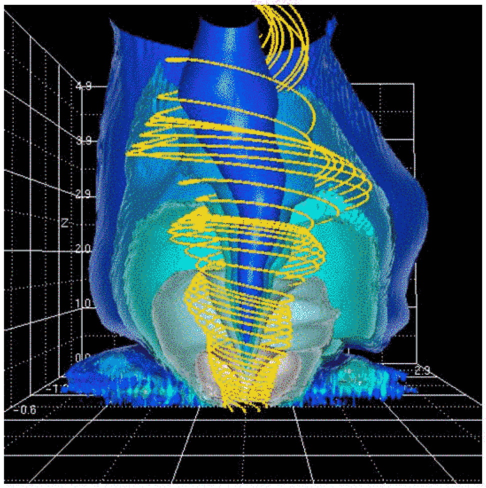
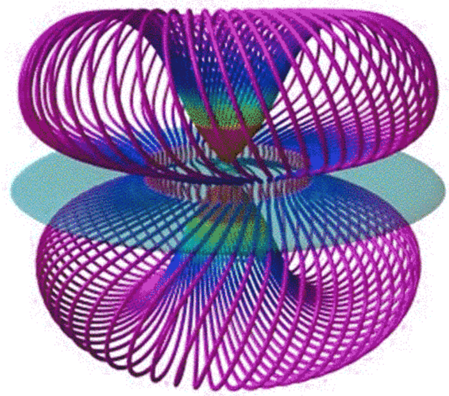
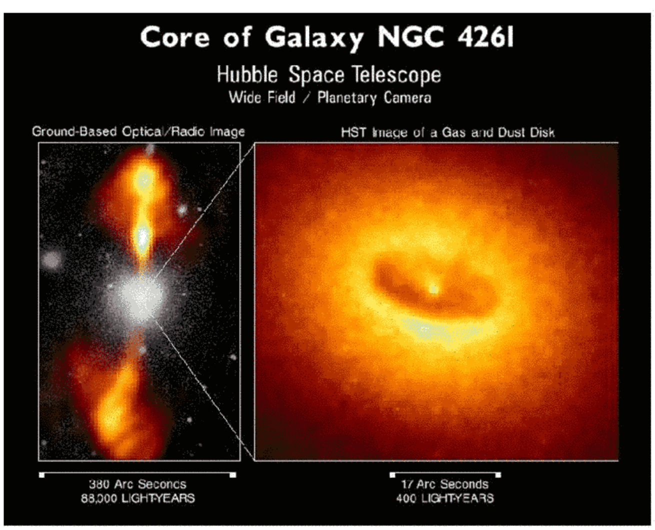
Simulations of Jets



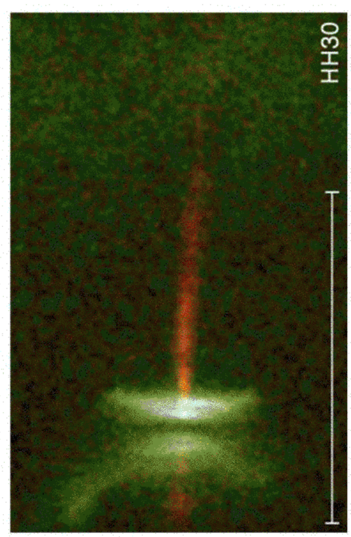


Ryoji Matsumoto （Chiba University)

Jets and Disks are Observed in Various Astrophysical Objects

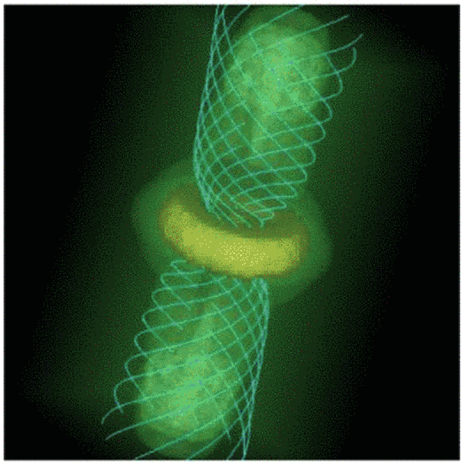


Active Galaxy



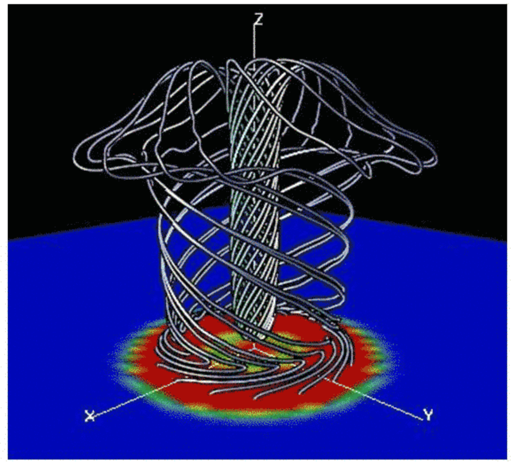
HST image of HH30

Two Geometries of MHD Jets Driven by Accretion Disks



Jets accelerated along open magnetic field lines

Blandford & Payne (1982)



Jets formed by opening up of closed magnetic loops

Lynden-Bell & Boily (1994)

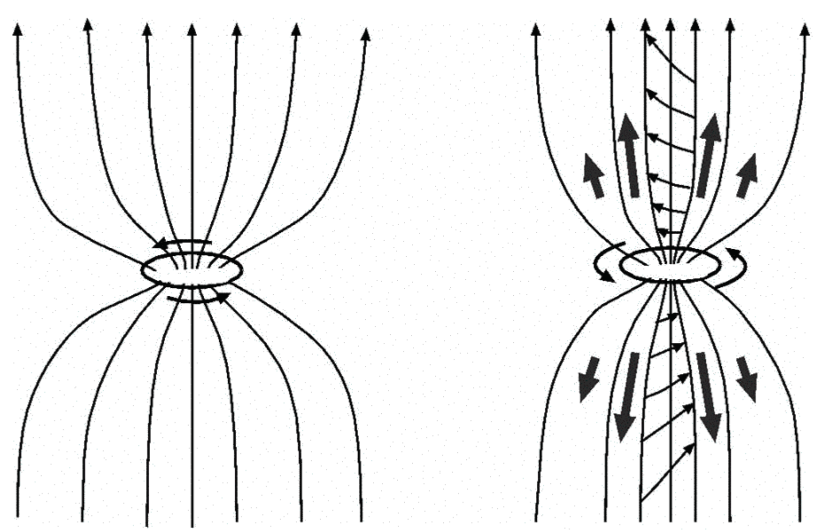
Contents of This Talk

- Global MHD Simulations of Jet Formation from Accretion Disks threaded by Large Scale Magnetic Fields
- Global MHD Simulations of Jet Formation through Magnetic Interaction between a Star and its Accretion Disk
- Relativistic Simulations
- Relation between State Transition and Jet Formation

Global Nonsteady MHD Simulatons of Jet Formation

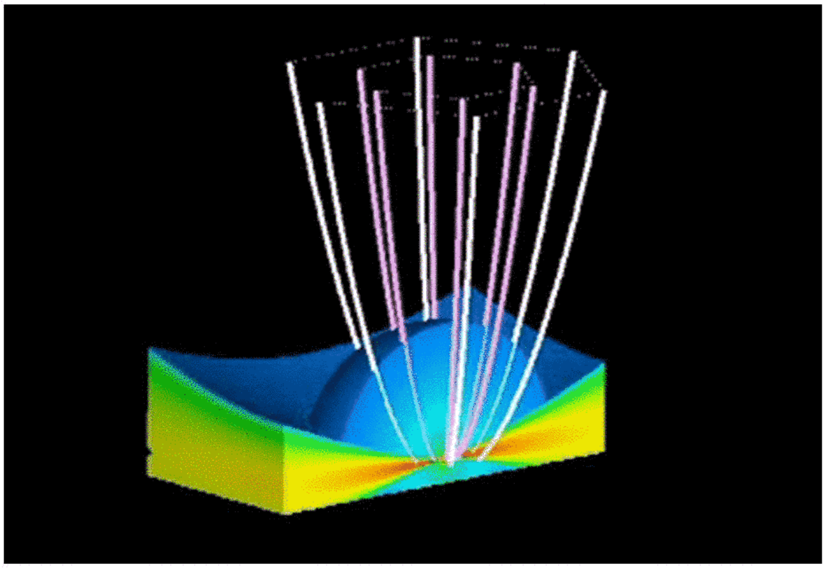
- Global simulations including accretion disks
  Magnetic Braking Enhances Accretion
  Uchida and Shibata 1985; Shibata and Uchida 1986; Stone and Norman 1994; Matsumoto et al. 1996; Kudoh et al 1998; Koide et al. 1998,1999
- Global simulations outside accretion disks
  Magnetic Braking of Disk is not included
  Ustyugova et al. 1995;Romanova et al. 1997; Ouyed and Pudritz 1997; Ouyed, Pudritz and Stone 1997: Meier et al. 1997 …

Sweeping Twist-Pinch Mechanism of Formation of Astrophysical Jets



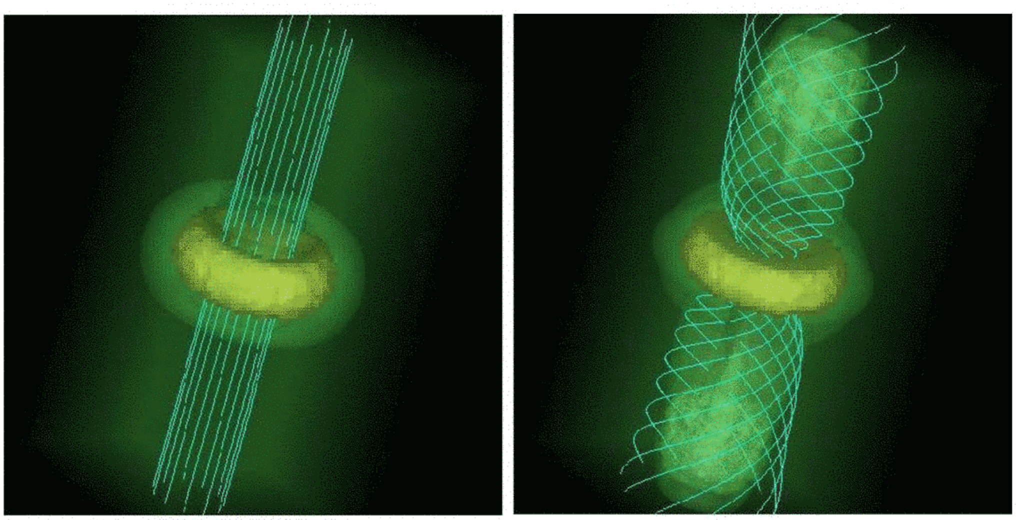
A schematic picture of Uchida-Shibata (1985) model. They carried out global 2D MHD simulation including accretion disk.

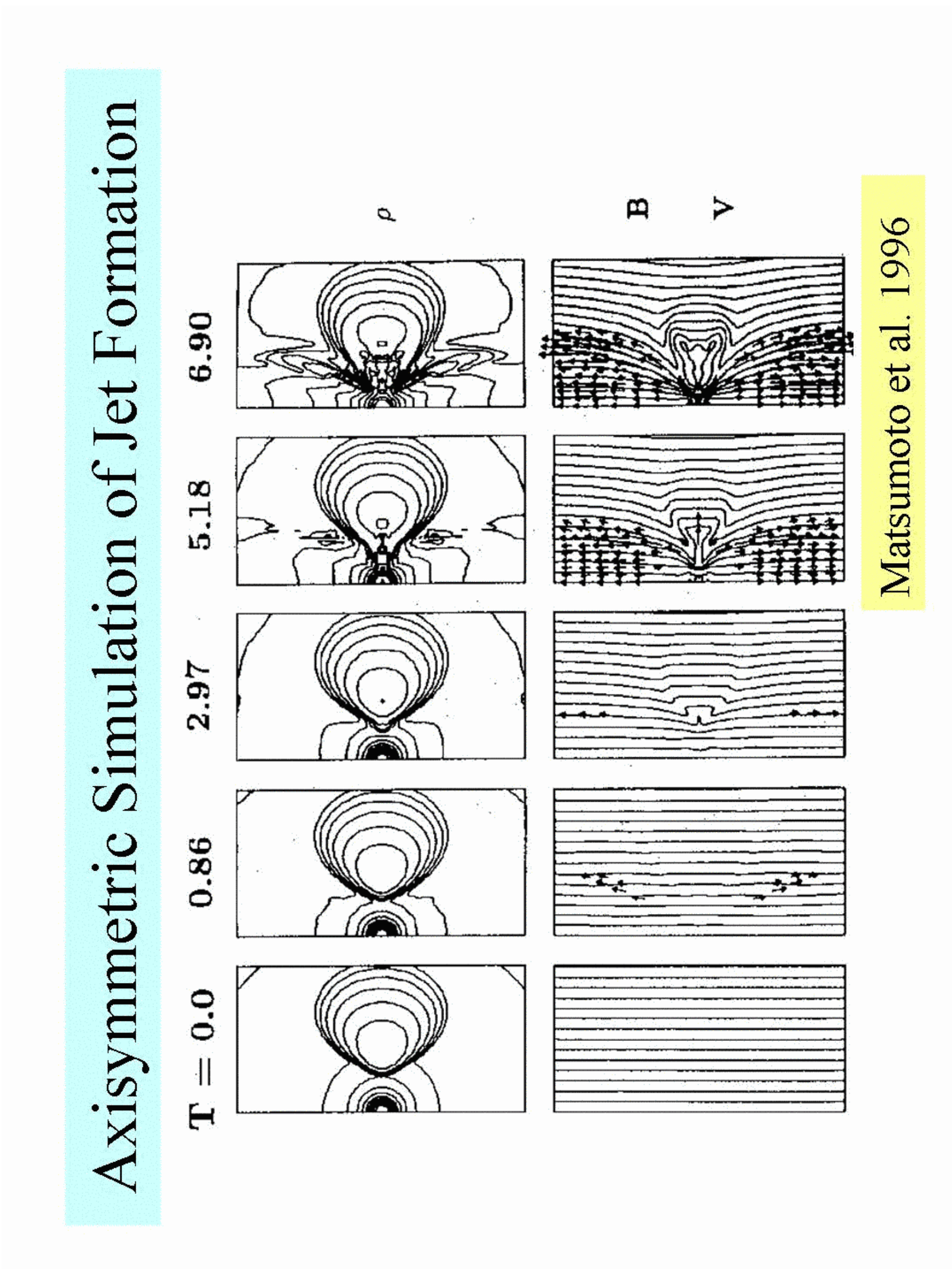
Visualization of Density Distribution and Magnetic Field Lines

