Phase lags of quasi-periodic oscillations across source states in the low-mass X-ray binary 4U 1636–53

de Avellar, M., Méndez, M., Altamirano, D., Sanna, A., Zhang, G. (2016)

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Quasi-periodic Oscillations (QPOs) and source states

QPOs

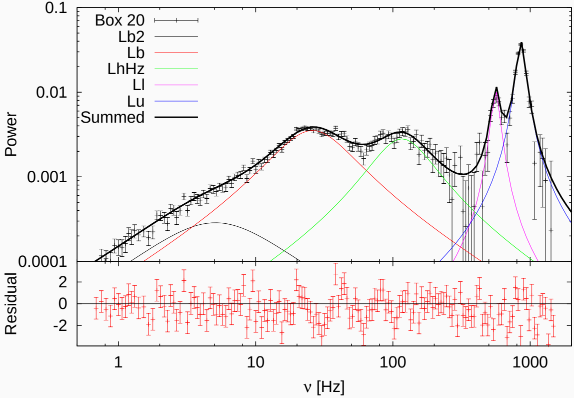


Figure 1: We fit the components with Lorentzians. The appearance of the components depend of the source position in the CCD.

Source states

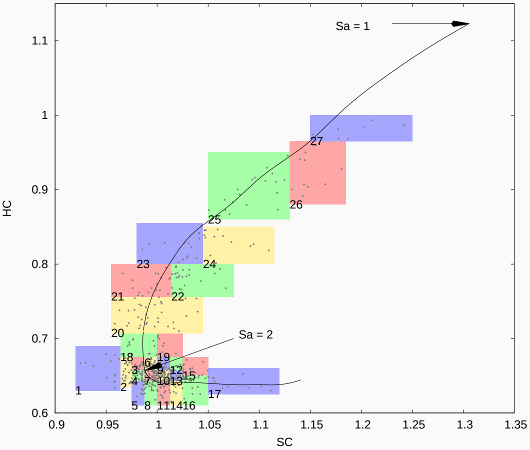


Figure 2: We divided the CCD in 37 regions. The line parametrises the position via the parameter S_a. We averaged the observations within each box.

Where do we find QPOs?

We see QPOs in very different systems:

- AGNs,
- ULXs,
- CVs **recall the talk by Solen Balman**,
- LMXBs ...

The "common structure" is some kind of the **accretion flow**.

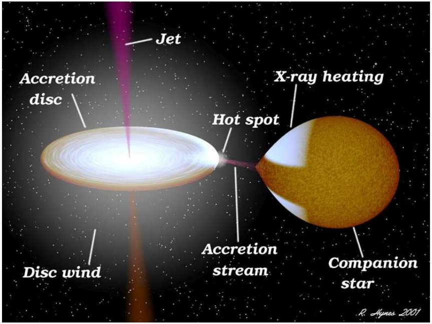


Figure 3: LMXBs scheme; we focus on the inner edge of the disc where the dominant emission is in X-rays.

Frequency correlations: benchmarks

Frequency correlations

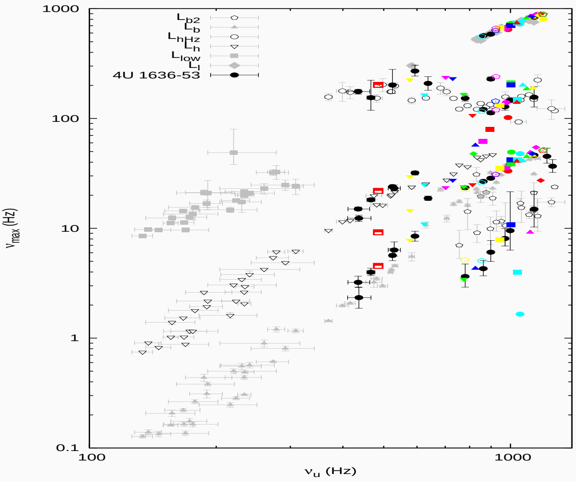


Figure 4: Altamirano (2008) plus Marcio's data. **Pay attention to the ν_l-ν_u relation in the upper right corner.**

