# Quasi-Periodic Oscillations are more than just frequencies

Peggy Varniere, APC, UMR 7164, University Paris Diderot, France.
Frederic H. Vincent, Observatoire de Paris / LESIA, France.
Raphael Mignon-Risse, APC, UMR 7164, Universit Paris Diderot, France.

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**Abstract**

Quasi-periodic oscillations (QPO) are an important probe of the timing properties of black-hole binaries and a ubiquitous feature of their PDS. For that reason, many attempts to explain their origin have also reduced them to their frequencies. In order to explore their behavior beyond this, we consider two simple classes of non-axisymmetrical models: elongated hot spots and spirals. We then study different timing AND spectral features of those models, such as how the amplitude evolves with frequencies, the impact of inclination and the consequence on the spectral fit; showing how studying characteristics beyond the frequency is a necessary step that could then be used to differentiate between models.

## 1 Introduction

When looking at the Power Density Spectrum (PDS) of microquasars the most striking features are the presence of Quasi-Periodic Oscillations (QPO). Those cannot be neglected, indeed, the Low-Frequency QPO (LFQPO) alone can have a rms of up to 30% but up to now most models only consider their frequencies. Here we take a simple approach considering two simple classes of non-axisymmetrical models: elongated hot spots and spirals whose temperature profiles are parametrized by

$$T(t,r,\varphi) = T_0(r) \times \left[1 + \gamma \left(\frac{r_c}{r}\right)^{\beta} \exp\left(-\frac{1}{2}\left(\frac{r - r_s(t,\varphi)}{\delta}\right)^2\right)\right] \quad (1)$$

with $T_0$ the equilibrium temperature profile, $\gamma$ the amplitude of the structure, $\delta$ its radial size, $\beta$ is related to how far in radius does the structure extend, and $r_s$ is the actual parametrization of the structure ($r_c$ for the azimuthal size of the blob or $r_c e^{\alpha(\phi - \Omega(r_c)t)}$ for a spiral with $r_c$ the corotation radius of the structure).

Using this parametrization we will then create 'simulated observations' of the flux coming from the disk, allowing us to compute how different parameters, such as the inclination of the system or the position of the structure, influence the observed modulation.

But we will not stop at studying the temporal behavior of the 'observed flux', indeed, it seems surprising that the same disk with a strong QPO is considered smooth with a monotonic temperature profile when trying to fit and explain its energy spectrum. If such a featureless disk can easily model states where there is no QPO or even if the QPO has a low impact (hence low rms), it is incoherent to use it to describe states with prominent QPOs. Using our simple model we can check if the structure at the origin of QPOs visible in the temporal analysis also has a measurable impact on the energy spectrum and its fits.

## 2 Amplitude of the observed modulation and inclination

While inclination has been predicted to play an important role in the origin of the modulation through general- relativity (GR) effects, the study of its impact with observations has just started. Indeed, Motta *et al.* (2015) explored the behavior of the rms amplitude as function of the QPO frequency across several systems encompassing two sets of inclinations (dubbed high and low). They show a distinct overall behavior for high-inclination and low-inclination systems, with the differences between the two changing with the QPO frequency.

Using the above mentioned temperature profile we have the advantage over observation to be able to obtain the flux for multiple observers at different inclinations with respect to the same system. This allows us to compare how the same physical processes occurring in the disk would be detected through observation depending if the system is at 20° or 70° inclination. Fig.1. shows for two models

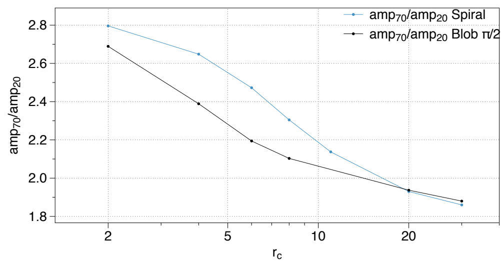


Figure 1: Evolution of the ratio of the amplitude at inclination 70° over the amplitude at inclination 20° as function of the position of the structure given in units of the ISCO radius.

(an elongated hot spot and a spiral) how the ratio between the rms amplitude viewed at 70° and the rms amplitude viewed at 20° changes depending where the structure is located, which is directly related to the frequency of the modulation $\Omega(r_c)$.

While we do see that the impact of inclination also depends on the frequency of the modulation it is hard to compare directly with observation for several reasons.

First of all, the different systems in Motta *et al.* do not all have the same mass, so comparing the amplitude as function of frequencies is a little misleading as the relation between the position of the structure and modulation frequency is dependent on the central mass. One way to solve that would be to show the data taking into account the mass dependence of the frequency. This would be easier to compare between objects.

Secondly, here we are comparing only the impact of inclination, the structure at the origin of the modulation stays the same. This is impossible to ensure in observation, while we can know the inclination of the system, when comparing the amplitude at the same frequency in two systems we do not know the physical state of the system and therefore could be comparing very different structures (a linearly growing versus a saturated instability). One way to limit this could be to study the time-dependence of this effect, as the frequency evolves during an outburst. With this in mind we are now able to use the same models to 'follow' the evolution of the LFQPOs through an outburst (Varniere & Vincent, 2016b).

## 3 Pulse profile and harmonic content

Another advantage of 'simulated observation' is the ability to look directly at the pulse profile of the modulation as we can get the the full lightcurve with enough time resolution. At low inclination the profiles for both models are close to a sinusoid for all the frequencies explored and the harmonic content is low.

