(\frac{2m+1}{2} \frac{2\pi j}{N} \right) \sin \left(\frac{\pi j}{N} \right) \right] + (1/N) \left[\sin^2 \left(\frac{m+1}{2} \frac{2\pi j}{N} \right) \sin^2 \left(\frac{\pi j}{N} \right) \right] \right\}$$

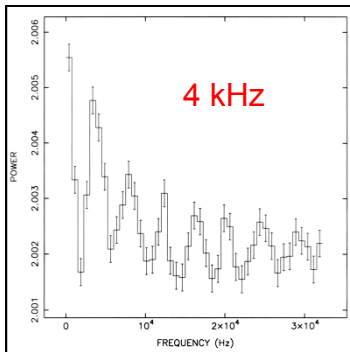
Zhang et al. 1995

- Differential deadtime

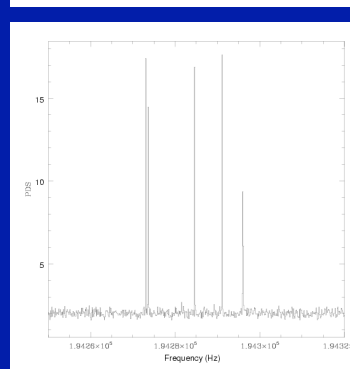
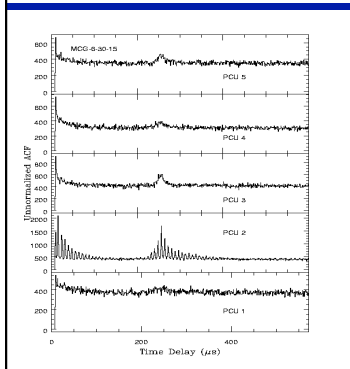
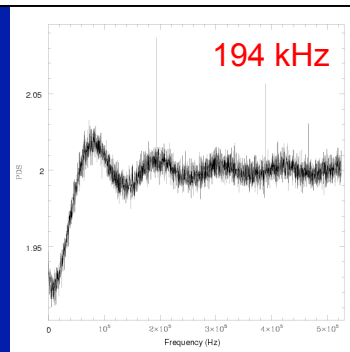
$$\frac{r_{true}}{r_{obs}} = \left(1 + \frac{\lambda}{f} \frac{df}{d\lambda} \right)^{-1}$$

- Deadtime induced channel cross-talk

Lewin et al. 1988, van der Klis 1989

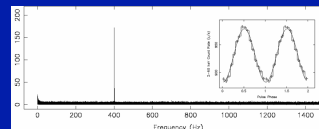
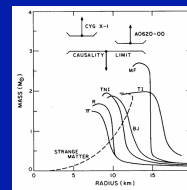
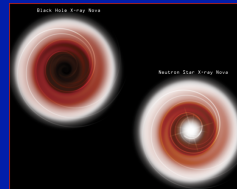


RXTE
PCA



Physics aims - 'holy grails'

