MHD Simulations of Black Hole Accretion Disks

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Jeremy Schnittman (NASA/GSFC)
Black hole X-ray binaries exhibit rich phenomena

X-ray hot matter serves as spacetime surveyors

- Black holes uniquely parameterized by mass (M) and spin (a) in GR
- Test GR, e.g., $|a/M| > 1$ ?
- Constraints on SN models, re: nascent spin/masses of their product BHs
- BH spin evolution, mass distribution --> important for establishing population models of GW events (e.g., LIGO, VIRGO,...)

- Useful for understanding high-energy physics in strong-field gravity
  - How do really hot plasmas operate near extreme gravitational curvature? (these are but a few places in the universe at these extremes)
  - Nearby jet laboratories (microquasars, e.g., GRS 1915+105)
  - Many results carry over to AGN physics as well

$M_{BH} \sim 10M_\odot$
$L \sim 0.1\dot{M}c^2$
$L \sim 10^{38}\text{erg/s}$
$T_{max} \sim 1\text{keV}$
Black Hole X-ray Binaries

- 41 BHB suspects
- 21 have dynamically confirmed masses
- 3 are persistent, “High Mass” BHBs (Cyg X-1, LMC X-1, LMC X-3)
- Remainder are intermittent
  - e.g. GRS 1915+105 “turned on” in 1992
- \( R_{\text{disk}} \sim R_\odot \sim 10^5 r_g \)
- Mass function
  \[
  f(M) = \frac{P_{\text{orb}} K^3}{2 \pi G} = \frac{M_{\text{BH}} \sin^3 i}{(1 + M_*/M_{\text{BH}})^2}
  \]
- \( M_{\text{BH}} \gtrsim 3 M_\odot \)
- Neutron stars “ruled out” for most BHBs via mass function limit and because BHBs lack surface emission

J. Orosz (c. 2011)
http://mintaka.sdsu.edu/faculty/orosz/web/
**Accretion States**

Temporal Variability:
- $P \sim \nu^\alpha$ \quad $-3 < \alpha < -1$
- QPOs  High & Low

Flux Components:
- Bulk  --> Thermal
- Corona  --> IC, Hard PL
- Reflection  --> Fe K Line

Done, Gierlinski & Kubota (2007)
Accretion States

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

- QPOs High & Low
Disk “Dichotomy”

**Thin Disks:**
- Dissipation Rate < Cooling Rate
- “Cold”, Optically Thick
- Thermal or Multi-temperature black body

**Thick Disks:**
- Dissipation Rate > Cooling Rate
- “Hot”, optically thin, outflows
- 2 Temperature flow, advected heat

- Shakura & Sunyaev (1973)
- Novikov & Thorne (1973)
- Narayan & Yi (1994-5) (ADAF)
- Blandford & Begelman (1999) (ADIOS)
- Quataert & Gruzinov (2000) (CDAF)

Narayan & Quataert (2005)
**Steady-state Thin Disk Models**

Novikov & Thorne (1973)

\[ L = \eta \dot{M} c^2 \]
\[ \eta = 1 - \epsilon_{\text{ISCO}} \]

- Stationary gravity
- Perfect radiator
- Work done by stress locally dissipated & radiated
- Zero stress at ISCO as boundary condition
- Luminosity as total liberation of binding energy up until plunge into ISCO

Shakura & Sunyaev (1973)

\[ T^r = -\alpha P \quad P = \rho c_s^2 \]
\[ t^r = -\alpha c_s^2 \]

No stress at sonic point:

\[ \rightarrow R_{\text{in}} = R_s \simeq R_{\text{ISCO}} \]

Muchotzeb & Paczynski (1982)
Abramowicz et al. (1988)
Magneto-rotational Instability (MRI)

- Velikhov (1959)
- Chandrasekhar (1960)
- Balbus & Hawley (1991)

