Métodos de Estimativa de Causalidade em Séries Temporais – Aplicação ao LMXB 4U 1636–53

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Quasi-periodic Oscillations (QPOs) and source states

Where do we find QPOs?

We see QPOs in very different systems, but all of them have some kind of **accretion flow** as a "common structure". We focus here in LMXBs.

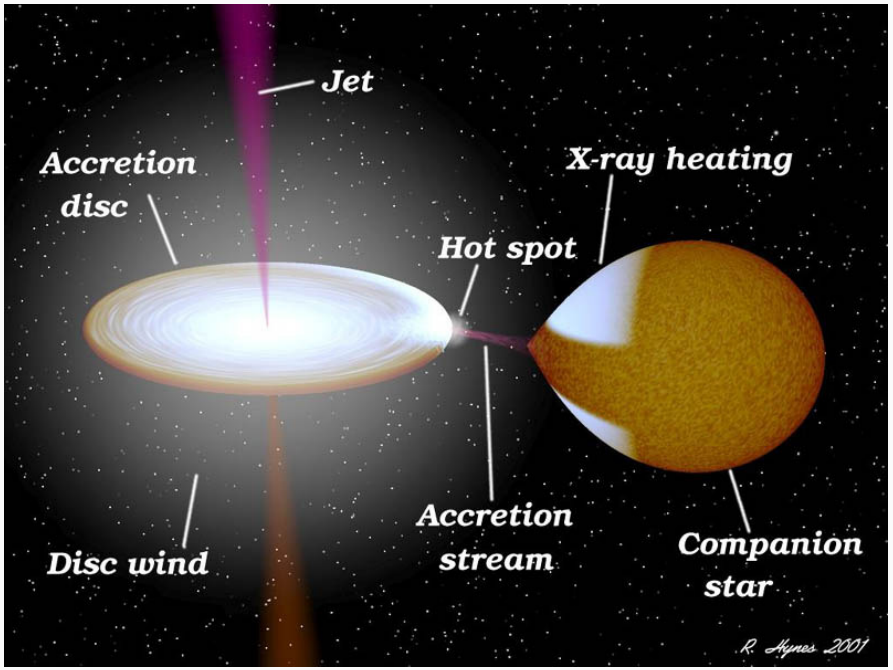

Figure 1: LMXBs scheme; we focus on the inner edge of the disc where the dominant emission is in X-rays.