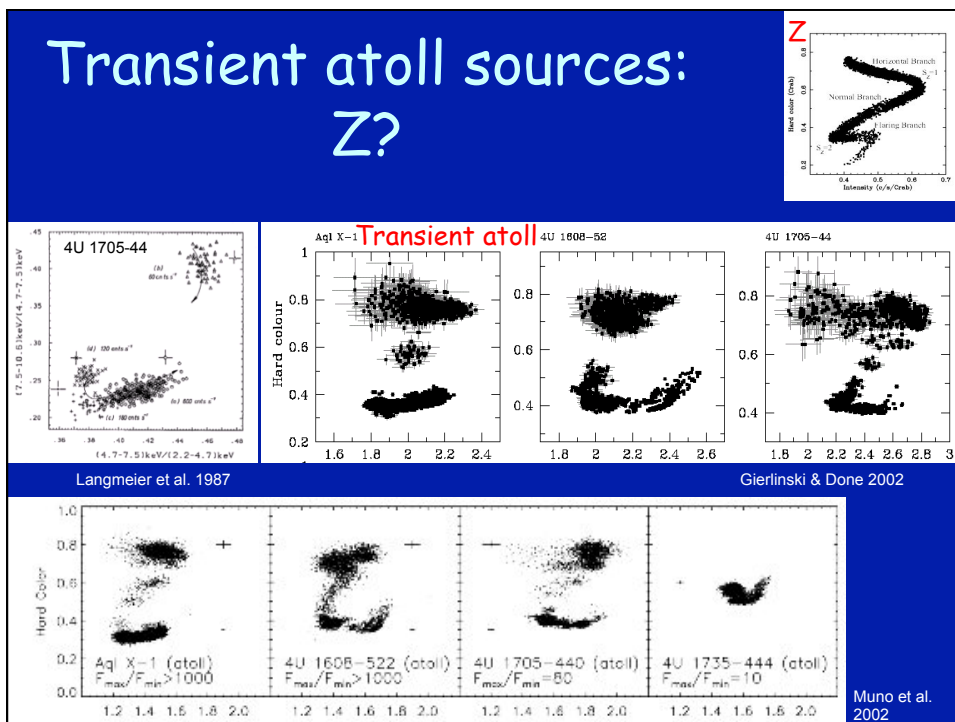
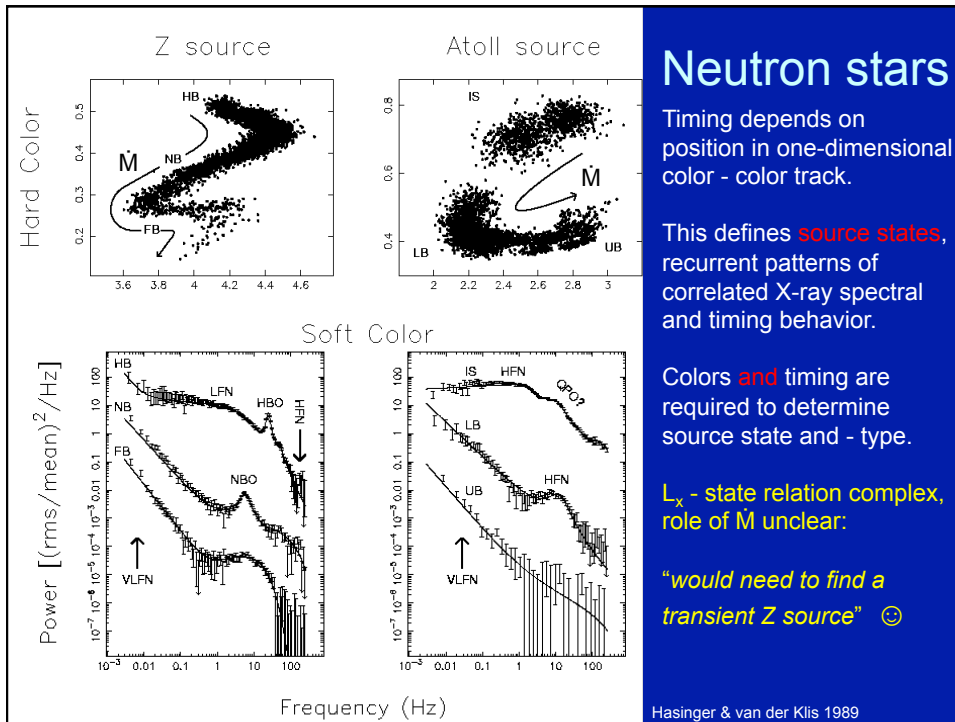
- General relativity in strong-field regime
 - ISCO, epicycles, black hole existence
- Equation of state supranuclear density matter
 - neutron star interiors
- Millisecond accreting pulsars
 - progenitors millisecond radio pulsars, recycling



