Accretion onto Black Holes

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UVa

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UIUC

## Astrophysical Disks

<table>
<thead>
<tr>
<th>Disk Type</th>
<th>Gravity Model</th>
</tr>
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<tr>
<td>Galaxies, Stellar Disks</td>
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Initial Conditions Are Important!!
Radiative Efficiency of Disks

- Radiatively Efficient (thin disks)
- Radiatively Inefficient (thick disks)

Narayan & Quataert (2005)
Probing the Spacetime of BHs

- Variability:
  - e.g. QPOs, short-time scale fluctuations

- Spectral Fitting Thermal Emission
  \[ L = A R_{in}^2 T_{max}^4 \]
  \[ R_{in} = R_{in}(M, a) \]

- Relativistic Iron Lines

- Directly Resolving Event Horizon
  (e.g., Sgr A*)
  - Silhouette size = D(M, a)

(See Doeleman et al. (2008) for sub-mm VLBI)
Accretion States of XRBs

\[ L = A R_{in}^2 T_{max}^4 \]

\[ R_{in} = R_{isco} \]

Done, Gierlinski & Kubota (2007)
Spectral Fits for BH Spin

**TABLE 1**
BLACK HOLE SPIN ESTIMATES USING THE MEAN OBSERVED VALUES OF M, D, AND i

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Observation Date</th>
<th>Satellite</th>
<th>Detector</th>
<th>$a_*$ (D05)</th>
<th>$a_*$ (ST95)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRO J1655–40</td>
<td>1995 Aug 15</td>
<td><em>ASCA</em></td>
<td>GIS2</td>
<td>~0.85</td>
<td>~0.8</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>GIS3</td>
<td>~0.80</td>
<td>~0.75</td>
</tr>
<tr>
<td></td>
<td>1997 Feb 25–28</td>
<td><em>ASCA</em></td>
<td>GIS2</td>
<td>~0.75*</td>
<td>~0.70</td>
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<tr>
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<td></td>
<td></td>
<td>GIS3</td>
<td>~0.75*</td>
<td>~0.7</td>
</tr>
<tr>
<td></td>
<td>1997 Feb 26</td>
<td><em>RXTE</em></td>
<td>PCA</td>
<td>~0.75*</td>
<td>~0.65</td>
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<td></td>
<td>1997 (several)</td>
<td><em>RXTE</em></td>
<td>PCA</td>
<td>0.65–0.75*</td>
<td>0.55–0.65</td>
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<tr>
<td>4U 1543–47</td>
<td>2002 (several)</td>
<td><em>RXTE</em></td>
<td>PCA</td>
<td>0.75–0.85*</td>
<td>0.55–0.65</td>
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* Values adopted in this Letter.

Shafee et al. (2006)

McClintock et al. (2006)
Steady-State Models: Novikov & Thorne (1973)

Assumptions:

1) Stationary gravity
2) Equatorial Keplerian Flow
   - Thin, cold disks
3) Time-independent
4) Work done by stress locally dissipated into heat
5) Conservation of $M$, $E$, $L$
6) Zero Stress at ISCO
   - Eliminated d.o.f.
   - Condition thought to be suspect from very start

(Thorne 1974, Page & Thorne 1974)

\[ \eta = 1 - \frac{\dot{E}}{\dot{M}} = 1 - \epsilon_{ISCO} \]
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(Thorne 1974, Page & Thorne 1974)

Magnetic Fields → Need dynamical evolution!!!

\[ \eta = 1 - \frac{\dot{E}}{\dot{M}} = 1 - \epsilon_{ISCO} \]
Steady-State Models: \( \alpha \) Disks

- Shakura & Sunyaev (1973):
  \[
  T^r_\phi = -\alpha P
  \]
  \[
  P = \rho c_s^2 \quad t^r_\phi = -\alpha c_s^2
  \]

- No stress at sonic point:
  \[
  \rightarrow R_{in} = R_s
  \]
  e.g.:
  Muchotrzeb & Paczynski (1982)
  Abramowicz, et al. (1988)

  (Schwarzschild BHs)

- Variable \( \alpha \)
  e.g., Shafee, Narayan, McClintock (2008)

\[
\eta \sim 1 - \epsilon_{isco}
\]
Dynamical Global Disk Models

- De Villiers, Hawley, Hirose, Krolik (2003-2006)

- MRI develops from weak initial field.