Light curve, a time series

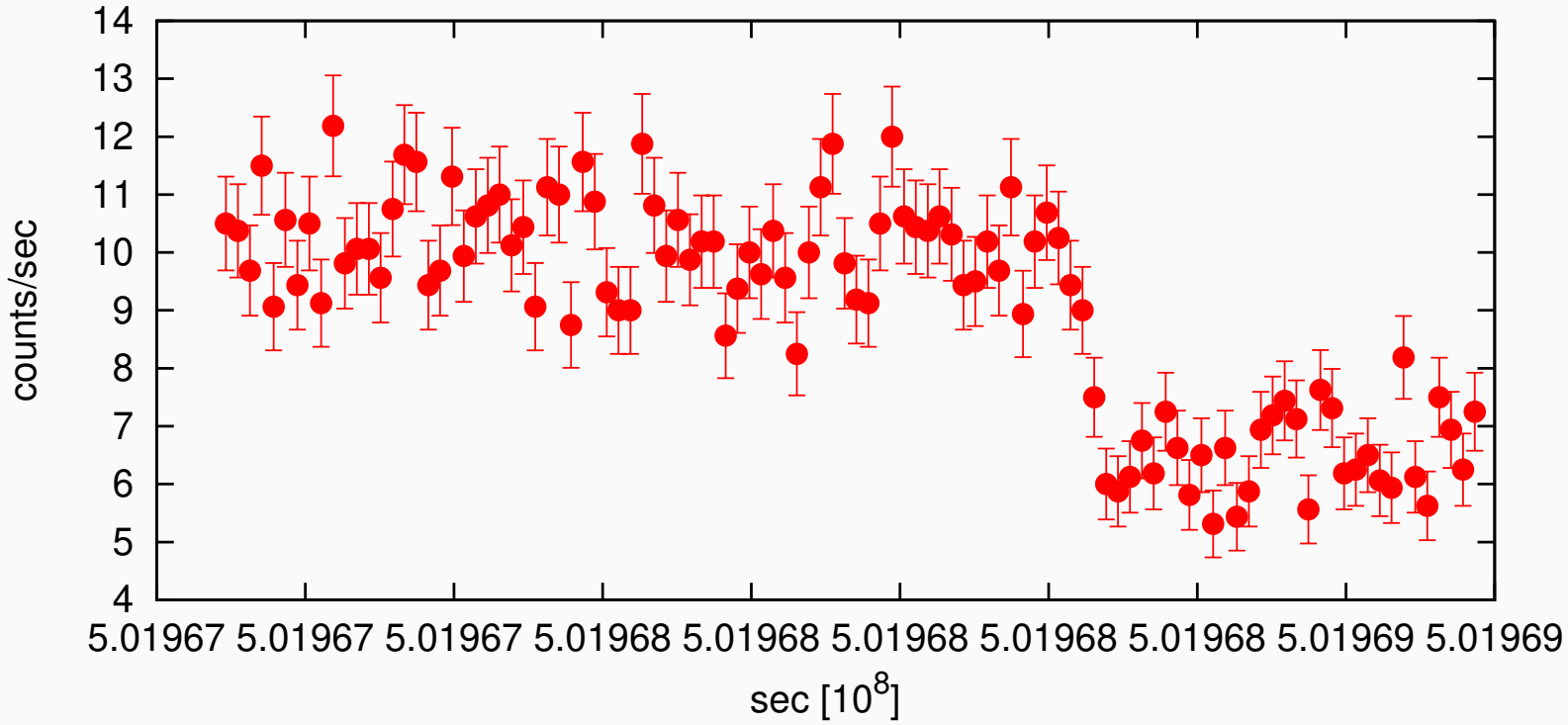

Figure 2: A segment of X-ray light curve from 4U1636 – 53.

QPOs and source states

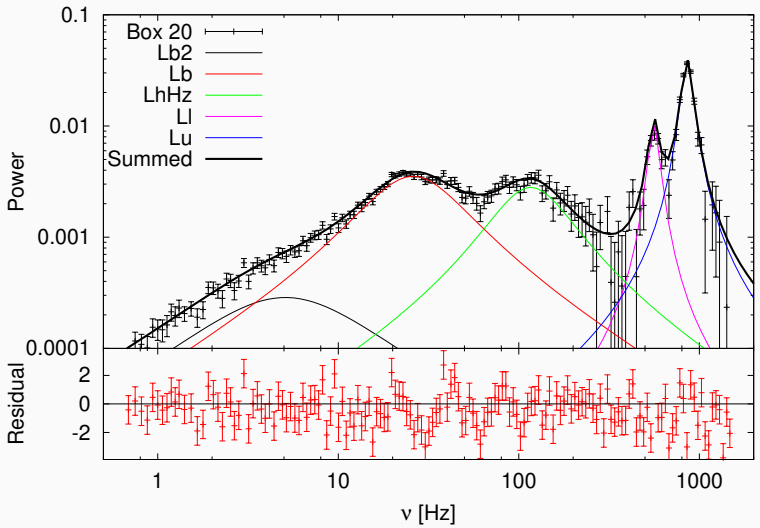

Figure 3: Notice the kHz QPOs.

