Baby beams and jumbo jets: investigating the relation between microquasars and AGNs

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Similar morphologies

GRS 1915+105, VLBA (Mirabel et al. 94)

3C120, VLBA

M87, VLA

3C273, VLA

3C120, VLBA

GRS 1915+105, MERLIN (Fender et al. 99)
Flat nuclear spectra

Low-hard state sources, Fender 2000

Flat/inverted spectrum sources:
- GS 1354-33
- GX 399-4
- GS 2023-338
- Cyg X-1
- 1E 1740.7-2942
- GRS 1758-258
- GRO J0422+32

Particle spectrum
- Particle powerlaw index $p$

Synchrotron spectrum
- Synchrotron powerlaw index $\alpha$

3C120, NED
AGNs are more radio loud than microquasars

Sams, Eckart, & Sunyaev 1996

Flat core emission:

\[ L_r \propto \dot{M}^{1.45} \]

Falcke & Biermann 1995

Opt. thin jets:

\[ T_b \propto \dot{M}^{-0.76} \]

\[ L_r \propto \dot{M}^{1.24} \]
Accretion rate correlation

Black holes in Galactic X-ray binaries:

- X-ray radio correlation in low/hard state

$$F_{\text{radio}} \propto F_{\text{x-ray}}^{0.7}$$

Gallo, Fender, & Pooley 2003
Comparing AGNs and microquasars

motivation:

- jets ↔ accretion
- jets from compact objects are relativistic
- morphologies: AGN & microquasars very similar
- spectra: AGN & microquasars very similar
- flat spectrum core emission: no messy ISM-interactions

questions:

- what produces radio loudness differences?
- are jets really similar at heart?
- disentangle dependence of flux on different parameters ($M_{BH}$, $m$, $\theta_{LOS}$, $a$)
The scale invariance Ansatz

parameters governing inner disk:

- black hole mass $M$
- accretion rate $m = \dot{M} / \dot{M}_{\text{Edd}}$

(Black hole spin $a$ ?)

Jet launched in the inner disk

$\Rightarrow$ inner jet governed by: $M, \dot{m}$

(Black hole spin $a$ ?)
Universal process of jet formation:

\[ \uparrow \quad \text{no qualitative difference for different } M \quad \downarrow \]

Jets are \textit{scale invariant}

\[ \uparrow \quad \text{only one scale: } r_g \quad \downarrow \]

similarity variable: \[ x = \frac{r}{r_g} \]

write any quantity \[ f \] as

\[ f(M, \dot{m}, a, r) = \phi_f(M, \dot{m}) \psi_f(r/r_g, a) = \phi_f(M, \dot{m}) \psi_f(x, a) \]
Synchrotron emission from the core:

scale invariance:

$$f(M, \dot{m}, a, r) = \phi_f(M, \dot{m}) \psi_f(r/r_g, a)$$

synchrotron theory:

The integrated synchrotron flux:

$$F = \int \frac{d \sum \Omega \epsilon}{d \Omega \epsilon} d \Omega \epsilon$$

Scaling of core radio flux with mass:

$$\frac{\partial \ln (F_\nu)}{\partial \ln (M)} = \frac{2p + 13 + 2\alpha}{p + 4} + \frac{\partial \ln (\phi_B)}{\partial \ln (M)} \left( \frac{2p + 3 + \alpha p + 2\alpha}{p + 4} \right) + \frac{\partial \ln (\phi_c)}{\partial \ln (M)} \left( \frac{5 + 2\alpha}{p + 4} \right) \equiv \xi_M$$

$$\Rightarrow F_\nu \propto M^{\xi_M}$$

NOTE: all model dependence absorbed into observables $\alpha$ and $p$
**radio-mass dependence**

\[ F_\nu \propto M^{\xi M} \]

**disk mode:**

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \frac{\dot{m}}{M} )</th>
<th>( B^2 )</th>
<th>( \xi_M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADAF</td>
<td>( \frac{\dot{m}}{M} )</td>
<td>( \frac{17}{12} \alpha )</td>
<td>( \frac{9}{10} )</td>
</tr>
<tr>
<td>rad. press.</td>
<td>( M^{-1} )</td>
<td>( \frac{17}{12} \alpha )</td>
<td>( \frac{9}{10} )</td>
</tr>
<tr>
<td>gas press.</td>
<td>( \dot{m}^{\frac{17}{20}} M^{-\frac{9}{10}} )</td>
<td>( \frac{17}{12} \alpha )</td>
<td>( \frac{9}{10} )</td>
</tr>
<tr>
<td>( W_{\text{jet}} \propto W_{\text{disk}} )</td>
<td>( \frac{\dot{m}}{M} )</td>
<td>( \frac{17}{12} \alpha )</td>
<td>( \frac{9}{10} )</td>
</tr>
</tbody>
</table>

**result:**

\[ F_\nu \sim M^{1.42-0.33\alpha} \]  \( \Rightarrow \) AGNs are more radio loud!
radio-accretion rate dependence

\[ F_\nu \propto \dot{m} \xi \dot{m} \]

<table>
<thead>
<tr>
<th>Disk Mode</th>
<th>( B^2 )</th>
<th>( \xi )</th>
<th>( \dot{m} )</th>
<th>( \dot{m} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADAF</td>
<td>( \frac{\dot{m}}{M} )</td>
<td>( \frac{17}{12} + \frac{2\alpha}{3} )</td>
<td>( \frac{17}{12} + \frac{2\alpha}{3} )</td>
<td>( \sim 1.42 + 0.66\alpha )</td>
</tr>
<tr>
<td>Rad. press.</td>
<td>( M^{-1} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gas press.</td>
<td>( \frac{\dot{m}}{M} )</td>
<td>( \frac{17}{12} + \frac{2\alpha}{3} )</td>
<td>( \frac{17}{20} )</td>
<td>( \sim 1.2 + 0.56\alpha )</td>
</tr>
</tbody>
</table>

For inefficient accretion:

\[ F_\nu \sim (\dot{m})^{1.42 + 0.66\alpha} \propto L_x^{0.71 + 0.34\alpha} \]
A fundamental plane of black hole activity

- past searches: no clear radio-mass correlation

Franceschini et al. 1998

Laor 2001

Lacy 2001

Woo & Urry 2002
A fundamental plane of black hole activity

- past searches: no clear radio-mass correlation
- should consider: mass and accretion rate
- 2-10 keV X-ray as proxy of inner disk
- Sample: ~100 AGNs 60 XRB observations with measured masses:
  - radio correlates with mass AND X-rays

Radio vs. X-ray & Mass: Merloni, Heinz, & DiMatteo 2003
A fundamental plane of black hole activity

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A fundamental plane of black hole activity

- plane equation:  
  \[ \log L_R = 0.78 \log M + 0.6 \log L_x + 7.33 \]

- scatter:  \[ \sigma \sim 0.9 \]

- consistent with inefficient accr.

- marg. consistent with jet X-rays

- inconsistent with efficient accr.

- scatter: beaming weak
Conclusions:

- Scale invariant jets: robust scaling relations, independent of model

\[ F \propto M^{\xi_m} \dot{m}^{\xi_m} \sim M^{1.42 - 0.33 \alpha} \dot{m}^{1.42 + 0.66 \alpha} \]

- Measuring correlations: test accretion physics

- Observational test finds: fundamental plane of radio-mass-x-rays

\[ L_r \propto M^{0.78} L_x^{0.6} \]

- consistent with inefficient accretion (\( L_x \propto \dot{m}^{2.3} \)), marginally consistent with jet X-rays, inconsistent with efficient accretion (\( L_x \propto \dot{m} \))