- Significant field within ISCO up to the horizon.

Dynamical Global Disk Models

Krolik, Hawley, Hirose (2005)

H/R ~ 0.1-0.15

Beckwith, Hawley & Krolik (2008)

- Models dissipation stress as EM stress
- Large dissipation near horizon compensated partially by capture losses and gravitational redshift.
- Used (non-conserv.) int. energy code (dVH) assuming adiabatic flow
Our Method: Simulations with HARM3D

- **HARM:**

- Axisymmetric (2D)

- Total energy conserving
  (dissipation → heat)

- Modern Shock Capturing techniques
  (greater accuracy)

- Improvements in HARM3D:
  - 3D
  - More accurate
    (parabolic interpolation in reconstruction and constraint transport)
  - Assume flow is isentropic when $P_{\text{gas}} \ll P_{\text{mag}}$

\[
\nabla_\nu F^{\mu\nu} = 0
\]

\[
\nabla_\mu (\rho u^\mu) = 0
\]

\[
\nabla_\mu T^\mu_\nu = 0
\]

\[
T^\mu_\nu = (\rho + u + p + b^2) u^\mu u_\nu + \left(p + \frac{b^2}{2}\right) \delta^\mu_\nu - b^\mu b_\nu
\]

SCN, Krolik, Hawley (2009)
Our Method: Simulations with HARM3D

• Improvements:
  – 3D
  – More accurate (higher effective resolution)
  – Stable low density flows

– Cooling function:
  • Controls energy loss rate
  • Parameterized by H/R
  • $t_{\text{cool}} \sim t_{\text{orb}}$
  • Only cool when $T > T_{\text{target}}$
  • Passive radiation
  • Radiative flux is stored for self-consistent post-simulation radiative transfer calculation

$$T(r) = \left( \frac{H}{R} \right)^2 r \Omega$$

$\nabla^\mu F^{\mu \nu} = 0$

$\nabla_\mu (\rho u^\mu) = 0$

$\nabla_\mu T^{\mu \nu} = -\mathcal{F}_\mu$

$$T^{\mu \nu} = (\rho + u + p + b^2) u^\mu u_\nu + \left(p + \frac{b^2}{2}\right) \delta^\mu_\nu - b^\mu b_\nu$$

SCN, Krolik, Hawley (2009)
\[ N_r \times N_\theta \times N_\phi = 192 \times 192 \times 64 \]

\[ r \in [r_{\text{hor}}, 120M] \]
\[ \theta \in \pi [0.05, 0.95] \]
\[ \phi \in [0, \frac{\pi}{2}] \]
\[ a = 0.9M \]
GRMHD Disk Simulations

\[ N_r \times N_\theta \times N_\phi = 192 \times 192 \times 64 \]

\[ r \in [r_{\text{hor}}, 120M] \]
\[ \theta \in \pi [0.05, 0.95] \]
\[ \phi \in [0, \frac{\pi}{2}] \]
\[ a = 0.9M \]
HARM3D vs. dVH

$\log(\rho)$

Uncooled  Cooled  dVH
Disk Thickness

![Graph showing Disk Thickness with curves labeled dVH and HARM3D.](image-url)
Accretion Rate

Steady State Period = 7000 – 15000M

Steady State Region = Horizon → 12M

Steady State Important because...