- Growth on orbital time scale.
- MRI develops from weak initial field --- relevant for any (partially) ionized gas.
- Magnetic coupling over different radii is not well described by local viscosity.
- Can explain high accretion rates where hydrodynamic viscosity cannot.
- Fastest instability known that feeds off free energy of differential rotation.
Hawley, De Villiers, Krolik, Hirose 2003+

GRMHD Simulations

Hirose et al. (2004)
• Non-conservative --> uncontrolled cooling
• 3D GRMHD
• H/R ~ 0.1 - 0.17
• Boyer-Lindquist Coordinates

Krolik, Hawley & Hirose (2005)
SCN, Krolik & Hawley (2009)

- **HARM3D:**
  - Based on Gammie’s Harm (2D) and HAM (non-rel) codes
  - 3D Ideal GRMHD
  - Kerr-Schild coordinates
  - Modern high-res. shock-capturing methods
  - Flux (energy) conserving
  - Contrained Transport scheme
  - Optically-thin cooling function
  - Maintains constant H/R
  - Cooling on orbital timescale

\[
\nabla_\mu T^\mu_\nu = -\mathcal{L} u_\nu
\]

\[
\mathcal{L} = \Omega_K u \Delta^q
\]

\[
T_\circ = \frac{\pi}{2} \left( \frac{H}{r} r \Omega_K \right)^2
\]

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

\[
r \in [r_{\text{hor}}, 120M] \quad \theta \in \pi [\delta, 1 - \delta] \quad \phi \in [0, \pi/2]
\]

\[
a = 0.9M
\]

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HARM3D:
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\[ T_{\circ} = \frac{\pi}{2} \left( \frac{H}{r} r\Omega_{K} \right)^{2} \]
Comparison to NT

- Retained Heat --> Stress Deficit
- Continuity through the ISCO

Fits approx. to Agol & Krolik (2000)
\[ \Delta \eta = 0.01 \quad \Delta \eta / \eta = 7\% \]

- ~5% flux deficit at all radii
  - Due to retained thermal and magnetic energy densities.
GR Radiative Transfer

\[
\frac{d}{d\lambda} \left( \frac{I_\nu}{\nu^3} \right) = \frac{j_\nu}{\nu^2}
\]

\[
j_\nu = \mathcal{L} / 4\pi
\]

- GR geodesic integration
- Doppler shift
- Gravitational redshift
- Relativistic beaming
- Interpolates simulation data in space & time

Allows us to explore dependence on time and disk orientation on the sky.
Angle & Time Average Bolometric Luminosity Profile

\[ L = \eta \dot{M} c^2 \]
\[ \eta_{NT} = 0.143 \]
\[ \Delta \eta/\eta = 6\% \]
\[ \Delta T_{\text{max}}/T_{\text{max}} = 7\% \]
\[ \Delta R_{\text{in}}/R_{\text{in}} = 80\% \]
\[ T \to 0 : \Delta \eta/\eta = 20\% \]

Suggests previous spectral fits may overestimate spin.

NT model may underestimate luminosity in some disks.

SCN, Krolik & Hawley 2009
<table>
<thead>
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**Motivation:**
- Explore H/R dependence;
- Resolve height with >60 cells (Davis++ 2009);
- Attempt at isotropic dissipation with nearly cubical cells;
ThinHR: \( H/R = 0.06 \)

\[ \rho \]

\( t/M = 0 \)

\[ 912 \times 160 \times 64 \]

\( a = 0M \)

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ThinHR: $H/R = 0.06$ 

$\rho$ 

$912 \times 160 \times 64$ 

$a = 0M$
ThinHR: $H/R = 0.06$  \quad 912x160x64  \quad \alpha = 0 M$

\[ \frac{t}{M} = 0. \]

\[ \rho \]

\[ \frac{y}{M} \]

\[ \frac{x}{M} \]

\[ -10 \quad -8 \quad -6 \quad -4 \quad -2 \]

\[ 0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30 \quad 35 \]
• No trend seen in Maxwell Stress
• Minor “sqrt” trend seen in spec. ang. mom.
  • Due to additional Reynolds stress for thicker disks

