Resistive MHD simulations

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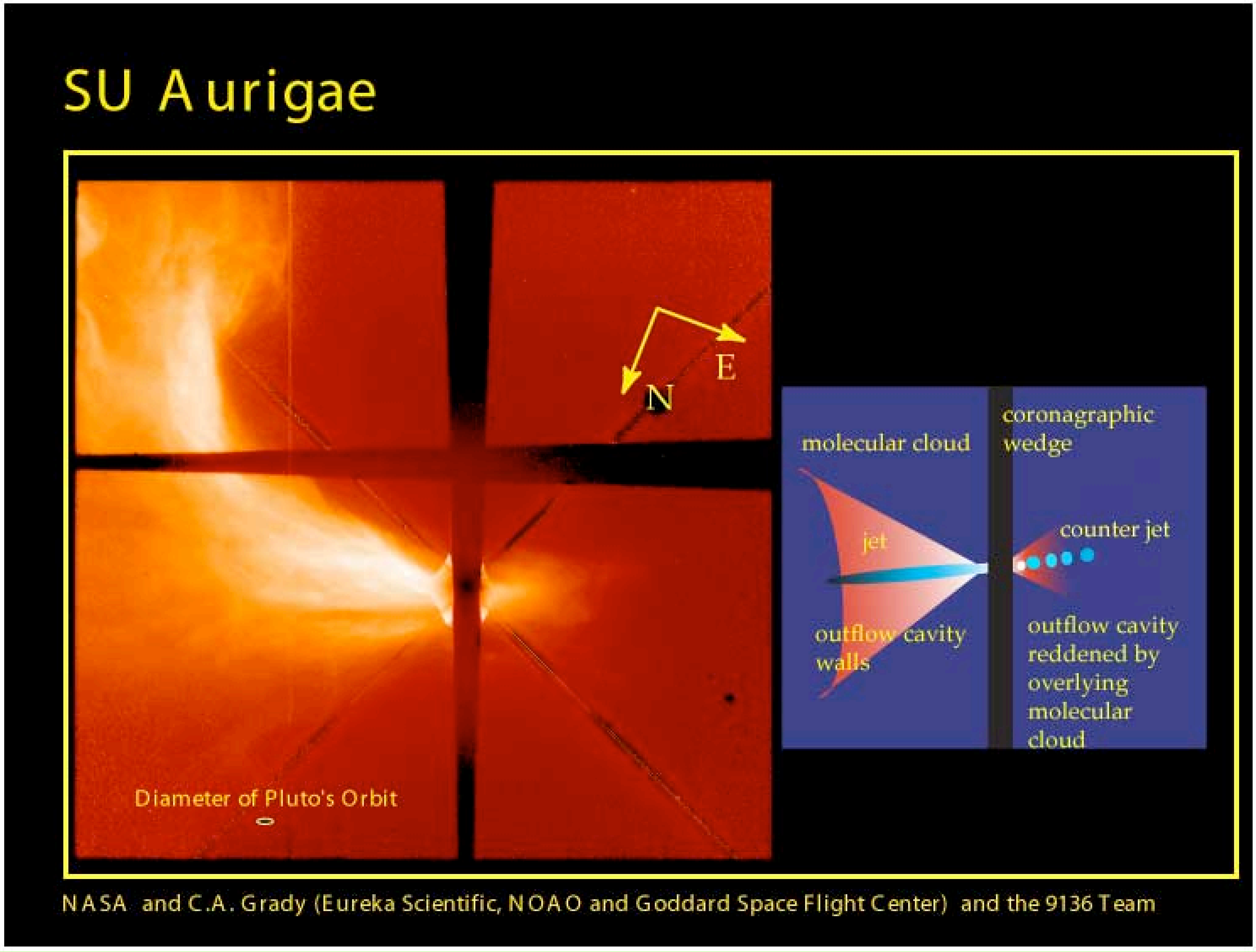
Outline