But when we look at higher inclinations we see on Fig.2., that, for both the elongated hot spot and the spiral, the profile increasingly departs from a sinusoid as the frequency decreases. Moreover this departure is different for each model which might lead to a way to differentiate them, not at the pulse

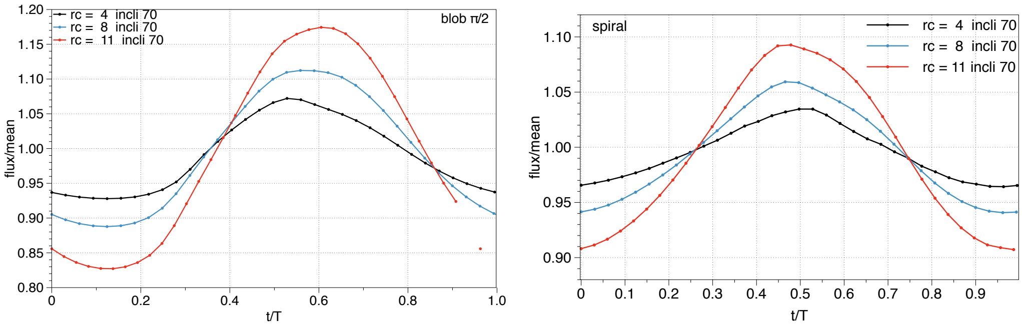


Figure 2: Normalized pulse profile for an elongated hot spot (left) and a spiral (right) seen at an inclination 70° for several position of the structure/frequency of the modulation.

profile level but when looking at the difference between the mean and median flux for each model. For that we would need a long observation in a high flux state with a stable low frequency QPO, like for example the Plateau states of GRS 1915+105.

Another way to look at the same information is by looking in the Fourier space, which is, up to now, the main way to look at QPO. Having such a departure from a sinusoid we expect those to have a high harmonic content. As a result, we see that both models predict that higher inclination systems will have have a stronger, but distinct, harmonic content (Varniere & Vincent, 2016a) which is something that could be looked at observationally.

## 4 Impact on the energy spectrum fitting

With our emission profile we created a model for `XSPEC` in order to use the procedure `fakeit` and simulate observations of the different structures. Those simulations were then fitted similarly as regular observations in order to see if the presence of the structure would be detectable.

For this we used the physical parameters of XTE J1550-564, for which we have numerous 'real' data to compare with. We ran several sets of parameters to reproduce a growing amplitude of the QPO modulation in a regular, diskbb-like, disk which we then fitted with XSPEC following the standard procedure. We took the 'origin point', meaning the disk with a QPO amplitude of 0, to be $(45, 0.7)$ on the $(r_{in}, T_{in})$ diagram.

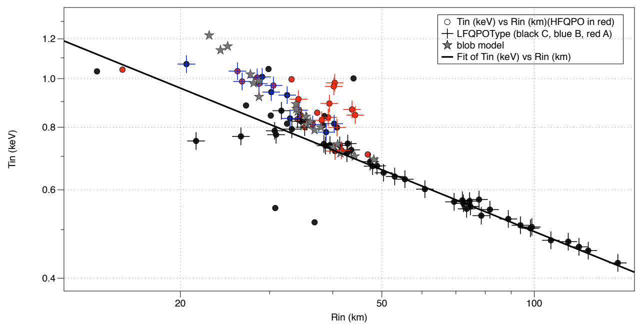


Figure 3: Correlation between the inner edge position and inner edge temperature as given by the spectral fits for the outburst of 98-99 and 2000 of XTE J1550-564. Red dots represent observations with HFQPOs detected while there is none in the black dots. The crosses represent the type of LFQPO, black for the common type C, blue for type B and red for type A. The grey stars are the result of the synthetic spectra fit.

We see on Fig.3 that as soon as the simulated QPO (grey star) has a non-zero amplitude there is a discrepancy between the disk parameters as given by the fit and the one we used as input for the simulation ($R_{in} = 45, T_{in} = 0.7$). On top of that the error is growing with the modulation/QPO amplitude but already with a 5% rms for the QPO we get an error of about 14% on $T_{in}$ and 12% on $r_{in}$ . Which means that even with RXTE resolution, neglecting the effect from the structure at the origin of the QPO in the spectral analysis leads to large errors. With ATHENA it will be even more important to fully model the disk structure in presence of QPOs.

It is also interesting to note that this set of simulated observations with a growing QPO occupy the same space as the HFQPO/type B LFQPO, strengthening the link between QPO, hot spot, and fit-difficulties. This could be used to detect, purely from spectral analysis, the possible presence of HFQPOs, that could then be investigated further in the time-domain.

## 5 Conclusions

Using a simple model of structures orbiting in the disk as a source of flux modulation we have compared two distinct models, an elongated hot spot and a spiral, and studied how the modulation is impacted by different parameters such as the inclination of the system or the position of the structure. We also took a look at the resulting energy spectrum to see if any hints of the structure were detectable.

Inclination does have an impact on the observed modulation amplitude, this impact is different depending on the structure at the origin of the modulation.

A more precise study against specific objects is needed to remove the impact of object mass and time into the outburst.

Looking at the harmonic content and the mean/median flux might be a way to explore the differences between models.

Very small amplitude QPOs have a negligible impact on the energy spectrum and can be ignored but above 5% rms amplitude we cannot neglect the presence of the hot structure as it leads to significant errors in the fits.

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