- Match to time-indep. solns
- Real disks are often steady (esp. AGN)
- Provides a baseline for more exotic behavior
- Only in 3D (anti-dynamo in 2D)

\[
M(r < r_i) \quad j(r_{\text{horizon}}, t)
\]
Magnetic Stress

Retained Heat → Stress Deficit
Stress Continuity through ISCO

Agol & Krolik (2000) model

$$\Delta \eta = 0.01$$

$$\Delta \eta / \eta = 7 \%$$
Our Method: Radiative Transfer

\[ j_\nu = \frac{f_c}{4\pi \nu^2} \]

- Full GR radiative transfer
  - GR geodesic integration
  - Doppler shifts
  - Gravitational redshift
  - Relativistic beaming
  - Uses simulation’s fluid vel.
  - Inclination angle survey
  - Time domain survey
Observer Frame Luminosity: Angle/Time Average

Assume NT profile for $r > 12M$.

$$\eta_{H3D} = 0.151$$

$$\eta_{NT} = 0.143$$

$$\Delta \eta / \eta = 6\%$$

$$\Delta R_{in} / R_{in} \sim 80\%$$

$$\Delta T_{max} / T_{max} = 30\%$$

If disk emitted retained heat:

$$\Delta \eta / \eta \sim 20\%$$

SCN, Krolik, Hawley (2009)
Counter Evidence


<table>
<thead>
<tr>
<th></th>
<th>Shafee et al.</th>
<th>Ours</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH Spin</td>
<td>a=0.0</td>
<td>a=0.9</td>
</tr>
<tr>
<td>Resolution</td>
<td>512x120x32</td>
<td>192x192x64</td>
</tr>
<tr>
<td>Azimuthal Extent</td>
<td>(\pi/4)</td>
<td>(\pi/2)</td>
</tr>
<tr>
<td># of B Loops</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>H/R</td>
<td>0.05-0.07</td>
<td>0.07-0.13</td>
</tr>
<tr>
<td>Code</td>
<td>HARM + 3D</td>
<td>HARM3D</td>
</tr>
</tbody>
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## Counter Counter Evidence

<table>
<thead>
<tr>
<th></th>
<th>Theirs</th>
<th>Our Original</th>
<th>Thin1</th>
<th>Medium1</th>
<th>Thick1</th>
<th>Thin2</th>
<th>Medium2</th>
</tr>
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<tr>
<td><strong>Resolution</strong></td>
<td>512x120x32</td>
<td>192x192x64</td>
<td>912x160x64</td>
<td>512x160x64</td>
<td>384x160x64</td>
<td>192x192x64</td>
<td>192x192x64</td>
</tr>
<tr>
<td><strong>φ Extent</strong></td>
<td>π/4</td>
<td>π/2</td>
<td>π/2</td>
<td>π/2</td>
<td>π/2</td>
<td>π/2</td>
<td>π/2</td>
</tr>
<tr>
<td><strong># of Loops</strong></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Actual H/R</strong></td>
<td>0.05 - 0.07</td>
<td>0.07 - 0.13</td>
<td>0.06</td>
<td>0.10</td>
<td>~0.17</td>
<td>0.087</td>
<td>0.097</td>
</tr>
<tr>
<td><strong>N_{cells} per H/r</strong></td>
<td>~60</td>
<td>15 - 30</td>
<td>80</td>
<td>100</td>
<td>40 - 70</td>
<td>60</td>
<td>35</td>
</tr>
<tr>
<td><strong>Initial Data</strong></td>
<td>“V. 1”</td>
<td>V. 2</td>
<td>V. 1</td>
<td>V. 1</td>
<td>V. 1</td>
<td>V. 2</td>
<td>V. 2</td>
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**V.1** : Initial disk starts:
- At target thickness
- With inner radius = 20M
- With $p_{\text{max}}$ at $r = 35M$

**V.2** : Initial disk starts
- At $H/R \sim 0.15$
- With inner radius = 15M
- With $p_{\text{max}}$ at $r = 25M$
Trends in Scaleheight

\[ W^r_\phi = p \alpha \]
Steady State and Mass Flow Equilibrium

![Graphs showing accretion rate over time and radius]
Resolution of the MRI

Steady Accretion
$t = 6000 M$

Accretion Decay
$t = 12000 M$

\[ \lambda_{MRI} \equiv \frac{1}{\sqrt{4\pi \rho \Omega(R)}} \frac{b_{\mu} \tilde{e}^{\mu}}{\Delta \zeta} \geq 6 \]

Sano et al. (2004)
Accreted Specific Angular Momentum

- Dependence is weak $\sim (H/R)^{1/2}$ instead of “expected” $(H/R)^2$
- Possible Dependence on Initial Field Topology
- Independent of Algorithm (modulo Shafee et al. 2008)
- Still need to transport radiated energy to infinity to find efficiency

