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

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About Marcio

Professional data

Post-doc at IAG-USP, São Paulo, Brasil, under supervision of prof. Dr. Jorge Horvath.

Now, visiting ITP under supervision of prof. Dr. Luciano Rezzolla.

Research:

- Information Theory applied to equation of state of compact objects;
- Entropy along stellar evolution;
- Magnetic field evolution in the context of red backs and black widows (in progress);
- Hybrid neutron stars (in its beginnings);
- **X-ray astrophysics of low-mass X-ray binaries (QPOs and time/phase lags).**

Quasi-periodic Oscillations (QPOs) and source states

Light curve and PDS

Light curve of an observation ⇔ time series.

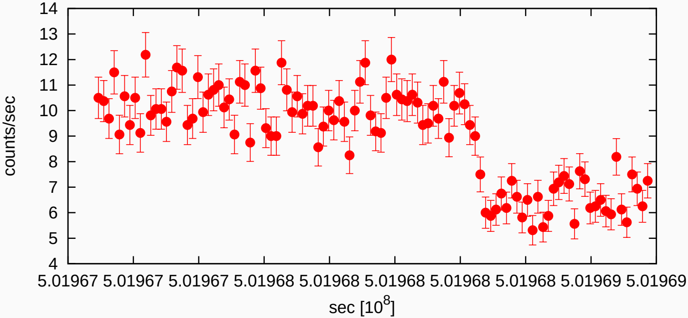


Figure 1: X-ray light curve of one observation of 4U 1636–53.

We look for periodicities and patterns ⇒ Fourier transform.

Components of the PDS and their appearance

We find many features in the PDS:

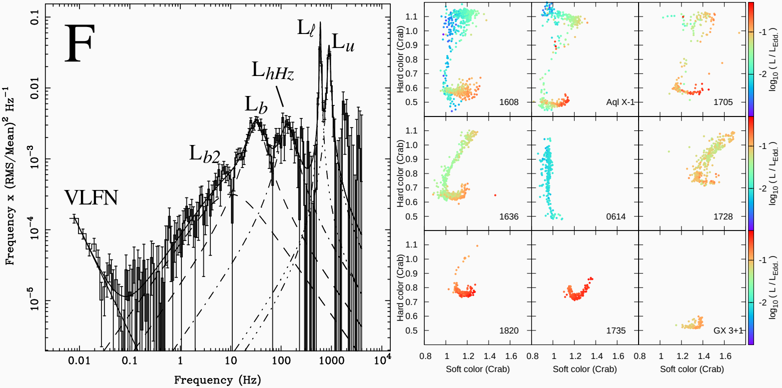


Figure 2: Left: PDS of a X-ray light curve (Altamirano 2008). Right: colour-colour diagram (CCD) plus luminosity (Linares 2009, thesis). **Pay attention to the kHz QPOs.**

Fits and related quantities

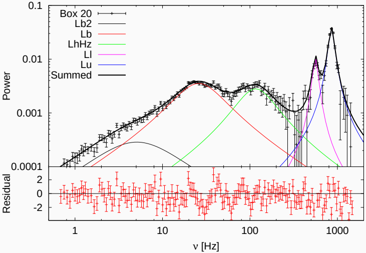


Figure 3: We fit the components with appropriate functions, i.e., a Lorentzian. **Pay attention to the kHz QPOs.**

$$P_\nu = \frac{\lambda}{(\nu - \nu_0)^2 + (\frac{\lambda}{2})^2},$$

where λ is the FWHM and ν_0 is the centroid frequency.

$$Q \equiv \frac{\nu_0}{\lambda} \; (quality \;\; factor).$$

Conventionally $Q \geq 2$ for QPOs.

$$rms \propto P^{1/2} \; where \; P = \int P_\nu d\nu.$$

Positive detection if $P \geq 3\sigma$.

A Lorentzian is the Fourier transform of a signal of the type

$$x(t) \propto e^{-t/\tau} cos(2\pi\nu_0 t) \; where \; \tau = \frac{1}{\pi\lambda}.$$

Where do we find QPOs?

We see QPOs in very different systems:

- AGNs,
- ULXs,
- CVs,
- LMXBs ...

