General Relativistic MHD Simulations of Black Hole Accretion Disks

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Charles F. Gammie (Illinois)

De Villiers & Hawley 2003, ApJ, 589, 458

De Villiers, Hawley & Krolik 2003, ApJ, 599, 1238

Hirose, Krolik, De Villiers, & Hawley 2004, ApJ, 606, 1083

De Villiers, Hawley, Krolik, & Hirose 2005, ApJ, 620, 878

Krolik, Hawley, & Hirose 2005, ApJ, 622, 1008

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Accretion questions

- What disk instabilities are present?
- What disk structures arise naturally?
- What are the properties of disk turbulence?
- Is there a dynamo?
- How are winds and/or jets produced?
- Origin of QPOs and Fe Kα line
- What are the properties of the inner disk?
- How does black hole spin affect accretion?
- How does accretion affect the black hole?

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Direct Numerical Simulations

- Long term evolution towards quasi-steady state
- No pre-existing large-scale magnetic field
- Seek evolution independent of boundary or initial conditions
- Self-consistent evolution of disk
- Accretion Flows are:
  - Magnetohydrodynamic
  - Three dimensional *(essential but hard!)*
  - Dynamically unstable
  - Turbulent

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Numerical Simulations Accretion Disks: Local to Global

- Local “Shearing boxes”
- Cylindrical disks (semi-global)
- Axisymmetric global
- Full 3D global simulations – Newtonian, pseudo-Newtonian
- Global simulations in Kerr metric

General Relativistic Magnetohydrodynamics Codes

- Wilson (1975)
- Koide et al. (2000)
- Gammie, McKinney & Toth (2003)
- Komissarov (2004)
- De Villiers & Hawley (2003)
- Duez et al. (2005)
- Fragile & Anninos
- Anton et al. (2005)

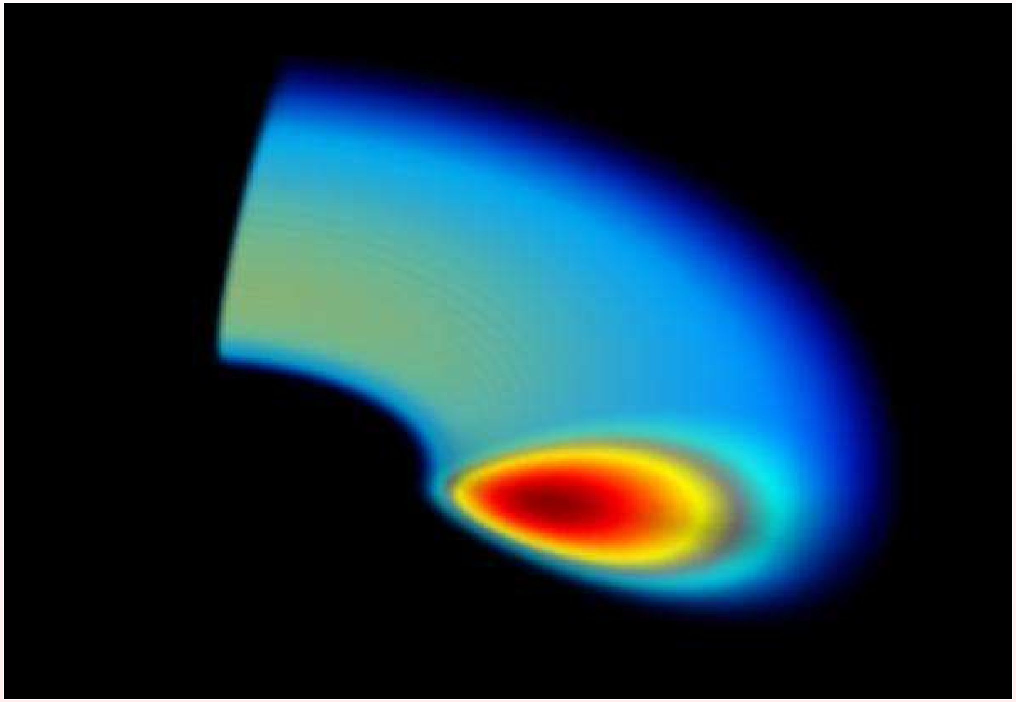
Accretion into Black Holes: GRMHD implementation

- Fixed Kerr Metric in spherical Boyer Lindquist coordinates
- Graded radial mesh - inner boundary just outside horizon; θ zones concentrated at equator
- Induction equation of form

$$F_{\alpha\beta,\chi} + F_{\beta\chi,\alpha} + F_{\chi\alpha,\beta} = 0$$

- Baryon Conservation, stress-energy conservation, entropy conservation (internal energy); no cooling
- First order, time-explicit, operator split finite differencing
- Similar to ZEUS code

Simulations around a Kerr hole from an Initial Magnetized Gas Torus



Initial poloidal field loops $\beta = 100$

Outer boundary 120M

Grid resolution 192x64x192
(r, ϕ, θ)