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

$$Q \equiv \frac{\nu_0}{\lambda} \geq 2.$$

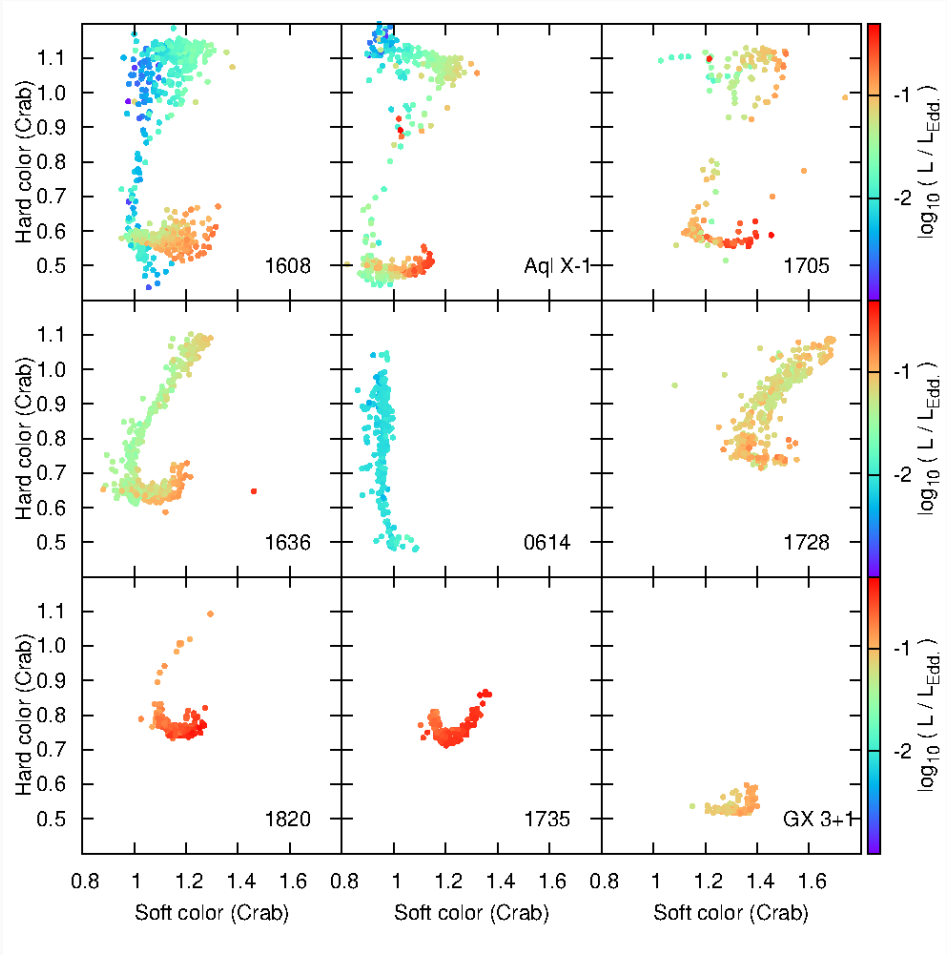

Figure 4: Colour-colour diagram (CCD) plus luminosity (Linares 2009, thesis).