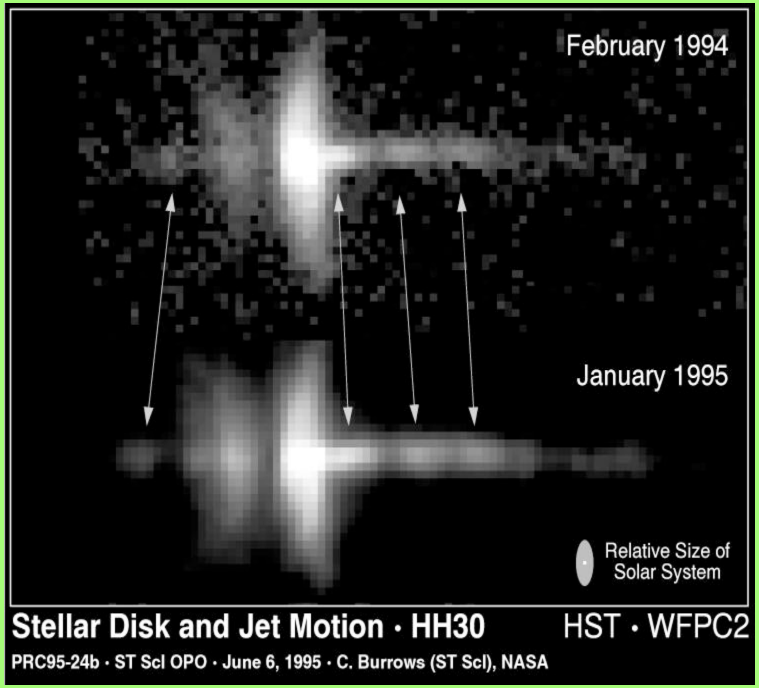
- Introduction
- Semi-analytical work: Self-similar models
- 2.5D Simulations: disk as a boundary
- 2.5D simulations: disk included
- Full 3D, why do we need it?
- Overview

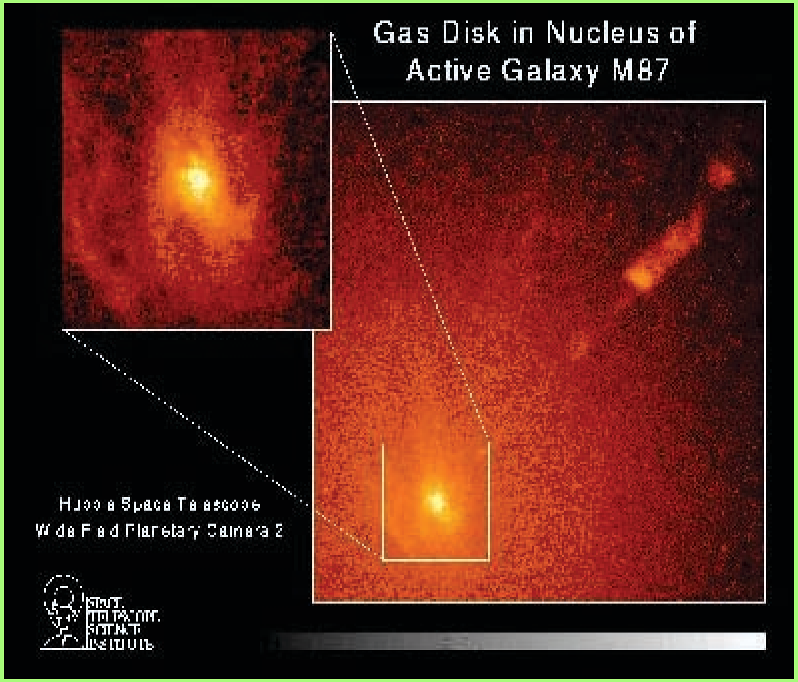
Dust disk-SU Aurigae



Introduction

- Outflows & jets in different scales, objects
- Eddington limit exceeded => mag. fields
- Protostellar jet launching problem: mechanism?
- Resistive vs. other dissipative processes





Resistive MHD

- Time-dependent **resistive** MHD equations.