Ensemble of black hole spins:
a/M = 0, 0.5, 0.9, -0.9, 0.93, 0.95, 0.99, 0.998

Colors indicate density

Pressure Maximum r = 25 M

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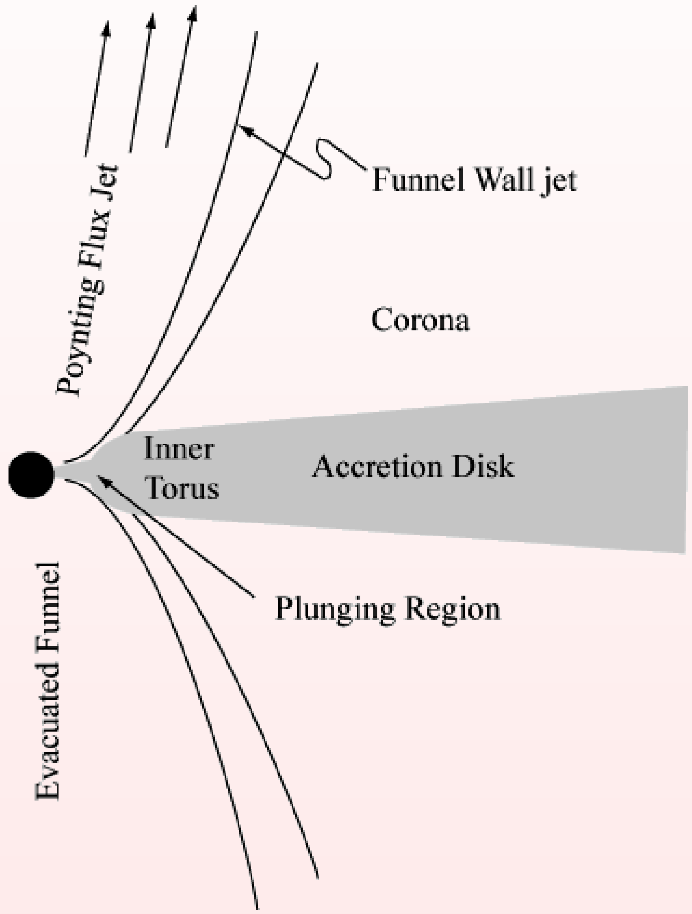
Accretion flow structures

- Accretion disk
- Inner torus and plunging region
- Magnetized corona
- Evacuated funnel
- Funnel wall jet
- Poynting flux jet



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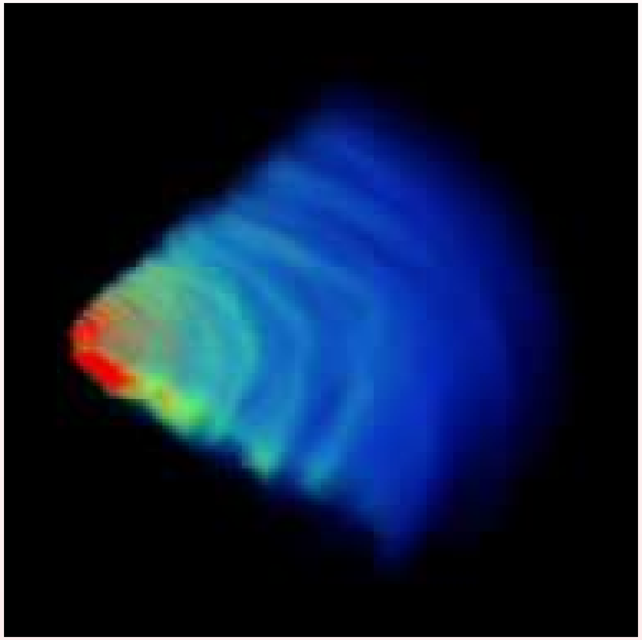
Disk Evolution

