From general relativity to spin and mass measurements through the Relativistic Precession Model

Time to weigh black holes

Sara Motta
and Tomaso Belloni, Luigi Stella, Teo Muñoz-Darias, Rob Fender

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X-RAY BINARIES

Diagram showing:
- Jet
- Accretion disc
- Hot spot
- Disc wind
- Accretion stream
- Companion star
- X-ray heating
X-RAY BINARIES: THEY VARY!

Dunn et al. 2010

X-ray light curves of 24 transient black hole X-ray binaries

(RXTE data over ~ 15 years)
...ON SEVERAL TIMESCALES

Periodic variability

Pulses from accreting X-ray pulsars

Low Frequency QPOs

Burst Oscillations

Quasi periodic variability

High Frequency QPOs

Aperiodic variability

Broad band Noise

kHz QPOs

Sco X-1

4U 1728-34

Bursty oscillations

GRS 1915+105

4U 1728-34

Aql X-1

Broad-band noise
...ON SEVERAL TIMESCALES

- Periodic variability
  - Low Frequency QPOs
  - High Frequency QPOs
- Quasi periodic variability
  - Burst Oscillations
- Aperiodic variability
  - Broad band Noise

Pulses from accreting X-ray pulsars

Examples:
- Aql X-1
- Sco X-1
- 4U 1728-34
- GRS 1915+105
- XTE J1859+226
WHAT IS A QPO?
QUASI PERIODIC OSCILLATION

- Quasi periodic signal in a light-curve (BHs, NSs, ULXs, even AGNs)
- Becomes apparent in a power density spectrum
- Associated to noise
- They come in different flavors
QPOs IN BLACK HOLES

LOW FREQUENCY

- Type A
- Too slow to be keplerian!
- Casella et al. 2004

Very common. Different shapes, frequency ranges, noise level...
We do not know what they are.

HIGH FREQUENCY

- Type B
- Might be keplerian!
- Strohmayer 2001

- Type C

Not common nor easily detectable (especially in pairs), and again...
We do not know what they are.
WHY DO WE CARE ABOUT QPOs?

• produced close to the central compact object
• They are very common
• Easy to study
• They allow to test General relativity!

But collecting pretty peaks is not enough...!
THE RPM
RELATIVISTIC PRECESSION MODEL
Stella & Vietri 1998, 1999, 1999a

If you have $\nu_\phi$, $\nu_{\text{per}}$, $\nu_{\text{nod}}$ together you can solve the system!

\[
\begin{align*}
\nu_\phi &= \nu_\phi (M, a, R) \\
\nu_{\text{per}} &= \nu_\phi - \nu_r = \nu_{\text{per}} (M, a, R) \\
\nu_{\text{nod}} &= \nu_\phi - \nu_\theta = \nu_{\text{nod}} (M, a, R)
\end{align*}
\]

≡ Orbital frequency
≡ Periastron precession frequency
keplerian frequency - radial epicyclic frequency
≡ Nodal frequency (or Lense-Thirring)
keplerian frequency - vertical epicyclic frequency

R in the same for all the equations
GRO J1655-40

\[
\begin{align*}
\nu_\phi &= \nu_\phi (M, a, R) \\
\nu_{\text{per}} &= \nu_\phi - \nu_r = \nu_{\text{per}} (M, a, R) \\
\nu_{\text{nod}} &= \nu_\phi - \nu_\theta = \nu_{\text{nod}} (M, a, R)
\end{align*}
\]

Those peaks are observed \textit{simultaneously}!

data from RXTE
GRO J1655-40

\[ \nu_{\phi} = \nu_{\phi}(M, a, R) \]

\[ \nu_{\text{per}} = \nu_{\phi} - \nu_{r} = \nu_{\text{per}}(M, a, R) \]

\[ \nu_{\text{nod}} = \nu_{\phi} - \nu_{\theta} = \nu_{\text{nod}}(M, a, R) \]

Type-C QPO \( \nu_{\text{nod}} \)

Nodal Frequency

Lower HFQPO \( \nu_{\text{per}} \)

Periastron precession frequency

Upper HFQPO \( \nu_{\phi} \)

Orbital frequency

Motta et al 2012

Strohmayer 2001

17Hz

300Hz (2-12 keV)

440Hz (13-27 keV)
YOU GET THE MASS AND THE SPIN!

In Hz

\[ \nu_\phi = 17.25 \pm 0.07 \]
\[ \nu_{\text{per}} = 298 \pm 4 \]
\[ \nu_{\text{nod}} = 440 \pm 3 \]

In solar masses and gravitational radii

\[ M = 5.31 \pm 0.07 \]
\[ a = 0.286 \pm 0.003 \]
\[ R = 5.68 \pm 0.04 \]

Beer & Podsiadlowski 2002
From Optical-Infrared

e.g. Shafee et al. 2006
From X-ray spectroscopy

M = 5.4 \pm 0.3 M_\odot
a = 0.65 \div 0.75
YOU GET THE MASS AND THE SPIN!

Motta et al. 2013
THE RPM FOR GRO J1655-40

Frequency vs radius

Frequency vs nodal frequency

Motta et al. 2013
The RPM + Type-C QPOs

Radius (gravitational radii)

Type-C QPOs

Frequency (Hz)

Nodal Frequency (Hz)

Number of occurrences

Type C QPO Frequency (Hz)

Hardness Ratio

Count Rate [Counts/s]

Frequency at ISCO
Frequency at R_{\text{Horizon}}
Orbital frequency
Periastron precession frequency
Observed LFQPO
Simultaneous QPOs
THE RPM + TYPE-C QPOs + PBK RELATION

Psaltis, Belloni, van der Klis 1999 (PBK correlation)

Motta et al. 2013
SUMMARIZING

what you do

• you start from GR
• you measure 3 frequencies
• you solve the RPM system system of equations
• you get reasonable mass and spin
• the predicted frequencies match the data

what you get

• you verify the validity of the RPM (relativistic precession and keplerian motion do explain QPOs!)
• you have a method to measure black hole spin and mass and to track the emission radius
• the PBK broad components and HFQPOs are unified by the RPM
IN CONCLUSION

You can do real hard core physics from timing!

From the timing you get a very precise measure of the fundamental parameters of a Black Hole