Jets from X-ray binaries
and their connection to accretion flows, black hole spin, mass and environment
When jets are formed I: Connection to spectra of accretion flow
In Fender, Belloni & Gallo (2004) we presented a ‘unified’ model for the disc-jet coupling in black hole X-ray binaries. Seven years later...

Empirical couplings demonstrated to be correct in much larger sample:

- Jet always on in hard state
- Jet off or [fading and optically thin] in soft state
- Major outbursts associated with hard → soft state transitions
- Reactivation of jet during return to hard state not well observed

Attempt to extend this to timing properties

- Clearly jets are stronger when variability is stronger
- Approximate but imprecise connection between rapid drops in variability power and major ejection events

Theoretical interpretation

- Disc radius changes at high Eddington ratios remain controversial – disc could be varying over small (~10 R\textsubscript{G}) range (or not). Below about 1% Eddington disc does seem to recede to larger radii (but may not keep going)
- Internal shocks model for major outbursts consistent but untested. We need a measurement of the hard state jet speed.

Fender, Homan & Belloni (2009)
The integrated rms X-ray variability is correlated with the spectral hardness.

The jet is on in hard states and flares, then switches off, in transitions → soft states.

The amount of time spent in hard vs soft states above 1% Eddington is consistent with numbers of radio loud / radio quiet AGN at high Eddington ratios.
What's new since Fender, Belloni & Gallo (2004)?

Empirical aspects of model have been confirmed with much larger samples (~20 c.f. ~4). No strong contradictions.

Theoretical interpretation remains more or less untested.

**Much more** information available about coupling to variability properties of accretion flow.

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**Fender, Homan & Belloni (2009)**
These patterns of behaviour probably also appear in AGN

(Koerding, Jester & Fender 2006)

Chatterjee et al. (2009, 2011)
[also Marscher et al. (2002)]
When jets are formed II: Connection to variability and winds
So how closely can we connect the X-ray variability to the jet?

On timescales $\geq 1$ sec there is strong IR variability from the jet and it is correlated with X-rays with a lag of $\sim 100$ millisec. This corresponds to $\sim 2000 \, R_{G}$ (for a jet moving at c).

Linear polarisation of this component is low ($\leq 2\%$) so magnetic field is not highly organised at this distance.

Casella et al. (2010), Russell & Fender (2009)
What drives the X-ray variability on these timescales?

- We can probe this with the energy spectrum of phase lags as a function of Fourier frequency.

Negative phase lags w.r.t. power law indicate the disc drives the variability on the same timescales $\geq 1$ sec.

Uttley et al. (2010)
The hard state flat spectrum from internal shocks (tackles the Blandford & Konigl reheating 'issue')

Many 1000s of shells injected on the timescale of most of the hard state power can reproduce the observed flat radio—IR spectrum (the infrared 'bump' is also observed).

Jamil, Fender & Kaiser (2009)
Based on Spada et al. (2001)

Jet power: 1e29 W
Jet opening angle: 5.0 degrees
Source distance: 2 kpc
Source Inclination: 70 degrees
Shell injection interval: 1.0 s
Shell bulk Lorentz factor range: 1.5 - 2.0
Note jets and RIAFs at low Eddington ratios direct from XRB studies.

In fact lower panel indistinguishable from a sketch for a BH XRB (circa 2004)

But don't forget at high Eddington ratios you can have both strong- and weak-jet modes

Models for AGN accretion states (Trump et al. 2011)
They have been observed. Chandra spectrum of GRO J1655-40 in outburst.

*Model in blue
Laboratory wavelengths in red*

Miller et al. (2006)
Presence of highly-ionised X-ray winds in BH XRBs. 
**Green** indicates a non-detection, **Red** indicates a detection.

The strong winds are only observed when two conditions are met: 
(ii) soft X-ray state (ii) viewed close to edge-on

This suggests that the radio-quietness of BAL QSOs is because they are in soft states.

Note Neilsen & Lee (2009) suggest that the wind physically shuts off the jet.
Radio loudness and radiative efficiency
Is there really a radio loud:radio quiet dichotomy, and is it drive by spin?

At low Eddington ratios there appear to be two tracks. At high Eddington ratios there is some mixing.

The interpretation presented is that spin affects the radio loudness – higher spin = more powerful jets, but at high Eddington ratios there are also state changes (like XRBs).