Frequency correlations

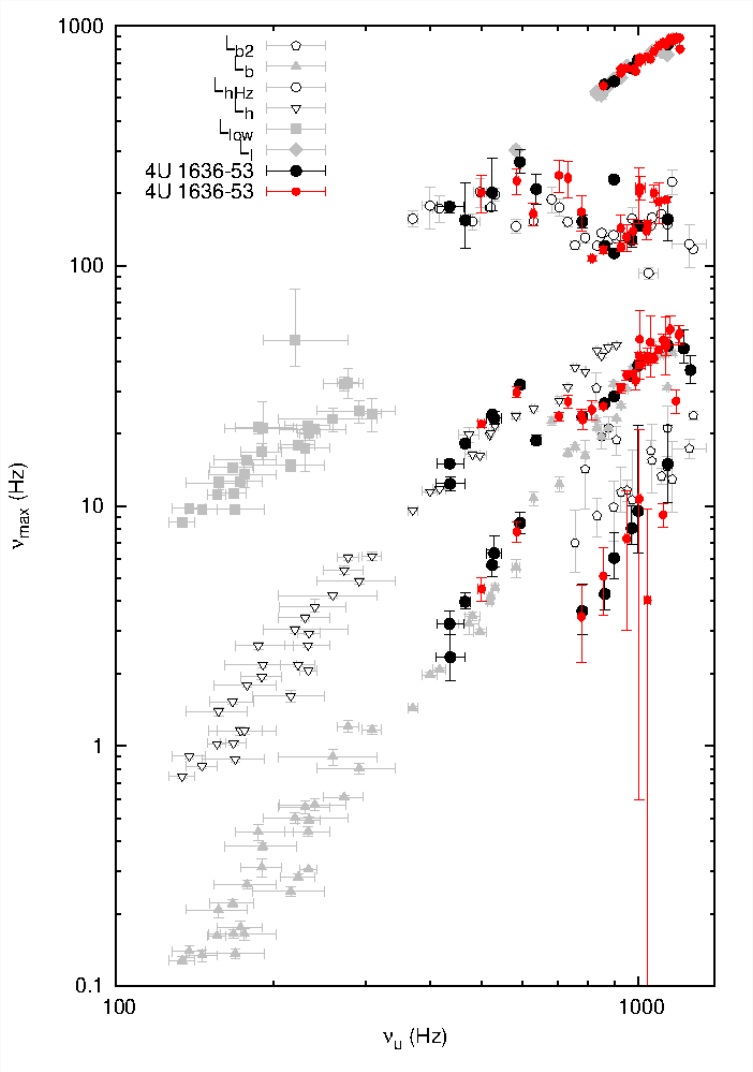

Figure 5: Altamirano (2008) plus Marcio's data. **Pay attention to the $\nu_l - \nu_u$ relation in the upper right corner.**

What is happening in the CCD?