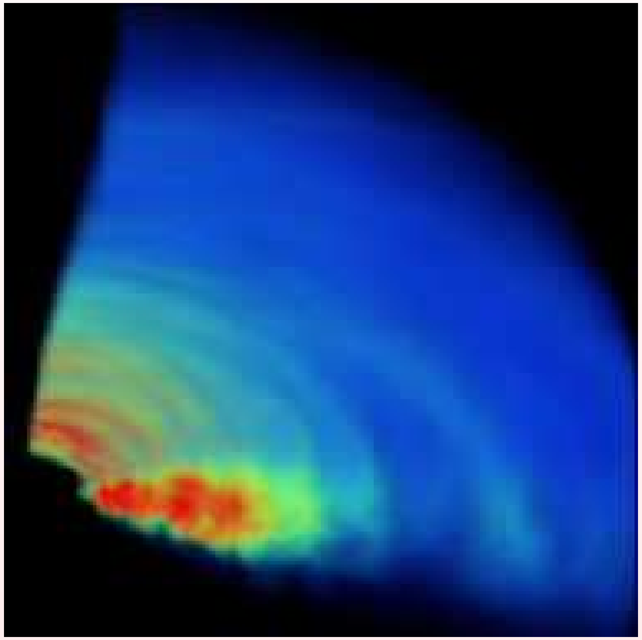
From r=0 to 60 M
Fluid density



Evolution time from
t=8000 – 10000 M

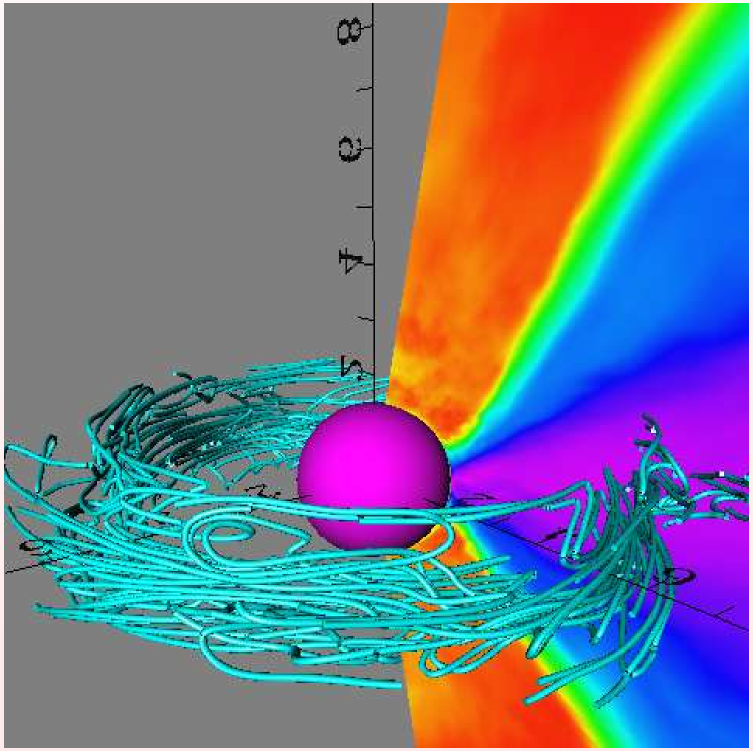
Inner Torus Evolution

From r=0 to 20 M
Fluid density



Magnetic Field in Disk

- Field is tangled; toroidal component dominates
- Field is sub-equipartion; $\beta > 1$
- Field is correlated to provide stress. Average stress values 0.1 to 0.01 thermal pressure; stress ~ ½ magnetic pressure
- Stress continues inside marginally stable orbit