Sikora, Stawarz & Lasota (2007)
The X-ray : radio correlation for BHXRBs – we thought it was like this (e.g. Gallo, Fender & Pooley 2003)

\[
\text{Log}_{10}(\text{GHz radio luminosity})
\]

\[
\text{Log}_{10}(1-10\text{ keV X-ray luminosity})
\]
But in fact it is like this (minus Cygnus X-1): Two tracks? (Calvelo et al. 2010)
An aside: Radiatively efficient jet producing hard states

If $L_{\text{radio}}$ goes as $P_{\text{jet}}^{1.4}$

and

$P_{\text{jet}} \sim \dot{m}$

Then for radiatively inefficient accretion where $L_x \sim \dot{m}^2$ then we expect

$L_{\text{radio}} \sim L_x^{0.7}$

and for radiatively efficient accretion where $L_x \sim \dot{m}$ we expect

$L_{\text{radio}} \sim L_x^{1.4}$

Which seems to be observed in neutron stars and some black holes.

Coriat et al. (2011), Rushton et al. (2011), Zdziarski et al. (2011)
Black hole spin
BHXRB data plotted as Sikora, Stawarz & Lasota (2007)
No evidence for spin-powering of jets in black hole X-ray binaries (Fender, Gallo & Russell 2010)

1. Take all reported spin measurements, sorted into those reached via disc and reflection (iron line) fitting

2. Use hard state radio emission as a proxy for ordering of jet power (absolute normalisation not important). Also look at transient jet power and speed. Repeated with near-infrared (base of jet).

3. Compare. There is no correlation.

4. Conclude that one or more of the following is true:

   (i) the calculated jet power and speed measurements are wrong,
   (ii) the reported spin measurements are wrong,
   (iii) there is no strong dependence of the jet properties on black hole spin

(see also Migliari, Miller-Jones & Russell 2011 for neutron stars)
Using only data from McClintock, Narayan et al. (2011)
Important case: Cygnus X-1

Well-studied jet, multiple power estimates

Radio normalisation in the middle of the distribution

Reported spin measurements:

Disc $a^* > 0.96$

Reflection $a^* = 0.05 \pm 0.01$
But what about AGN . . .?
Revisiting and extending Sikora, Stawarz & Lasota (2007)

This is for **total** radio power whereas fundamental plane uses **core** radio power. What happens to this sample if we use **core**?
Gap closes. Now we're using cores we can apply the fundamental plane mass correction (at same Edd ratio, radio loudness $\sim M^{0.4}$) [Merloni, Heinz & Di Matteo 2003]
Gap closes further. Mean separation between the 'two tracks' is now ~1.6 dex which corresponds to ~1 dex in jet kinetic power. Recall that strong powering of jets which can predicts up to $10^4$ difference in jet power between $a^*=0$ and $a^*=1$. 

La Franca et al. (2010), using a completely different approach, also finds no evidence for a radio loudness bimodality in AGN.
Beaming ? Total vs core radio power

Broderick & Fender (2011)
'Bolometric fundamental plane' with SSL07 AGN sample and latest BH XRB sample

Based on Merloni, Heinz & Di Matteo (2003)  
Broderick & Fender (2011)
On the mass term...
Beware of cheap imitations
(or, who needs an event horizon?)
Neutron stars and White Dwarfs do it too

Radio flaring and hysteresis observed from Cataclysmic Variable SS Cyg

(Koerding et al. Science, 2008)
Circinus X-1: neutron star
Sub-arcsecond moving jets with shocks
Miller-Jones et al. (2011)

Calvelo et al. (2011)
Conclusions

Jets in black hole binaries provide a rich phenomenology which is directly relevant to supermassive black holes in AGN.

New data strongly suggest a rapidly variable jet in the hard state driven by variability in the accretion disc on timescales $\geq 1$ sec, and the presence of a flattened accretion disc wind in all soft states.

There are radiatively efficient jet-producing hard states.

There is no correlation between radio luminosity and reported spin measurements (or any subset of) in black hole binaries.

The radio loud:radio quiet 'dichotomy' in AGN is strongly reduced if you use mass-corrected core luminosities rather than extended emission (this does not 'solve' anything, just shows it is complex).

Neutron star binaries still have a lot to teach us.