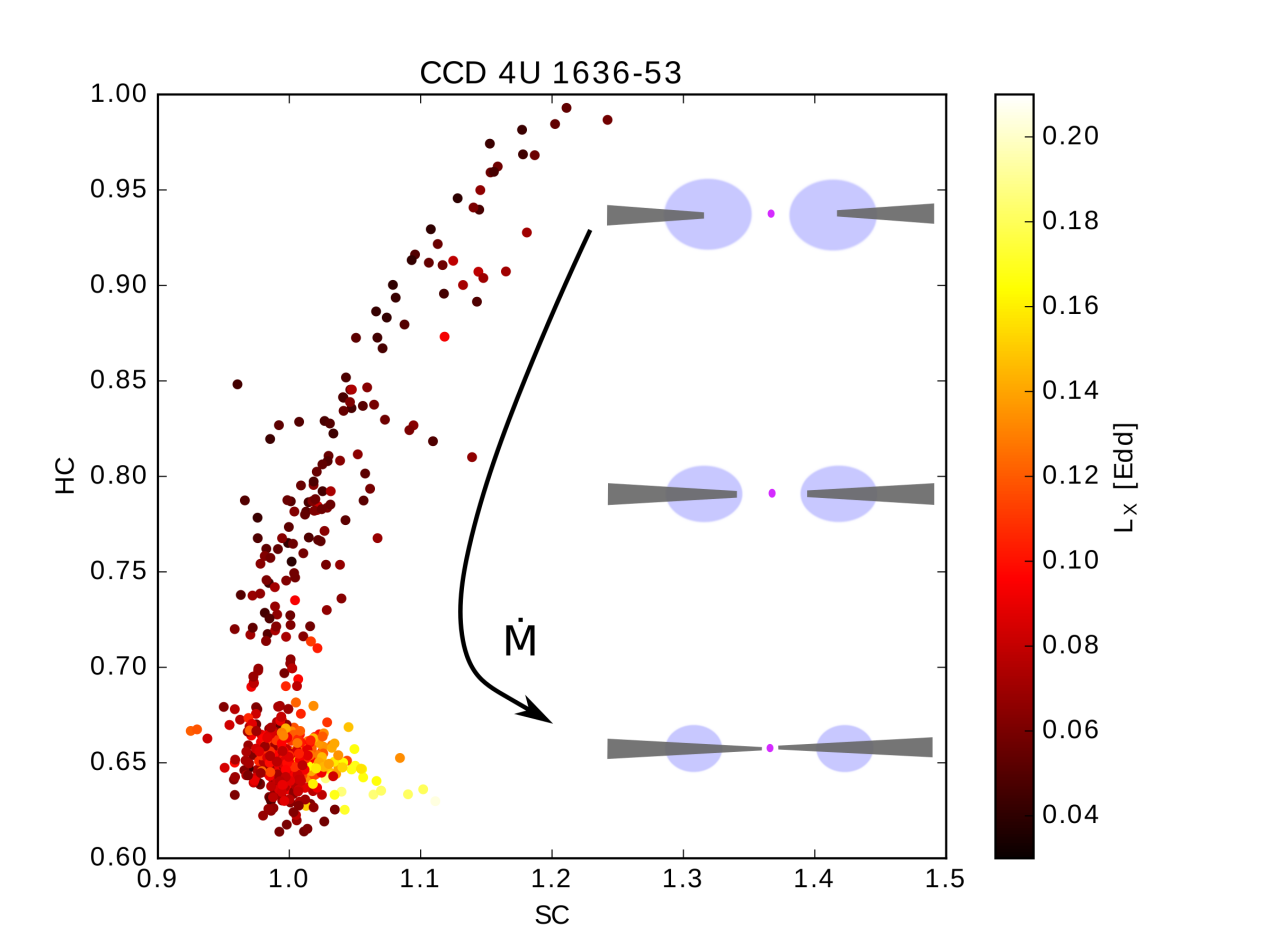

Figure 6: Source states change as a function of accretion rate.

Motivation: why to study these systems?

RG and EoSs — extreme physics

Radiative models

- 90% of gravitational energy is released in the inner 100 km of the system. ($T \sim 10^7$ K $\Rightarrow$ X-rays.)

General relativity

- $v_\phi = (GM/R)^{1/2} \sim 0.5c \Rightarrow \tau_{dyn} \sim 0.1 \ - \ 2ms$;
- Non-geodesic effects in the motion due to magnetic fields, viscosity and pressure forces;
- Lense-Thirring effect, epicyclic frequencies.

Equation of state of dense matter

- To what extent do the space-time metric and the frequencies in the light curve depend upon the compact star parameters?

Partial Directed Coherence — PDC

New informations

- As far as we know, there are no records in the literature of a statistical study of causality inference between these spectral patterns.
- PDC is a quantitative approach used to evaluate the mutual influence between multiple and simultaneous time series in the frequency domain.
- Performed by means of joint and parametric modeling of the kHz QPO data detected in two energy bands of the same light curve and the use of the asymptotic behavior of the frequency estimators (Baccalá 2013).
- **With this technique it is possible to infer the direction of information flow between quasi-periodic oscillations, which, in this case, is unidirectional.**

Time/phase lags

- for all QPOs detected in the LMXB 4U 1636–53, de Avellar et al (2016) studied the phase lags between the corresponding light curves as a function of frequency (ν), as a funtion of energy (E) and as a function of the spectral position in the CCD (parametrized by S_a).

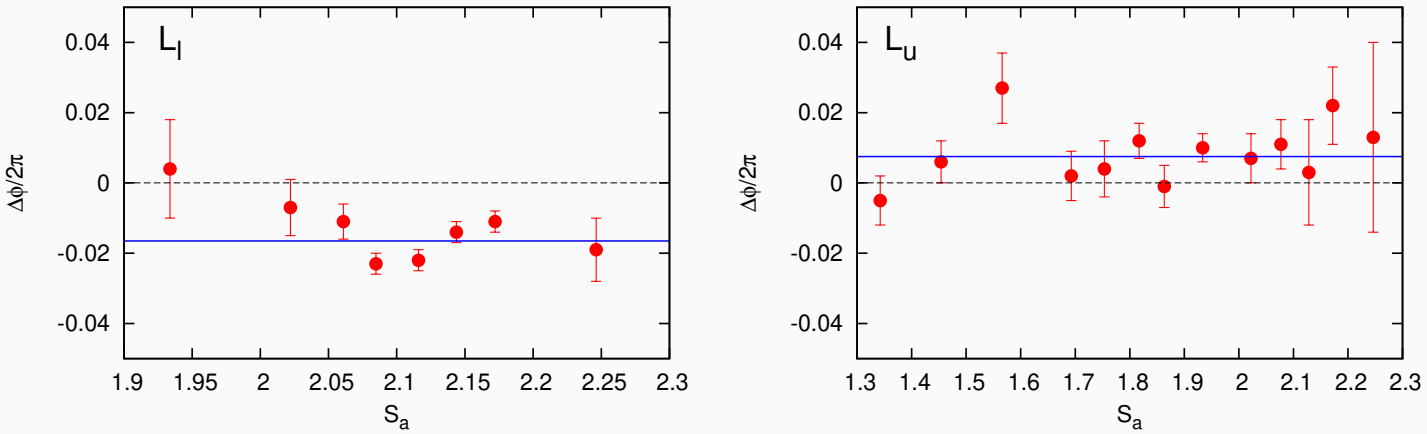

Figure 7: One representative result regards the **kHz QPOs**.