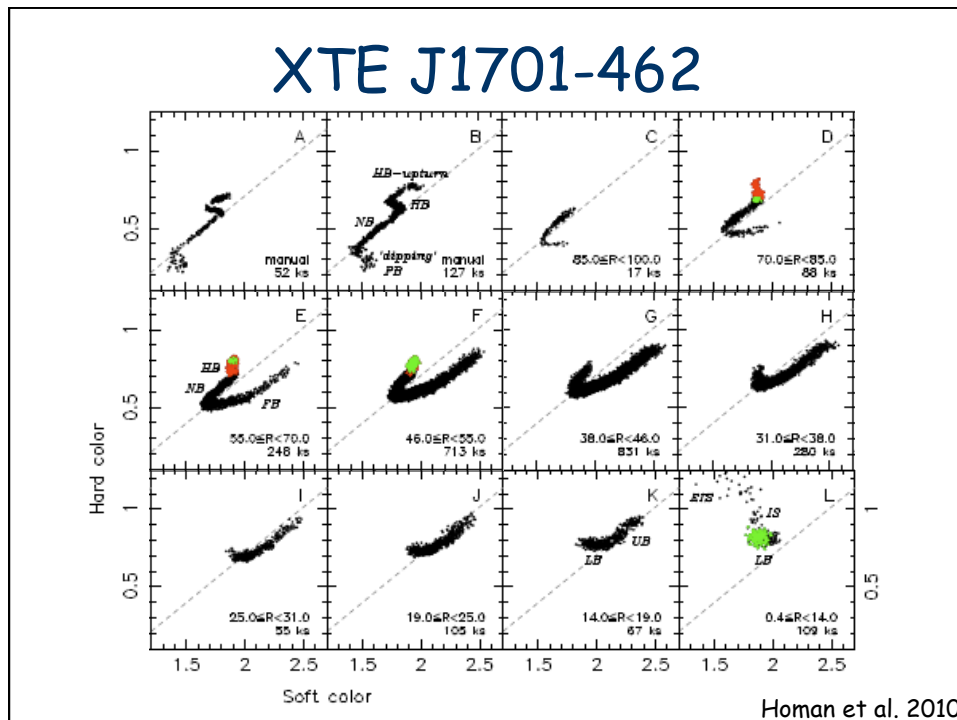
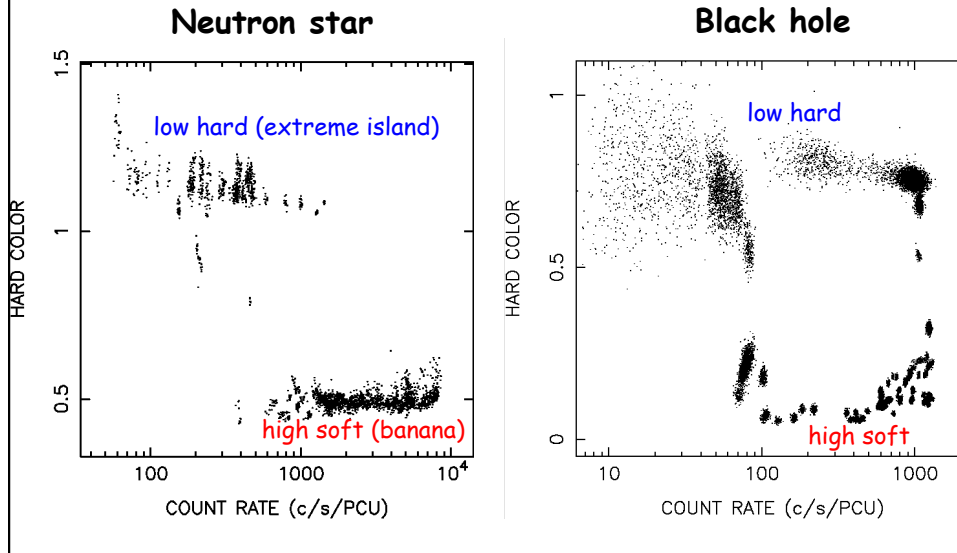
ONE DOWN, TWO TO GO!

Themes

- Distinction Z & atoll sources
 - Relation \dot{M} , L_x with spectral/timing states
- Nature of black hole states
 - Relation \dot{M} , L_x with spectral/timing states
- Lack of msec pulsars
 - Relation with burst oscillations
- Link of kHz QPOs with orbital motion & spin
 - Models



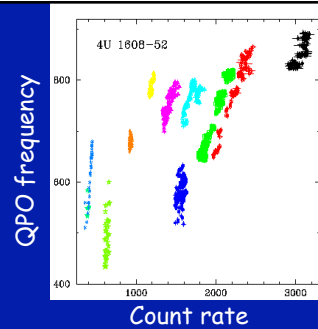
Transient atoll is like a transient black hole



Toy model

Observed: state (ν) depends not on L_x , but on $L_x / \langle L_x \rangle$

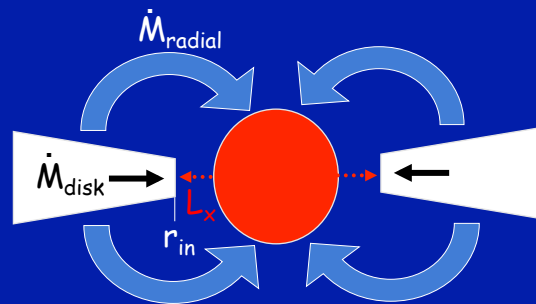
Model: state is set by r_{in} , which depends on balance between L_x and \dot{M}_{disk}



