3D GRMHD Simulations of Black Hole Accretion Disks

Ramesh Narayan
Astrophysical black holes nearly always have observable accretion disks around them. These accretion disks provide information on accretion physics, e.g., different spectral states, enabling us to check our models. Conversely, observations of disk emission allow us to study the BH: $M$, $a_*$, event horizon. Our group has estimated spin parameters of a number of stellar mass BHs in X-ray binaries by fitting the disk spectrum.
Our Team

Jeff McClintock    Ramesh Narayan
Shane Davis, Lijun Gou, Li-Xin Li, Jifeng Liu, Jon McKinney,
Jerry Orosz, Bob Penna, Mark Reid, Ron Remillard, Rebecca Shafee,
Jack Steiner, Sasha Tchekhovskoy
# BH Masses and Spins

<table>
<thead>
<tr>
<th>Source Name</th>
<th>BH Mass (M_☉)</th>
<th>BH Spin (a_*)</th>
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<td>5.9—9.2</td>
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Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); Gou et al. (2009); Steiner et al.
Any method of measuring $a_\ast$ is only as good as the theoretical model behind it.

Our method assumes that the accretion disk is well described by the GR disk model of Novikov & Thorne (1973).

In particular, we assume that the disk luminosity profile $L(r)$ takes the form predicted by the NT model.
Novikov & Thorne $L(r)$

$L(r)$ peaks at a different radius for each value of the dimensionless BH spin parameter $a_*$.

Therefore, the observed spectrum depends on $a_*$.

This is what enables us to estimate $a_*$ from observations.
Different representations of the luminosity profile
Novikov-Thorne Model

![Graphs showing $J_{in}/M$ and Binding Energy Flux $(1-E/M)$ vs. $r/M$.]
But How Good is the Novikov-Thorne Model?

- The NT model assumes a geometrically thin disk.
- It assumes that the "viscous" torque vanishes at the ISCO (Shakura & Sunyaev 1973; Novikov & Thorne 1973).
- But magnetic fields could produce significant torque at and inside the ISCO (Krolik 1999; Gammie 1999).
- Afshordi & Paczynski (2003) suggested that the effect is probably not important for a THIN disk (Shafee et al. 08).
- Can we verify this?
Testing the Novikov-Thorne Model using 3D GRMHD Simulations

- 3D MHD simulations in the Kerr metric
- Magnetic fields self-consistently generate “viscous” torques via the MRI (Balbus & Hawley 1991)
- We must simulate geometrically thin disks – numerically very challenging
- Reynolds & Fabian (2008); Shafee et al. (2008); Noble, Krolik & Hawley (2009)
We use the GRMHD code HARM (Gammie, McKinney & Toth 2003)

Conservative code, runs in 3D in the stationary Kerr metric

We add an ad hoc cooling where we specify the target entropy of the gas as a parameter:

\[
\frac{du}{d\tau} = - \frac{\Omega_K \left( u - u_{\text{target}} \right)}{2\pi}
\]

This parameter lets us tune the disk thickness
Our Fiducial Run

- A very thin disk ($<|h|>/r \sim 0.05$) around a non-spinning BH ($a_*=0$)
- $256 \times 64 \times 32$ grid ($\varphi$-wedge angle: $\pi/2$)
- Gas is initially in a torus beyond $r=20M$
- Simulation is run for a time of $17000M$
- Steady state after $t \sim 12000M$

Penna et al. (2009)
Mass Conservation

\[ \rho u^\alpha \frac{\partial u}{\alpha} = 0 \]

Mass Flux = \[ \int \int \rho u^r \sqrt{-g} \, d\theta \, d\phi \]

\[ = M(r) = \text{constant (steady state)} \]

\[ \theta \text{ integral } = 0 - \pi : \text{all the fluid} \]

\[ \theta \text{ integral } = \frac{\pi}{2} \pm \frac{2h}{r} : \text{limited to disk} \]
Fiducial Run: Mass Accretion Rate

Penna et al. (2009)
Angular Momentum Conservation

\[ T^\alpha_{\phi;\alpha} = \text{ang mm tm loss via radiation} \]

\[
\text{Flux} = \iiint \left[ \left( \rho + \Gamma u + b^2 \right) u^r u^\phi - b^r b^\phi \right] \sqrt{-g} \, d\theta \, d\phi
\]

\[
= J(r) = \text{nearly constant}
\]

\[
J(r) = J_{\text{in}}(r) + J_{\text{out}}(r) \quad \text{(for comparing with NT)}
\]

\[
J_{\text{in}}(r) = \iiint \left( \rho + \Gamma u + b^2 \right) u^r \left\langle u^\phi \right\rangle \sqrt{-g} \, d\theta \, d\phi
\]
Our New Fiducial Run ($a^* = 0$): Penna et al. (2009)
The results from the two runs appear to be similar. We view the deviations as a measure of the errorbar.
Thin Disks: Other Values of $a_*$

Pretty good agreement with Novikov-Thorne, except at the largest value of $a_*$.
Thicker Disks with $a_* = 0$

The accretion flow becomes quite sub-Keplerian as the disk thickness increases.
Angular Momentum: Summary

- Thin disks with $h/r<0.1$ behave quite a lot like the Novikov-Thorne model.
- Deviations are larger for larger values of $a_*$, but the dependence is modest.
- However, deviations increase rapidly as the disk thickness increases.
- Therefore, the NT model is not trustworthy for thick disks.
Energy Conservation

\[ T^\alpha_{t;\alpha} = \text{energy loss via radiation} \]

\[ \text{Flux} = \iiint \left[ \left( \rho + \Gamma u + b^2 \right) u^r u_t - b^r b_t \right] \sqrt{-g} \, d\theta \, d\phi \]

\[ = E(r) : \text{increases with radius (radiation)} \]

\[ \left( 1 - \frac{E}{M} \right) = \text{Binding energy released per unit mass} \]

\[ \frac{dL}{d \ln r} = - \frac{d}{d \ln r} \left( 1 - \frac{E}{M} \right) \]
Fiducial Run: Energy Flux

!!Very Preliminary!!

a* = 0
256x64x32

Binding Energy Flux (1 - \( \tilde{E} / M \))
\( a^*=0 \)

Cyan: 256 x 64 x 32 (Penna et al. 2009): \(~5000M\)
Magenta: 512 x 128 x 32 (Shafee et al. 2008): \(~2000M\)
Thin Disks: different $a_*$

$$a_*=0.7$$

$$a_*=0.98$$

$$a_*=0.9$$

$dL$/d$lnR$ vs $r/M$
Thicker Disks: $a_*=0$

Distinction between the disk and the plunging region becomes washed out as the disk becomes geometrically thicker.
Energy and Luminosity: Summary

- Thin disks with $h/r<0.1$ seem to behave like the Novikov-Thorne model.
- Deviations are larger for larger BH spins, and may be serious as $a_* \to 1$.
- Deviations increase rapidly as the disk thickness increases.
- Accretion luminosity/efficiency is not very different from NT value.
Current (very preliminary!) indication: geometrically thin accretion disks behave quite a lot like the Novikov-Thorne model

Suggests that our spin estimates are probably okay...

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