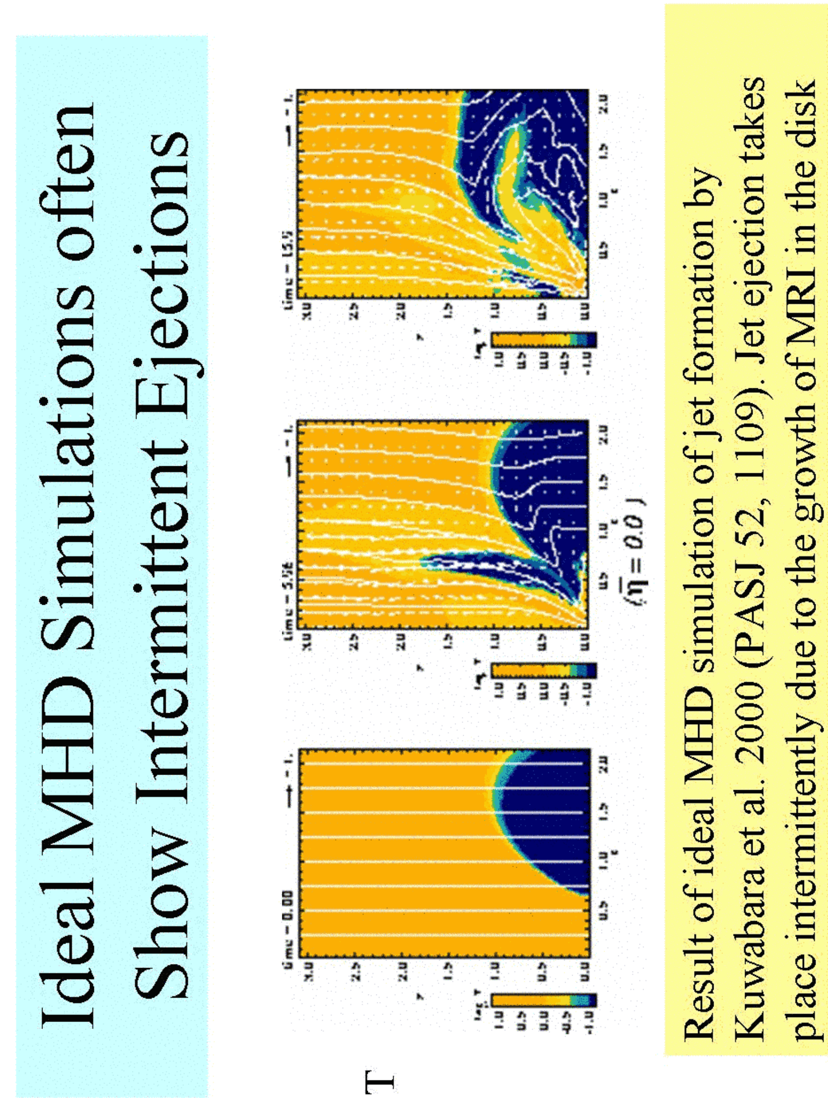


Kodoh et al. 2002

Global MHD Simulations of Jet Formation from a Torus




Axisymmetric Simulation of Jet Formation
T = 0.0
0.86
2.97
5.18
6.90
ρ
B
V
Matsumoto et al. 1996


Ideal MHD Simulations often Show Intermittent Ejections
T
Result of ideal MHD simulation of jet formation by Kuwabara et al. 2000 (PASJ 52, 1109). Jet ejection takes place intermittently due to the growth of MRI in the disk

Questions for Nonsteady MHD Models of Jet Formation

- Are you simulating transient phenomena depending on the initial condition ?
- Does the system approach to a steady state ?

A: In ideal MHD simulations the jet formation is time dependent and intermittent but we can understand the acceleration mechanism of nonsteady jets by applying steady theory of magnetically driven jets

Steady Model of Axisymmetric Jet
(Kudoh and Shibata 1997)

$$P = K\rho^{\gamma} ,$$

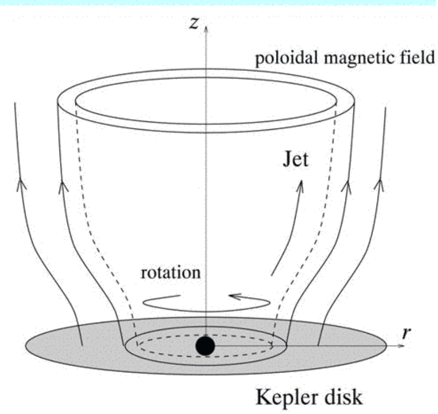
$$\rho v_p = \lambda B_p ,$$

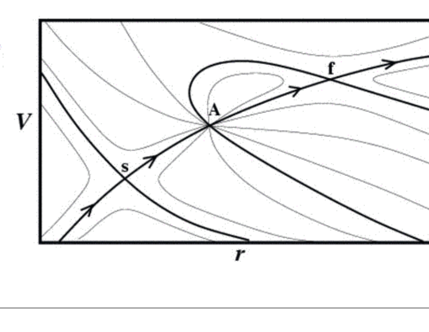
$$(v_\phi - \Omega r)B_p = v_p B_\phi ,$$

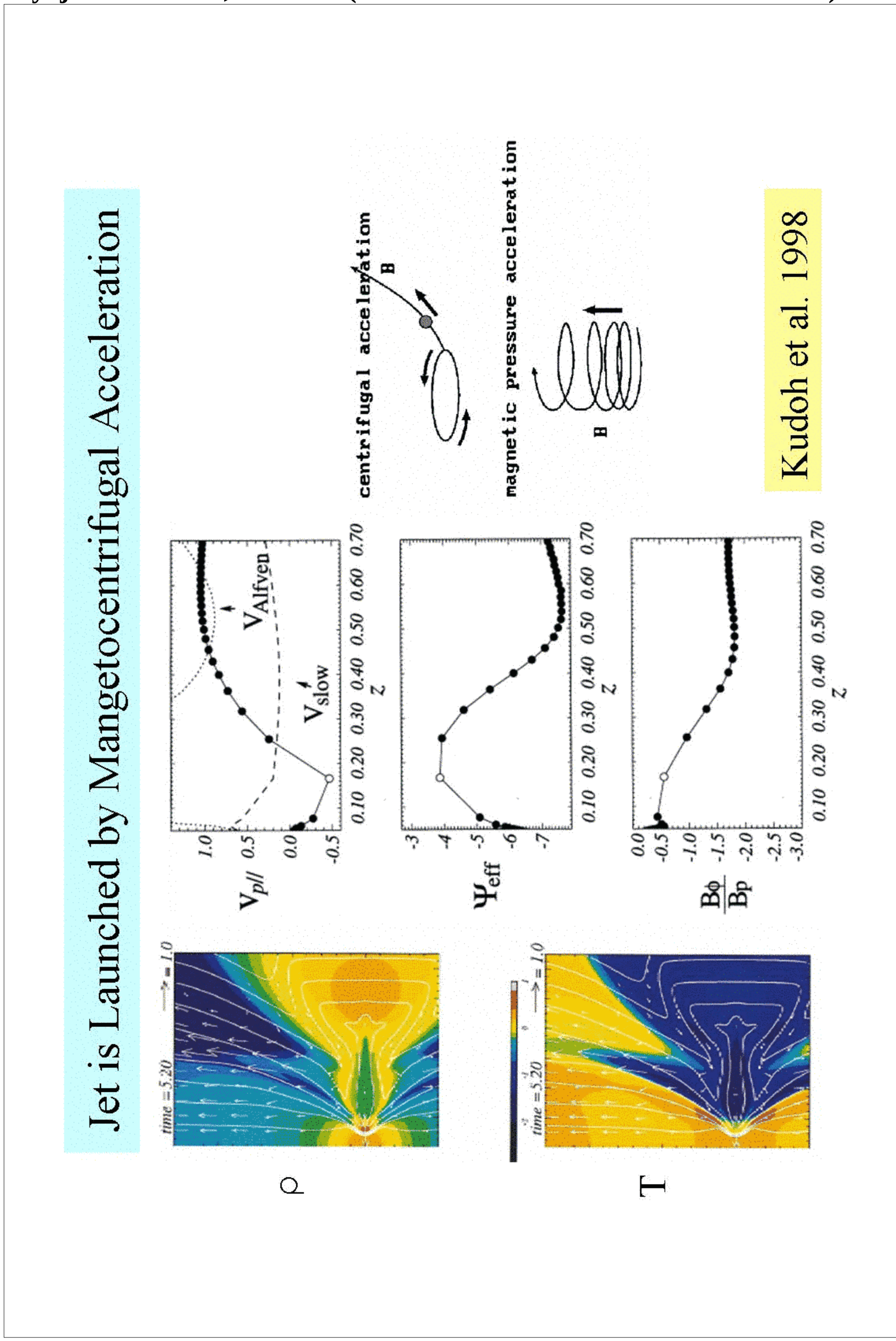
$$r\left(v_\phi - \frac{B_\phi}{4\pi\lambda}\right) = L ,$$

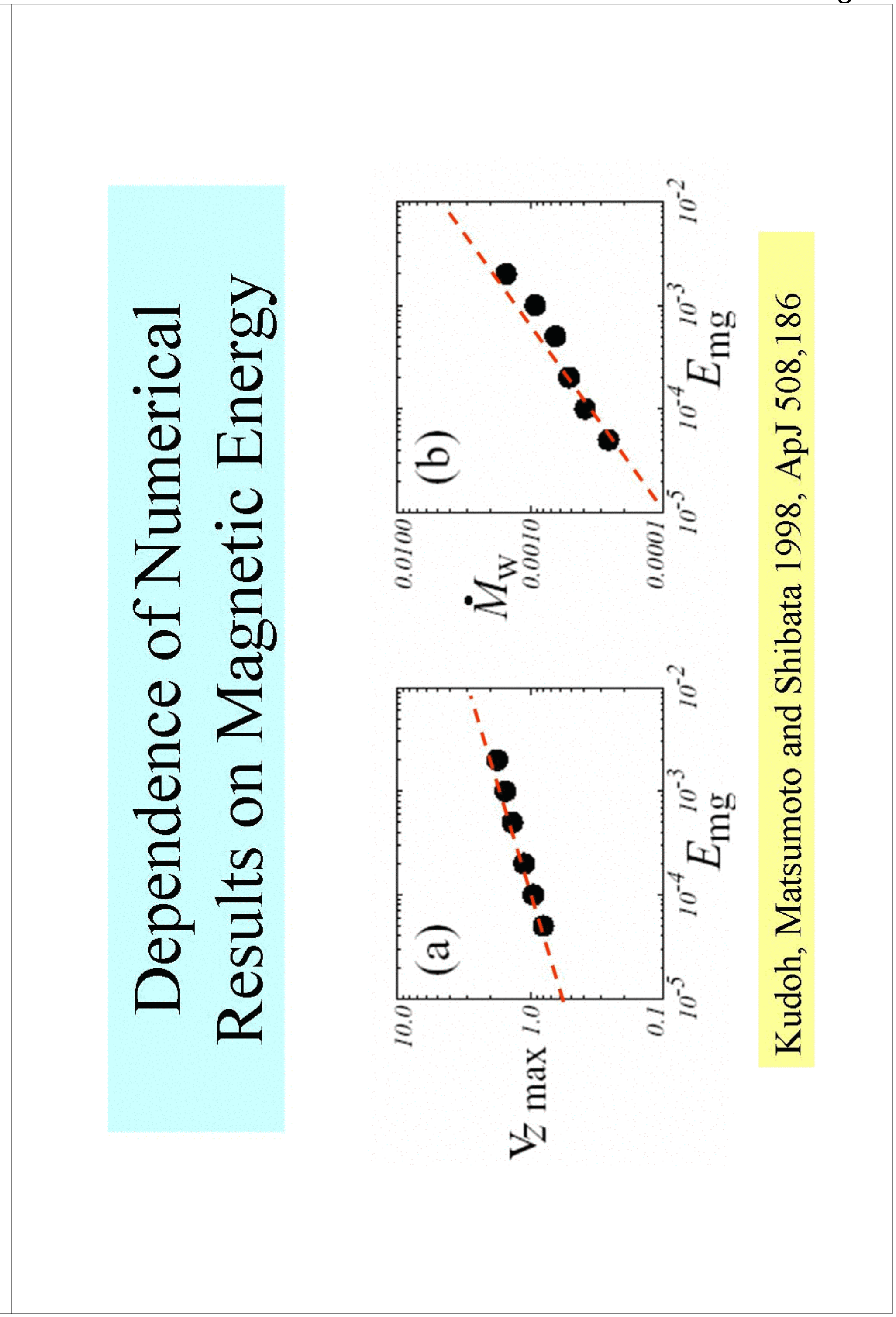
$$\frac{1}{2} v_p^2 + \frac{1}{2} v_\phi^2 + \frac{\gamma}{\gamma - 1}\frac{P}{\rho} + \Psi_g - \frac{r\Omega B_\phi}{4\pi\lambda} = E$$