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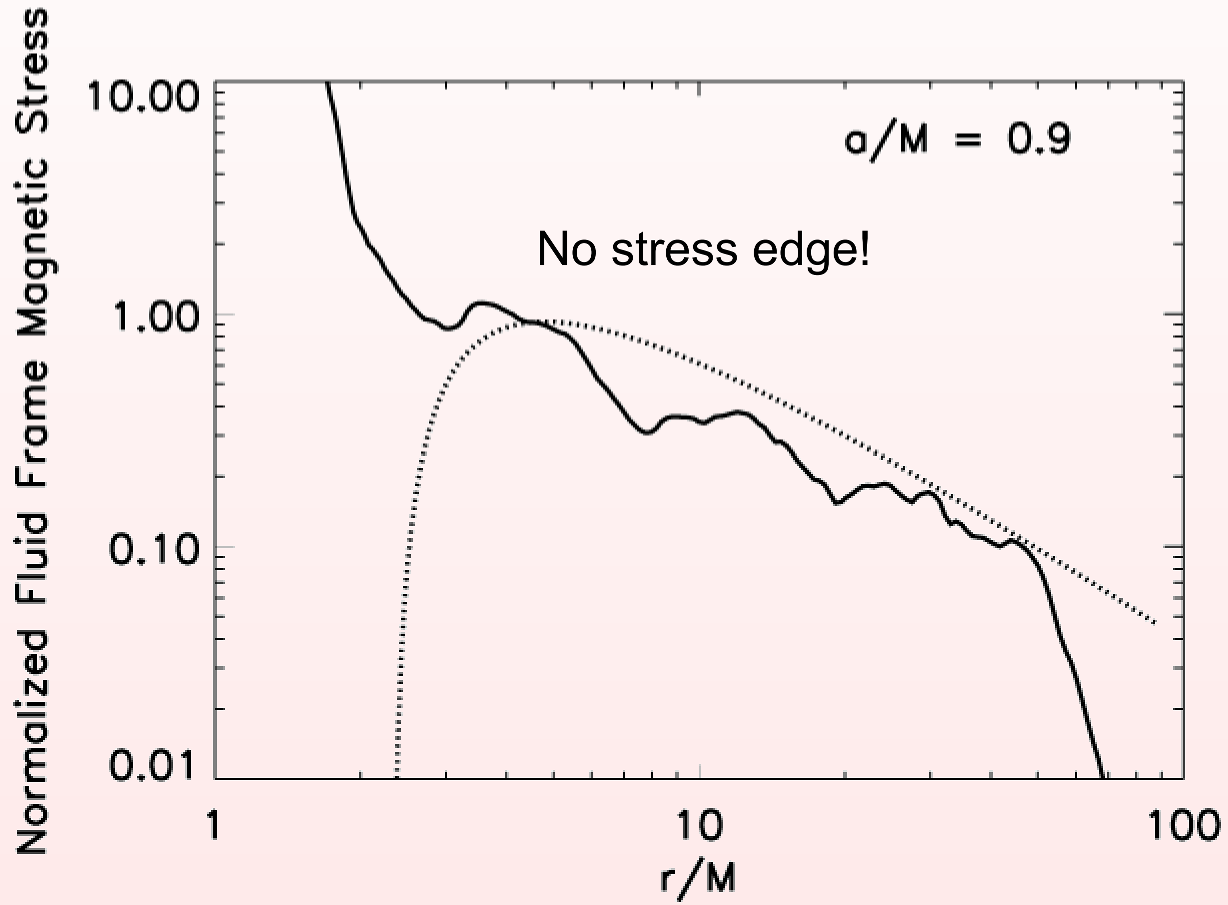
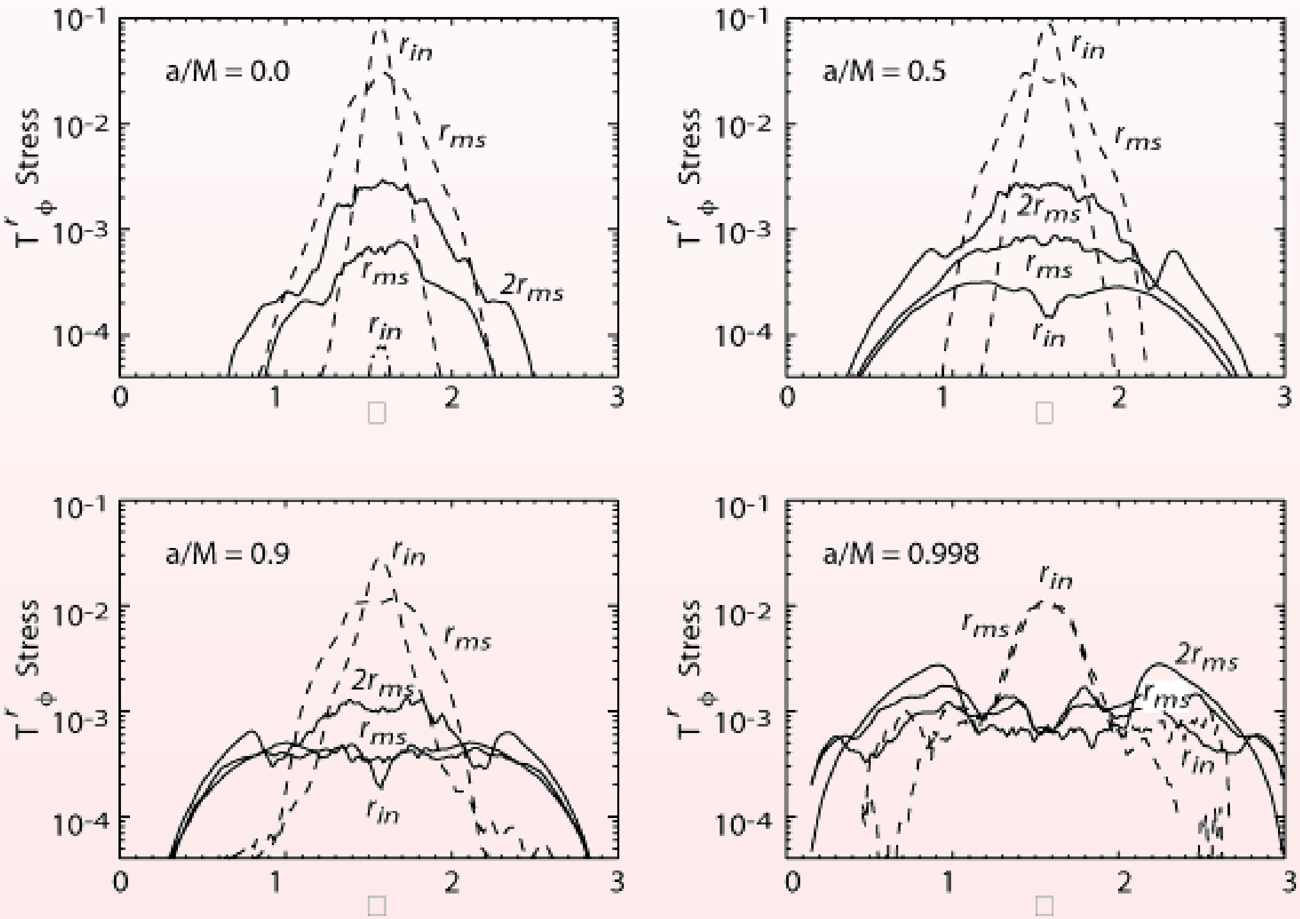
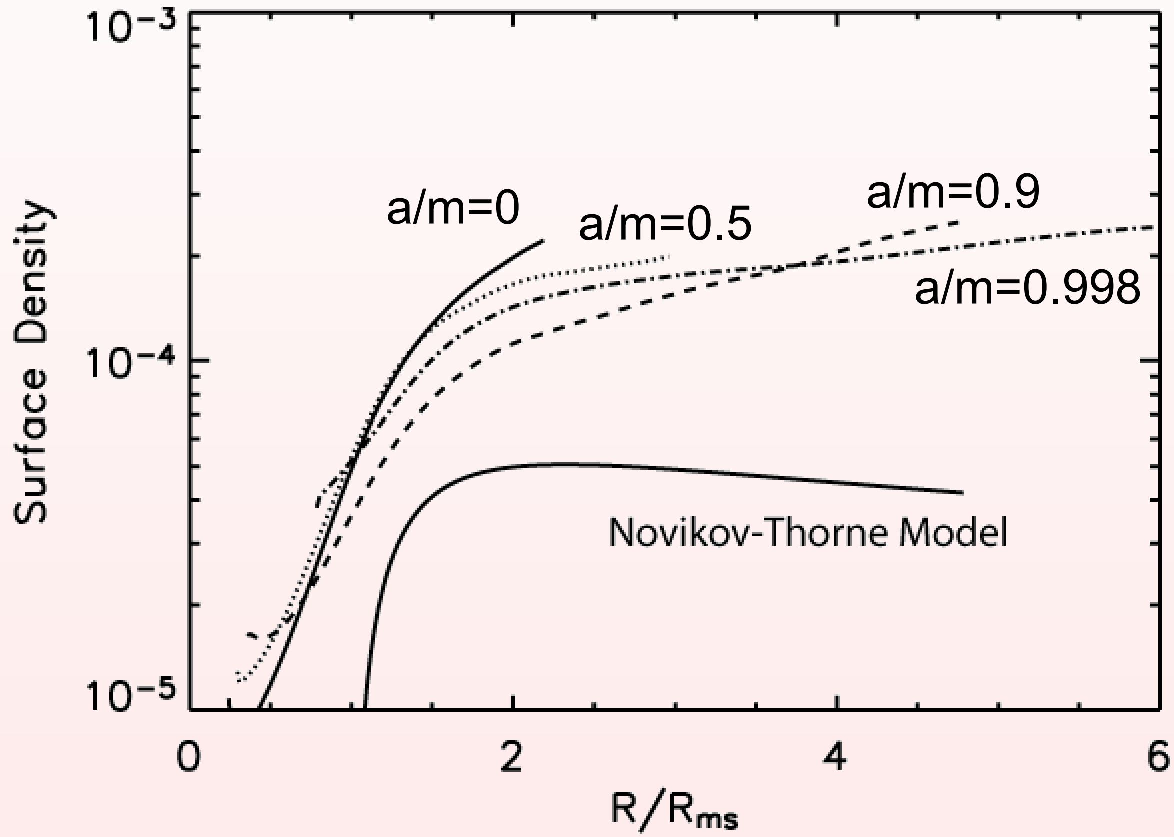
Magnetic Stress vs. Novikov-Thorne Model