$$\nu \propto \left(\dot{M}_{disk} / L_x \right)^\beta$$

$$L_x \propto \dot{M}_{disk} + \dot{M}_{radial}$$

$$\dot{M}_{radial} \propto \langle \dot{M}_{disk} \rangle$$

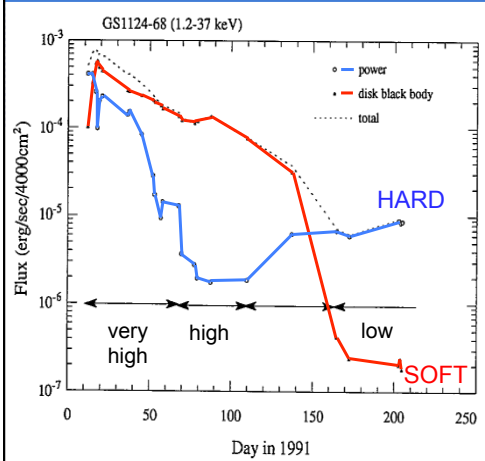


van der Klis 2001

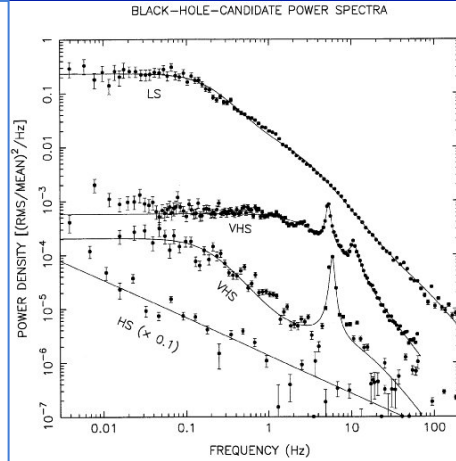
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Black hole states 1-dim - Ginga



Miyamoto et al. 1993

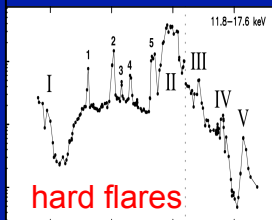
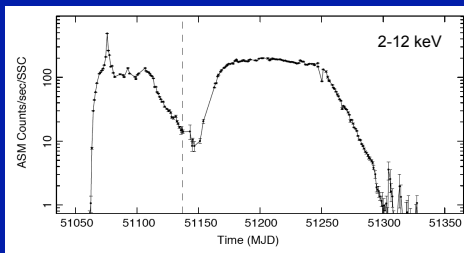


van der Klis et al. 1995

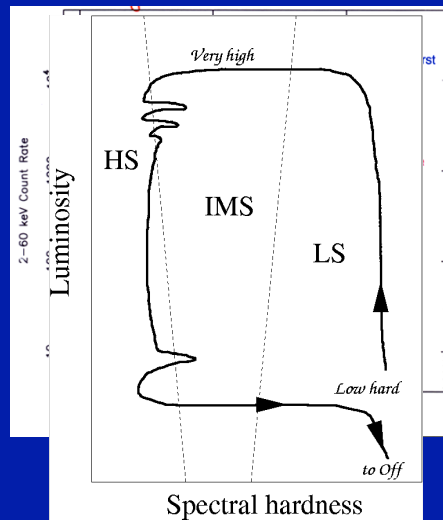
Mendez&vdK 1997, Belloni et al. 1997:

intermediate state, power spectra like very high state, but lower L_x

Black hole states 2-dim in XTE J1550-564



hard flares



RXTE msec timing discoveries

NS spin

- Accreting msec pulsars
- Burst oscillations

NS flow

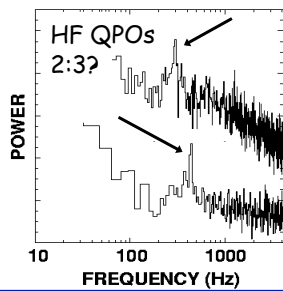
- Kilohertz QPOs
- Hectohertz QPOs
- more ...

BH flow

- High-frequency QPOs



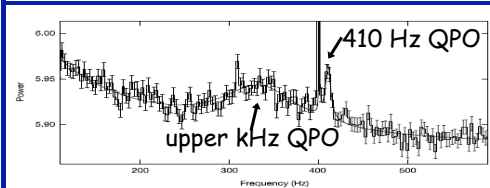
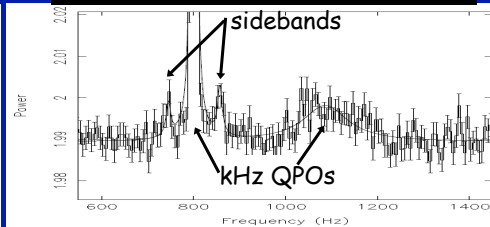
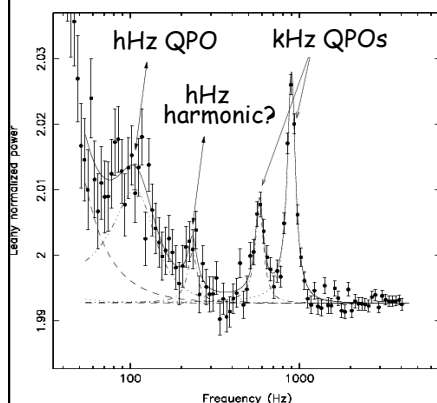
Rossi X-ray Timing Explorer
30 december 1995 - now



Numerous high frequency QPO types

Seven in neutron stars, two in black holes >100 Hz - likely more still hiding

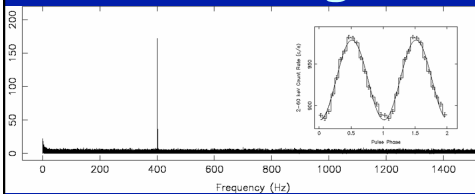
nearly all have hard spectra!