Along a Magnetic Field Line

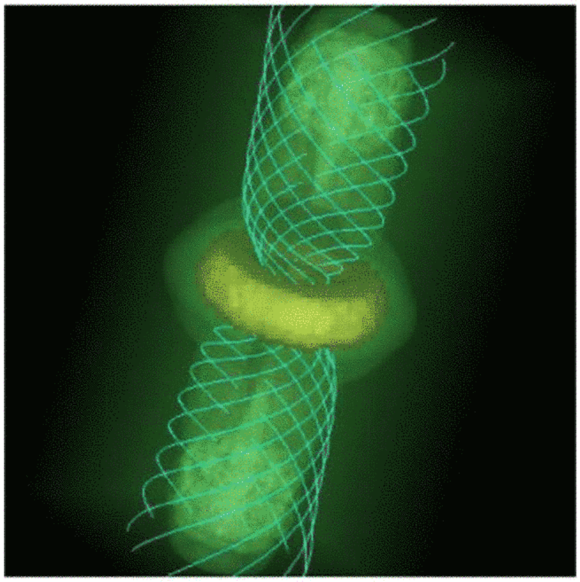





Jet is Launched by Mangetocentrifugal Acceleration
ρ
T
Vp//
Ψeff
Bφ/Bp
VAlfven
Vslow
Z
centrifugal acceleration
magnetic pressure acceleration
B
Kudoh et al. 1998


Dependence of Numerical Results on Magnetic Energy
(a)
(b)
Vz max
Ṁw
Emg
Kudoh, Matsumoto and Shibata 1998, ApJ 508,186

MHD Simulation including Resistivity



$$E_{th} = \frac{V_{S0}^2}{\gamma V_{K0}^2} = 5\times 10^{-2}$$

$$E_{mg} = \frac{V_{A0}^2}{V_{K0}^2} = 5\times 10^{-4}$$

$\eta = 0.0125\, r_0 V_{k0}$

(Rm = 80)

Kuwabara et al. 2000
PASJ 52, 1109

Similar simulations have been carried out by Casse and Keppens (2002,2004)

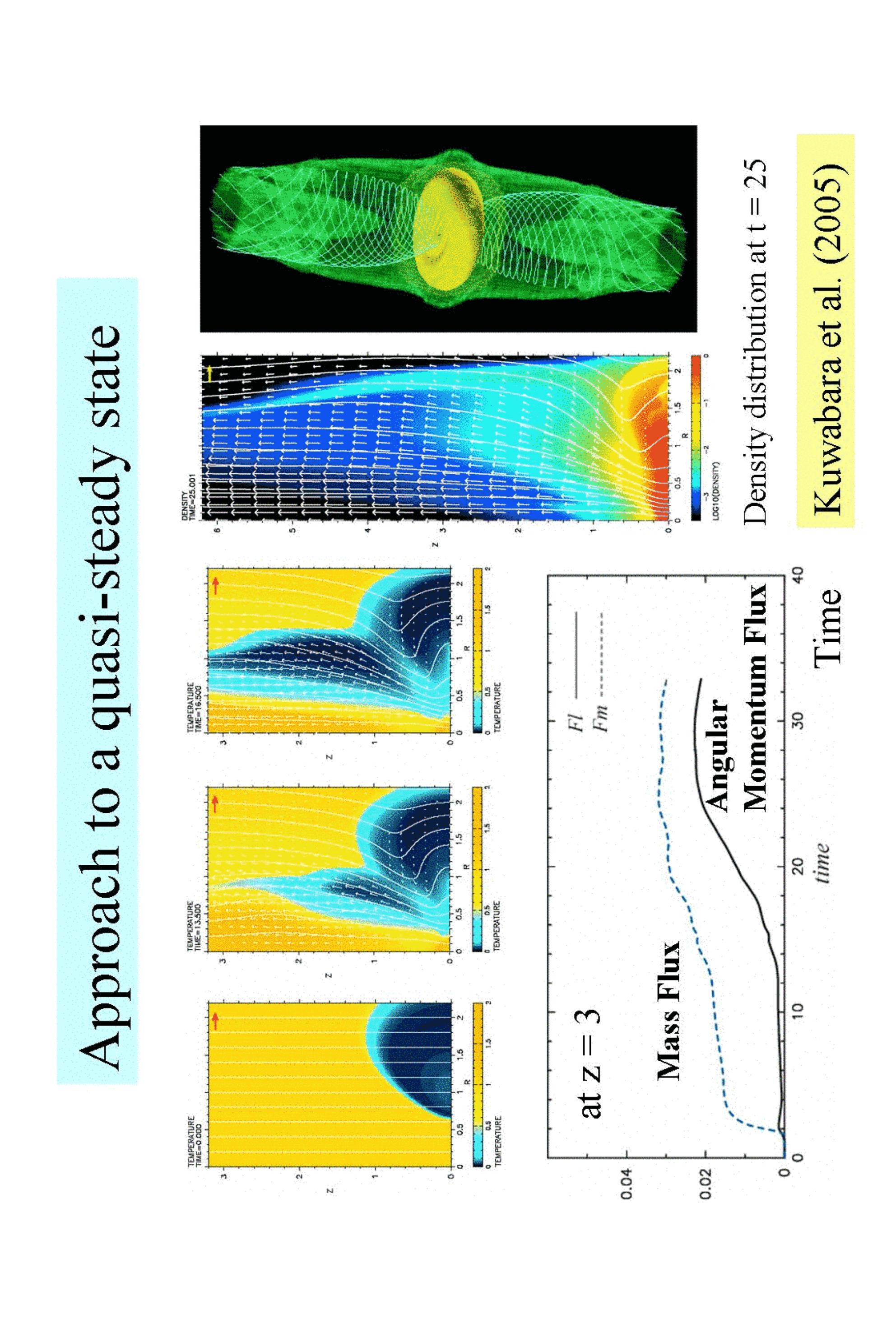
Basic Equations

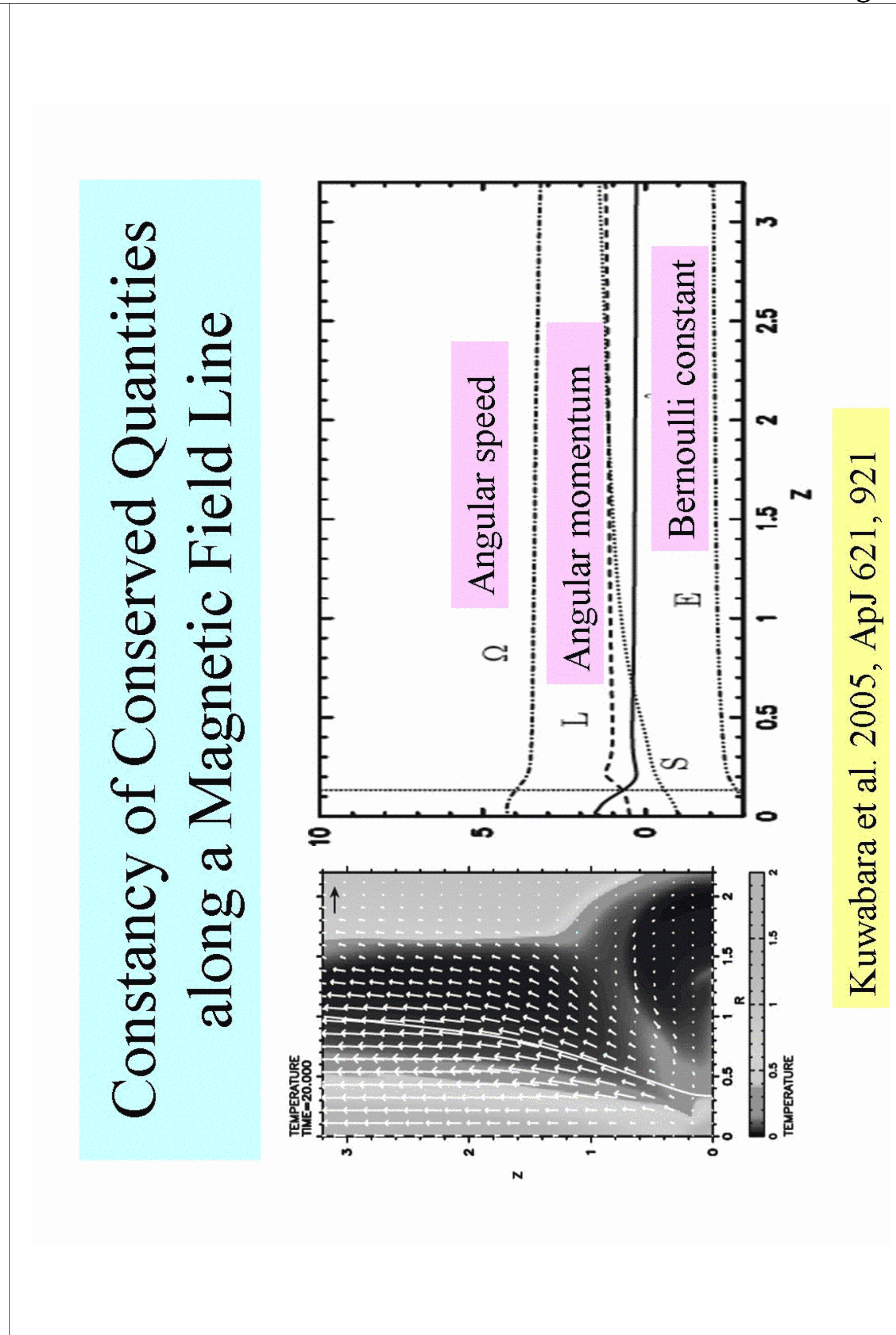
$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \mathbf{v}) = 0$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla P + \frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{4\pi} + \rho\mathbf{g}$$

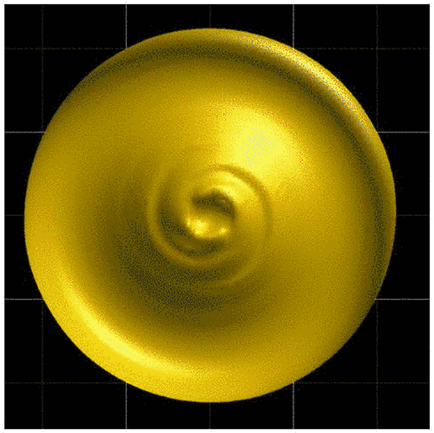
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}) + \eta\nabla^2\mathbf{B}$$

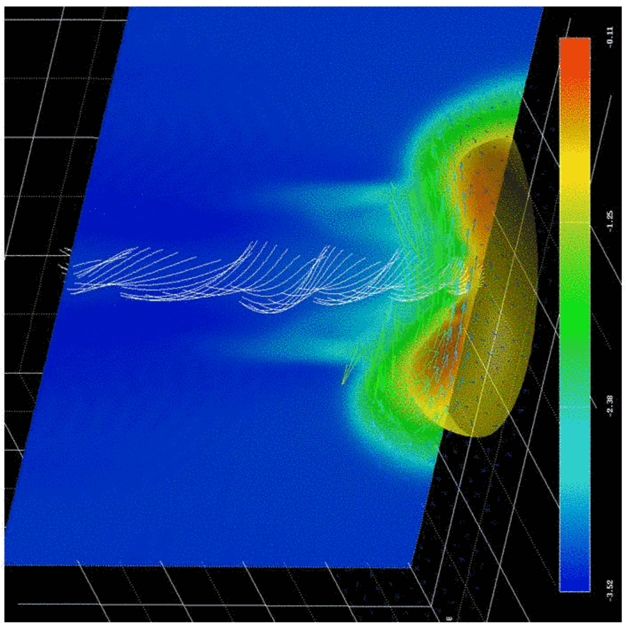
$$\frac{\partial \rho\varepsilon}{\partial t} + \nabla\cdot(\rho\varepsilon\mathbf{v}) + P\nabla\cdot\mathbf{v} = Q_J + Q_{vis} - Q_{rad}$$


Approach to a quasi-steady state
Density distribution at t = 25
Kuwabara et al. (2005)
at z = 3
Mass Flux
Angular Momentum Flux
Fl
Fm
Time
time
0
0.02
0.04
0
10
20
30
40

