Magnetic Torques in Disks (ITP Black Holes Conference 2/27/02)

Magnetic Torques in Accretion Disks

Chris Reynolds
Department of Astronomy
University of Maryland

3/18/02 ITP 2002 Black Holes Meeting

External torques: The Blandford-Payne model


3/18/02 ITP 2002 Black Holes Meeting
Outline for this talk

- The magneto-rotational instability (MRI)
  - Linear and non-linear properties
  - Local and global simulations
- MHD properties of the innermost disk
  - Inner “edge” of the disk is important!
  - Interesting magnetic/MHD effects occur
  - Simulations (global and cylindrical)
- Reality…some data from XMM-Newton
  - MCG-6-30-15 and XTE J1650-500
- Also see coming talk by Neal Turner

I: The Magneto-Rotational Instability (MRI)

- The magneto-rotational instability (MRI)
  - Generic instability in MHD accretion disks
  - Balbus & Hawley (1991) rediscovered this instability and realized importance for accretion disks
  - The resulting MHD turbulence produces the angular momentum transport that drives accretion
Magnetic Torques in Disks (ITP Black Holes Conference 2/27/02)

- Linear theory (Balbus & Hawley 1991)
  - Perturbations of linearized ideal MHD equations with shear
  - Instability if and only if $\frac{d\Omega^2}{dr} < 0$
  - Fastest mode grows on dynamical timescale (independent of magnetic field strength).
  - Fastest growing mode has wavenumber $k \sim \Omega/v_A$
  - Do not get hydrodynamics in limit as $B \rightarrow 0$
- Non-linear evolution
  - Sustained MHD turbulence
  - Investigated in local and global simulations

Shearing box (local) models
Global disk models

Hawley, Balbus & Stone (2001)

Summary of simulation results

- Simulations by several groups
  - Armitage, Brandenburg, Gammie, Hawley, Miller, Stone, Turner, and others...
- Local (shearing box simulations)
  - MHD turbulence produced and sustained
  - Angular momentum transport
  - Effective $\alpha$ depends upon net flux threading box
    - $\alpha \sim 0.01$ for zero net field
    - $\alpha \sim 0.1$ for significant net field
- Global simulations (zero net field)
  - Can only do relatively hot, adiabatic disks
  - MHD turbulence, with significant power on large scales
  - $\alpha \sim 0.1$; characteristic of local simulations with net field
II: The innermost regions of the accretion disk

- Properties of inner boundary are extremely important
  - Determines the radiative-efficiency of disk
  - Determines existence/nature of coupling to black hole spin
- "Standard" model (Page, Novikov & Thorne)
  - Generalization of Shakura & Sunyaev (1973) model
  - Assume internal torque goes to zero at ISCO
  - This determines efficiency of disk.

\[ L = \eta \dot{M} c^2 \]
\[ \eta = 0.42 \] for maximal Kerr hole

---

Analytic arguments

- General arguments (Krolik 1999)
  - Within ISCO (i.e. plunging region), assume
    - Dynamically-weak field frozen into plasma
    - Material pushed into plunging region by magnetic forces
      - [axisymmetry and time-independence]
  - Then...
    - Find that plasma-\(\beta\) decreases rapidly in plunging region
    - Magnetic field will become dynamically significant
    - Can produce interesting effects within plunging region
    - Field could causally-connect plunging region to rest of disk
Particular disk models
- Gammie (1999)
  - 1-D MHD model of plunging region
  - Significant torques at ISCO
  - Significant enhancement of disk efficiency
- Agol & Krolik (2000)
  - Extended Page & Thorne model, with torque at ISCO
  - Significant enhancement of efficiency

Back to simulations…
- “Toy” model of Schwarzschild accretion disk…
  - Non-relativistic MHD (ZEUS algorithm)
  - Approximate GR using Pseudo-Newtonian potential.

\[ \Phi = \frac{M}{r - 2M} \]

- Global models
  - Moderately hot, adiabatic accretion tori
  - Sustained turbulence with effective \( \alpha \sim 0.1 \)
  - Verified importance of magnetic torques at ISCO
Cylindrical simulations