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

LMXBs

System configuration

LMXBs are binary systems with a neutron star or a black hole and an ordinary low-mass star ($M \lesssim 1.3M_{\odot}$) in the following configuration:

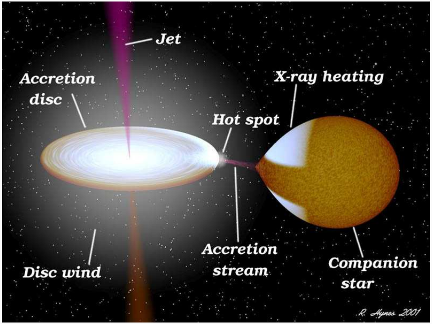


Figure 4: LMXBs scheme; we focus on the inner edge of the disc where the dominant emission is in X-rays.

Motivation

RG and EoSs

Possibility to study extreme physics not possible in laboratories:

- $v_\phi = (GM/R)^{1/2} \sim 0.5c \Rightarrow \tau_{dyn} \sim 0.1 - 2$ ms.
- Turbulence and magnetic structures $\Rightarrow$ emission varies due to motion of inhomogeneities.
- 90% of gravitational energy is released in the inner 100 km of the system. ($T \sim 10^7$ K $\Rightarrow$ X-rays.)

Extreme physics: motion of matter in strong gravitational field regime and the physics of dense matter in neutron stars. **It is thought that the kHz QPOs can probe the inner regions of the disc, very near the central compact object.**

Frequency correlations: benchmarks

Frequency correlations

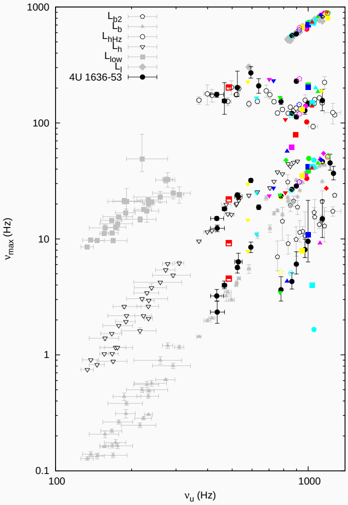
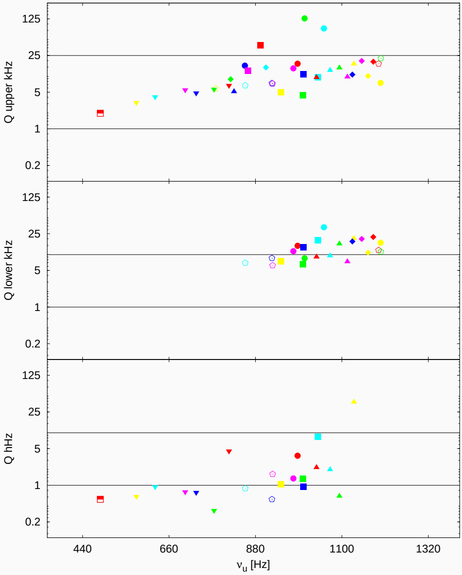
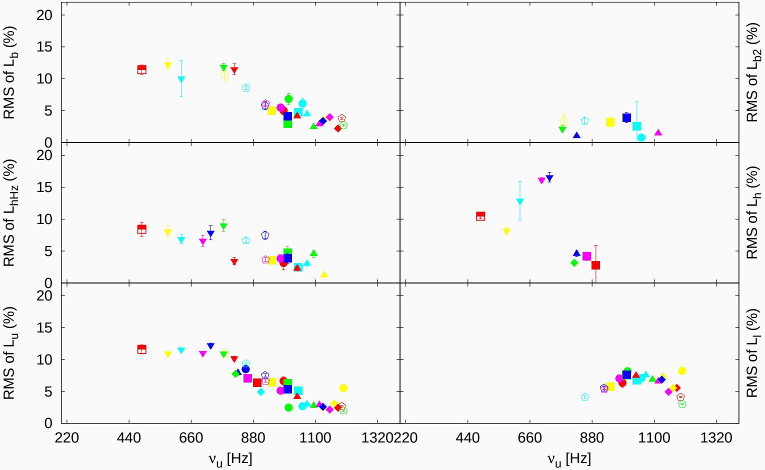


Figure 5: Altamirano (2008) plus Marcio's data. **Pay attention to the ν_l-ν_u relation in the upper right corner.**

Frequency correlations



Frequency correlations



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).

As mentioned we Fourier transform the signals:

$$F(\nu) = \int_{-\infty}^{\infty} f(t) e^{-i(2\pi\nu t)} dt \Leftrightarrow f(t) = \int_{-\infty}^{\infty} F(\nu) e^{+i(2\pi\nu t)} d\nu.$$

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

Thus, 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),

we can find the phase lags of h(t) with relation to s(t) calculating the *cross-density spectrum* (CDS):

$G_{xy} = S(\nu)^* H(\nu) \sim e^{\Delta\phi(\nu)}$, or

$$\Delta\phi(\nu) = arctan\left[\frac{Im(G_{xy})}{Re(G_{xy})}\right]$$

and the corresponding time lags

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

ps: the * is the conjugate.