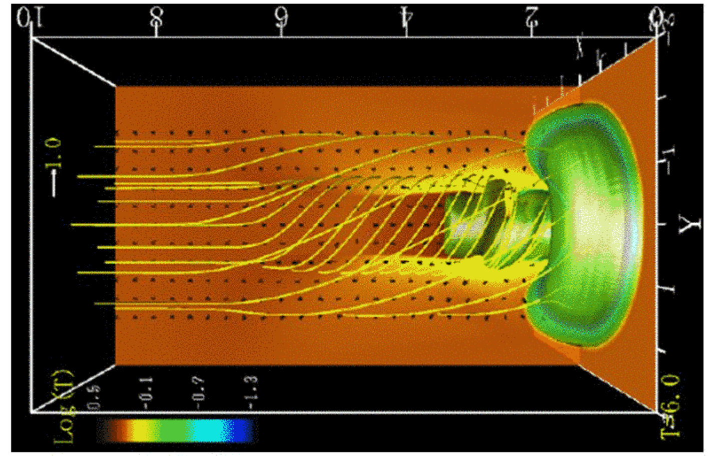

Constancy of Conserved Quantities along a Magnetic Field Line
Angular speed
Angular momentum
Bernoulli constant
Ω
L
E
S
Z
Kuwabara et al. 2005, ApJ 621, 921

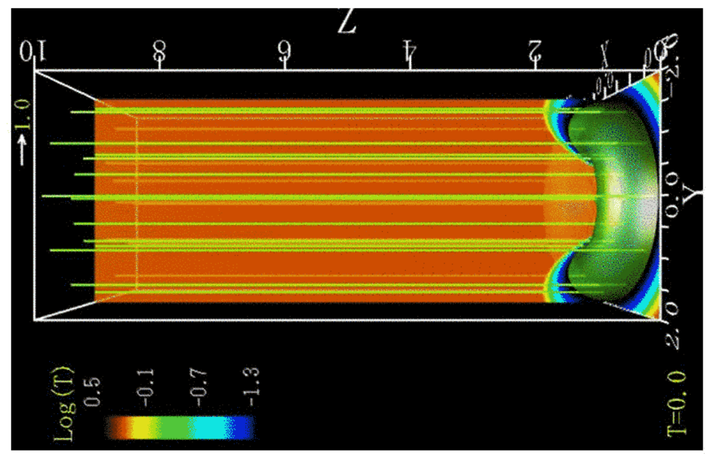
Global 3D MHD Simulation of Jets from Accretion Disks

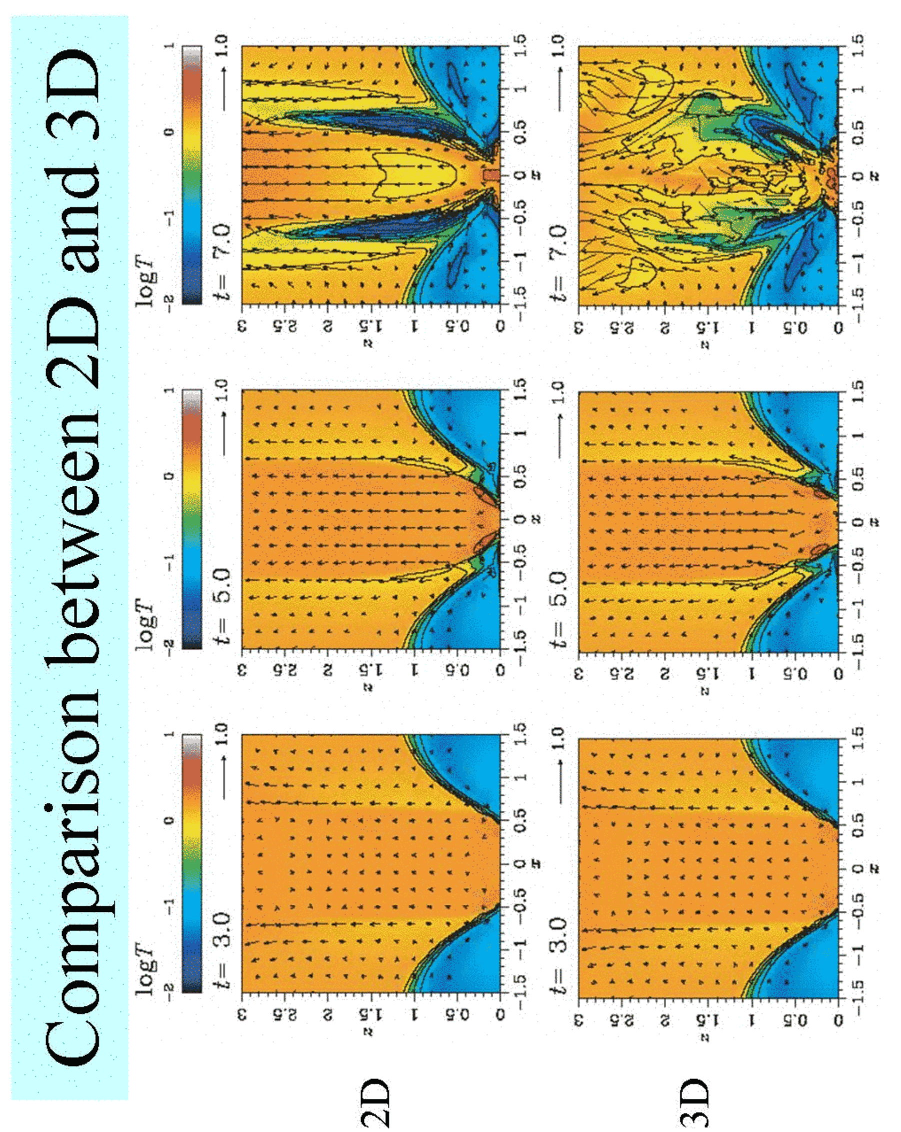


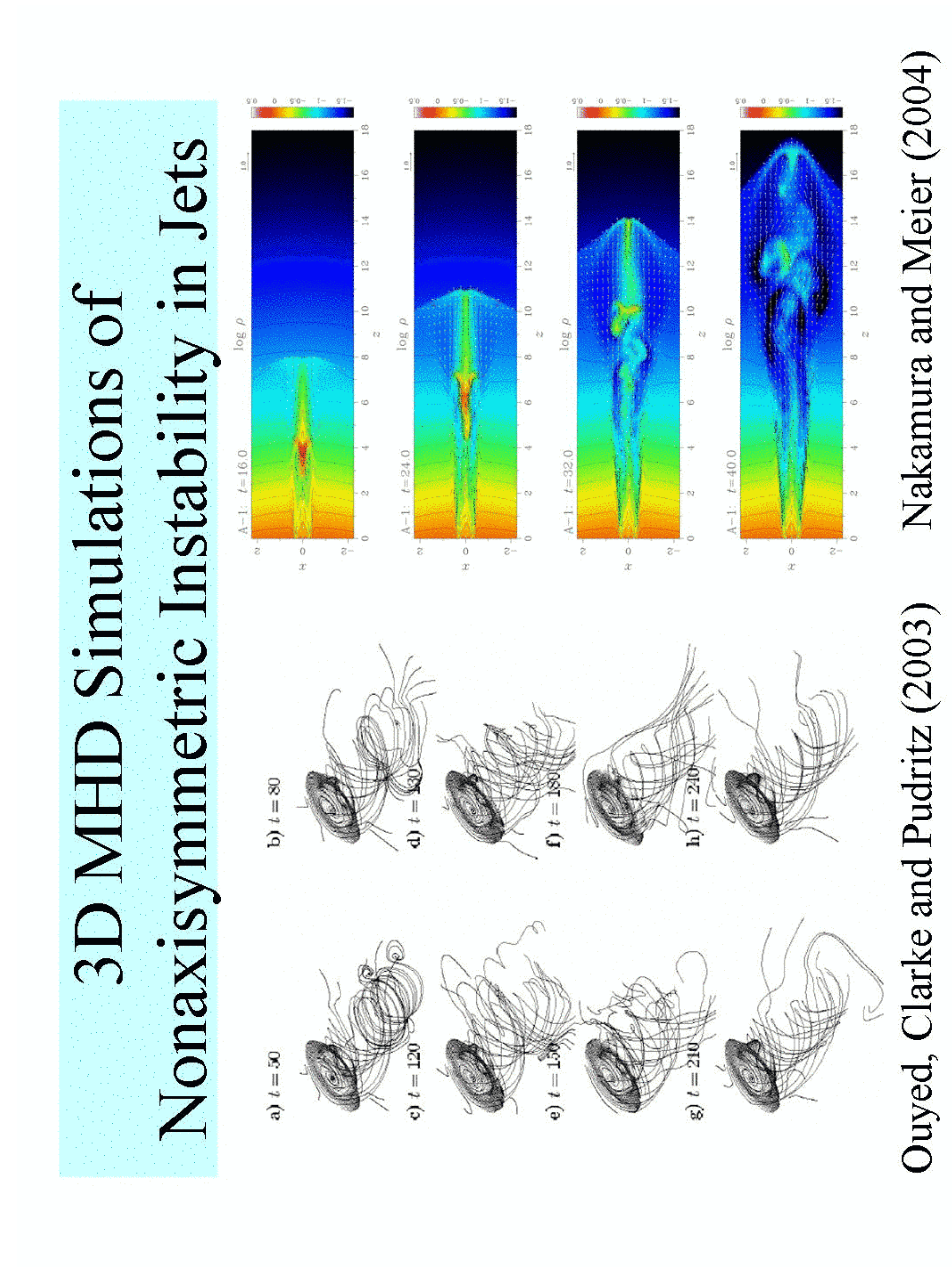


3D MHD Simulation (Kigure et al. 2005)

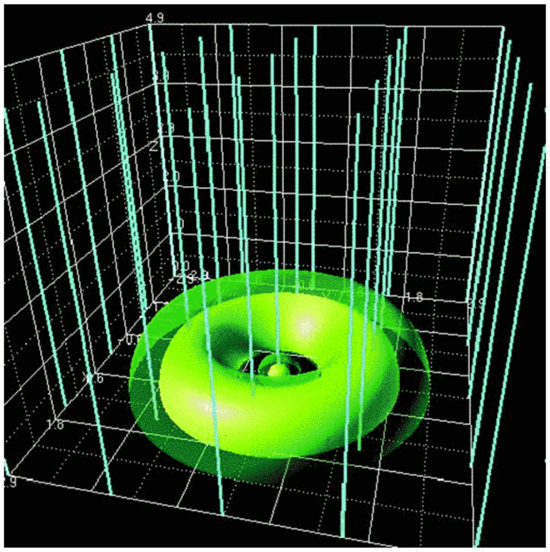




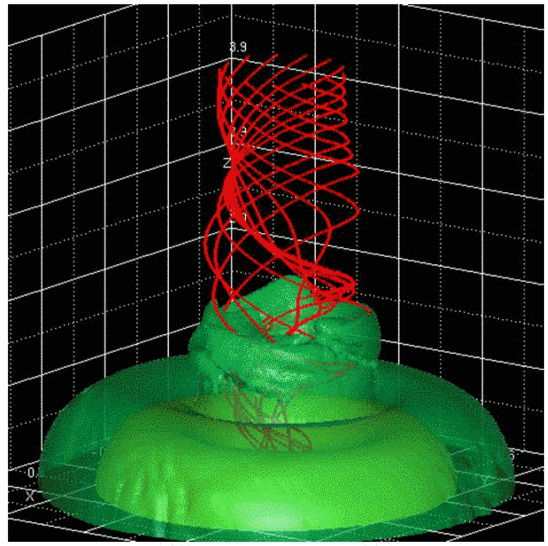

Comparison between 2D and 3D
2D
3D
logT
t= 3.0
t= 5.0
t= 7.0


3D MHD Simulations of
Nonaxisymmetric Instability in Jets
Ouyed, Clarke and Pudritz (2003)
Nakamura and Meier (2004)

Global 3D MHD Simulations Using Cartesian Grid

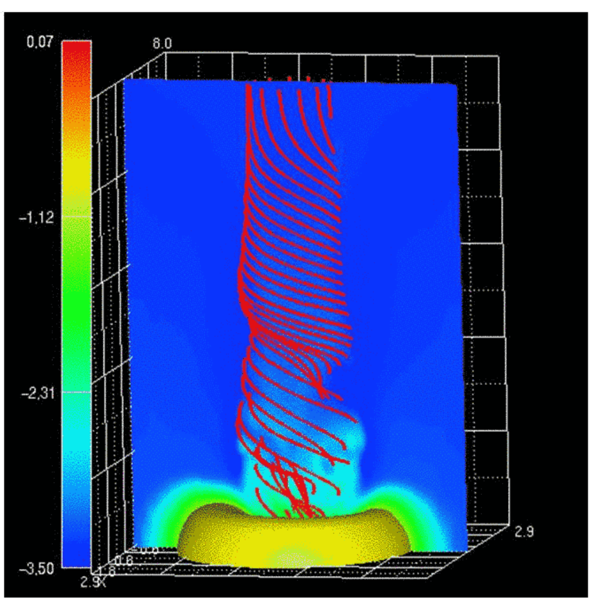


350×350×193 mesh points

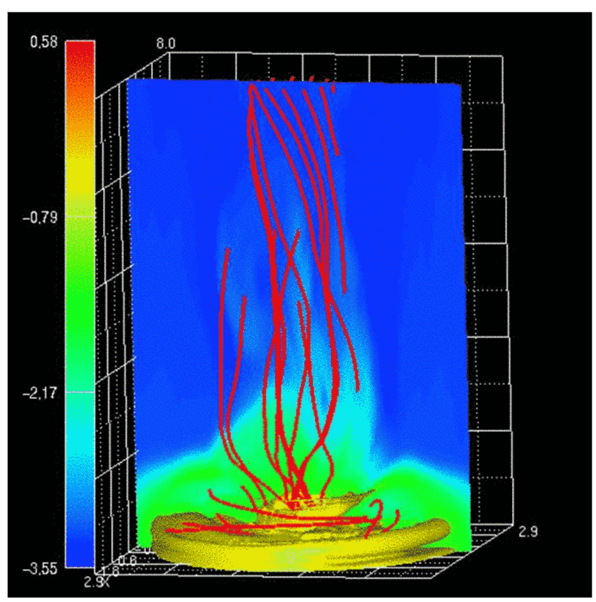


Kuwabara et al. (2005)