Time/phase lags

Concepts

Time/phase lags are Fourier-frequency-dependent measurements of the time (phase) delays between two concurrent and correlated signals, i.e. two light curves of the same source, in two different energy bands, s(t) and h(t). If

$S_{xx} = S(\nu)^* S(\nu) = |S(\nu)|^2$ is PDS of s(t) and

$H_{yy} = H(\nu)^* H(\nu) = |H(\nu)|^2$ is PDS of h(t),

$$\Delta\phi(\nu) = arctan\left[\frac{Im(S(\nu)^* H(\nu))}{Re(S(\nu)^* H(\nu))}\right]$$

and the corresponding time lags

$$\Delta t = \frac{\Delta\phi}{\nu}.$$

Differences in photon arrival times give information about the source size and propagation speeds.

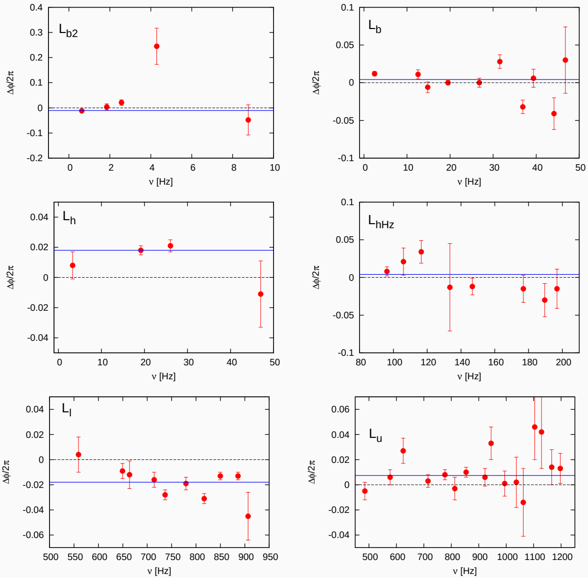
Concepts

We then studied the **frequency dependence**, the **position dependence** and the **energy dependence** of the phase lags of each QPO, since:

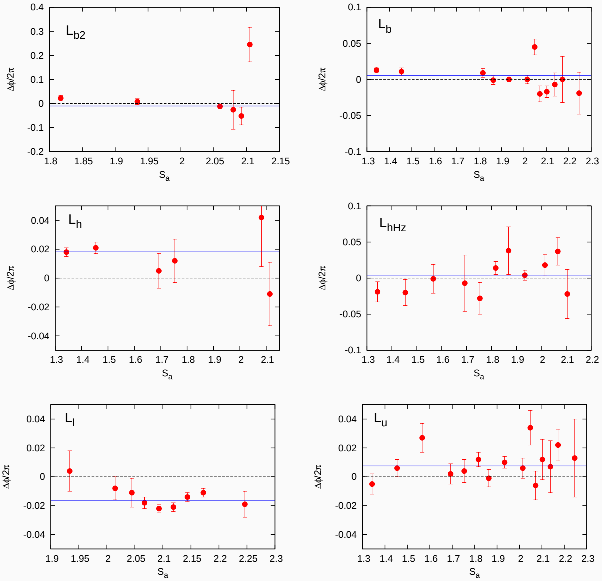
- Dependence on frequency/S_a $\Rightarrow$ geometry of the medium.
- Dependence on energy $\Rightarrow$ physical conditions of the medium (T, ρ, radiative processes).

We look for trends of the phase lags with the quantities.