Angular dependence of Stress



Surface Density in Inner Disk



Properties of the Accretion Disk

- Accretion disk angular momentum distribution near Keplerian
- After several thousand M of time, models have come into approximate steady state
- Disk is MHD turbulent due to the magnetorotational instability
- No abrupt changes at marginally stable orbit; density, velocity smooth & continuous
- Large scale fluctuations and low-m spiral features
- No stress edge; evidence for transfer of angular momentum from hole to disk
- Relative accretion rate drops as a function of increasing black hole spin

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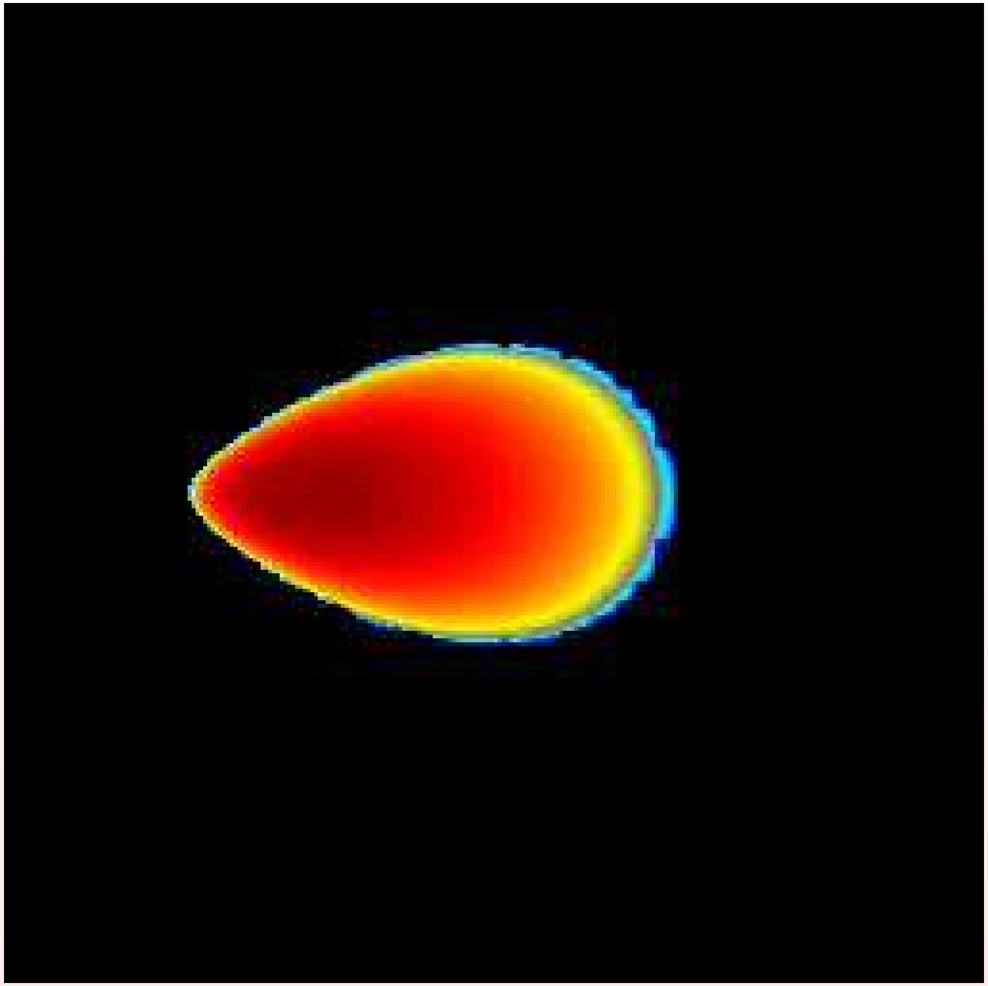
Corona formation: a/m=0.9 model

