A two-component Comptonisation model for the type-B QPO in MAXI J1348-630 revealed by NICER

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**C. Bellavita (La Plata, ARG)**
The corona geometry and its evolution is still unknown...  
(wonderful NICER datasets of MAXI J1820+070)

(Kara+2019)

~500 Rg! during the state transition  
(Wang+2021)
Motivation

- X-ray variability in LMXBs → study physics and geometry of accretion flows
- Power Density Spectra show a variety of QPOs → characteristic frequencies containing dynamical and geometrical information of the innermost regions.
- In this talk, we will focus on the radiative properties of these QPOs and what we can learn from them using a Comptonisation model.

Outline

- The spectral-timing Comptonisation model in a napkin:
  - The lower kHz QPOs in 4U1636-53
- Low-frequency QPOs in BH XRBs:
  - The Type-B QPO in MAXI J1348-630 seen by NICER.
The Comptonisation spectral-timing model

**Physical parameters of the model**
- Corona temperature, $kTe$
- optical depth, $\tau$
- Soft-photons source, $kTs$
- feedback fraction, $\eta$
- corona size, $L$
- QPO frequency

The complex spectrum is found solving the linearised time-dependent *Kompaneets* eq. for Comptonisation

$$n_\gamma = n_{\gamma,0}(1 + \delta n_\gamma \ e^{-i\nu_{qpo}t})$$

Spectrum = Steady State + Variability at QPO frequency

Karpouzas+ (2020)
Kumar & Misra (2014)
Lee & Miller (1998)
The Comptonisation spectral-timing model

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- Corona temperature, $kT_e$
- Optical depth, $\tau$
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- Corona size, $L$

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The complex spectrum is found solving the linearised time-dependent Kompaneets eq. for Comptonisation. Escaping photon

Karpouzas+(2020)
Kumar & Misra (2014)
Lee & Miller (1998)
Energy-dependent variability (rms) and phase-lags

- rms increases with energy, showing a pivot point at low energies for low feedback ($\eta$)
- lags strongly depend on the feedback ($\eta$):
  - low $\eta \Leftrightarrow$ hard lags whereas high $\eta \Leftrightarrow$ soft lags
The lower kHz QPO in 4U 1636–53
(Karpouzas+2020, MNRAS 492, 1399-1415)

Zhang+2017 and Ribeiro+2017 measured the energy-dependent rms and lags of the lower kHz QPOs in the NS XRB 4U 1636–53 in the 570–920 Hz frequency range.

We fitted these data for 11 QPO frequencies, to study the frequency-dependent properties of the compact Comptonising region surrounding the NS.

We found two solutions: cold seed (blue) and hot seed (red). The cold seed (blue) leads to more reliable power-law indices and shows that the frequency-dependent properties are mainly driven by the size L evolution of the thick (τ~10) and compact (L ~ 5–10 km) corona.

Karpouzas, Méndez, .., FG (2020)
The recent outburst of MAXI J1348–630

- MAXI J1348 is a recently-discovered BH transient (Yatabe+2019, Tominaga+2020).
- It went into outburst in Jan 2019 and transitioned from the Hard to the Soft State ~1 week later (Nakahira+2019, Cangemi+2019).
- During the transition, it showed a prominent Type-B QPO in the 4–5 Hz frequency range.
The type-B QPO in MAXI J1348–630

- In a recent paper (Belloni+2020) measured the spectral-timing properties of this QPO using NICER data (down to low energies ~0.8 keV).

- They found increasing-with-energy fractional variability (rms) and a particular lag-energy spectrum, with positive phase-lags with respect to a reference band at mid energies of 2–2.5 keV.

- They also fitted the time-averaged spectra with a \textit{diskbb*simpl} model and found:
  \[
  kT_{\text{dbb}} \sim 0.6 \text{ keV}, \quad \Gamma \sim 3.5 \text{ (with } kT_e > 10 \text{ keV)}
  \]
We used our Comptonisation model to fit the spectral-timing data of the QPO.

Our model can roughly describe the data:

- Overall rms trend is found (increasing rms with $E$).
- Lag spectrum shape is recovered (but with bad $\chi^2$).

