The Radiative Efficiency of Thin Accretion Disks

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Outline

• How do we “see” black holes?
  • Disk Emission -> Spacetime Lighthouses
  • Measure properties of black hole (M,a)

• Standard (thin) disk model

• How can we improve upon these models?
  • Dynamical MHD Disks in GR.
Radiative Efficiency of Disks

- Radiatively Efficient (thin disks)

- Radiatively Inefficient (thick disks)

Narayan & Quataert (2005)
Relativistic Iron-Lines

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

Tanaka et al. (1995)
MCG 6-30-15

Reynolds & Nowak (2003)

Also, see talk by Brenneman this session
Electromagnetic BH Measurements

- Directly Resolving Event Horizon:
  - (e.g., Sgr A*)

\[ D(M, a) \]

1mm synchrotron emission from 3D GRMHD simulation

\[ a=0.9M, \ i = 45^\circ \]
Electromagnetic BH Measurements

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

- Spectral Fitting of Thermal Emission

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

\[ T \sim (H/r)^2 r^{-1} \]

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

\[ P = 2\pi \Omega^{-1}(M, a) \]

\[ T_{max} \]

Shafee et al. (2006), McClintock et al. (2006)

Done, Gierlinski & Kubota (2007)
Thin Disk Model: Novikov & Thorne (1973)

Assumptions:

1) Stationary gravity
2) Equatorial Keplerian Flow
   - Thin, cold disks
3) Time-independent
4) Work done by stress is locally dissipated into heat and radiated instantly
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)
Steady-State Models: Novikov & Thorne (1973)

\[ L = \eta \dot{M} c^2 \]

\[ \eta = 1 - \frac{\dot{E}}{\dot{M}} = 1 - \epsilon_{\text{ISCO}} = \eta \left( \frac{a}{M} \right) \]
Dynamical Global GRMHD Disk Models

- Realistic Hydrodynamic shear viscosities cannot explain observed accretion rates

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

  - Magneto-Rotational Instability (MRI) develops from weak initial field, efficiently transports angular momentum outward.

  - Significant field within ISCO up to the horizon.

Dynamical Global GRMHD Disk Models

Krolik, Hawley, Hirose (2005)
H/R ~ 0.1 - 0.15

Shafee et al. (2008)
H/R ~ 0.05
Our Method: Simulations

- **HARM:**

- Axisymmetric (2D)

- Total energy conserving
  (dissipation → heat)

- Stationary Metric

- Modern Shock Capturing techniques

- Improvements:
  - 3D
  - More accurate (parabolic interp. In
    reconstruction and constraint transport
    schemes)
  - Assume flow is isentropic when $P_{\text{gas}} \ll P_{\text{mag}}$
Our Method: Simulations

- **Improvements:**
  - 3D
  - More accurate (higher effective resolution)
  - Stable low density flows

- **Cooling function:**
  - Control 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

\[ \nabla_{\nu} F_{\mu\nu}^* = 0 \]
\[ \nabla_{\mu} (\rho u_{\mu}) = 0 \]
\[ \nabla_{\mu} T_{\nu}^\mu = -\mathcal{F}_{\mu} \]

$H/R \sim 0.08 \quad a_{\text{BH}} = 0.9M$
Cooling Function

- Optically-thin radiation:
  \[ T^\mu_{\nu;\mu} = - F_{\nu} \]

- Isotropic emission:
  \[ F_{\nu} = f_c u_{\nu} \]

- Cool only when fluid's temperature too high:
  \[ f_c = s \Omega u (\Delta - 1 + |\Delta - 1|)^q = 0 \text{ for } \Delta < 0 \]

\[ \Delta = \frac{u}{\rho T} \]

\[ T(r) = \left( \frac{H}{R} r \Omega \right)^2 \]
GRMHD Disk Simulations

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

\[ r \in [r_{\text{hor}}, 120M] \]

\[ \theta \in \pi [0.05, 0.95] \]

\[ \phi \in [0, \frac{\pi}{2}] \]

\[ a = 0.9M \]
GRMHD Disk Simulations

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

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

Reaching to within 5% of Target Temperature

Cooling Rate $\geq$ Diss. Rate
Disk Thickness

![Graph showing disk thickness as a function of r/M](image)

- dVH
- HARM3D
HARM3D vs. dVH

\[ \log(\rho) \]

- Uncooled
- Cooled
- dVH
HARM3D vs. dVH

\[ \rho \rho_{\text{max}}^{-1}(r) \]

Time average

Uncooled Cooled dVH
Accretion Rate

Steady State Period = 7000 – 15000M

Steady State Region = Horizon – 12M
Departure from Keplerian Motion

HARM3D

dVH

Specific Ang. Mom.

