A New Connection Between Plasma Conditions Near Black Hole Event Horizons and Outflow Properties

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Jets at all scales

- Accreting black holes are responsible for producing the fastest, most powerful outflows of matter in the Universe.
- How is the jet produced? Necessary ingredients accretion flow and magnetic field.
- Can we compare jets that are produced in systems with different black hole mass?
- Are the jets self-similar?
- How is the accretion coupled to jet production?
- Is there a connection between jet properties and accretion rate/mode, or black hole spin?
Accretion states in XRBs – disk/jet connection

What is observed? Two distinct states of accretion:

- “Hard state” with Comptonisation dominated (i.e. power law with a cutoff) X-ray spectrum from a “corona” and a jet
  - Thermal Comptonisation dominated accretion flow (Zdziarski+98)
  - Radiatively inefficient accretion flow (Yuan+03)
  - Base of the jet (Markoff +05)

- “Intermediate state” in between of hard and…

- “Soft state” with disk dominated (i.e. blackbody) X-ray spectrum and no jet

Hard X-ray state (jet + corona)

Soft X-ray state (no jet, no corona)
What is the link between the jet and the corona?

Can we find other observational evidence apart from their mutual existence?

AGN disk fraction/luminosity diagram: SDSS quasars, LLAGN (Ho+1999)

AGN type $\longleftrightarrow$ Accretion state
What is the link between the jet and the corona?

**Shopping list:**
- Clear X-ray view to the central region of the black holes
- Well-sampled, unobscured, low-accretion rate, nuclear jet spectrum with jet break
- High-spatial, and consistent resolution (no lobes/ISM etc.) from radio to UV
- Different accretion states (hard + intermediate in XRBs), different black hole masses (AGN)

**Recipe:**
- Estimate the location of the jet break and the flux density at the jet break —> probe the acceleration region
- Fit simultaneously observed X-ray spectrum with power law —> probe the particle distribution in the corona

\[ n_e = \int K \gamma^{-p} d\gamma, \quad \frac{d^2E}{dtdVdE} = E \left(\frac{1-p}{2}\right) \]
Observations from XRBs

List of sources (11):
- 4U 1543-47
- Cyg X-1
- GS 1354-64
- GX 339-4
- MAXI J1659-152
- MAXI J1836-194
- V404 Cyg
- V4641 Sgr
- XTE J1118+480
- XTE J1550-564
- XTE J1752-223

Hard state:
\[ \nu_b = 10^{13} - 10^{15} \text{ Hz} \]

Intermediate states:
\[ \nu_b = 10^{10} - 10^{13} \text{ Hz} \]

Soft states:
no compact jet

References:
- Corbel+13
- Gandhi+11
- Rahoui+11
- Russell, D.+12
- Russell, D.+13
- Russell, T.+14
- van der Horst+13

Direct measurement

Indirect measurement
Observations from XRBs

Quasi-simultaneous (~1 day) X-ray data from RXTE (PCA+HEXTE) and Swift XRT

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Hard state:
- $\Gamma \sim 1.5$

Intermediate states:
- $\Gamma \sim 2.0-2.5$
Observations from AGNs

- Only small sample available due to lack of high-resolution NIR/MIR observations
- Mostly LLAGN with little dust
- Sub-arcsecond measurements from radio to UV with adaptive optics low-angular resolution data from archives
- Steep optically thin spectra, $\alpha < -1.0$ (quasi-thermal/fast cooling)
- Well-measured X-ray power law photon indices from literature

List of sources (7): 5 LLAGN/LINERs (NGC 1052, NGC 1097, Sgr A*, M87, NGC 4594), Cyg A, 3C 120 (Fernandez-Ontiveros+12, Canalizo+03, Lopez-Rodriguez+14, Lee+08, Asmus+14, Doi+13, NED, WISE, Akari, 2MASS)
Jet break: $v_b = 10^{11} - 10^{14}$ Hz

Power law indices: $\Gamma \sim 1.5-2.5$
Anti-correlation between the jet break and X-ray power law photon index

- Correlation analysis using Monte Carlo bootstrap:
  - Random data sets chosen from the normal distribution of the original data with normal errors, or from uniform distribution of the original data with limits
  - $R = -0.76$
  - Significance 4.6σ
  - Linear least-squares regression:

$$\log v_b = -3.4^{+0.9}_{-1.4} \Gamma + 18.8^{+2.5}_{-1.6} \text{ Hz}$$

Koljonen+, in prep.
Anti-correlation between $L_b/L_{5\text{GHz}}$ and X-ray power law photon index

- $L_b = $ Luminosity at the jet break
- $L_{5\text{GHz}} = $ Luminosity at 5 GHz
- $L_b/L_{5\text{GHz}} = \nu_b S_{\nu,b}/\nu_{5\text{GHz}} S_{\nu,5\text{GHz}}$
  $= (\nu_b/\nu_{5\text{GHz}})^{1+\alpha}$
  = excess luminosity caused by the variable break frequency over the radio luminosity
- Varies between sources by six orders of magnitude
- Jet luminosities should be recalibrated taking the break frequency into account
- Monte Carlo linear least-squares regression:

$$\log L_b = \log L_{5\text{GHz}} - 3.5^{+0.9}_{-1.0} \Gamma + 9.8^{+2.0}_{-1.6} \text{ erg/s}$$
Correlation between the intrinsic rms and X-ray power law photon index

- Only for XRBs (long timescales needed)
- Not very surprising considering the anti-correlation between $\Gamma$ and rms (Fender, Homan & Belloni 2009).
- But it is possible that the rms is the main driver?
- Internal shock model? (Malzac 13, 14)
What affects the jet properties?

**Conditions in the corona?**

- New correlation: the jet break (and $L_b/L_{5GHz}$) is anti-correlated with the X-ray power law photon index in our sample of XRBs and AGN.
- Ties in the conditions in the corona (electron distribution) to conditions in the jet (particle acceleration).
- Unifying link: Magnetisation regimes (MHD processes in the jet, electron distribution in the corona)?
- Benchmark that should be reproduced by the jet formation models.
- No mass scaling! Unexpected in the light of the fundamental plane (Heinz & Sunyaev 2003): $L_X \sim L_{acc} \sim \eta c^2 \dot{M}$
- Lack of strong scaling with BH mass, accretion rate or spin hints at stable/self-similar feature.

The internal properties of jets rely most critically on the conditions of the plasma close to the BH, rather than other parameters such as the BH mass, accretion rate or spin.