The data is fitted using a single Comptonisation region of $\sim7000$ km ($\sim400$ Rg for $10$ Msun BH) with intermediate feedback ($\eta \sim 50\%$) which explains the change from soft to hard lags at $E \sim 2.5$ keV.

F. García et al. (2021, MNRAS 501, 3173)
A two-component variable-Comptonisation model

- We then explored the possibility that the QPO spectrum arises from two Comptonisation regions:

\[
N(E,t,\omega_0) = N_1(E) e^{i\omega_0 t} + N_2(E) e^{i(\omega_0 t + \phi)}
= \left(N_1(E) + N_2(E) e^{i\phi}\right) e^{i\omega_0 t} = |N(E)| e^{i\Phi(E)} e^{i\omega_0 t},
\]

(1)

- By doing this, we can get the variability amplitudes and phase-lags by combining two Comptonisation models, this way:

\[
|N(E)| = \left[|N_1(E)|^2 + |N_2(E)|^2 - 2|N_1(E)||N_2(E)| \cos(\phi_2(E) - \phi_1(E) + \phi)\right]^{1/2}
\]

\[
\tan(\Phi(E)) = \frac{\text{Im}\{N_1(E)\} + \text{Im}\{N_2(E) e^{i\phi}\}}{\text{Re}\{N_1(E)\} + \text{Re}\{N_2(E) e^{i\phi}\}}
\]

García+2021
Fitting a two-component Comptonisation model

- With this model, we obtain remarkably better fits to both the \textit{rms} and \textit{lag} spectra.
Fitting a two-component Comptonisation model

- The data is well fitted invoking two Comptonisation regions of ~500 km (25-30 Rg) and ~10 000 km (550 Rg).

- In the fits, we recover compatible temperatures for the soft-photon source ($kT_s$) with the time-avg spectrum, in both cases.

- This points to the innermost parts of the disk as the main source of soft-photons (and variability).

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<tr>
<th>Component</th>
<th>$kT_s$ (keV)</th>
<th>$L$ ($10^3$ km)</th>
<th>$\eta$</th>
<th>$\delta H_{ext}$ (%)</th>
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<td>Small (1)</td>
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\[ \chi^2_{\nu} = 1.92 \text{ (23 dof)} \]
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Garcia+2021
Switching to a *diskBB* as the soft-photon source
*(preliminary results)*

\[ \chi^2 = 1.71 \text{ (23 dof)} \]

- The data is **best fitted** invoking two Comptonisation regions of \(~350 \text{ km (20 Rg)}\) and \(>12 \text{ 000 km (>650 Rg)}\).

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- In the fits, we recover compatible temperatures for the soft-photon source \((kT_s)\) with the time-avg spectrum (0.6 keV for a diskBB).

- The most important change is in the feedback fraction of the large component.
Switching to a *diskBB* as the soft-photon source

*(preliminary results)*

- The data is **best fitted** invoking two Comptonisation regions of \(~350 \text{ km (~20 Rg)}\) and \(>12,000 \text{ km (~650 Rg)}\).

- In the fits, we recover compatible temperatures for the soft-photon source \((kT_s)\) with the time-avg spectrum \((0.6 \text{ keV for a diskBB)}\).

- The most important change is in the feedback fraction of the large component.

(see Carotenuto+2021)

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Summary

- Comptonisation dominates the spectra in the hard and intermediate states in BH XRBs.
- We have shown that a spectral-timing Comptonisation model can fit well the energy-dependence of the low-frequency QPOs in these sources.
- The QPO lags can be used to constrain the size of the Comptonising region, information that cannot be attained from the typical time-averaged spectra.
- A feedback term is required to produce soft QPO lags as those seen in the low energy band in the type-B QPO of MAXI J1348.
- In this case, a good fit is obtained when two Comptonisation regions are considered, possibly revealing a more complex underlying corona structure (García+2021).
- Finally, we note that thanks to recent spectral-timing analyses, new evidence has been gathered regarding the evolution of the size of the Comptonisation region (corona) during BH outbursts, mainly thanks to NICER (Kara+2019, Wang+2021, and see our recent... Karpouzas+2021).
Thank you very much for your attention!

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