New Results on Time lags of quasi-periodic oscillations in the low-mass X-ray binary 4U 1636–53

Marcio G. B. de Avellar[1], **Mariano Méndez**[2], **Diego Altamirano**[3], **Andrea Sanna**[4], **Guobao Zhang**[5]

[1]Instituto Astronômico, Geofísico e de Ciências Atmosféricas, Universidade de São Paulo, São Paulo, Brasil.
[2]Kapteyn Astronomical Institute, Groningen, The Netherlands.
[3]School of Physics and Astronomy, University of Southampton, Southampton.
[4]Dipartimento di Fisica, Università degli Studi di Cagliari.
[5]New York University, Abu Dhabi, UAE.

1. Introduction

4U 1636–53 is a neutron star LMXB with an ordinary low-mass star ($M \lesssim 1.0 M_\odot$). Systems like this one (and the ones containing a black hole), and accreting systems in general, show a myriad of variability features in the power density spectra, ranging from millihertz to kilohertz. When the feature is narrow it is called QPO.

Here we extend our previous work [1] using a proper subset of that data set to analyse the frequency-dependent time and phase lags of the QPO at the break frequency and of the hHz QPO (see [2]). Our methodology allowed us to study, for the first time, the dependence of the lags upon the frequency of the QPO itself for these two QPOs in a NS-LMXB.

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

We gently refer the reader to our paper [1] to a more complete discussion about the data set and the used techniques and the results for the kHz QPOs of this source. Otherwise it will be a pleasure to personally talk to you.

2. Time lags vs. QPO frequency (QPO at break frequency)

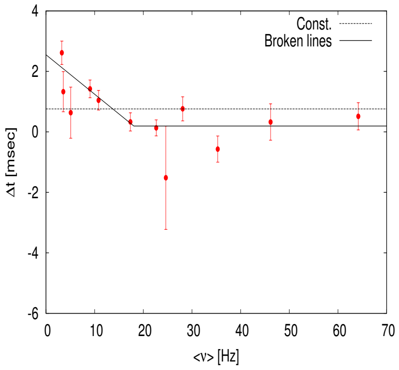

Figure 1: *Time lags vs. QPO frequency for photons with energy in the 12–20 keV band with respect to photons with energy in the 4–12 keV band for the QPO at the break frequency. The fits show a significant dependence of the time lags upon the frequency. The lags are* **hard** *and measures 0.76 msec in average.*

3. Time lags vs. QPO frequency (hHz QPO)

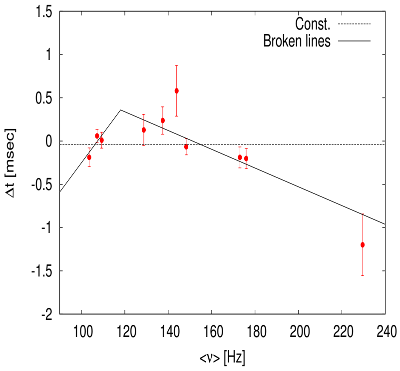

Figure 2: *Time lags vs. QPO frequency for photons with energy in the 12–20 keV band with respect to photons with energy in the 4–12 keV band for the QPO at the break frequency. The fits show a weaker dependence of the time lags upon the frequency. The average lag is* **soft** *and measures 0.041 msec.*

4. Time and phase lags vs. QPO frequency (all QPOs studied)

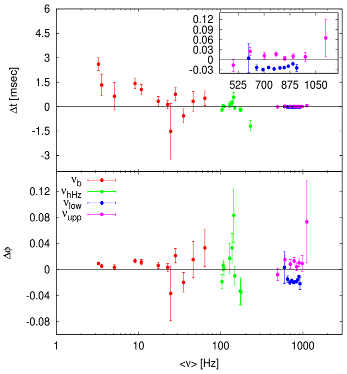

Figure 3: *Upper panel: Time lags versus average centroid frequency of the QPO for all QPOs. Lower panel: Phase lags versus average centroid frequency of the QPO for all QPOs. In general, the magnitude of the time lags decreases when the frequency of these different QPOs increases; the magnitude of the phase lags remains constant. In both cases, notice the lower kHz QPO (dark blue): this feature is statistically different from the others.*

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5. Discussion of the results

1. We find a statistically significant **dependence of the time lags upon the frequency** for the QPO at the break frequency and for the hHz QPO. The lags for these two QPOs are 1 to 2 orders of magnitude higher than the lags for the kHz QPOs and because of the complicated frequency dependence we cannot draw a complete picture of the energy dependence yet.

2. Light travel time arguments give a **upper limit for the size of the medium** in which the time lags are produced. The average value of the lags for the break frequency QPO ($+0.193\ msec$) and for the hectoHertz QPOS ($-0.041\ msec$) give that the size of the medium is $58\ km$ and $12\ km$, respectively. However, if one takes the most positive lag of the hHz QPO ($+0.580\ msec$) and the most negative one ($-1.20\ msec$), the size can be as big as $260\ km$ or $460\ km$ while if one takes the less negative and the less positive lag of the hHz QPO would give us sizes about $10-20\ km$.

3. The authors in [7] and [8] explain the $\sim 30\ sec$ **soft lags** for frequencies $\geq 5 \times 10^{-4}\ Hz$ **seen in AGNs** as the **reflection** of coronal photons off the accretion disc. This scenario could apply to explain at least partially the soft lags seen in the lower kHz QPO of NS-LMXBs, but the model cannot address other properties of this particular QPO such rms increase with energy in these systems (which, by the way is also difficult to reconcile with Compton down-scattering models). See also [9] for an extensive review of this issue.

4. Recently, [10] studied the **phase lags frequency dependence** of high-frequency QPOs in four **black hole candidates**. For one source, GRS 1915+105, the phase lag of the QPO at $35\ Hz$ is soft and the phase lag of the QPO at $67\ Hz$ is hard and inconsistent with the phase lags show by the QPO at $35\ Hz$. One suggestion is that the **same mechanism** that produces the (inconsistent) phase lags of the QPOs at $35\ Hz$ and $67\ Hz$ also applies to the lower and upper kHz QPOs of 4U 1636–36 (see Figure 3); the hHz QPO of 4U 1636–36 could be somehow related to the QPO of the black hole candidates spanning the range $180-450\ Hz$.

5. **Our results for the QPO at the break frequency, for the hectoHertz QPO and for the kiloHertz QPOs, disfavour simple models of Comptonization and also the reflection model. Our results could be signalising that variable corona or a multi-component system may be operating for producing the time/phase lags.**

References

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