Ideal MHD Simulation using 3D Cartesian Grid



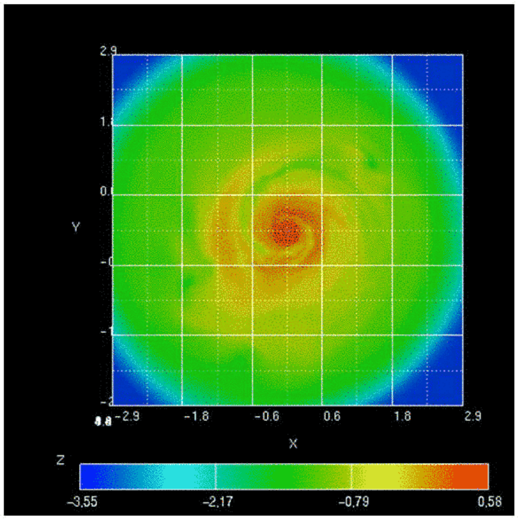
t = 7

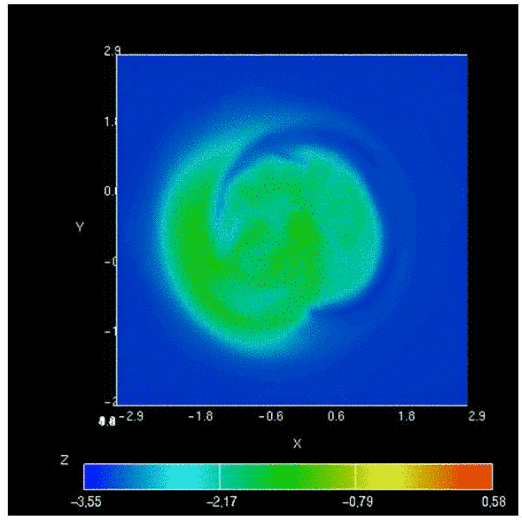


t = 16

Nonaxisymmetric Structure

ρ



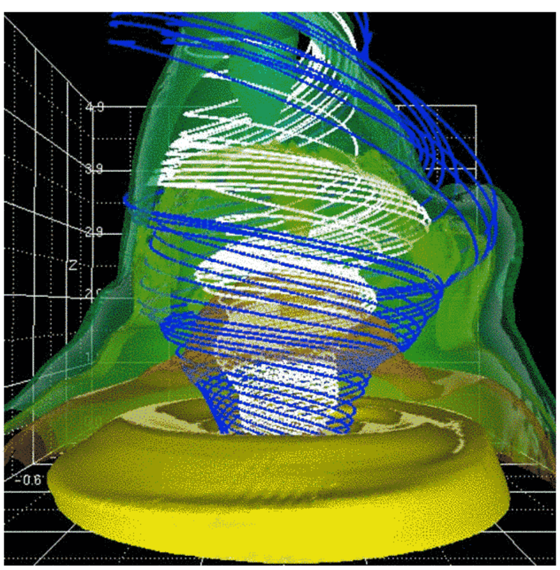


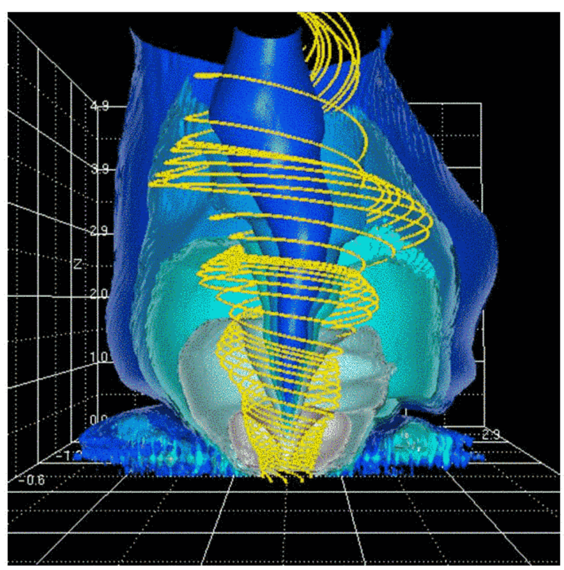
Disk equatorial plane

Jet

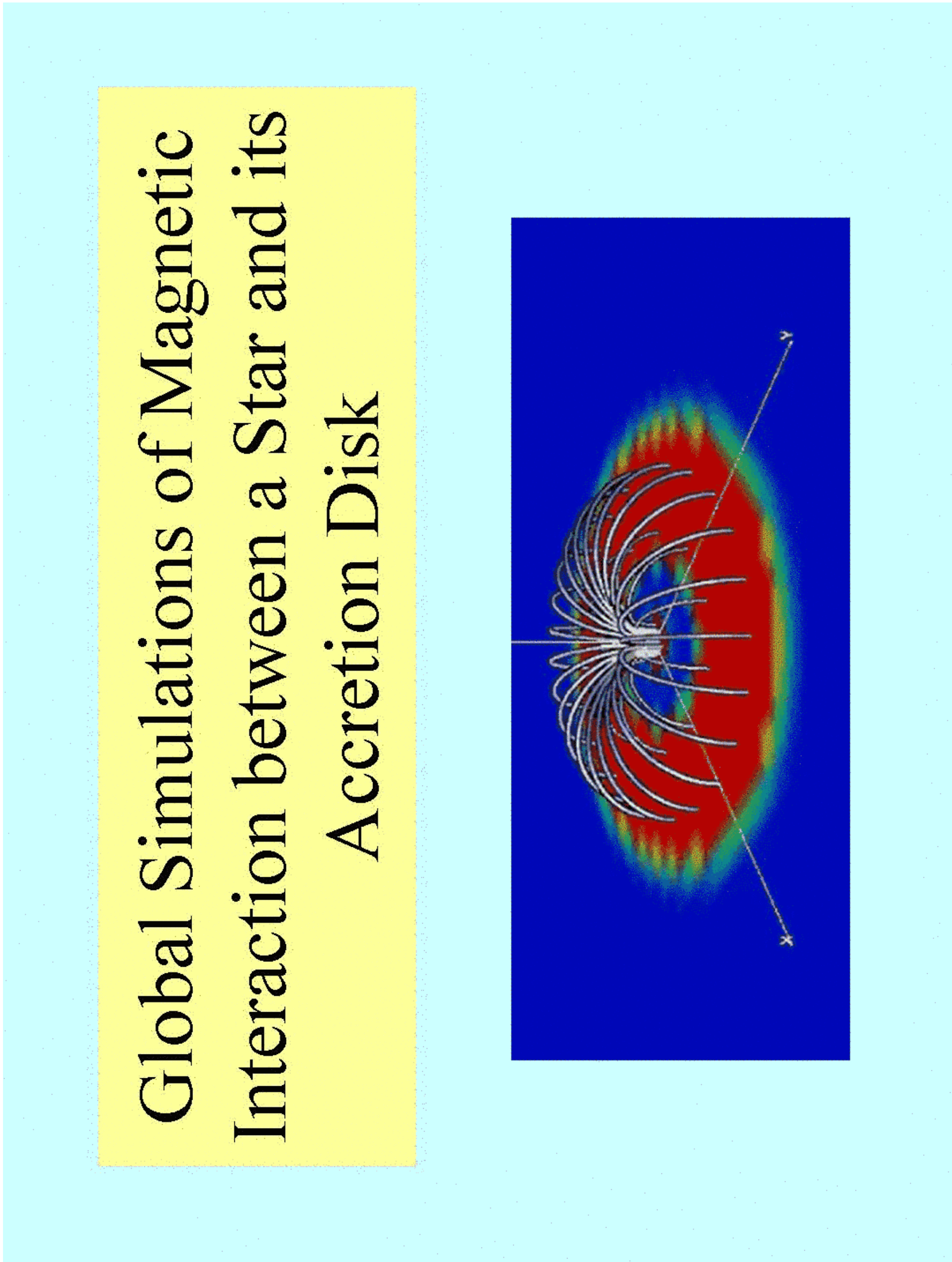
t = 16

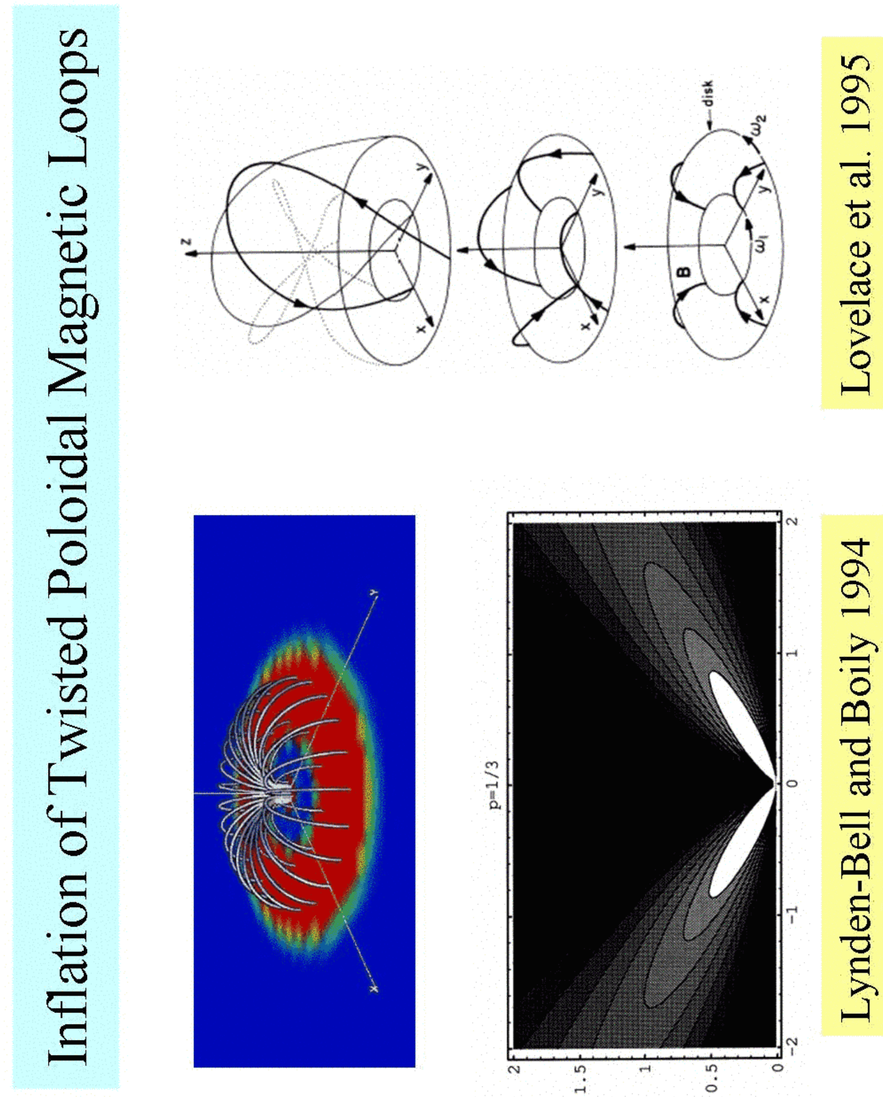
Numerical Results for a Resistive Model with Weaker Magnetic Field