De Villiers & Hawley code
Vertical field with De Villiers & Hawley code
• No trend seen in Maxwell Stress
• Minor “sqrt” trend seen in spec. ang. mom.
  • Due to additional Reynolds stress for thicker disks

- De Villiers & Hawley code
- Vertical field with De Villiers & Hawley code
Other GRMHD simulations show weaker intra-ISCO stress levels and angular momentum transport. 
Shafee et al. (2008), Penna et al. (2010)
Preliminary Results!!!
Time-averaged ThinHR

NT

10^{-3} 10^{-2} 10^{-1} 1

50 M
Possibly, more light can be generated from retained heat and magnetic field.

\[
R_{NT} = 11.4 \\
R_{ThinHR} = 10.3 \\
\Delta T_{\text{max}}/T_{\text{max}} = 8\% \\
\Delta R_{\text{in}}/R_{\text{in}} = 11\% \\
\Delta \eta/\eta = 10\% \\
\Delta \eta/\eta = 4\% \\
\Delta \eta/\eta = -1\% 
\]
Thermal Spectral Fitting for BH Spin

Integrated Stefan-Boltzmann Law for Multi-T BB Disks

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

\[ R_{\text{in}} = R_{\text{in}} (M, a) \approx R_{\text{ISCO}} \]

Table 1. Spin Results to Date for Eight Black Holes

<table>
<thead>
<tr>
<th>Source</th>
<th>Spin $a_*$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRS 1915+105</td>
<td>$&gt; 0.98$</td>
<td>McClintock et al. 2006</td>
</tr>
<tr>
<td>LMC X–1</td>
<td>$0.92^{+0.05}_{-0.07}$</td>
<td>Gou et al. 2009</td>
</tr>
<tr>
<td>M33 X–7</td>
<td>$0.84 \pm 0.05$</td>
<td>Liu et al. 2008, 2010</td>
</tr>
<tr>
<td>4U 1543–47</td>
<td>$0.80 \pm 0.05$</td>
<td>Shafee et al. 2006</td>
</tr>
<tr>
<td>GRO J1655–40</td>
<td>$0.70 \pm 0.05$</td>
<td>Shafee et al. 2006</td>
</tr>
<tr>
<td>XTE J1550–564</td>
<td>$0.34^{+0.20}_{-0.28}$</td>
<td>Steiner et al. 2010b</td>
</tr>
<tr>
<td>LMC X–3</td>
<td>$&lt; 0.3^b$</td>
<td>Davis et al. 2006</td>
</tr>
<tr>
<td>A0620–00</td>
<td>$0.12 \pm 0.18$</td>
<td>Gou et al. 2010</td>
</tr>
</tbody>
</table>

*Errors are quoted at the 68% level of confidence.

*Provisional result pending improved measurements of $M$ and $i$. 

McClintock et al. (2011)
Spectral Fitting NT to Simulations

Simulation:
- ThinHR: $a=0$, $H/R=0.06$
- Snapshots spaced $dt=500M$

GR Ray-tracing (Schnittman’s code):
- Time-average snapshot spectra;
- Includes reflection radiation;
- Results shown use $i_{\text{sim}} = 60^\circ$

Case A: “A Band” fit over $[0.2,10]$ keV
Case B: “B Band” fit over $[1.0,10]$ keV

Free parameters:
$D, M_{\text{BH}}, \dot{M}, i$

Can constrain some by other observations, though are sometimes quite uncertain;
Problem is degenerate in $D$, so we eliminate it from the fitting procedure;

<table>
<thead>
<tr>
<th>Case #</th>
<th>Knowns (constraints)</th>
<th>Unknowns (fitting parameters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$D$</td>
<td>$i, a, M, \dot{M}$</td>
</tr>
<tr>
<td>2</td>
<td>$D, M$</td>
<td>$i, a, \dot{M}$</td>
</tr>
<tr>
<td>3</td>
<td>$D, M, i$</td>
<td>$a, \dot{M}$</td>
</tr>
</tbody>
</table>