Beautiful and easy in theory...

Alert: real signals are discrete and finite

- in dealing with low frequencies, we need to clean the signal of from bursts, instrumental spikes and dropouts;
- better statistics if we divide the signal and pieces, Fourier transform each piece and average the pieces;
- we need to take into account the gain of the instrument and its ageing;
- we need to clearly state what a positive detection is;
- etc.

It is a very delicate work.

The paper

Observations

- 511 RXTE observations up to May 2010 in which Sanna et al (2012) detected kHz QPOs $\Rightarrow$ make use of the correlations in frequency.
- Seven narrow energy bands whose mean energies are 4.2 keV, 6.0 keV, 8.0 keV, 10.2 keV, 12.7 keV, 16.3 keV and 18.9 keV.
- Two broad bands whose mean energies are 7.1 keV and 16.0 keV.
- In 15 years the gain of the instrument changed significantly $\Rightarrow$ adjustment of our channel selections for different groups of observations, depending upon the epoch.
- We ordered the observations chronologically and cleaned the observations.
- We subtracted the Poisson noise.
- etc.

Assumption

Our assumption: The variability features depend on the position of the source in the CCD.

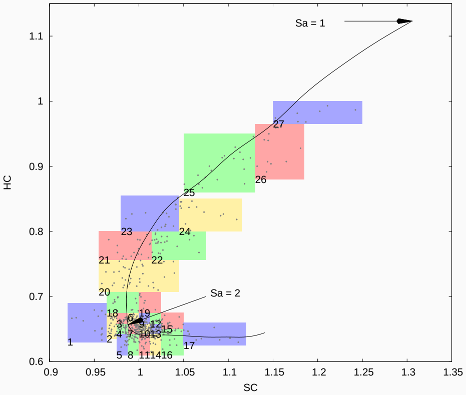


Figure 6: We divided the CCD in 37 regions. The line parametrises the position. We statistically compared the individual PDSs in each box in order to verify our assumption. We averaged the observations within each box.

What do we see? A few examples

Table 1: Detected QPOs of the NS-LMXB 4U 1636–53 through the colour-colour diagram.

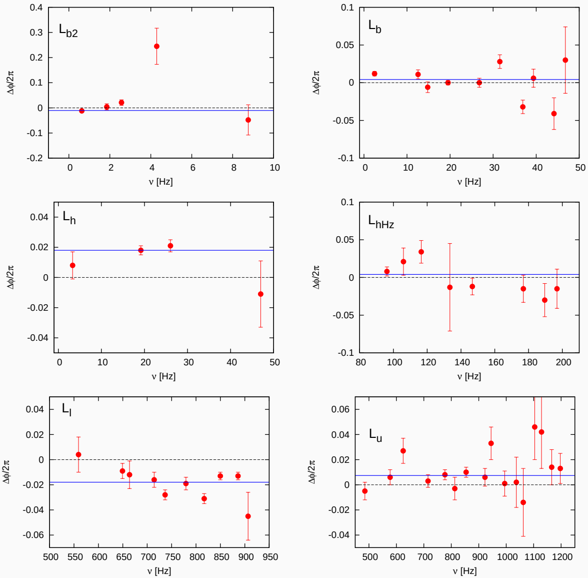
Box	Detected QPOs					
...						
Box 3		L_b		L_{hHz}	L_l	L_u
Box 4-1	L_{b2}	L_b		L_{hHz}	L_l	L_u
Box 4-2			L_h		L_l	
Box 5	L_{b2}	L_b		L_{hHz}	L_l	L_u
...						
Box 27		L_b	L_h	L_{hHz}		L_u