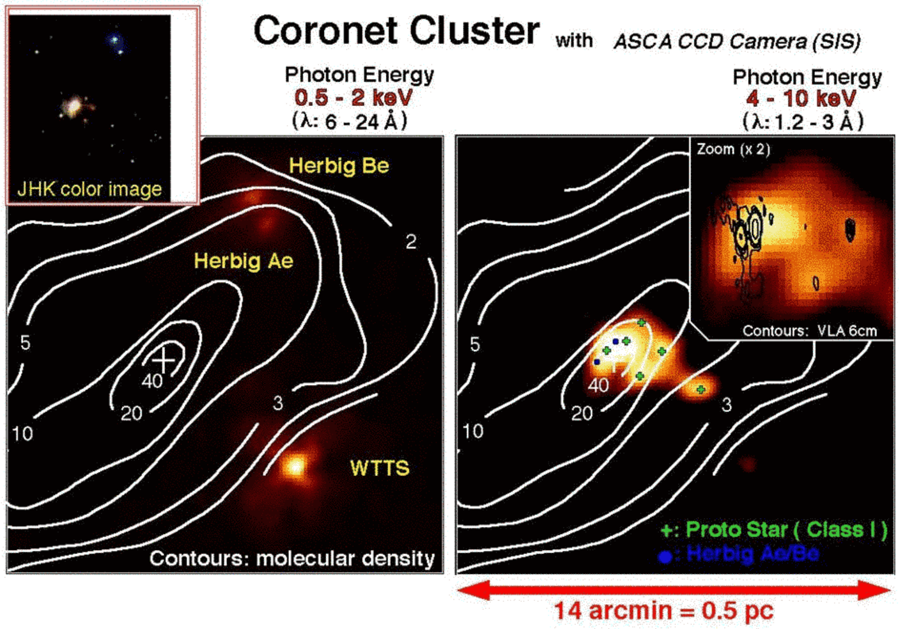


Kuwabara et al. (2005) Rm=150 t = 38

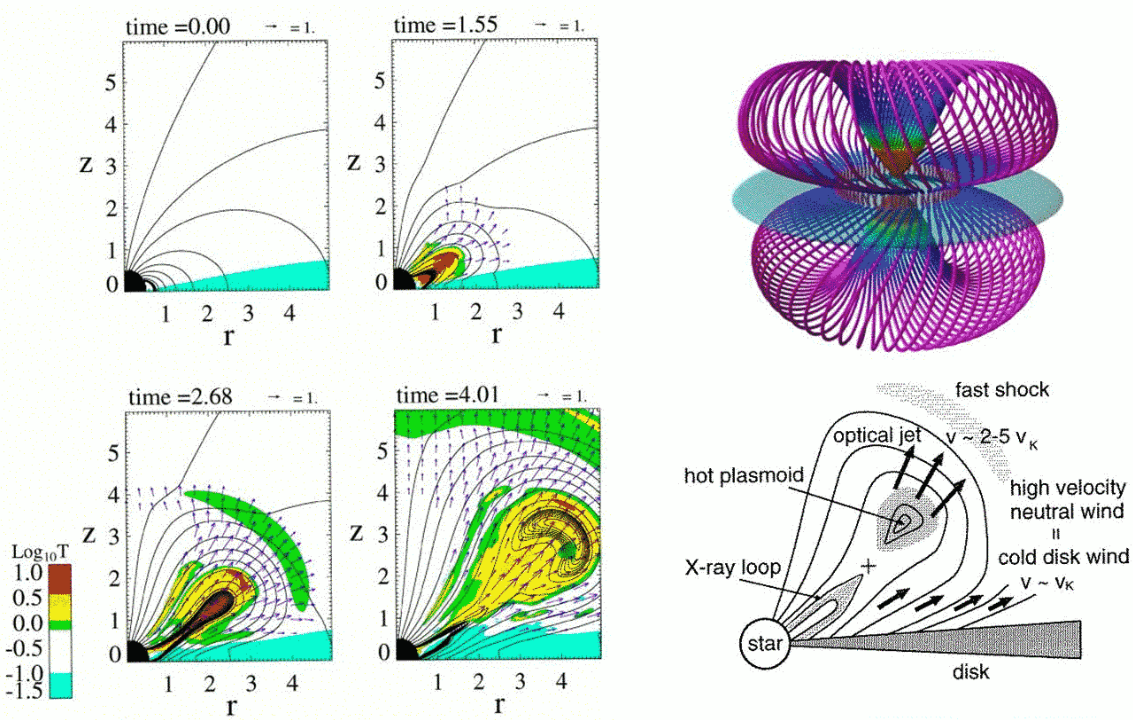

Global Simulations of Magnetic
Interaction between a Star and its
Accretion Disk


Inflation of Twisted Poloidal Magnetic Loops
Lovelace et al. 1995
Lynden-Bell and Boily 1994
p=1/3

X-ray Flares in Protostars

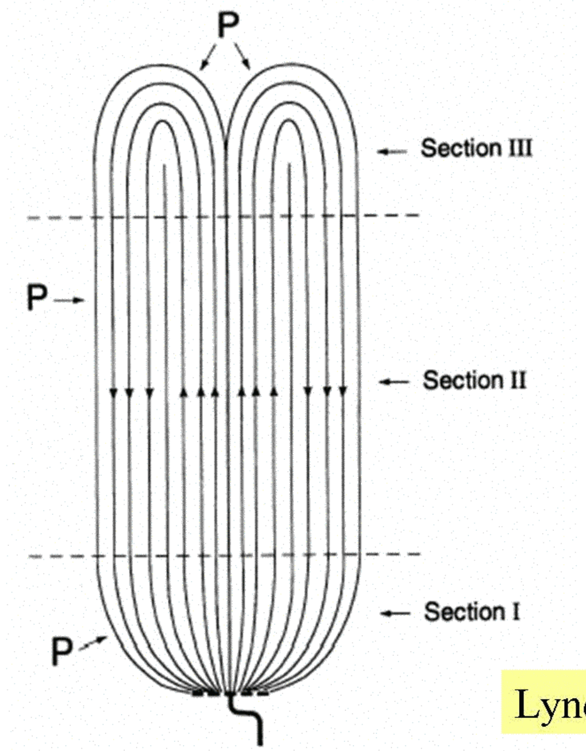


MHD Simulation of Protostellar Flares



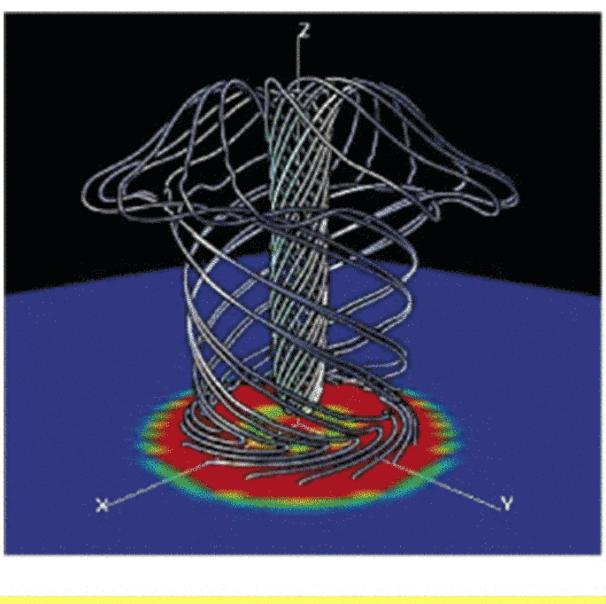
Hayashi, Shibata and Matsumoto 1996

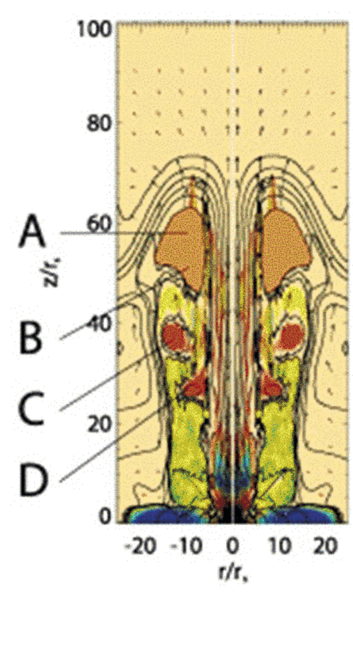
Magnetic Tower



Lynden-Bell 1996

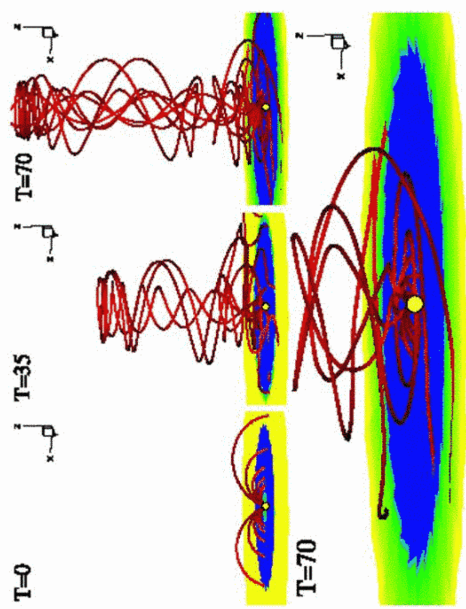
Numerical Simulation of the Magnetic Tower Jet



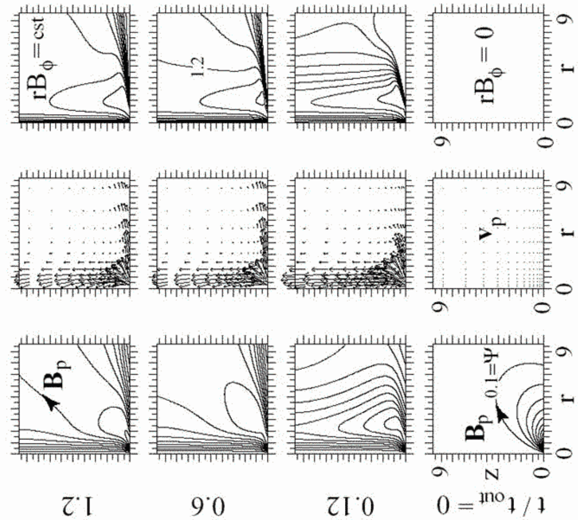


Kato, Hayashi, Matsumoto (2004)

Other Magnetic Tower Simulations

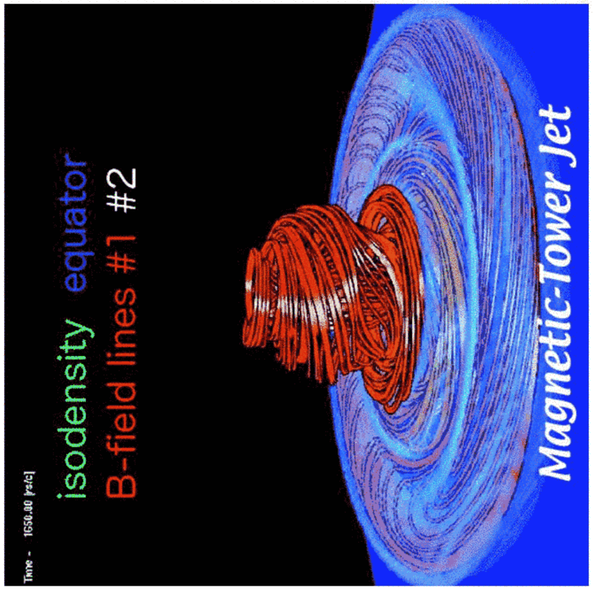


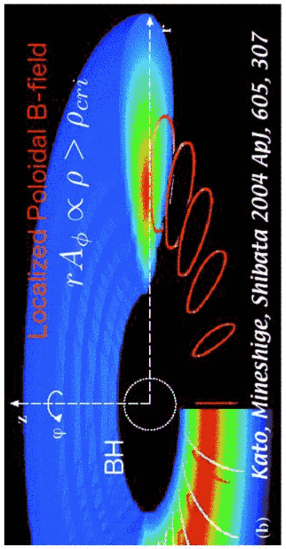
Romanova et al. 2004

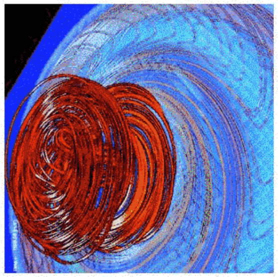


Lovelace et al. 2002

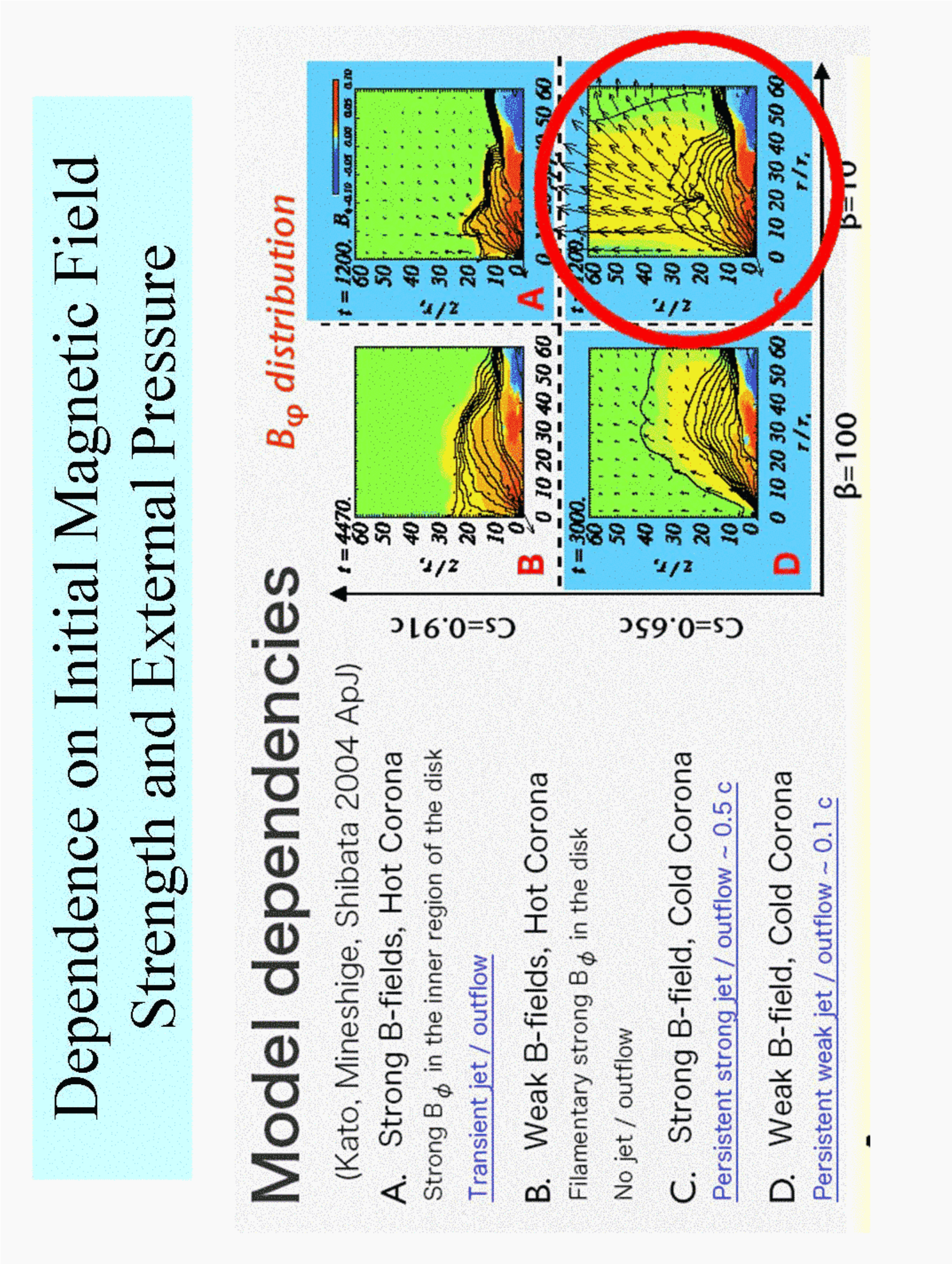
Formation of Magnetic Tower Jet from Localized Fields in Disks