For the kHz QPOs, they found that the phase/time lags are statistically inconsistent with each other in more than 3σ in all cases.

Preliminary results using PDC

Used 4U 1636–53 light curves

- We used the light curves at $\bar{E} \simeq 7.1$ and $\bar{E} \simeq 16.0$ keV.
- Small segments for testing: $16s$ and $1280s$.

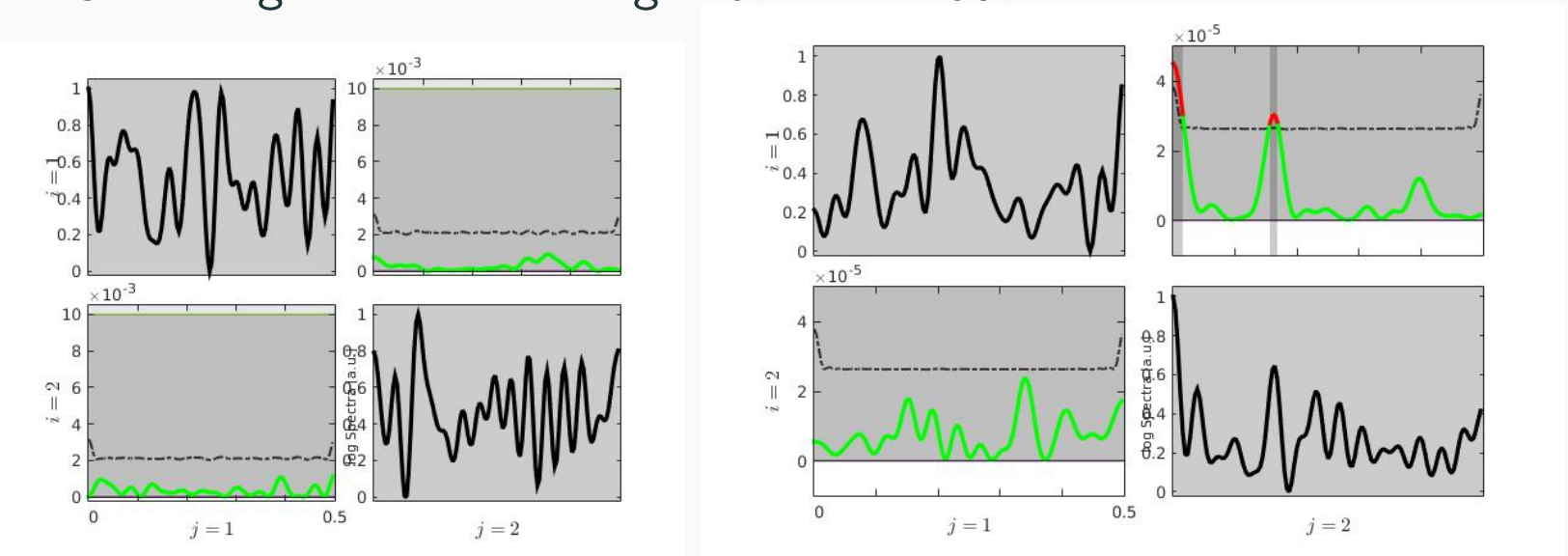

Figure 8: We found causality in the light curve with $1280s$.

Under a robust statistical detection criterion (Baccalá 2013) using a significance of $\alpha = 1\%$, this suggests that the generation mechanism of kHz QPOs in low energy bands is coupled to the generation of kHz QPOs in high energy bands.

Next steps

Work in progress

- Adapt the code for creating the PDS and PDCs apropriately using the X-ray standart techniques,
- apply the PDC technique to complete light curves in many observations as in de Avellar (2016),
- study the PDC as a function of ν, E and S_a,

Questions?

Thanks.