Themes

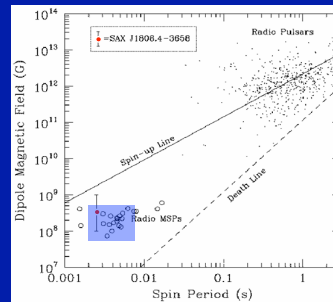
- Distinction Z & atoll sources
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 - Models

Accreting millisecond pulsars

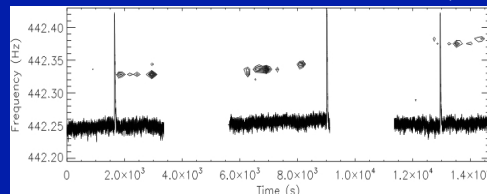


Wijnands & van der Klis 1998

Source	Freq.
Swift J1756.9-2508	182.1
XTE J0929-314	185.1
XTE J1807-294	190.6
NGC 6440 X-2	205.9
IGR J17511-3057	244.8
XTE J1814-338	314.4
HETE J1900.1-2455	377.3 i
SAX J1808.4-3658	401.0
XTE J1751-305	435.3
SAX J1748.9-2021	442.4 i
Swift J1749.4-2807	517.9
Aql X-1	550.3 s
4U 1636-53	581.9 s
IGR J00291+5934	598.9

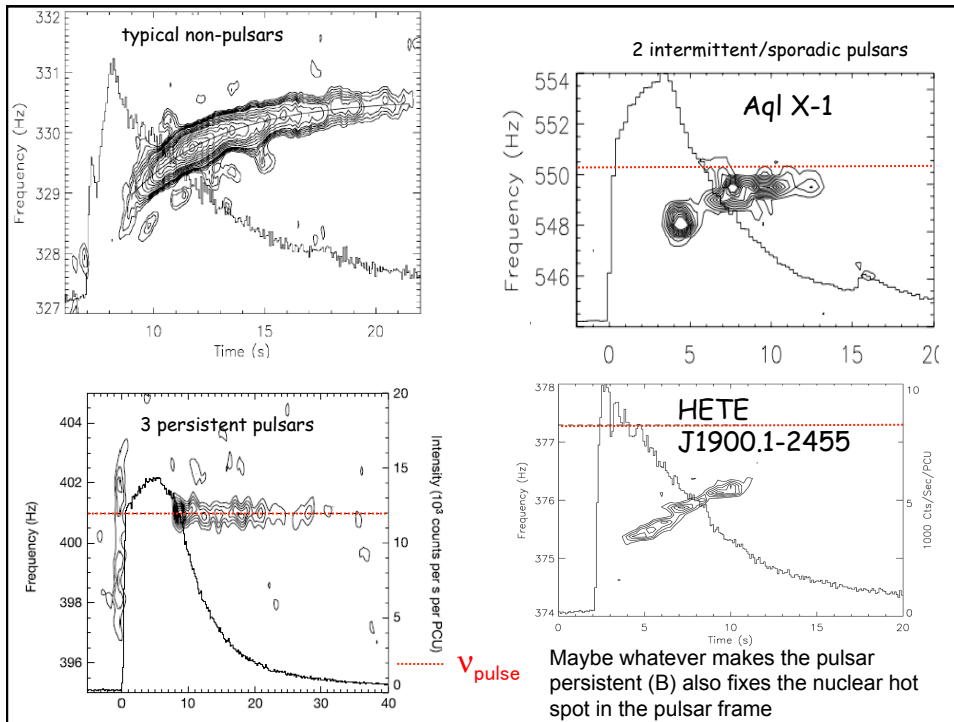


Psaltis & Chakrabarty 1999



Altamirano et al. 2008

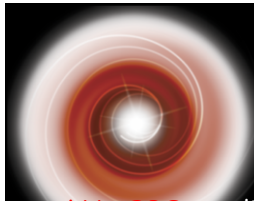
13 AMXPs known; some are intermittent or sporadic pulsars - clue to why so few?