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

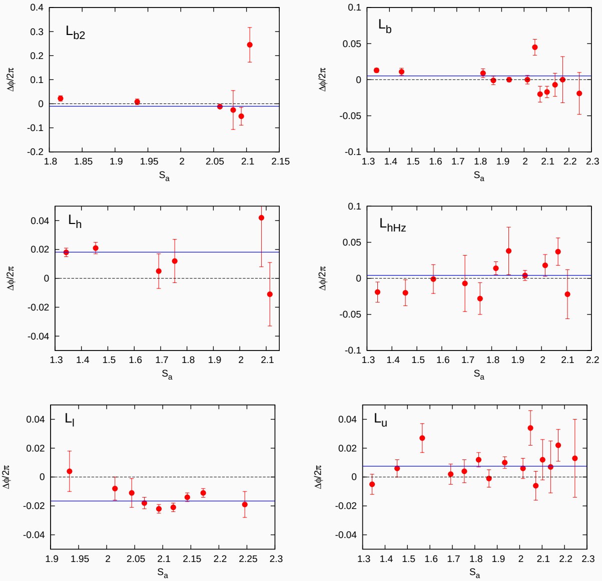
- Dependence on frequency/S_a $\Rightarrow$ geometry of the medium.
- Dependence on energy $\Rightarrow$ physical conditions of the medium (T, ρ, radiative processes).

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

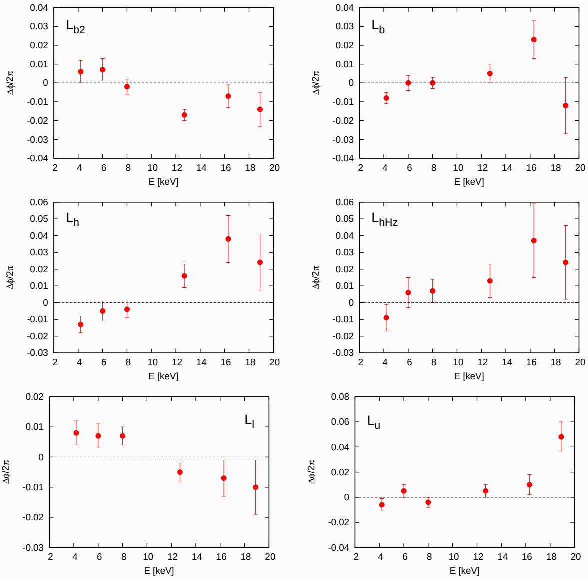
Frequency dependence



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 2: 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.

Reflection in AGN and the scale with the mass

- Kotov et al (2001) and Zoghbi et al (2010, 2011): hard lags seen for frequencies $\leq 5 \times 10^{-4}$ Hz are due to inward propagation of fluctuations in the disc, the soft lags seen above this frequency are due to reflection. The same reasoning for L_{b2} and L_{hHz} (similar lag-spectrum) **(?)**
- De Marco et al (2013a,b): **scaling** between **black hole mass** and **soft X-ray time lags** in AGNs and in ULX NGC 5408 X-1, suggesting that the relation holds all the way down to neutron stars binary systems. This scaling $\Rightarrow$ signature of reverberation of the accretion disc in response to changes in the continuum. **Holds only in the context of L_l.**

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 ⇒ ν_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.

What about the energy dependence of the lags?

- 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

Summary

Simulate a torus around the neutron star in 4U 1636–53. Assumptions:

- an appropriate space-time geometry;
- polytropic EoS for the fluid;
- realistic EoS for the neutron star;
- some appropriate angular momentum distribution.

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.

Summary

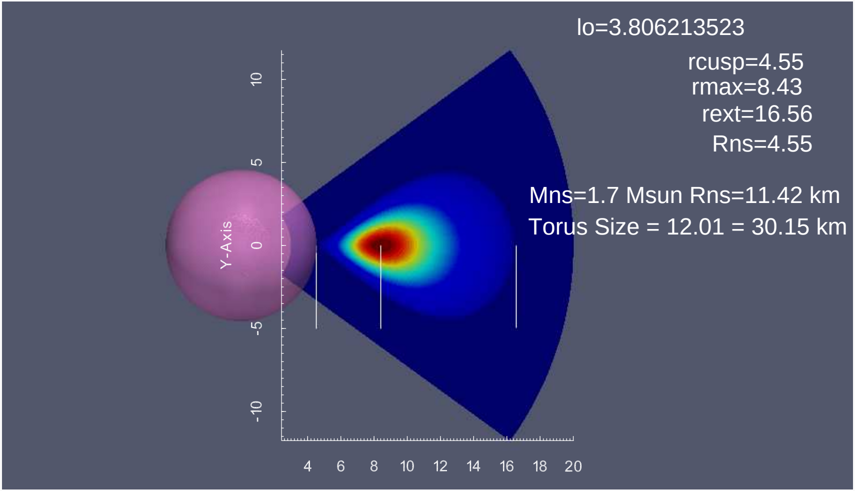


Figure 7: The biggest torus around this star. Constant angular momentum distribution.

Questions?

Thanks.