- Trouble with global simulations...
  - Very computer intensive (no parameter survey yet)
  - Limited spatial resolution in central regions
- Cylindrical simulations
  - Armitage, Reynolds & Chiang (2001); Reynolds & Armitage (2001); Hawley (2001)
  - Distills out essential physics (complements global models)
  - Look at 3-D wedge of disk.
  - Ignore vertical component of gravity
  - Use pseudo-Newtonian potential
  - Isothermal gas, with \( h/r \approx 0.08 \) at ISCO
  - Use ZEUS-3D & ZEUS-MP codes
- Perform set of simulations with “tunable” saturation field strengths (Reynolds & Armitage 2001)
  - Tune saturation strength by changing initial vertical fields (hence different net fluxes).
  - Angular-momentum (& energy) transport in plunging region correlates with B-field strength in final turbulent state.
  - ISCO torques tremendously variable on dynamical timescale!
  - Accretion efficiency may vary on short timescales.

- Another way of phrasing this…
  - Saturation field affects value of effective $\alpha$
  - Presence of ISCO torques correlates with effective $\alpha$
• Significant fluctuations between independent timeslices
• $\mathcal{U}$ flattens in plunging region

• Larger saturation field $\Rightarrow$ stronger torques in plunging region
• Very large fluctuations
• Especially strong torques in plunging region during red period
• Good agreement with Hawley & Krolik (2000) during these times
Beyond the Simulations…

- Relativistic effects around rotating black hole
  - Effects of frame-dragging and gravitational redshifting?
  - Charles Gammie’s talk; Koide et al. (1999), Meier et al. (2000)
- What about colder/thinner disks?
  - Do ISCO torques occur in thinner disks?
  - May be limited by reconnection of tightly wound field
- Development of large-scale fields
  - Inverse turbulent cascade, or advection of pre-existing field?
  - Black hole will “integrate” accreted magnetic flux
    - Field strength may be limited by field pressure in body of disk (Ghosh & Abramowicz 1997, Livio et al. 1997)?
    - Much greater fields may be permitted due to inertial confinement by accretion flow in plunging region.

XMM-Newton observations of MCG-6-30-15

- Wilms, Reynolds, Reeves et al., 2001, MNRAS.
- XMM-Newton satellite
  - Recently launched European X-ray observatory
  - Several co-aligned instruments
    - Reflection Grating Spectrometer (RGS)
    - European Photon Imaging Camera (EPIC)
    - Optical Monitor (OM)
  - Superb for obtaining high S/N spectra of accreting black holes (AGN and GHBCs)
- Model soft X-rays
  - Ionized absorption
  - Soft X-ray emission features
  - Fit to RGS spectrum
- Isolate spectral features from disk

X-ray reflection...
Basic result

- Model within context of rapidly rotating BH
  - Requires extreme degree of broadening!
  - Implies very centrally concentrated X-ray source
  - $F(r) \sim r^{-\beta}$, $4.5 < \beta < 6.0$
  - $R_\in < 2.0 \text{GM}/c^2$

- If BH slowly rotating:
  - more extreme $\beta$ required
  - Need emission down to $3\text{GM}/c^2$

Spin extraction hypothesis

- Suppose that X-ray emissivity is proxy for disk dissipation profile.
- Spin extraction hypothesis…
  - steep emissivity profile due to torquing of inner disk
  - Inner disk torquing by plunging region in extreme Kerr geometry (Penrose)…
  - …or, torquing by direct magnetic connection between disk and horizon (Blandford-Znajek 1977, Li 2000)
  - In either case, much of extra energy originates from spin of black hole!
The Tower of Power...

- Suppose X-ray source is on-axis above the black hole at r~3GM/c² or less.
- Then, gravitational focusing gives
  - Very broad line, as observed
  - Very strong reflection signatures (R=4)
- Examined by Martocchia, Matt & Karas (2002).
- But, some potential concerns...
  - Would predict significantly stronger reflection than observed.
  - Marginal disagreement with lack of time-lags observed for this object (Reynolds 2000).

Same thing in a GBHC? XTE1650-500

Miller et al. (2002, astro-ph/0202375)
Conclusions

- MRI-driven turbulence excellent candidate for angular momentum transport mechanism
- Magnetic torques across ISCO
  - Magnitude depends upon $\beta$ in turbulent state
  - Torques highly variable (changing efficiency?)
  - Physical realization of Penrose effect
- Observations already pushing at these frontiers
  - XMM-Newton data MCG-6-30-15 & XTEJ1650-500
  - Steep emissivity may require inner disk torques (and/or direct magnetic connection to spinning black hole?)