New Results on the Time lags of the Quasi-Periodic Oscillations in the Low-mass X-ray Binary 4U 1636–53

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A general view of the system

4U 1636–53 is a neutron star LMXB with an ordinary low-mass star ($M \lesssim 1.0 M_{\odot}$) in the following configuration:

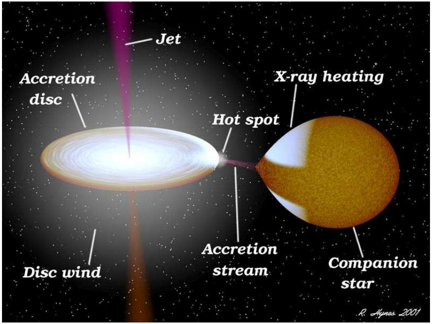

Figure: LMXBs scheme; the X-ray emission comes mainly from the inner edge of the disc.

Variability and correlations

These systems (and the ones containing a black hole) show a myriad of variability features:

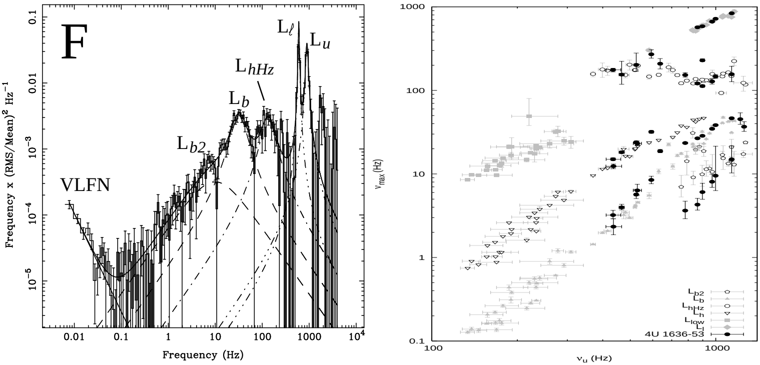

Figure: We see features in the whole frequency space. The black dots on the right panel is 4U 1636–53.

More correlations

Plotting BH systems frequencies against NS systems frequencies reveals similar correlations:

- physically similar phenomena can be the cause of the frequencies;
- these phenomena are extremely tunable;
- this suggests that they arise in the disk.

Models: the QPOs originate in the disk

- kHz QPO models: beat-frequency (Miller et al, 1998), relativistic precession (Stella et al, 1998) and relativistic resonance (Kluźniak et al, 2001) models $\Leftrightarrow$ clumps of matter orbiting the star
  $\nu_u \Leftrightarrow$ orbital frequency at a preferred radius in the disk $\Rightarrow$ this could constrain the EOS.

- $\nu_{hHz} \sim$ const. $\Rightarrow$ diskoseismic modes.
  Fragile et al. (2001): $\nu_{hHz} \Leftrightarrow$ orbital frequency at the radius where a warped disk is forced to the equatorial plane by the Bardeen & Petterson effect.
  Titarchuk (2003): Rayleigh-Taylor gravity waves at the disk-star boundary layer as the origin of hHz QPOs.

- Similar models apply to the QPO at the break frequency.

Definition

Time/phase lags and coherence are Fourier-frequency-dependent measures of the time/phase delay and of the degree of linear correlation between two concurrent and correlated signals, in this case light curves of the same source, in two different energy bands.

These two phenomena generally appear in systems with accretion, and the proposed mechanisms usually involve Compton scattering or reflection off the disc.

Objective

If accretion takes place we can use such mechanisms to:

- study the physics of accretion near the neutron star, since the *time lags* encode information about the size and geometry of the scattering medium or reflector...
- ... so we want to find out the dependence of the *time lags* on the frequency of the QPO and on energy. In order to do so, we divided the data in energy bands and in frequency ranges.

Previous results: the kHz QPOs

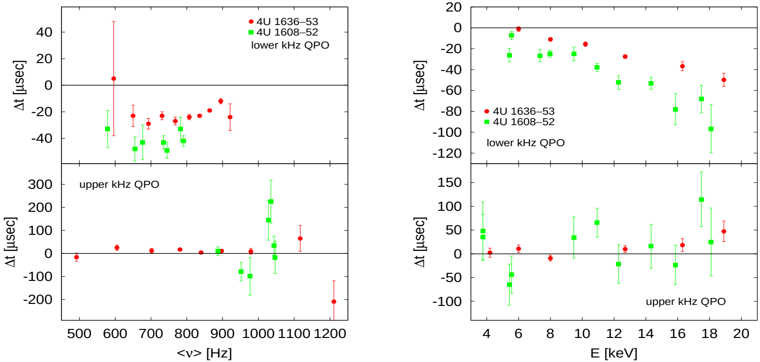

Figure: **Left:** $\nu_{low1636}$: $\bar{\Delta t} = -21.0 \pm 0.6\mu s$; $\nu_{low1608}$: $\bar{\Delta t} = -42.9 \pm 0.3\mu s$
$\nu_{upp1636}$: $\bar{\Delta t} = +11 \pm 3\mu s$; $\nu_{upp1608}$: $\bar{\Delta t} = +5 \pm 15\mu s$
Right: $\nu_{low1636}$: Decay=$3.6 \pm 0.3\mu s/keV$; $\nu_{low1608}$: Decay=$5.0 \pm 0.5\mu s$/keV
$\nu_{upp1636}$ $\bar{\Delta t} = +4 \pm 3\mu s$; $\nu_{upp1608}$ $\bar{\Delta t} = +13 \pm 13\mu s$

Consequences

This was the first study of the dependence of both kHz QPOs upon frequency and the first on energy in the case of the upper kHz QPO.