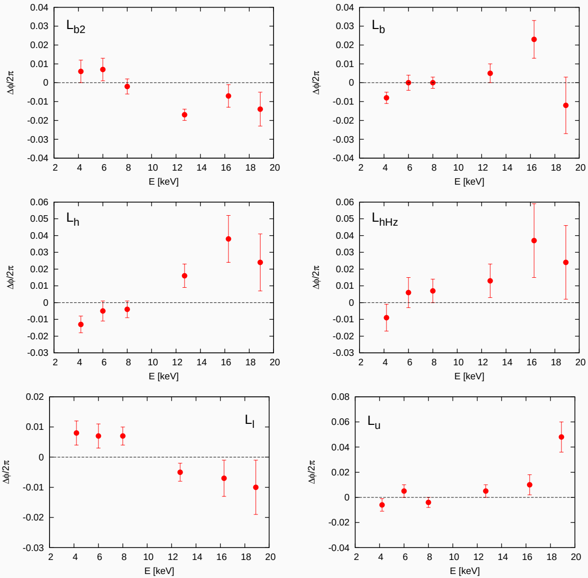
Frequency dependence



Position dependence



Energy dependence



Summary and implications

Recalling, we looked for trends in the phase lags with ν, S_a and E.

- Dependence on frequency/S_a $\Rightarrow$ geometry of the medium.
- Dependence on energy $\Rightarrow$ physical conditions of the medium.

Except for the **lower kHz QPO**, the phase lags of all the other QPOs are independent of the frequency or S_a.

Except for **the lower kHz QPO** and **the hump QPO**, the phase lags of all the other QPOs are independent of the energy.

ps: when we say "there is no trend" we actually mean that we cannot discern with these data a constant from a linear increase/decrease.

Models that involve reflection off the disc or Comptonization

$c\langle\Delta t\rangle \Rightarrow$ upper limit to the size of the medium in which the time lags are produced.

$$a \sim c\langle\Delta t\rangle \frac{k_b T_e}{m_e c^2} \frac{4\tau}{ln(E_2/E_1)}.$$

Table 1: a is the size scale and n_e is the electronic density of the medium. Here, $E_2 = 16.0$ keV, $E_1 = 7.1$ keV, $k_b T_e = 5$ keV, $\tau = 5$, $n_e = \tau/(a\sigma_T)$.

QPO	$c\Delta t$ [km]	a [km]	n_e [10^{20} cm^{-3}]
L_{b2}	2610 ± 630	628.6 ± 151.7	0.0012 ± 0.0003
L_b	15 ± 27	3.6 ± 6.5	0.21 ± 0.37
L_h	240 ± 30	57.8 ± 7.2	0.013 ± 0.002
L_{hHz}	2.4 ± 10.5	0.58 ± 2.53	1.3 ± 5.7
L_l	6.3 ± 0.6	1.52 ± 0.14	0.50 ± 0.05
L_u	3.0 ± 0.6	0.72 ± 0.14	1.04 ± 0.21

Notice the very low densities.

BHC systems

- Méndez et al (2015): for GRS 1915+105: the **(soft) lags** of $\nu_1 = 35$ Hz are **inconsistent** with the **(hard) lags** of $\nu_2 = 67$ Hz. Similarly to the **kHz QPOs of 4U 1636–53**.
- L_{hHz} in NS-LMXBs could be related to the QPOs of BHC in the 180-450 Hz range.

Placing the upper kHz QPO

- Bult and van der Klis (2015): SAX J1808.4-3658 $\Rightarrow \nu_u$ results from azimuthal motion at the inner edge of the disc.
- Bachetti (2010) and Romanova and Kulkarni (2009): can produce high frequency QPOs with 3D simulations of the accretion flow onto a magnetized neutron star.

SAX J1808.4-3658 is a accreting ms X-ray pulsar classified as an atoll source (like 4U 1636–53). We suggest that:

- The **phase lags of the upper kHz QPO** encode the **properties of the medium at the magnetospheric radius** (where the upper kHz QPO would be produced, 6 to 11 km from the surface in our estimations).
- The **phase lags of the lower kHz QPO** encode the **properties of the medium at the boundary layer** and nearby (where the lower kHz QPO would be produced).

What about the energy dependence of the lags?