Log density,

azimuthal slice



Corona: summary

- Magnetic field and low density material blown up and out into a corona with mild outflow
- Field near equipartition on average; β varies ~ 0.1-10.
- Corona is bound, although less bound than original torus
- Large-scale motions rather than turbulence

What about Jets? A combination of Rotation, Accretion, Magnetic Field

- Young stellar objects
- X-ray binaries – accreting NS or BH
- Symbiotic stars – accreting WD
- Supersoft X-ray sources – accreting WD
- Pulsars – rotating NS
- AGN – accreting supermassive BH
- Gamma ray burst systems

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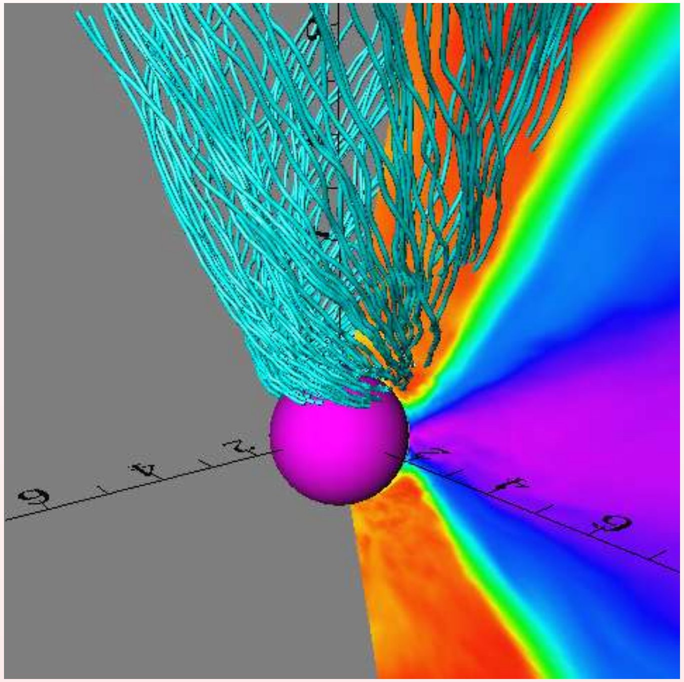
Funnel Properties

- Funnel is evacuated
- Poloidal radial field created by ejection of field from plunging inflow into funnel
- Field in pressure equilibrium with corona
- Toroidal field can be generated by black hole spin – outgoing Poynting flux – sign of angular momentum flux same as black hole in retrograde case
- Unbound mass outflow at funnel wall



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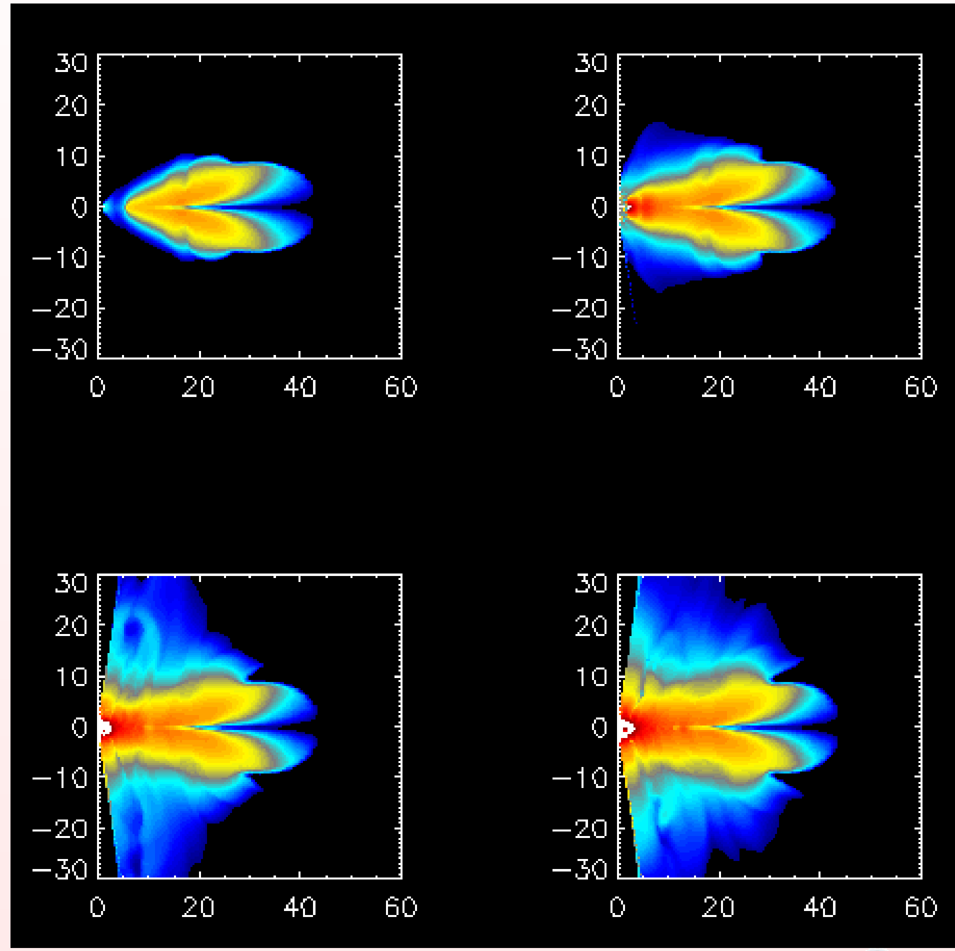
Funnel Field Formation