--> 6 types of fits
Case 1: Fitting with $a$, $i$, $M$, $M_{\text{dot}}$

Case 2: Fitting with $a$, $i$, $M_{\text{dot}}$

Case 3: Fitting with $a$, $M_{\text{dot}}$

$a = 0.2-0.3$

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Summary & Conclusion:

- Moving towards fully self-consistent accretion models;
- Magnetic fields can change the “thin disk” picture within the ISCO;
- Radiative efficiency increases with decreasing disk thickness (no surprise!)
- Our two spin cases suggest that radiative efficiency accretion may be ~10% more efficient
- Our ray-traced simulation calculation suggests that present thermal spectrum fits may over-estimate black hole spin
  - Error (in the case presented) is at least as large as other uncertainties

Future Work and Open Questions:

- More H(R)/R and spins: (use simulations to fit to observations);
- Does variability depend on disk thickness?
- Is the simulation’s variability within the observed near-constancy of Rmin?
- How are state transitions triggered?
- What are “realistic” (and realizable) initial disk conditions?
Incomplete List of Outstanding Issues in BH Accretion

**Warped Disks**
- Fragile et al. 2007-2009

**Initial Field Topology**
- Beckwith et al. 2008

<table>
<thead>
<tr>
<th>Poloidal</th>
<th>Quadrupolar</th>
<th>Toroidal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet</td>
<td>Jet</td>
<td>&quot;No&quot; Jet</td>
</tr>
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</table>

**Full 2π Evolutions**
- McKinney & Blandford 2009
- Gammie et al (unpub.)

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Binary Black Hole Accretion

$t=0.00$

$\text{zscale}=1.000e-15$

$46 \times 47$

$[-16.000,16.000], [-12.750,12.750]$
Variability
Variability Models

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

Lyubarskii et al. 1997
- Total variability is a superposition of independent variability from larger radii modulating interior annuli on inflow (viscous) times scales

Churazov et al. 2001
- Outer radius of corona may be cause of (temporal) spectral slope

Armitage & Reynolds 2003
Machida & Matsumoto 2004
Schnittman et al. 2006
Reynolds & Miller 2009

- Accretion rate modulation modeled as variability of \( \alpha \) (disk parameter)
- Predicts phase coherence at frequencies longer than inverse of inflow timescale
- Used accretion rate or stress as dissipation proxies
- PLD breaks at local orbital frequency per annulus
- Composite PLD \( \rightarrow \alpha \approx -2 \)
SCN & Krolik 2009

- Use “thin disk” cooling rate in corona as emissivity
- Thomson Opacity model (e- scattering)
- Integrate to photosphere \((\tau = 1)\)
- Include finite light speed effect
- Parameterized by accretion rate and inclination
• Dissipation approximately follows accretion rate
• Not all accretion rate modes are dissipated
• Variability at infinity follows local dissipation var.
• Mostly incoherent between adjacent radii and frequencies;
• Possible coherence at
  \[ \nu < \frac{1}{T_{\text{inflow}}(r)} \]
  • Need longer runs to verify;

• Degenerate Result;
• No inclination angle effect;
• Consistent w/ observed power-law exponents
• See no QPOs, though we lie between LFQPO and HFQPO range
Degeneracy Explanation

\[ \alpha_a > -2 \]
\[ \alpha_c < -2 \]
\[ \alpha_b > -2 \]
\[ \alpha_d < -2 \]
\[ i \sim 0^\circ \]
\[ \alpha_i \sim -2 \]
Probing the Spacetime of BHs

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

- Polarization (e.g. Schnittman & Krolik 2009)

- Spectral Fitting of Thermal Emission

\[ L = A R_{\text{in}}^2 T_{\text{max}}^4 \quad R_{\text{in}}^2 = f(a, M) \]

