Outbursts

GX 339-4
RXTE ASM light curve
High energy spectra of BH X-ray binaries

Non-thermal emission: ‘the corona’

Thermal emission: accretion disk

Hot plasma:
- accretion disk
- corona
- hot accretion flow
- jet

from Done et al. 2007
Radio jets

Compact partially absorbed jets (mas scale) (Stirling et al. 2001)

Discrete ejections (superluminal, ballistic) (Mirabel et al. 1994)
Spectral evolution during outbursts of BHBs

Soft State

Hard State

no jet detection

compact jet

discrete ejections

state transition

hard state

soft state

Hardness

rate

Energy (keV)

Hardness

Energy (keV)
Hot flow = hot Jet Emitting Disc solution
Ferreira et al. 2006; Petrucci et al. 2008; Petrucci et al. 2010; Marcel et al. 2018a, 2018b, 2019
(see talk by Petrucci)
Alternative accretion geometry in hard state:
compact ‘lampost model’

Maxi 1820+070 in hard state:
Only narrow iron core emission (from large radii) changes significantly
→ Inner disk radius does not change
→ change in the extension of the corona is inferred
Constraints on geometry from X-ray polarisation measurements

- PoGO+ balloon observations of Cyg X-1, constrains polarization degree <8.6% in 20-180 keV band and alignment of the polarisation angle with radio jet axis
- Consistent with predictions from a truncated disc model with transition radius ~15 Rg (see e.g. Schnittman & Krolik 2010)

- Parameters obtained from spectral fits with lamp-post model are not consistent with low observed polarisation degree (see e.g. Dovciak et al. 2010, 2011).
  - Large lamp-post height is required.
  - Observed polarisation angle not explained in the lamppost model.

Chauvin et al. 2018
Emission in excess of thermal comptonization detected in several sources in hard state. 
(Mc Connell et 2002; Del Santo et al. 2008)

IC emission from non-thermal electrons in the corona (hybrid thermal/non thermal models) 
(Coppi & Poutanen 1998)

INTEGRAL polarization measurements in Cyg X-1 suggests excess is strongly polarized (PD: 76%+/−15% above 230 keV).

Jet synchrotron emission? 
(Jourdain et al. 2012, Laurent et al 2012, but see Zdziarski et al. 2017)
Nature of OIR emission

Synchrotron from non-thermal particles in hot-flow/corona?

(Fabian et al. 1982; Veledina et al. 2011, Veledina et al. 2018)

Synchrotron jet emission?

(Kanbach et al. 2001; Chaty et al. 2003; Malzac et al. 2004)
Fast X-ray variability

Broad-brush dependence of variability on state

Hard

Intermediate

Soft

Broadband noise dominates

Strong quasi-periodic oscillations (QPOs)

Broadband noise dominates
Propagating fluctuations model of variability

Accretion flow fluctuations propagate inward, modulated at faster times scales at smaller $R$

(Lyubarskii 1997)
Changing radius of stable disc + unstable hot flow?

Churazov et al. (2001), Done et al. 2007): disk moves in, variability power concentrates in narrower range of time-scales/frequencies. Can also explain weak variability in disk-dominated soft state.
**Power-law variations: hard band vs medium band**
- hard photons lag behind variations at softer energies
- time-lags increase towards lower frequencies (longer time-scales)
- lag vs energy dependence is approximately log-linear

(Nowak et al. 1999; Kotov 2001)

**Disk vs power-law variations:**
- At low Fourier frequencies, ‘disk’ leads PL by a few 0.1 s
- At high Fourier frequencies, ‘disk’ lags behind PL by a few ms (reverberation lags?)

(Utley et al. 2011)
Models for the hard lags


—> Can produce large lags (viscous time-scale) if corona is strongly radially extended
—> Energy dependence of lags is included in an had-hoc way
—> 3 radii in the hot flow with enhanced emission (inner disc, inner hot flow and jet launching radius) Mahmoud & Done 2018
Models for the hard lags

Propagation through the disc: accounting for seed photon variability

\[ \Gamma \propto \left( \frac{L_{\text{seed}}}{L_{\text{heat}}} \right)^{1/6} \]

(Uttley & Malzac in prep.)
Interpreting the thermal reverberation lags

Assuming zero intrinsic reverberation lag relative to coronal heating:

The thermal reverberation lags are relative to seed rather than coronal heating – depend on propagation delays and coronal geometry, not just light-travel time.

(Uttley & Malzac in prep.)
Lense-Thirring Precession of the hot inner accretion flow. The flow precesses like a solid body if $H/R > \alpha$.

Modulation due to relativistic light bending and Compton anisotropy.

QPO rms amplitude up to $\sim 10\%$.

Predict precession frequencies in observed range with little spin dependence.

Modulation of polarisation angle and amplitude predicted.

QPOs also in optical and infrared

The case of the IR QPO of GX 339-4

- Simultaneous IR / X timing data with VLT/ISAAC and RXTE (Kalamkar et al. 2016)
- IR QPO @ ~0.08 Hz
- X-ray QPO @ ~0.16 Hz

Main X-ray QPO and IR QPO frequencies are different but in harmonic

Precession model: Depending on hot flow geometry, orbital inclination and precession angle, X-ray QPO can be dominated by second harmonic.

Veledina et al. 2013
Nature of OIR QPOs

Synchrotron from non-thermal particles in the same precessing hot flow that produces the X-ray QPO.

Veledina et al. 2013

Synchrotron emission from precessing jet.

Kalamkar et al. 2016; Malzac et al. 2018

Liska et al. 2018
The case of GX 339-4:
Combining X-ray and IR QPO information

Assuming X-ray and IR emission are both from hot accretion flow

Calculations based on precessing hot-flow model by Veledina et al. 2013

Amplitude of both fundamental AND harmonic of X-ray QPOs
Amplitude of IR QPO reproduced by IR synchrotron emission from hot flow

→ IR and X-ray QPO amplitudes cannot be reproduced simultaneously

Boughelilba, Master Thesis
The case of GX 339-4: Combining X-ray and IR QPO information

Assuming X-ray QPO from hot flow
IR QPO from jet precession

Both IR and X-ray QPOs amplitudes can be reproduced
Jet velocity must be < 0.16 c

Boughelilba’s Master Thesis
Conclusions

Because accreting black holes in X-ray binaries are bright and strongly variable they constitute a unique laboratory to study relativistic accretion.

The combined use of
  - multi-wavelength observations,
  - spectral,
  - timing,
  - and polarization techniques,

can disentangle the intricacies of accretion onto a black hole.

The truncated disc scenario can explain many of the observed spectral, timing and polarization properties. The details need to be worked out. Alternative models must also be explored.

The future is bright: eXTP, IXPE, XRISM, Athena...