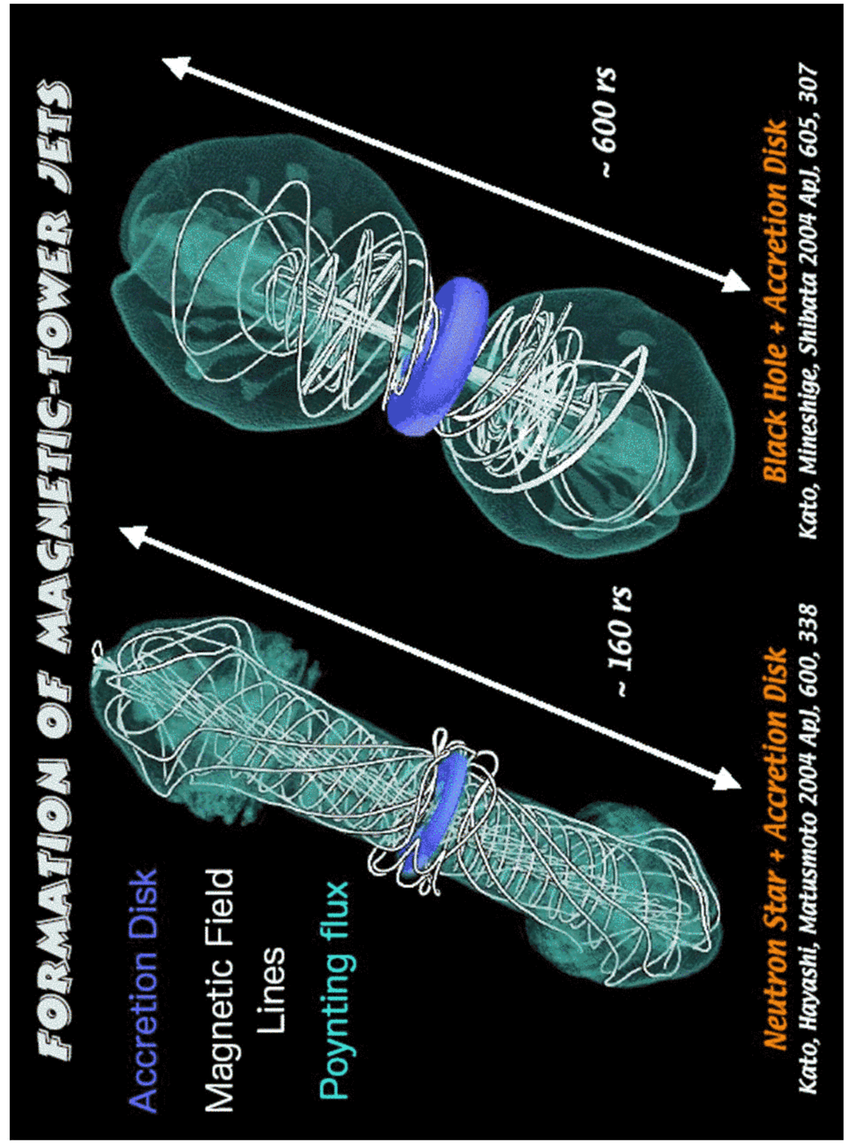




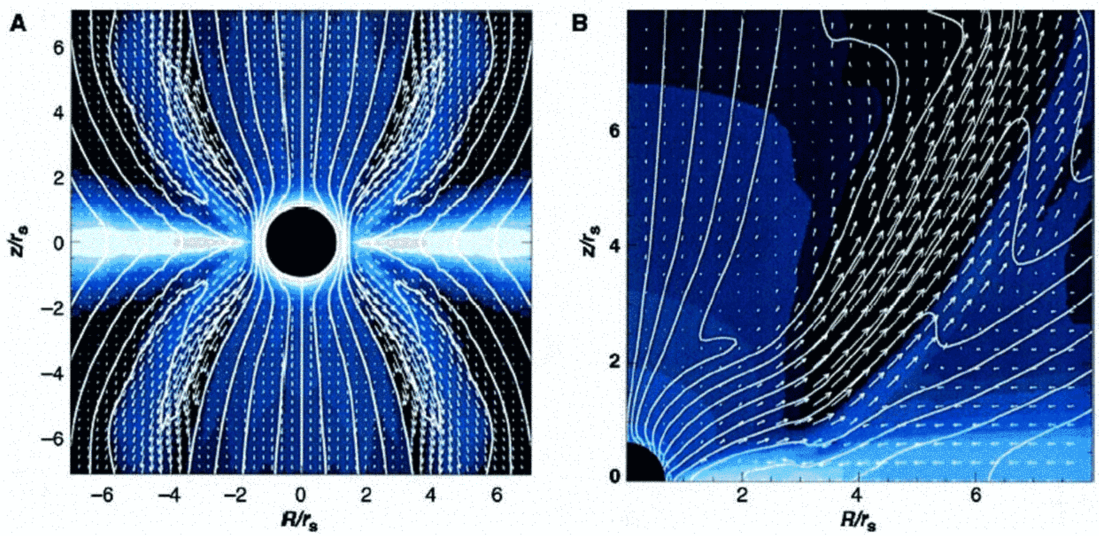


3D MHD Simulation using Cylindrical Coordinates


Dependence on Initial Magnetic Field Strength and External Pressure
Model dependencies
(Kato, Mineshige, Shibata 2004 ApJ)
A. Strong B-fields, Hot Corona
Strong B_ϕ in the inner region of the disk
Transient jet / outflow
B. Weak B-fields, Hot Corona
Filamentary strong B_ϕ in the disk
No jet / outflow
C. Strong B-field, Cold Corona
Persistent strong jet / outflow ~ 0.5 c
D. Weak B-field, Cold Corona
Persistent weak jet / outflow ~ 0.1 c
B_φ distribution
Cs=0.91c
Cs=0.65c
β=100
β=10


FORMATION OF MAGNETIC-TOWER JETS
Accretion Disk
Magnetic Field Lines
Poynting flux
~ 160 rs
~ 600 rs
Neutron Star + Accretion Disk
Kato, Hayashi, Matsumoto 2004 ApJ, 600, 338
Black Hole + Accretion Disk
Kato, Mineshige, Shibata 2004 ApJ, 605, 307

2D GRMHD Simulation



Koide et al. 1998
Schwarzschild Hole

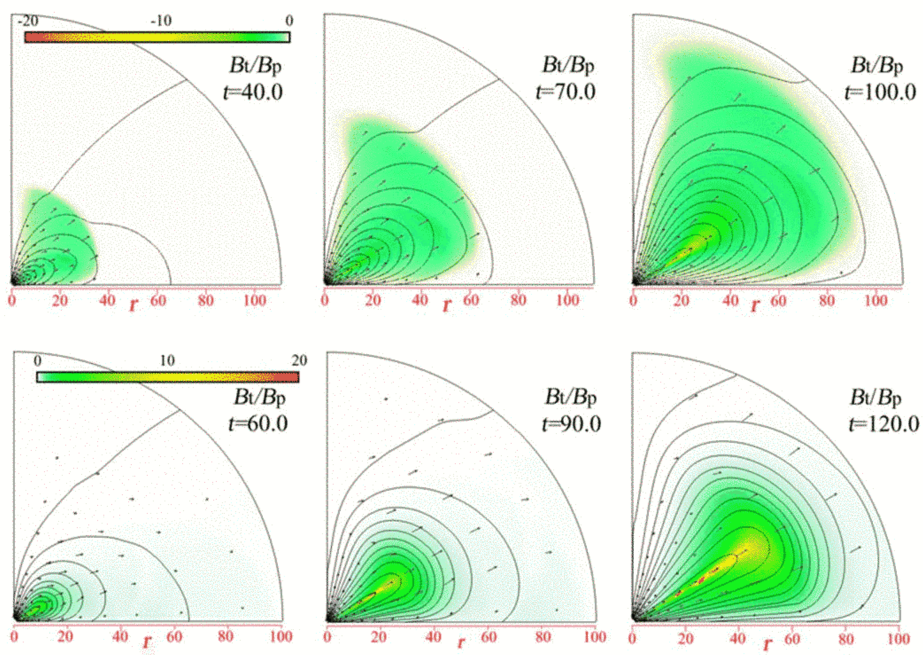
Koide et al. 1999
Kerr Hole

$\Gamma=2.7$

Relativistic Force-Free Simulations

Rotating
Central Star

Rotating
Disk



Asano, Uchida and Matsumoto 2005, PASJ 57, 409

Relativistic Force-free Equations

$$\frac{\partial \boldsymbol{P}}{\partial t} + \nabla \cdot \boldsymbol{\mathcal{M}} = 0$$

$$\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times \boldsymbol{E} = 0$$

$$\boldsymbol{P} = \frac{1}{4\pi c^2}\boldsymbol{E} \times \boldsymbol{B}$$

$$\mathcal{M}^{ij} = -\frac{1}{4\pi}\left\{E^i E^j + B^i B^j - \frac{1}{2}\delta^{ij}\left(\boldsymbol{E}\cdot\boldsymbol{E} + \boldsymbol{B}\cdot\boldsymbol{B}\right)\right\}$$

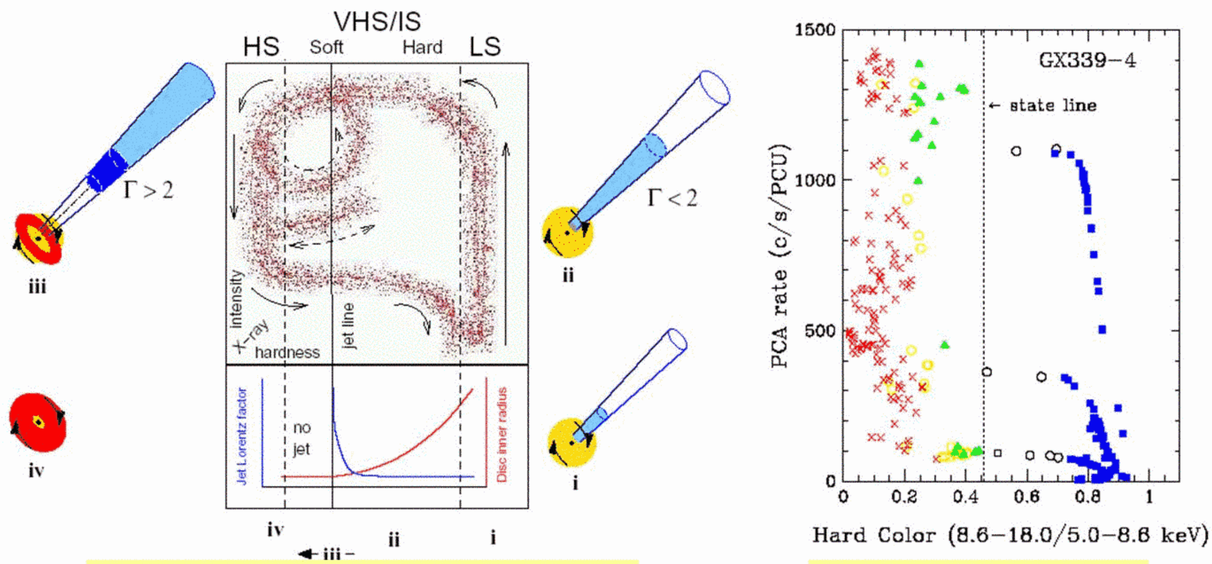
Force-free Approximation:

$\rho E + J \times B = 0$

Numerical Scheme : Upwind Difference by Harten-Lax-vanLeer method

Relation between the State Transition in Black Hole Candidates and Ejection of Relativistic Jets

