Correlated spectral and timing properties of neutron stars

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Marginally Stable Orbit (MSO)

\[ V_{\text{eff}}(R) = V(R) + \frac{\ell^2}{2mR^2} \]
Marginally Stable Orbit (MSO)

Radius of the marginally stable orbit (MSO)

Effective Potential

Schwarzschild

Newtonian
Kilohertz quasi-periodic oscillations (QPOs)

\[ \nu_{\text{Kepler}} (r=15 \text{ km}) \approx 1180 \text{ Hz for a } 1.4 M_\odot \text{ star} \]
The frequencies of the two QPOs change with time.
Initial observations suggested the frequencies of the QPOs, $\nu_l$ and $\nu_u$, were well correlated with the intensity of the source.
As the radius of the inner edge of the accretion disc decreases, probably driven by the rate of mass accretion through the disc, the orbital frequency at that radius increases.

But this frequency cannot be higher than the Keplerian frequency at the MSO.
MSO: Observational evidence?

![Graph showing 2-60 keV Rate (c/s) vs. Freq (Hz) for 4U 1820–30 with observational data points and a dashed line labeled $\nu_{\text{MSO}}$.]
"Parallel Tracks"

Mendez et al. 1998; Mendez & van der Klis 1999

Mendez et al. 1998; Mendez & van der Klis 1999
MSO: Upper frequency bound?
The other properties of the (kHz) QPOs

- Either width (≡ FWHM) or coherence ($Q = \nu / \text{FWHM}$; a.k.a. Quality Factor)
- Amplitude (% rms $\equiv r$)
Drop of Q and rms at high frequencies: MSO?

4U 1636–53

Coherence of the kHz QPOs across sources

Amplitude of the kHz QPOs across sources

Jonker et al. 2000; Mendez et al. 2001
Max. Q and $rms$ of the kHz QPOs across sources
Q and $rms$ of the kHz QPOs across sources

Mendez 2006

Barret et al. 2006
Q and $rms$ of the kHz QPOs across sources

12 sources (max values)

single source (4U 1636–53)

Mendez 2006

Barret et al. 2006
Q and $rms$ of the kHz QPOs across sources

12 sources (max values)

Quality factor

RMS (%)

single source (4U 1636–53)

Lower QPO freq. (Hz)

Barret et al. 2006

Mendez 2006
Q and $rms$ of the kHz QPOs across sources

$Q_{\text{max}}$ and $Q_{\text{rms}}$ as a function of $L/L_{\text{edd}}$ for two energy bands: 40–80 keV and 13–25 keV.

Mendez 2006

$I_{40–80 \text{ keV}} / I_{13–25 \text{ keV}}$
About Z’s and Atolls

Hasinger & van der Klis 1989
Individual sources vs. the population: Similar mechanism?

**Individual sources:**

- QPO coherence and amplitude drop at high QPO frequencies.
  - Higher frequencies generally imply source is brighter
  - Sources become softer as they become brighter.

→ *QPO coherence and amplitude drop when the source becomes brighter and softer.*

**The population of sources:**

- Maximum QPO coherence and amplitude drop in brighter sources.
  - Brighter sources (Z) are softer than weaker sources (Atoll).

→ *Maximum QPO coherence and amplitude drop for bright and soft sources.*
The transient XTE J1701–462: The first Z source to convert into an Atoll source

Homan et al. 2007
The transient XTE J1701–462:
The first Z source to convert into an Atoll source
The transient XTE J1701–462: The first Z source to convert into an Atoll source
The transient XTE J1701–462: The Z and Atoll type of kHz QPOs

\[ \nu_l \sim 600 \text{ Hz} \quad \nu_u \sim 900 \text{ Hz} \]
\[ Q_l \sim 8 \quad Q_u \sim 10 \]
\[ R_l \sim 3\% \quad r_u \sim 3\% \]

\[ \nu_l \sim 800 \text{ Hz} \]
\[ Q_l \sim 100 \]
\[ r_l \sim 10\% \]

Sanna et al. 2009
The transient XTE J1701–462: Amplitude vs. frequency

Upper limit for $Q=20,50$ Atoll phase, in 256s

Upper limit for $Q=100$ Z phase, in 128s, 256s and 512s

Sanna et al. 2009
The transient XTE J1701–462: Coherence vs. frequency

Minimum $Q$ for a 3-sigma detection of a 5% QPO in 256s, Atoll phase, 3PCUs

Minimum $Q$ for a 3-sigma detection of a 5% QPO in 128s, Z phase, 4 PCUs

Sanna et al. 2009
Oscillation vs. Modulation

**Oscillator:** Probably in the disc; e.g.:

- Orbital, radial or vertical epicyclic frequencies,
- Resonances.

**Modulator:** Probably in a Comptonizing corona or boundary layer:

- QPO amplitudes larger than disc contribution to total flux.
- QPO rms spectrum increases steeply with energy.
- High amplitude at energies where disc contribution is negligible.

- Coherence of the QPO: Either lifetime of the oscillator, or time dependent efficiency of the modulator.
- Amplitude of the QPO: Energy-dependent efficiency of the modulator.

\[ f(t) \propto A(E) \times e^{-t/\tau} \sin(2\pi\nu t) \]
Modulation mechanism

– Using a time-dependent Comptonization model, Lee & Miller (1998) find that the ability of a Comptonizing corona to modulate the oscillations decreases as the corona becomes cooler and more optically thick; this is also the regime at which the high-energy part of the emission becomes softer (e.g. Gierlinski & Done 2002).

– Gilfanov et al. (2003) find that the rms spectrum of the QPOs in 2 sources can be explained as variability in the flux of the boundary layer. They also find that the relative contribution of the boundary layer to the total flux decreases as inferred mass accretion rate increases (i.e., when sources become brighter).
Conclusions

1. Similar behavior of $Q$ and $r$ in individual sources and in the population of sources suggests that these QPO parameters are most likely determined by the same mechanism in both cases.

2. 4U 1701-462 converted from a bright and soft Z source into a hard and weak Atoll source; the amplitude and coherence of the kHz QPOs changed accordingly, in line with what was known for other Z and Atoll sources.

The MSO cannot be the (only) cause of the drop of $r$ and $Q$ at high QPO frequencies in individual sources.