Energy spectra of X-ray quasi-periodic oscillations in the Lense-Thirring precession model

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X-ray QPO

Low-$f$ QPO
Observed energy spectra of QPO

Disk emission is not present in the QPO spectra.

When time averaged spectra are soft, the QPO spectra are harder than the time averaged spectra.
Observed energy spectra of QPO

Hard spectral state

Intermediate state

When the time averaged spectra are **hard**, the QPO spectra are **softer** than the time averaged spectra
(Thermal) Comptonization is described by two main parameters: heating rate and cooling rate of the plasma. Spectral slope determined by the ratio of the two quantities. Variability (broad-band or QPO) may be driven by variations of $l_h$ and/or $l_s$.

In the specific situation of multi-phases accretion flows (soft photons from reprocessing) one can also imagine variations of the geometry of the flow, leading to variations of the viewing geometry (e.g. viewing angle), heating-to-cooling ratio and/or reflection amplitude.
Modulation of heating rate

Spectral variability folded with QPO period

r.m.s./mean variability

Energy spectra

QPO energy spectrum is *harder* than the time averaged spectrum

Życki & Sobolewska 2005
Modulation of cooling rate

Spectral variability folded with QPO period
r.m.s./mean variability
Energy spectra

QPO energy spectrum is softer than the time averaged spectrum
Modulation of the covering factor of the cold matter

Fe Kα line present in the QPO spectrum
Lense-Thirring precession model for low-$f$ QPO

Formulated by Stella & Vietri (1998)

Recent hydrodynamical simulations suggest that the hot flow behaves (precesses) like a solid body.

Inner radius of the flow is determined by properties of the bending waves. It is approximately independent of the spin of the black hole. As a result the maximum precession frequency does not depend on the spin)

(C. Done, A. Ingram, C. Fragile)
Two geometrical scenarios:
1. precession axis perp. to the outer disk
2. Precession axis inclined to the outer disk (based on Bardeen-Peterson effect)
Geometry
geometrically thick torus; to be compared with the blue curve

coplanar config.

prec. axis perp. to the outer disk

prec. axis inclined to the outer disk
Results

Precession scenario 1 (precession axis *perpendicular* to the outer disk axis)
Precesion scenario 2 (precession axis *inclined* to the outer disk axis) precession axis *towards* the observer
Precession scenario 2 (precession axis *inclined* to the outer disk axis)
precession axis *away from* the observer
Variations of the iron K$_\alpha$ line

Ingram & Done 2012

RXTE PCA: 5ks

XMM EPIC–pn: 5ks

LOFT LAD: 5ks

XMM EPIC–pn: 100ks