QUASI PERIODIC OSCILLATIONS IN BLACK HOLE BINARIES

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“The Extremes of Black Hole Accretion” ESAC 8 - 10 June 2015
X-ray binaries

Fig. 1.

Results of BHXRB systems, the companion donor star is of lower mass and variable BHXRB, GRS 1915+105 (\(L < 0.7\)).

At luminosities in the range of 10 to 10^5 L\(_{\odot}\), the x-ray spectrum is characterized by a spectral flattening. Even more striking than the spectral evolution is the change in the x-ray variability properties of the BHXRB. The characteristic frequencies of BHXRBs in outburst begin to change (50% of the Eddington luminosity, the x-ray spectrum is typically soft). In the hard state, a more blackbody-like component that peaks in power at ~100 keV, probably corresponding to a geometrically thick, optically thin flow. This state shows strong and rapid variability in x-rays, with up to 50% of the Eddington luminosity as the blackbody-like component at some point it reaches ~4000 K and atmosphere as the mass accumulates, until the disc cools again, the viscosity drops, along with the hydrogen starts to become ionized, leading to a jet.

In the brightest hard states, a more blackbody-like spectrum in follow-low-mass BHXRB. The major components are blackbody-like and jet-like, with variable blackbody-like components.

The outbursts of low-mass systems are likely to be triggered by a wind outburst (including in some cases multiple outbursts) that has allowed us to make steady. Initially, the mass transfer rate onto the central black hole can change by orders of magnitude in just intervals between these cycles can last from months to years. It is the detailed study of these intervals that approach the Eddington luminosity, as detected by x-ray all-sky monitors. Sources in quiescence are rarely regularly monitored but optically thin flow. This state shows strong and rapid variability in x-rays, with up to 50% of the Eddington luminosity as the blackbody-like component at some point it reaches ~4000 K and atmosphere as the mass accumulates, until the disc cools again, the viscosity drops, along with the hydrogen starts to become ionized, leading to a jet.

The hard-to-soft spectral transition sometimes replaces by a single QPO, indicating strong oscillations in the state transitions, but at a certain point, the outburst takes place in this state. In the hard state, the x-ray source is typically soft. In the hard state, a more blackbody-like component that peaks in power at ~100 keV, probably corresponding to a geometrically thick, optically thin flow. This state shows strong and rapid variability in x-rays, with up to 50% of the Eddington luminosity as the blackbody-like component at some point it reaches ~4000 K and atmosphere as the mass accumulates, until the disc cools again, the viscosity drops, along with the hydrogen starts to become ionized, leading to a jet.

In recent years, it has become apparent that the major steps of the past decade was the realization of the soft photons that are inverse Compton scattering in a relatively narrow range of frequencies above the hot corona component, and a good candidate is the outburst through Fig. 2, top; a sketch of likely X-ray emission (\(L < 0.7\)).

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X-ray binaries: they vary!

24 BH transients in the RXTE era

Dunn et al. 2010
X-ray binaries: they vary!

Hardness Intensity diagram

Disk emission dominates
Low variability

Hard emission dominates
High variability
...on several timescales

- Low Frequency QPOs
- High Frequency QPOs
- Burst Oscillations
- Quasi periodic variability
- Aperiodic variability
- Broad band Noise
- Pulses from accreting X-ray pulsars

(Aql X-1, 4U 1728-34, Sco X-1, XTE J1859+226, GRS 1915+105)
What is a QPO?
Quasi-Periodic Oscillation

- Quasi periodic signal in the flux (CVs, BHs, NSs, ULXs, even AGN)
- Becomes apparent in a power density spectrum
- They come in different flavours
- Associated to noise
Why should we care?

- They are useful! Common and easy to study, they help identifying source states
- Produced close to the central compact object
- Geometry constraints and strong gravity tests.
Low frequency QPOs in Black Holes

- Discovered in the 80s in NS (EXOSAT, GX 5-1) and BHs (Ariel 6, GX 339-4)
- First “types” from Ginga data
- Very common
- Seen in NSs as well (HBOs, NBOs, FBOs…)

