Quasi-periodic Oscillations
(the high-frequency ones)

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Viscous timescale:
Time it takes for a perturbation to travel through the disc.

\[ \tau_{\text{visc}} \propto \frac{R^2}{\alpha H c_s} \approx 10^5 \text{ s.} \]

Dynamical timescale:
Crossing time close to the neutron star.

\[ \tau_{\text{dyn}} \approx \frac{R_{\text{NS}}}{v_{\text{free-fall}}} = \sqrt{\frac{R_{\text{NS}}^3}{2GM_{\text{NS}}}} \approx 10^{-3} \text{ s.} \]
kHz QPOs

Sco X-1

width

amplitude $\nu_0$
Maximum observed frequencies confirm that variability originates in regions where the gravitational field is strong (potential energy $\sim$ rest mass energy), and GR effects are important.
Disc orbital-frequency interpretation

- In most models, $\nu_2$ orbital frequency at inner edge of Keplerian disk.
- If true, this constrains neutron star mass and radius.
- QPOs vary in frequency, but remain always below $\sim$1.2 kHz.
- An ISCO frequency of 1.2 kHz corresponds to a $\sim$2 $M_{\odot}$ neutron star.
• Frequencies drift by 10-50 of Hz over ~1000 seconds.

• Probably associated to perturbation patterns moving across the accretion disc (viscous timescales).
Frequencies drift, but separation remains more or less constant
Beat-frequency models

\[ \nu_{\text{burst}} = \begin{cases} \nu_{\text{spin}} \\ 2 \times \nu_{\text{spin}} \end{cases} \]

\[ \Delta \nu = \nu_{\text{spin}} \]

SAX J1808

Miller et al.; Lamb & Miller
Systematic decrease of $\Delta \nu$ as $\nu_{\text{QPO}}$ increase.

van der Klis et al.; Mendez et al.
Relativistic precession model

Relativistic epicycle precession frequencies.

Stella & Vietri
Bouloukos et al. 2006
‘At particular fixed radii in the disk resonances can occur between relativistic orbital and epicyclic frequencies’

*Kluzniak & Abramowicz*
Persistent pulsars
Intermitent pulsar
Burst oscillations
Persistent pulsars
Intermitent pulsar
Burst oscillations
Broad-band variability

Scorpius X–1

High-frequency QPOs
Low-frequency QPOs
van Straaten et al.; Linares et al.; Altamirano et al.

\[ \nu_2 \text{ (Hz)} \]

- Atoll sources
- Low luminosity bursters
- XTE J1814–338
- SAX J1808.4–3658
- XTE J1751–305
- XTE J0929–314
Further progress: Models

- Move from epicyclic frequencies, test particles, and blobs in the disc, to full (M)HD simulations of the accretion disc in GR

- Not just QPO frequencies (dynamics), but also QPO amplitude (energetic) and coherence (lifetime)
Further progress: Observations

– Find kHz QPOs in systems with spin that is either low, high, or in the gap (e.g., Ter 5, spin $\sim$ 11 Hz)

– In one of the bright LMXBs with kHz QPOs find a spin that is either low, high or in the gap (e.g., 4U 0614+09 putative spin $\sim$415 Hz)
Fe line and kHz QPOs
Fe line and kHz QPOs

4U 1636-53

![Graph showing data and continuum model for observations in 2005, 2007, and 2008.](Image)
Perspective for ASTROSAT

- Extend detection of kHz QPOs to the softest part of the color diagram (inner disc radius is possibly the smallest)

- Simultaneous Fe line and kHz QPOs → ASTROSAT time frame should match lifetime of XMM-Newton / Suzaku.
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