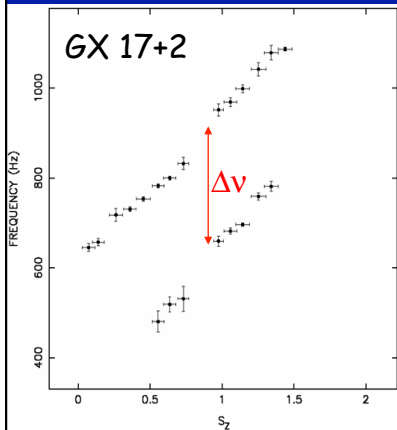
Themes

- Distinction Z & atoll sources
 - Relation \dot{M} , L_x with spectral/timing states
- Nature of black hole states
 - Relation \dot{M} , L_x with spectral/timing states
- Lack of msec pulsars
 - Relation with burst oscillations
- Link of kHz QPOs with orbital motion & spin
 - Models

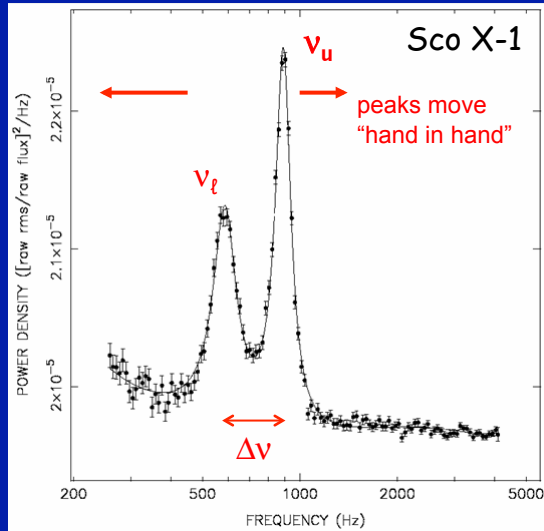
Kilohertz quasi-periodic oscillations



KHz QPOs: a direct signal from strong field gravity



Homan et al. 2002



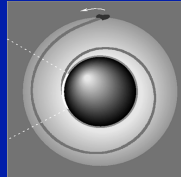
van der Klis et al. 1995

QPO models

- **Beat frequency model**

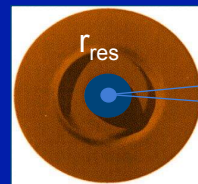
- Spin and orbit interact

$$\nu_{\text{beat}} = \nu_{\text{orb}} - \nu_{\text{spin}}$$



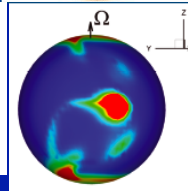
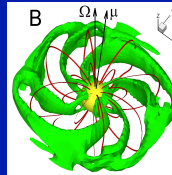
- **Relativistic/spin resonances**

- At preferred radii in the disk, GR orbital and epicyclic frequencies, and spin resonate.



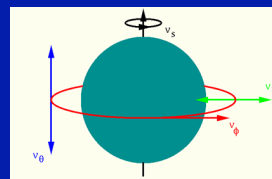
- **RMHD disk & hot spot frequencies**

- Various radiation-MHD disk modes and surface processes may produce QPOs



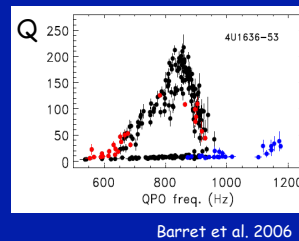
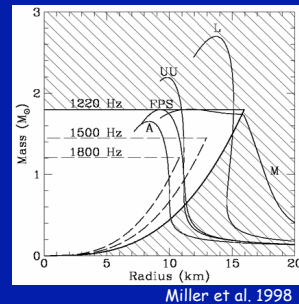
- **Relativistic precession**

- Relativistic epicyclic motion provides additional frequencies



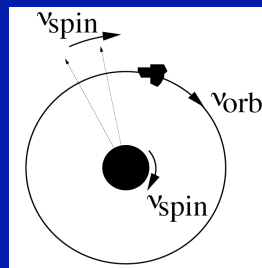
kHz QPO orbital interpretation

- Upper kHz QPO frequency interpreted in most models as GR orbital frequency at preferred radius in the disk (e.g. edge)
- **If true, immediately constrain neutron star parameters**
- QPOs vary in frequency, but always ≤ 1.3 kHz (while observations sensitive to > 2 kHz)
- **An ISCO frequency of 1.3 kHz corresponds to a neutron star mass of $\sim 2 M_{\odot}$**