\( r/M \)

Specific Energy

\( r/M \)
Magnetic Stress

\[ W_\phi \text{ (fluid-frame stress)} \]

- dVH
- HARM3D
- NT

\[ r/M \]
Radiative Transfer: From Disk to Observer

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

- 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 Intensity: Inclination

$i=5^\circ$

$i=65^\circ$

$i=89^\circ$
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:

\[ \Delta \eta / \eta \sim 20\% \]
Summary & Conclusions

• We now have the tools to self-consistently measure $dL/dr$ from GRMHD disks
  • 3D Conservative GRMHD simulations
  • GR Radiative Transfer

• Similarity to previous simulation with different algorithm implies robustness of our results.

• Luminosity from within ISCO diminished by
  • Photon capture by the black hole
  • Gravitational redshift
  • $t_{\text{cool}} > t_{\text{inflow}}$

➢ Possibly greater difference for $a_{\text{BH}} < 0.9$ when ISCO is further out of the potential well.
Future Work

- Explore parameter space:
  - More spins
  - More H/R ‘s
  - More H(R) ‘s

- Time variability analysis
  - Impossible with steady-state models
Variability of Dissipated Flux

\[ \theta = 5 \text{ deg.} \]
\[ \theta = 35 \text{ deg.} \]
\[ \theta = 65 \text{ deg.} \]
\[ \theta = 89 \text{ deg.} \]
HARM3D vs. dVH \( y(\phi - \text{avg}) \)
HARM3D vs. dVH \[ \log(\rho) \]

192x192x64
\[ a = 0.9 \ M \]
HARM3D vs. dVH $\log(P)$

$192 \times 192 \times 64$
$a = 0.9 \, M$
HARM3D vs. dVH

\[ \log(P_{\text{mag}}) \]
Cooled #1 vs. Cooled #2

\[ \log(P) \]

From \( t = 0 \) M

From \( t = 4000 \) M
HARM3D vs. dVH

$\log(P_{mag})$
HARM3D vs. dVH \( \log(\beta) \)

Uncooled  Cooled #2
HARM3D vs. dVH

log(P)

Uncooled  Cooled #2  dVH
HARM3D vs. dVH

- Cooled from $t=0M$
- Cooled from $t=4000M$
- Uncooled
- Non-conservative
Cooling Methods

\[ \log(\rho) \]

From \( t = 0 \) M to \( t = 4000 \) M
Cooling Methods

From $t = 4000$ M

From $t = 0$ M
Cooling Efficacy

- Cooled from $t=0M$
- Cooled from $t=4000M$
- Uncooled
Spectral Fits for BH Spin

**TABLE 1**

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Observation Date</th>
<th>Satellite</th>
<th>Detector</th>
<th>$a_*$ (D05)</th>
<th>$a_*$ (ST95)</th>
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<tbody>
<tr>
<td>GRO J1655–40 ……</td>
<td>1995 Aug 15</td>
<td>ASCA</td>
<td>GIS2</td>
<td>~0.85</td>
<td>~0.8</td>
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<tr>
<td></td>
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<td></td>
<td>GIS3</td>
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<td>~0.75</td>
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<tr>
<td></td>
<td>1997 Feb 25–28</td>
<td>ASCA</td>
<td>GIS2</td>
<td>~0.75&lt;sup&gt;a&lt;/sup&gt;</td>
<td>~0.70</td>
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<td></td>
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<td>~0.7</td>
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<tr>
<td></td>
<td>1997 Feb 26</td>
<td>RXTE</td>
<td>PCA</td>
<td>~0.75&lt;sup&gt;a&lt;/sup&gt;</td>
<td>~0.65</td>
</tr>
<tr>
<td></td>
<td>1997 (several)</td>
<td>RXTE</td>
<td>PCA</td>
<td>0.65–0.75&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.55–0.65</td>
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<tr>
<td>4U 1543–47 ………</td>
<td>2002 (several)</td>
<td>RXTE</td>
<td>PCA</td>
<td>0.75–0.85&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.55–0.65</td>
</tr>
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</table>

<sup>a</sup> Values adopted in this Letter.

Shafee et al. (2006)

**Power Law**

<table>
<thead>
<tr>
<th>Object</th>
<th>Mean</th>
<th>Standard Deviation</th>
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<tbody>
<tr>
<td>GRS 1915+105&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.998</td>
<td>0.001</td>
</tr>
<tr>
<td>GRS 1915+105&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.998</td>
<td>0.001</td>
</tr>
</tbody>
</table>

McCintock et al. (2006)
HARM3D vs. dVH \( \log(P_{mag}) \)
Fluid Frame Flux

Agol & Krolik (2000) model

\[ \Delta \eta = 0.01 \]

\[ \Delta \eta / \eta = 7\% \]
Observer-Frame Intensity: Time Average

$\theta = 5^\circ$ (deg.)

$\theta = 65^\circ$ (deg.)

$\theta = 89^\circ$ (deg.)

NT

HARM

$i=5^\circ$ $i=65^\circ$ $i=89^\circ$