- Inconsistency of the lags of the lower and the upper;
- light travel time arguments $\Rightarrow$ the region where the lags are produced should be $\sim 3 - 30km$;
- the small variation of the lags with frequency implies that the geometry varies very little, $\sim 1km$.

We kindly refer to:

de Avellar, Marcio G. B.; Méndez, Mariano; Sanna, Andrea; Horvath, Jorge E. **MNRAS, 433, 3453, 2013**

Modelling the lags

So far, the model for lags that better explains our results is

- Lee, Misra and Taam model: explains the soft lags via inverse Comptonization;
- the temperature of the corona and of the source of soft photons oscillate coherently at the kHz QPO frequency;
- can explain the dependence of the lags and of the rms on energy;
- natural consequence: if the lower kHz QPO shows soft lags, then the upper shows hard lags.

Time lags for two other QPOs

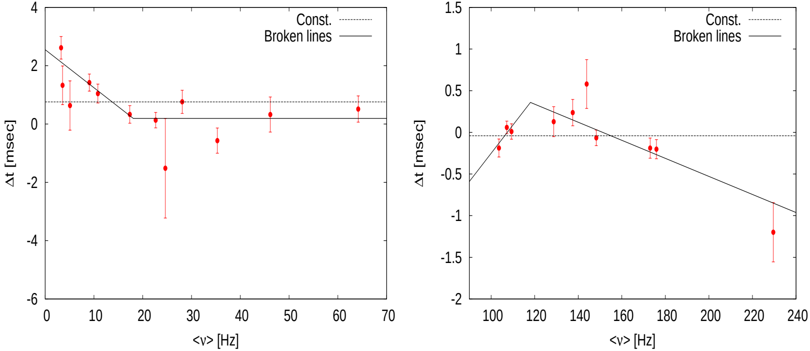

Figure: Time lags for the QPO at the break frequency (left) and for the hHz QPO (right).

Time lags for two other QPOs

From the plots:

- The fits imply a statistically significant dependence of the time lags upon the frequency for the QPO at the break frequency and the hHz QPO;
- for the break frequency QPO, the lags are hard; for the hHz QPO, the lags alternate with a general pattern soft-hard-soft;
- the lags for these two QPOs are 1 to 2 orders of magnitude higher than the lags for the kHz QPOs;
- because of the complicated frequency dependence we cannot draw a complete and consistent picture of the energy dependence yet.

Summary of the time lags

Summarizing our results for all QPOs studied:

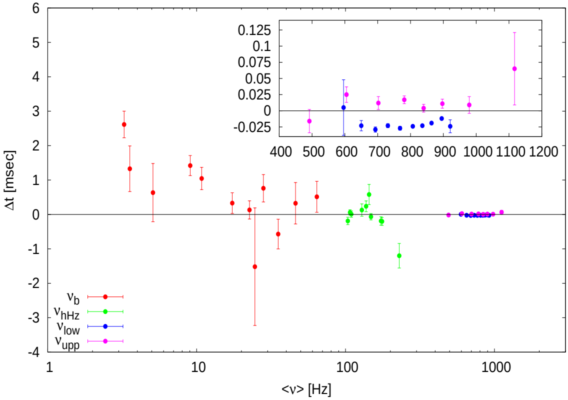

Figure: Time lags *vs* QPO frequency for all QPOs studied.

Discussion and open problems

- Taking the value of the constant fit to the break frequency QPO ($+0.193$ *msec*) and to the hectoHertz QPO (-0.041 *msec*) as simple estimators, one concludes that the geometry of the medium varies by 58 *km* and 12 *km*, respectively.
- However, taking seriously the frequency dependence, specially for the hHz QPO, the variation of the geometry of the scattering medium can be as big as 460 km, much bigger than for the kHz QPOs.
- Again we see inconsistency between the lags.

Discussion and open problems

- Lee, Misra and Taam model cannot explain these lags because there is not a tight link between the hHz QPO and the QPO at break frequency as we see between the two kHz QPOs.
- If the place where the hHz QPO is nearby the location where the kHz QPOs are produced, then there is another mechanism operating and discriminating among the frequencies.
- If Compton scattering is responsible for the lags, we need a denser medium for the hHz QPO and an even denser medium for the QPO at the break frequency in order to produce the 1–2 orders of magnitude bigger lags.
- If the hHz QPOs are somehow related to the compact object parameters, could the lags say something about them?
- ...

Fim

Thank you for the attention and have a nice trip back home!