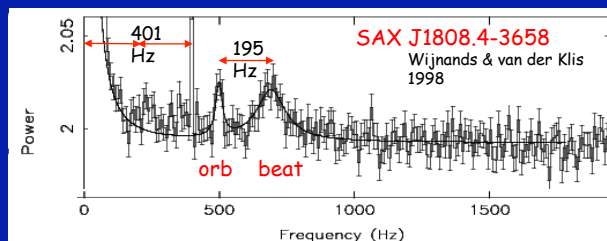


kHz QPOs and spin

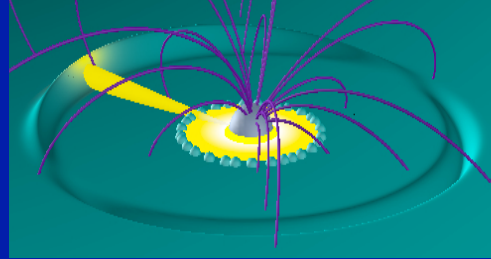
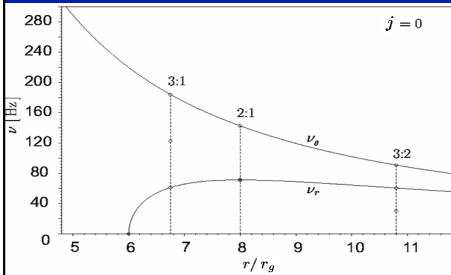
- Beat frequency model predicts $\Delta \nu \approx$ the spin.
- $\nu_{\text{beat}} = \nu_{\text{orb}} - \nu_{\text{spin}}$
 $\rightarrow \nu_{\text{orb}} - \nu_{\text{beat}} = \nu_{\text{spin}}$



- **SAX J1808 disproves this: $\Delta \nu \approx$ half the spin.**



Resonance models



'At particular **fixed** radii in the disk resonances can occur between relativistic orbital and epicyclic frequencies'

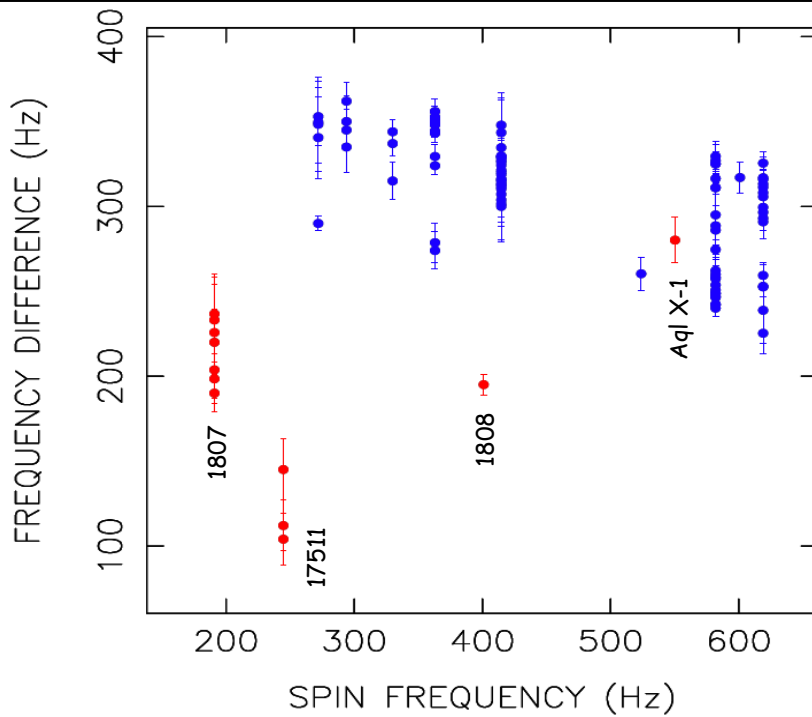
$$\nu_1 / \nu_2 = n / m, \text{ e.g., } = 2/3$$