3D HARM w/ 2 Poloidal Loops
Shafee et al. (2008)

HARM3D 1 Poloidal Loop

GRMHD (dVH) 1 Poloidal Loop

GRMHD (dVH) Vertical Field
Beckwith, Hawley, Krolik (2009)
X-ray Variability of Accretion

- X-ray var. always dominated by corona
- XRB var. dependent on spectral state

\[ P \sim \nu^\alpha \]
\[-3 < \alpha < -1\]

XRBs: Remillard & McClintock (2006)

AGN: Markowitz et al. (2003)
Variability Models

\[ P \sim \nu^\alpha \]

Lyubarskii (1997)
Total variability is a superposition of independent variability from larger radii modulating interior annuli on inflow time scales

Churazov, Gilfanov, Revnivtsev (2001)
Outer radius of corona may be cause of (temporal) spectral slope.

\[ \tau_a = \left[ \alpha \left( \frac{H}{r} \right)^2 \Omega_K \right]^{-1} \]

Accretion rate modulation modeled as variability of \( \alpha \)

Predict phase coherence at frequencies longer than inflow freq.

Schnittman et al. (2006)
Reynolds & Miller (2009)

- Used accretion rate or stress as dissipation proxies
- PLD breaks at local orbital frequency per annulus
- \( \alpha_{\omega<\Omega} \sim -1 \quad \alpha_{\omega>\Omega} \sim -3 \)
- Composite PLD \( \alpha \sim -2 \)
Our Variability Model
Noble & Krolik (2009)

Simulation: \( a = 0.9M \) \( H/R = 0.07 - 0.13 \)

- Assume Thomson Scattering
- Optical depth set by \( \dot{m} = \frac{L}{\eta L_E} \)
- Integrate emission up to photosphere
- Include effect of finite light speed
- Parameterized by \( \theta, \dot{m} \)

\( \dot{m} = 0.003 \)

\( \theta = 41^\circ \)
Spectra of Annuli

- No PL break at $\Omega$
- Each annulus $\alpha \sim -2$
- More power at smaller $r$
- No feature at ISCO

\[ F(t, r) = \frac{dL}{dr}(r, t) \]
\[ \hat{F}(\nu, r) = \frac{1}{N} \sum_{n=0}^{N-1} F(t_n, r) e^{-2\pi i \nu t_n} \]
\[ P(\nu, r) = \frac{2T}{F^2} |\hat{F}(\nu, r)|^2 \]
Origin of Variability

\[ \frac{P_{\text{diss}}(\nu, r)}{\dot{M}(\nu, r)} \]

Epicyclic motion not dissipated

Dissipation not well proxied by \( \dot{M} \)

\[ \frac{P_{\text{inf}}(\nu, r)}{P_{\text{diss}}(\nu, r)} \]

\( \theta = 5^\circ \)

Observed var. \( \sim \) local dissipation var.
Phase Coherence

- Possible coherence below inflow frequency (ala Lyubarskii)
- Otherwise dissipation is incoherent over all scales
Complete degeneracy!!
Degeneracy Explanation
Degeneracy Explanation

\[ \alpha_a \geq -2 \]

\[ \alpha_c \leq -2 \]

\[ \alpha_d \leq -2 \]

\[ \theta \sim 0^\circ \]

\[ \alpha_i \approx 2 \]
Summary & Conclusions

- Closer to ab initio calculations of accretion disk dynamics
- Magnetic stress is important within ISCO
- Stress does not vanish with disk height (at least for $a = 0$)
- Dissipation variability approximates observed coronal variability

What about

... other spins?
... other cooling models?
  $H = \text{const.}, \ H = H(t,r)$ Hysterisis? State Transitions?
... other initial magnetic field topologies?
... radiation pressure? (ugh)

Near-merger BBH Disks ...
... are magnetized and different from gap-forming hydro disks
  (magnetic stress can work over extended regions unlike visc.)
... most likely will not have large gaps
... will most likely be bright and variable before merger