- Plot of log magnetic pressure at times 560, 640, 720, 800 M



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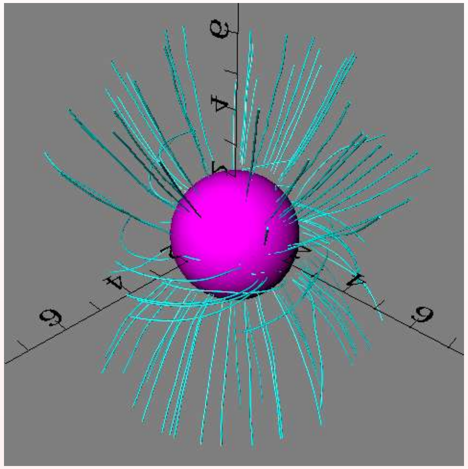
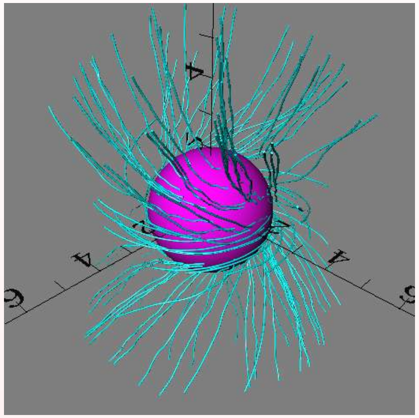
Field lines and rotating Black Holes