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<tr>
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<th>A</th>
<th>B</th>
<th>C</th>
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<td>$\sim6$ Hz</td>
<td>$\sim6$ Hz</td>
<td>0.1-30 Hz</td>
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<tr>
<td>Q</td>
<td>1-3</td>
<td>$\geq6$ ($\geq2$)</td>
<td>$\geq6$ ($\geq2$)</td>
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<tr>
<td>rms</td>
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<td>$\sim1-10%$</td>
<td>$\sim1-25%$</td>
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<td>noise</td>
<td>weak red</td>
<td>weak red</td>
<td>strong flat-top</td>
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see e.g. Van der Klis et al. 1985 and Motch et al. (1983), Miyamoto et al. 1991, Wijnands et al. 1999; Homan et al. 2001; Remillard et al. 2002; Casella et al. 2005, …
Type-A QPOs

- Very few detections (~10 in the RXTE archive)
- Observed is soft states, close to type-B QPOs
- Broad and faint
- Origin: possibly related to type-B QPOs. Disk instabilities?
Type-B QPOs

- Fairly common QPO
- Observed in intermediate states
- Strong peak(s) and weak red noise
- Origin: probably associated to jets. Disk instabilities? (e.g. Varnière et al. 2002, 2012)
Type-C QPOs

• The most common QPO of all, they vary a lot in frequency

• Observed in hard and soft states

• Strong peak(s) and strong flat-top noise

• Origin: instabilities or geometrical effects (i.e. precession)
Type-C QPOs

- Oscillations of boundary layers/coronae
  (e.g. Titarchuk & Fiorito 2004 and Cabanac et al. 2010)

- Accretion-ejection instability

- Relativistic precession
  (Stella & Vietri 1998, Schnittman et al. 2006, Ingram et al. 2009...15)

see Ingram’s and Rapisarda’s talks
One last fun-fact: inclination effects

- Stellar mass Black holes in binaries
- Supermassive black holes in AGN

“different” objects at different inclinations

- Winds only in high-inclination sources
- Hotter disks in high-inclination sources

Ponti et al. 2012
Moñuz-Darias et al. 2013
QPOs and noise amplitude depend on inclination

Motta et al. 2015
Take home message

• **Type-C, type-B QPOs** and the associated **noises** are **very different** phenomena.

• The **relativistic precession** of the inner flow is the only mechanism that explain the properties of Type-C QPOs and their noise.

• **Type-B QPOs** might be indeed related to the relativistic **jet** (no other obvious mechanism stronger face-on).
High frequencies QPOs in Black Holes

- Discovered with RXTE in the 90s in GRS1915+105
- Quite rare, and difficult to detect, especially in pairs
- Exist in neutron stars as well (as kHz QPOs)

HFQPO sources

- XTE J1550-564
- GRO J1655-40
- XTE J1859+226
- H 1743-322
- GX 339-4
- XTE J1752-223
- 4U 1630-47
- GRS J1915+105
- IGR J17091-3624

High frequencies QPOs in Black Holes

- Observed at high luminosity
- Frequencies close to the keplerian values
- Several models: relativistic precession and resonances models

Relativistic precession model (Stella & Vietri 1999); modified relativistic precession model (Bursa 2006);
Non-linear resonance model (Aliev & Gal’tsov 1981); keplerian non-linear resonance model (Abramowicz & Kluzniak 2004), warped-disk model (Kato 2004)
Models can be tested: the Relativistic Precession Model

Stella & Vietri 1998, Stella et al. 1999

- The RPM predicts three frequencies: orbital, periastron precession and nodal precession

\[
\begin{align*}
\nu_{\phi} &= \pm \frac{1}{2\pi} \left( \frac{M}{r^3} \right)^{1/2} \frac{1}{1 \pm a \left( \frac{M}{r^3} \right)^{3/2}} \\
\nu_{\text{per}} &= \nu_{\phi} \left( 1 - \left( 1 - \frac{6M}{r} - 3a^2 \left( \frac{M}{r} \right)^2 \pm 8a \left( \frac{M}{r} \right)^{3/2} \right)^{1/2} \right) \\
\nu_{\text{nod}} &= \nu_{\phi} \left( 1 - \left( 1 + 3a^2 \left( \frac{M}{r} \right)^2 \mp 4a \left( \frac{M}{r} \right)^{3/2} \right)^{1/2} \right)
\end{align*}
\]
Let us test it

- **GRO J1655-40**: 3 simultaneous QPOs and a dynamical measurement of the mass

- **XTE J1550-564**: 2 simultaneous QPOs and a dynamical measurement of the mass

Bonus: in both cases, you get a BH spin!
Take home message

• You can do amazing things with X-ray timing, even measure black hole spins and masses

• QPOs can tell a lot about accretion and about black holes (if you understand them)

• QPOs are fun…and useful!
Thank you!