McClintock et al. 2006, Shafee et al. 2006

- Relativistic Iron Lines

- Directly Resolving the BH Silhouette
  - e.g. Sgr A* with sub-mm/mm VLBI

2 It is conceivable that the disk material might contain extremely strong magnetic fields, and that these fields might transport a torque from the infalling material at $r < r_{ms}$ to the disk at $r \geq r_{ms}$. In this case the boundary condition at $r_{ms}$ would be modified, and the solution for $f$ would be changed. It seems to us unlikely that the changes would be substantial, except very near $r_{ms}$ (i.e., at $r - r_{ms} \ll 0.1r_{ms}$). But when constructing explicit disk models, one should examine this possibility carefully.

Page & Thorne (1974)

In these three cases it seems almost certain that the ultimate, limiting value of $a_*$ will not exceed our value of 0.998—and, hence, that the efficiency for converting rest mass into escaping radiation will not exceed 30 percent.

Other ways in which our assumptions may fail are these:

i) Magnetic fields attached to the disk may reach into the horizon, producing a torque on the hole (Ya. B. Zel’dovich and V. F. Schwartzman, private communication).

ii) The disk will recapture some of the photons it emits, thereby preventing them from going down the hole.

iii) The time-averaged, radial disk structure will be changed by photon recapture and resultant heating, and by magnetic torques that couple the innermost parts of the disk to the hole and couple them to matter that has fallen out of the disk and is plunging down the hole. The result will be deviations of the emitted photon flux $F(r)$ from the law derived in Paper I, and deviations of the specific energy and angular momentum of the infalling matter from $E^+_{ms}$ and $L^+_{ms}$.

Thorne (1974)

Gammie (1999)

- Magnetized inflow model matched to thin disk
- Efficiency tied to mag. flux BC

Agol & Krolik (2000)

- Magnetic torques at ISCO can affect radiative efficiency
"The sharp edge of a disk is difficult to resolve; thus the wise say the path to Solution is hard."
"The sharp edge of a disk is difficult to resolve; thus the wise say the path to Solution is hard."
Inflow Equilibrium

Defined to be when:
1) Accreted specific angular momentum ($j_{\text{net}}$) is steady;
2) Mass flux shows no trends in time over radius;

Remember these are turbulent MHD flows—-they need not reach any kind of steady-state!
Steady-state Accretion $t = 6000M$

Accretion Decay $t = 12000M$

Suggestions from local shearing box simulations:

Sano et al. 2004

$$\lambda_{MRI} \equiv \frac{1}{\sqrt{4\pi\rho\Omega(R)}} b_\mu \hat{e}_\mu^{(\theta)}$$

$$\frac{\lambda_{MRI}}{\Delta z} > 6$$

Davis, Stone, & Pessah 2009

$$\frac{H}{\Delta z} > 60$$

Track MRI Resolution for all time!

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Spin Over-estimation

\[ a/M = 0.16 \]

\[ a/M = 0.92 \]
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- Resolve height with >60 cells (Davis++ 2009);
- Attempt at isotropic dissipation with nearly cubical cells;
\[ \frac{\Delta \eta}{\eta} = -1\% \]

\[ \frac{\Delta \eta}{\eta} = -3\% \]

\[ \frac{\Delta \eta}{\eta} = -12\% \]

\[ \frac{\Delta \eta}{\eta} = -1\% \]
ThinHR

\[ \frac{\Delta \eta}{\eta} + 7\% \]

\[ \frac{\Delta \eta}{\eta} + 18\% \]

\[ \frac{\Delta \eta}{\eta} + 5\% \]

\[ \frac{\Delta \eta}{\eta} + 10\% \]
The Exciting World of Black Hole Accretion!

AGN!!

XRBs!!

Feedback!!

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Mass function

Provides firm lower bounds on mass of the black hole

Actual Mass $M_1$ is found by modeling the light bending from the companion star to get the inclination angle

Neutron stars ruled out for most XRBs, as their predicted maximum mass is $3M_{\odot}$

Lack of stellar surface emission lends credence to presence of an event horizon.