Relation between State Transition and Jet Formation

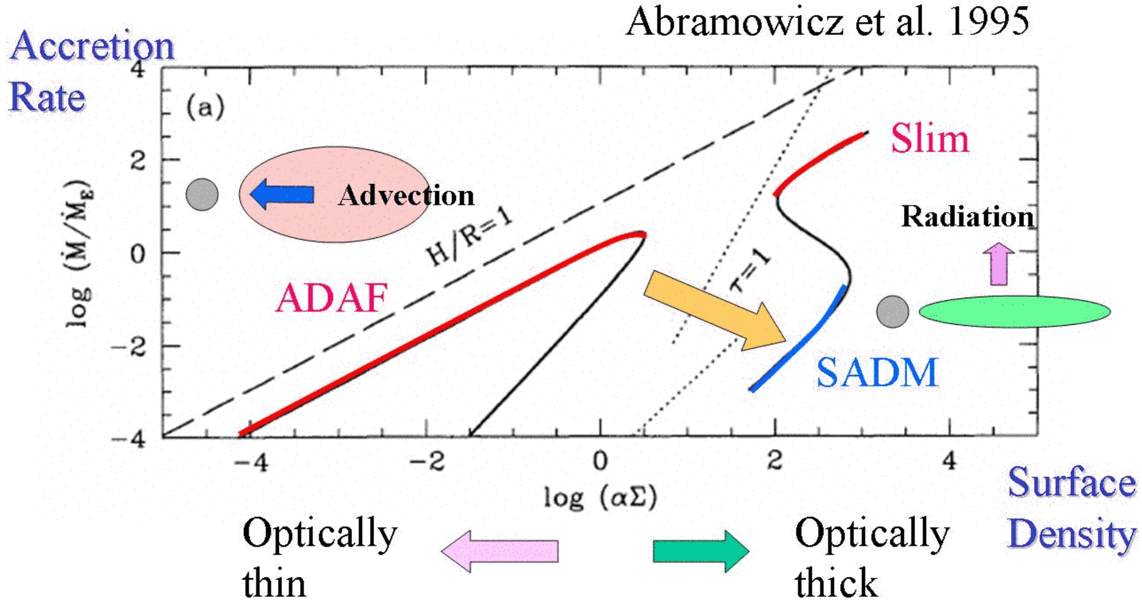


Fender, Belloni, Gallo 2004

Remillard 2005

Theory of State Transition in Black Hole Accretion Disks

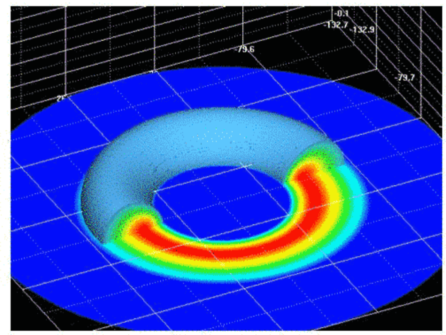
Abramowicz et al. 1995



Global Three-dimensional MHD Simulations of Black Hole Accretion Flows

Gravitational potential : $\phi = - GM/(r-r_g)$

Initial torus : constant angular momentum torus threaded by toroidal magnetic field



Pgas/Pmag = β = 100

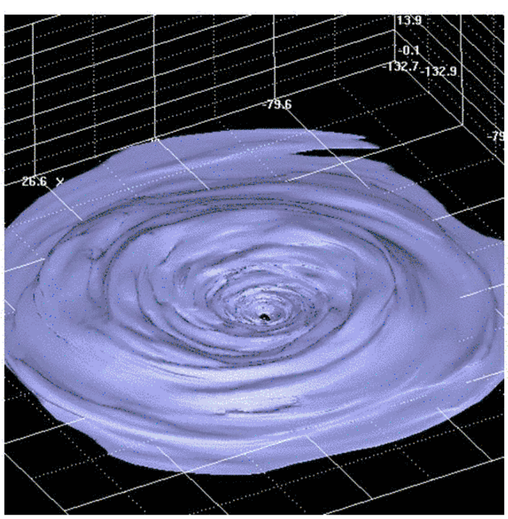
Anomalous Resistivity

250*64*192mesh

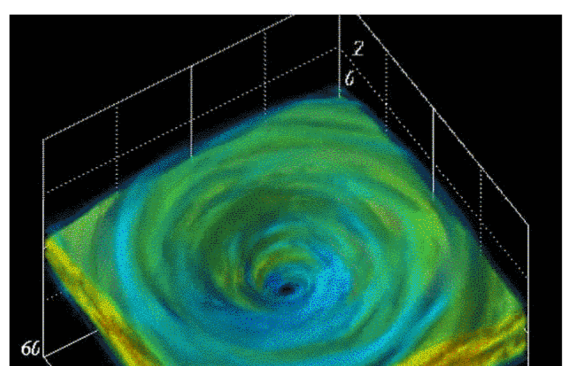
$\eta = (1/Rm) \max [(J/\rho) / v_c - 1, 0.0]^2$

Machida and Matsumoto (2003), Machida et al. (2005)

Formation of a Nonradiative Accretion Disk



Isosurface of Density



Volume rendered image of density

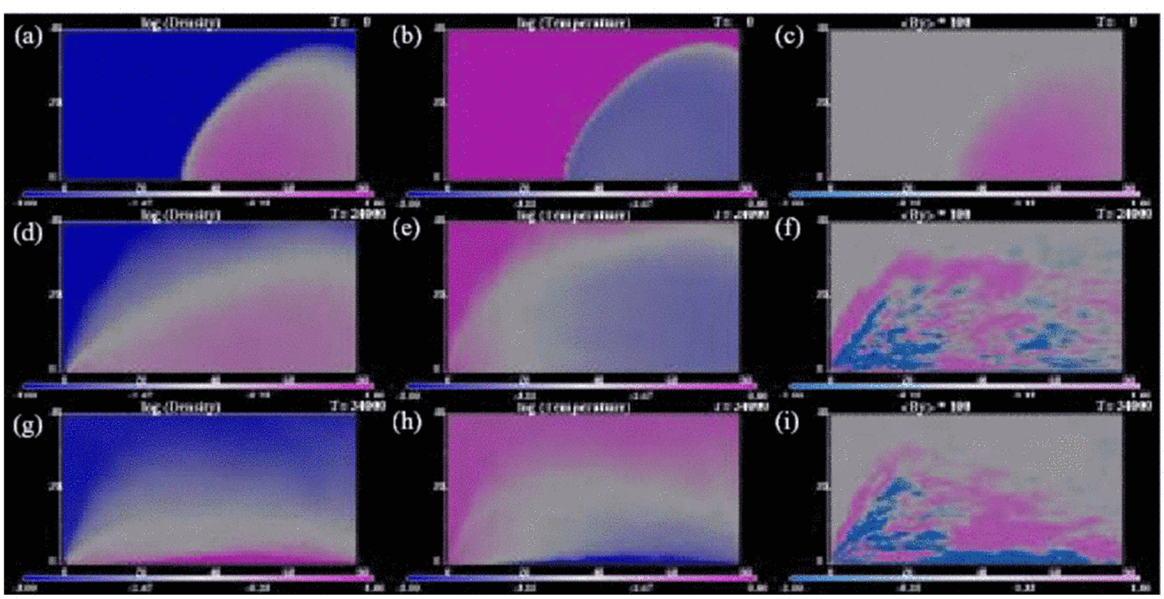
We Included Optically Thin Radiative Cooling

- Cooling term is switched on after the accretion flow becomes quasi-steady
- We assume bremsstrahlung cooling

  $Q_{rad} = Q_b \rho^2 T^{1/2}$

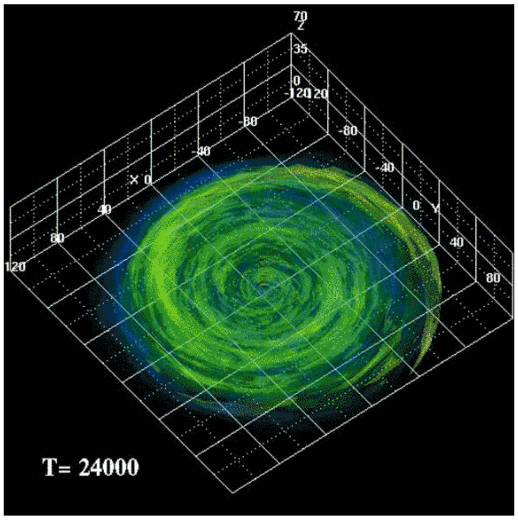
  (ions are cooled through Coulomn collision)
- Cooling is not included in rarefied corona where $\rho < \rho_{crit}$

Transition to Cool Disk

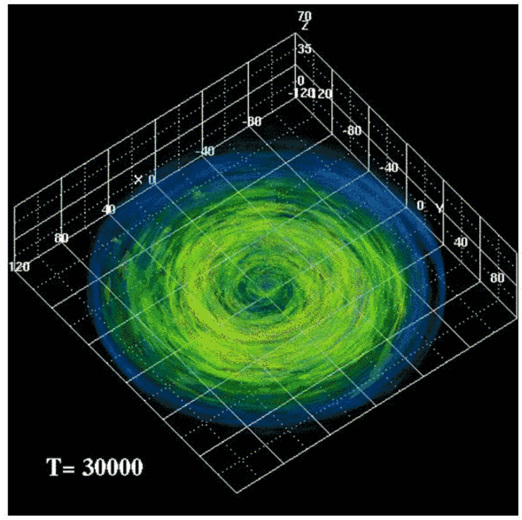


density temperature Toroidal field

Formation of Low-beta Disk

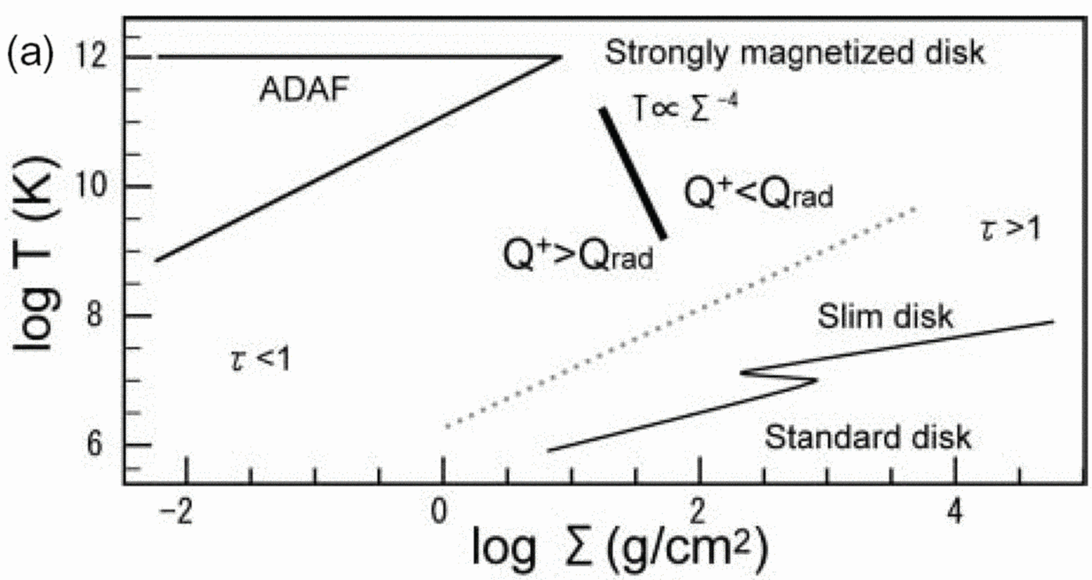


Before the transition



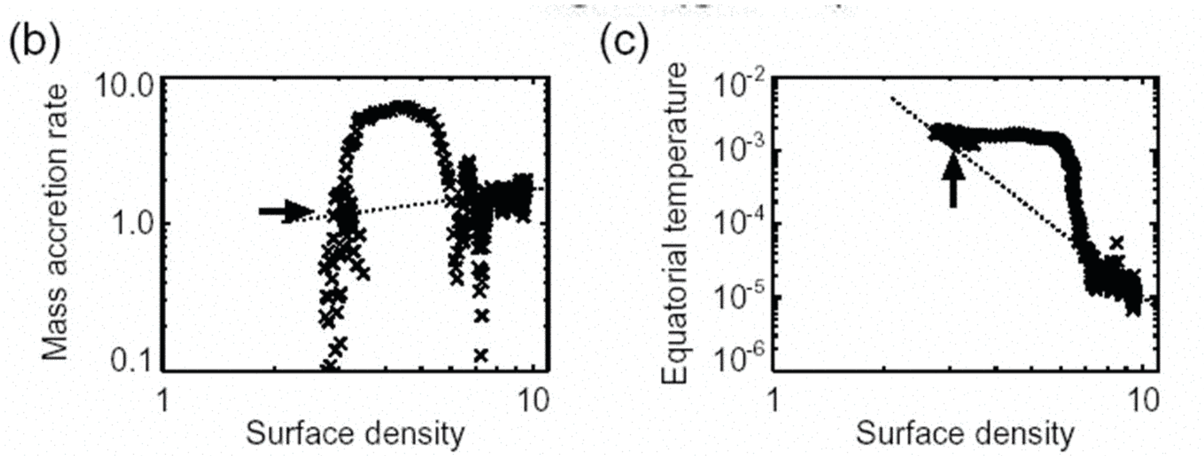
After the transition

Thermal Equilibrium Curve of Optically Thin Strongly Magnetized Disk



Machida, Nakamura and Matsumoto (2005)

Approach to The Steady State of Optically Thin Strongly Magnetized Disk



Summary

- Accretion disks can drive two types of MHD jets/outflows
  - Magnetocentrifugally driven jets/outflows. Disk material is accelerated along open magnetic field lines threading the disk.
  - Magnetic tower jet. This jet is dominated by Poynting flux. Low density matter in the disk corona is accelerated. Hot plasmoids are injected into the tower due to magnetic reconnection.
  - Both types of jets can co-exist (e.g., neutral wind and optical jets in protostars)
- Ideal MHD jets are ejected intermittently due to the turbulent motions of the footpoints of magnetic field lines anchored to the disk.
- We can obtain steady magnetocentrifugally driven jets/outflows by including magnetic diffusivity inside the disk.
- Non-axisymmetric instabilities grow in the jet but they do not disrupt the jet.
- During the transition from low/hard state to high/soft state, optically thin, magnetically supported disk is created. Magnetic energy release in such disks can be the origin of relativistically moving blobs observed in microquasars.