- Lee, Misra, Taam (2001): up-scattering Comptonization Model for the **soft lags of L_l** where **the corona and disc temperatures oscillates coherently at the QPO frequency** $\Rightarrow a \sim 5$ km; explain also the rms% vs E. Cannot explain the other lags.
- Kumar and Misra (2014): a thermal Comptonizing plasma that oscillates at QPO frequency. The **soft lags of L_l** are seen only when **the heating rate of the corona varies and a significant fraction of the photons impinge back onto the source of soft photons** $\Rightarrow a \sim 1$ km; explain also the rms% vs E. Cannot explain the other lags.

Picture to have in mind

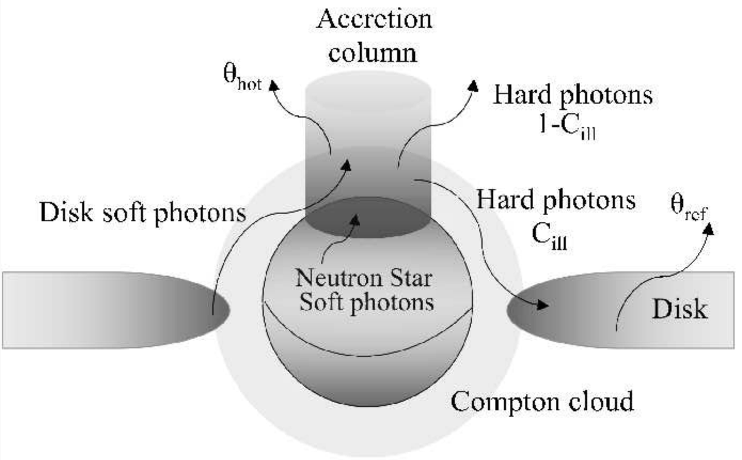


Figure 5: From Falanga and Titarchuk (2007).

Conclusion

- Peille et al (2015): QPO spectrum is compatible with a black body spectrum with $T_{bb} > T_{continuum}$; lags of L_l are systematically different from the lags of L_u.

  Their scenario: if lags of L_u are reverberation-dominated, then L_u comes simply from variation in luminosity at the inner edge of the disc, a response to variations in $\dot{M}$ onto the boundary layer.

  $\Rightarrow$ The similarity between the lag-energy spectrum of L_u and of the L_b, L_h, L_{hHz} found here would imply similar origins.

If extended to include all the other QPOs, these models provide an opportunity to study the dynamic and physical conditions of the Comptonising corona in neutron-star low-mass X-ray binaries.

Marcio @ ITP

Using observational data we want

Identify frequencies, not only ν_l and ν_u, but also other frequencies that could be linked to other QPOs and infer the neutron star parameters.

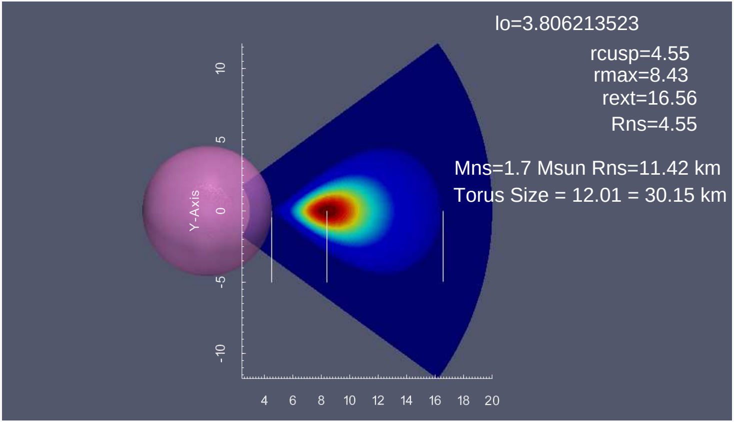


Figure 6: The biggest torus around this star. Constant angular momentum distribution.

Questions?

Thanks.