Tilted Disks around Black Holes: Investigating the Alignment Mechanism

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I use Blue Waters for the capstone simulations in a series of numerical experiments that probe the mechanisms by which external torques align accretion disks

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Accretion Disks in Astrophysics

- Gravity + angular momentum
- Quasars, active galactic nuclei, black holes, neutron stars, white dwarfs, proto-stellar and proto-planetary systems
- Basic concepts are understood, but details are complex and observations difficult
Disks may be tilted and twisted

• Multiple angular momentum vectors: disk, central star (black hole) spin, orbital angular momentum of binary

• No necessary reason for these to be initially aligned

• Do they become aligned? If so, at what radius? (Implications for observations, jets, etc.)
Tilts Make Torques

Rotating solitary mass: \( T = 2\left(\frac{G}{c^2}\right)J \times \frac{L}{r^3} \)

\( \Omega_{\text{prec}} \sim \left(\frac{c}{r_g}\right)\left(\frac{r}{r_g}\right)^{-3} \)

- **Differential precession** induced by torques
- **Dissipation** between neighboring rings leads to alignment
- Questions remain regarding mechanisms of alignment and location of alignment transition, *nature of dissipation*
Key Challenge: Dissipation and Disk Alignment

• Dissipation between rings is key to alignment. But what is the nature of that dissipation and how does it work?
• Most analytic (and many numerical) studies of disk alignment have made use of the “alpha viscosity” parameterization, assuming the presence of an actual viscous stress
  \[ \alpha c_s H = \nu \]  
  Viscosity parameterized as proportional to sound speed times scale height
• Assumption made that a low Re viscous disk is equivalent to a high Re turbulent disk
• Generally treated as an isotropic viscosity
• **However:** The source of accretion stress is MHD turbulence driven by the magneto-rotational instability. The \( (r, \phi) \) component of the stress tensor is strongly favored by the MRI
• “A large-Reynolds-number turbulent disk is simply not a laminar disk with a much smaller Reynolds number.”
• Existing analytic theory is, at best, suspect.
This Investigation

• No assumed viscous stress; MRI-driven MHD turbulence provides internal stress (no viscosity except bulk viscosity)

• *Numerical experiments* on an idealized problem – include/exclude various terms, adjust parameters for contrast

• MHD models are contrasted with pure hydrodynamic models with no accretion stress

• Simplified gravity: Newtonian potential and post-Newtonian external torque term

• Aim: Elucidate physical processes involved in disk alignment through numerical experiments

• First study: effect of sound speed (temperature) and tilt angle of black hole with respect to accretion disk
Numerical Approach

- Time-explicit, operator-split, finite-difference compressible MHD ("constrained transport") in spherical coordinates (ZEUS algorithm)
- Domain decomposition, MPI parallelization, minimal global communications, excellent weak scaling
- Newtonian gravity with lowest order post-Newtonian terms to account for torque
- Isothermal equation of state to isolate effect of sound speed on alignment. Set of three sound speeds and three tilt angles studied
Why Blue Waters?

- Investigation involves Three-dimensional, time-dependent turbulent MHD simulations
- Multiple timescales: Orbital frequency $\Omega \propto r^{-3/2}$; Precession frequency $\Omega_p \propto r^{-3}$; Sound speed over scale height $c_s / H$; Alfven speed $v_a$
- Multiple length scales: Black hole radius, accretion disk extent, pressure scale height $H$ (should be $<< r$), turbulent eddy size ($<< H$)
- Limit these scales through problem definition; but still require high resolution, long time duration simulation
- Lower resolution simulations, hydrodynamic comparison simulations, etc. can be done on university cluster (order few hundred cores)
- Thinner (colder) disks require greater resolution, as do larger tilt angles
- Capstone simulations require Blue Waters, long running times, ~600M grid zones
- Blue Waters provides the peak of the HPC ecosystem
Lense-Thirring and Disk Alignment

MHD turbulent disk without torque

MHD turbulent disk after 15 orbits with torque
Three Isothermal Disks
12 degree tilt, 3 soundspeeds

Isothermal Keplerian Disk
H/r ~ 0.1 (Krolik & Hawley 2015)
(352x384x1024)

Isothermal Keplerian Disk
H/r ~ 0.05
(704x770x1024)

Isothermal Keplerian Disk
H/r ~ 0.035
(765x765x1024)
Location of 75% alignment as a function of sound speed

$r_{\text{align}} \sim c_s^{-4/5}$
Comparison of three tilt angles

Tilt = 6 degrees
Tilt = 12 degrees
Tilt = 24 degrees

No evidence for "disk breaking" for these three tilts
Alignment angle: three tilts

Absolute value of alignment angle

Ratio of Alignment to tilt
Results Summary

- Primary dynamical forces are hydrodynamic in nature (bulk Reynolds stresses from radial pressure gradients)
- MHD turbulence does not produce isotropic stress; no significant out-of-plane MHD stress
- The difference between pure hydro and MHD is that the latter is turbulent. MHD turbulence disrupts internal wave motion and inhibits evolution toward solid-body precession
- Transition front determined by balance between external torque and warp induced inward mixing of angular momentum
- Diffusion model predicts alignment radius $R_T \sim c_s^{-4/5}$ – results consistent with this
- Warp amplitude is the relevant physical discriminant for characterization as wavelike or diffusive
- Alignment process depends only weakly on tilt angle (up to 24 degrees)