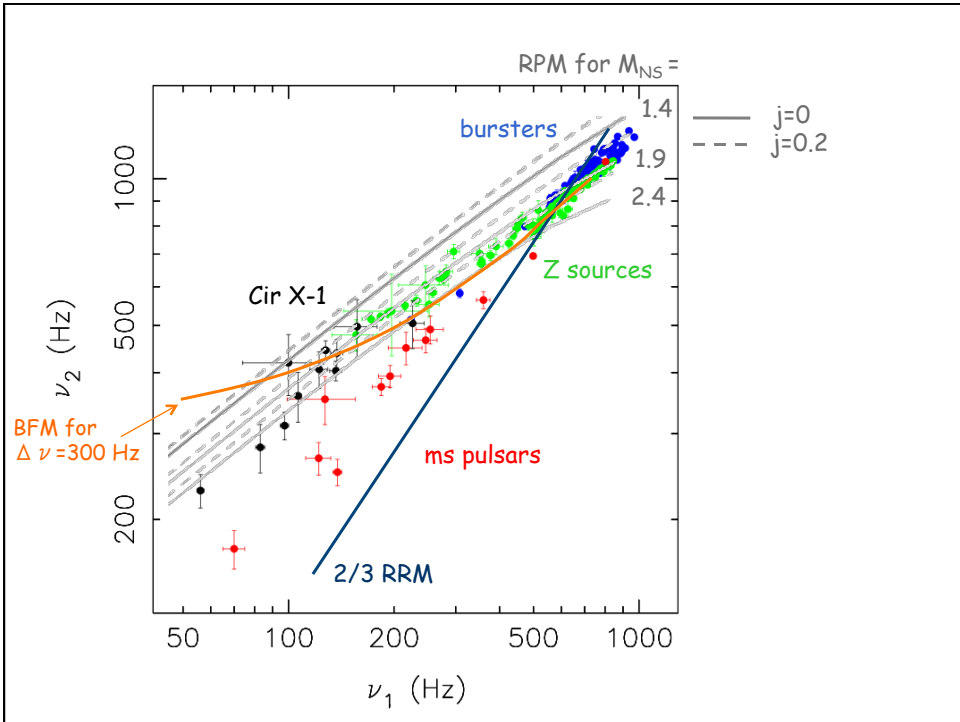
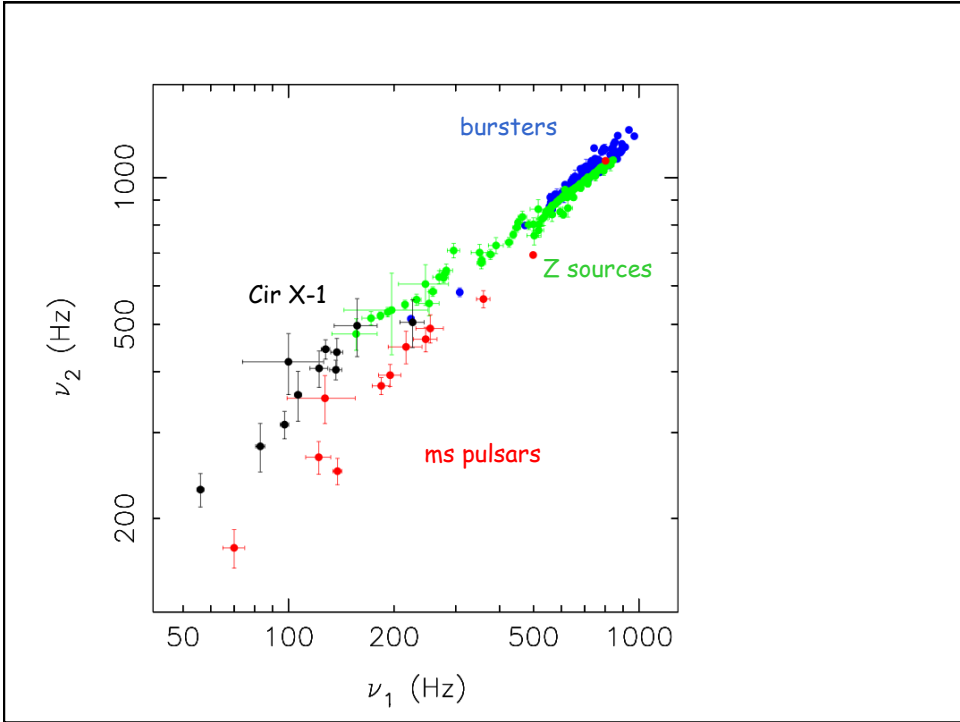
Kluźniak and Abramowicz 2001

'Under certain conditions such resonances might also involve the spin frequency'

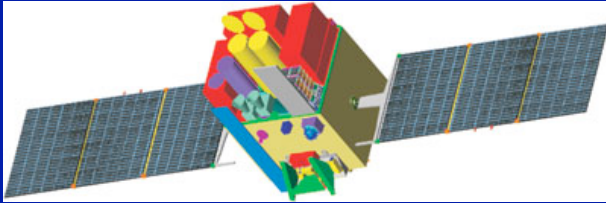
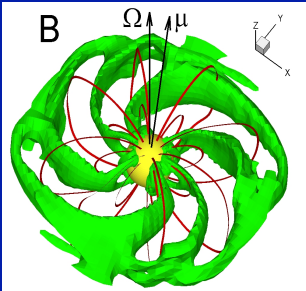
$$\nu_1 - \nu_2 = n \nu_{\text{spin}} / m, \text{ e.g., } = \nu_{\text{spin}} / 2$$

Kluźniak et al. 2004, Lamb and Miller 2004





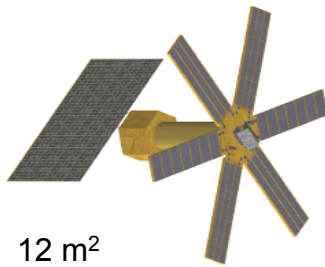
Prospects



4 m²



ASTROSAT
AXTAR
LOFT



12 m²