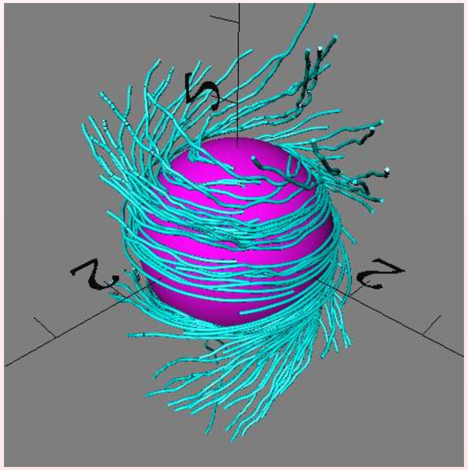
a/m = 0



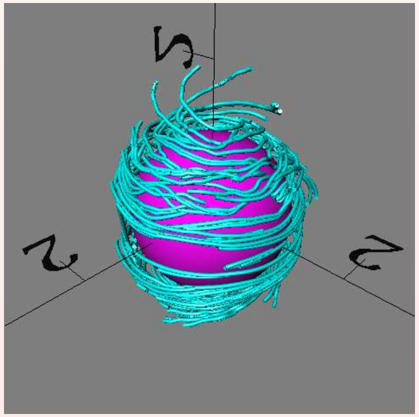
a/m=0.5



a/m=0.9



a/m=.998



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a/M = 0.9 Kerr Hole

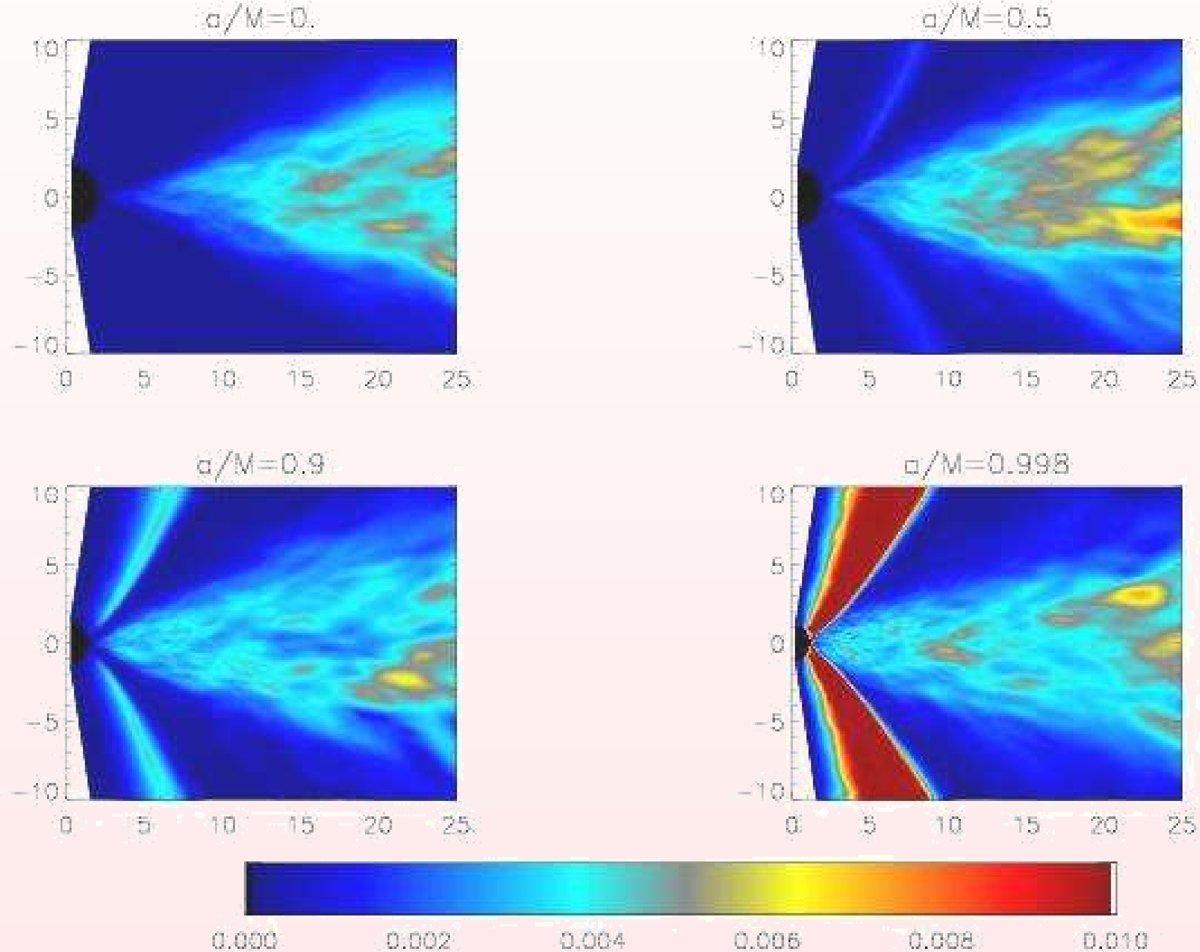
Total evolution time
10,000 M

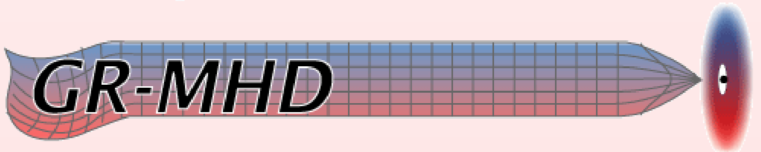
Visualization of EM
Poynting flux

Outer boundary of
movie at r=100 M

Web Page:
http://www.astro.virginia.edu/VITA/jetmovie.html

Poynting Flux for Different Black Hole Spins





Funnel Wall Jet

- Unbound mass flux along hollow cone
- Accelerating force is pressure rather than magneto-centrifugal
- Collimation due to hot corona
- Mass flux increases with black hole spin: Jet flux < 1% accretion rate for a/M=0, increasing to ~10% for a/M=0.9
- Funnel wall jet velocity increases with spin from 0.2*c* to 0.4*c*

Jet Luminosity

a/M	η_{jet}	η_{jet} / η_{ms}	Poynting
0.0	0.002	0.03	0.06
0.5	0.013	0.16	0.34
0.9	0.029	0.27	0.47
- 0.9	0.15	3.85	0.27
0.93	0.13	0.77	0.55
0.95	0.19	1.0	0.59
0.998	0.33	0.56	0.87

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Funnel and jets: a summary

- Outflow throughout funnel, but only at funnel wall is there significant mass flux
- Outgoing velocity ~0.4 - 0.6 c in mass flux
- Poynting flux dominates within funnel
- Jet luminosity increases with hole spin
- Fraction of jet luminosity in Poynting flux increases with spin
- Both pressure and Lorentz forces important for acceleration

Conclusions

What disk structures arise naturally?

Near-Keplerian disks, surrounded by magnetized corona

What are the properties of disk turbulence?

Turbulence is driven by the MRI. Highly correlated fluctuations transport angular momentum, large scale fluctuations and low-m spiral features. Toroidal fields dominate. Stress ~ ½ magnetic pressure

Is there a dynamo?

Yes, magnetic field is amplified and sustained at sub-thermal equipartition levels; funnel filled with large-scale radial field initially created in the plunging accretion

Conclusions (cont)

Are winds and/or jets produced?

Winds are a natural outcome (without cooling); funnel wall jet; evacuated funnel with magnetic field forms ("magnetic tower"). Poynting flux jet powered by hole spin.

What are the properties of the inner disk edge?

Location of inner edge time varying; physical quantities vary smoothly; stress not zero at or inside marginally stable orbit. Interaction between spinning black hole and disk.

How does black hole spin affect accretion?

Increasing efficiency with increasing spin. Black hole spin adds to jet power. High spin holes are being spun down. Black hole transfers angular momentum to accretion flow.

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