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

$$\rho\left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\,\mathbf{u}\right] + \nabla p - \rho\nabla\left(\frac{GM}{\sqrt{r^2+z^2}}\right) - \frac{\mathbf{j}\times\mathbf{B}}{c} = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla\times\left(\mathbf{u}\times\mathbf{B} - \frac{c\mathbf{j}}{\sigma}\right) = 0$$

$$\rho\left[\frac{\partial e}{\partial t} + (\mathbf{u}\cdot\nabla)\,e\right] + p(\nabla\cdot\mathbf{u}) - \frac{\mathbf{j}^2}{\sigma} = \mathbf{0}$$

$$\nabla\cdot\mathbf{B} = \mathbf{0}$$

$$\frac{4\pi}{c}\mathbf{j} = \nabla\times\mathbf{B}$$

$$p = K\rho^{\gamma},\ e = \frac{p}{\gamma-1},\ \gamma = \frac{5}{3}$$

Induction eq.

$$\frac{\partial \mathrm{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathrm{B}) + \eta\nabla^2\mathrm{B}, \quad \eta = \frac{c^2}{4\pi\sigma}$$

Resistive MHD estimates

- Microscopic diffusivity insufficient: From induction eq.=>magnetic Reynolds number $Rm=UL/\eta$.
- $\eta=c^2/(4\pi\sigma)\sim r_e c(u_{th}/c)^{(-3)}$, $Rm\sim10^{(15)}$ for $u_{th}=(k_B T/m_e)^{(1/2)}$ for electron thermal speed and for $T=10^4$ K as typical protostellar case L=100AU.
- In astronomy L is LARGE=>R_m also large, no effect.
- We need **anomalous diffusivity**: parametrization as Shakura/Sunyaev "alpha": $\eta=\alpha UL$, where now $U=U_{Alfven}$. $U_A=B_P/(4\pi\rho)$.
- With $\alpha\sim0.1$ => $Rm\sim10$.
- In terms of timescales we define *local* Rm on a grid with scale L, then $Rm=t_{diff}/t_{dyn}=\min(L^2/\eta)/\min(L/U_A)$

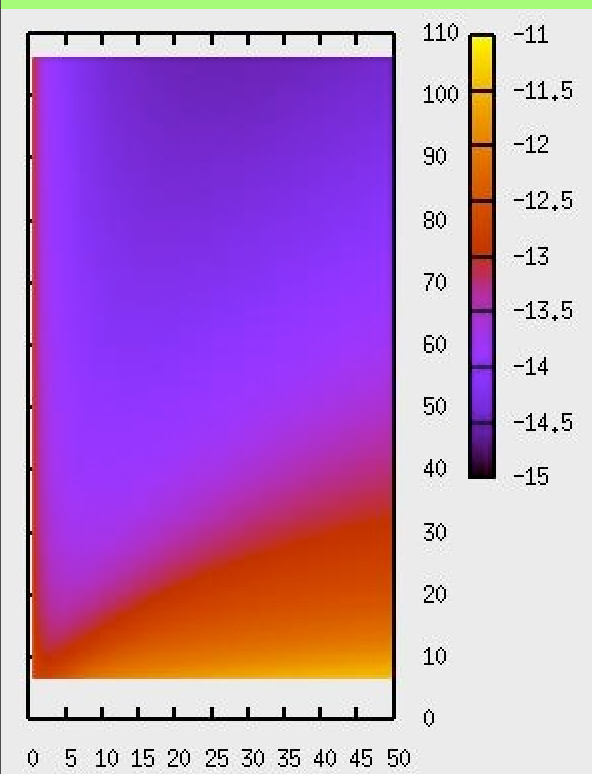
Numerical simulations

- Semi-analytical i.c.: self-similar models
- 2.5D Simulations: disk as a boundary
- 2.5D simulations: disk included
- Full 3D

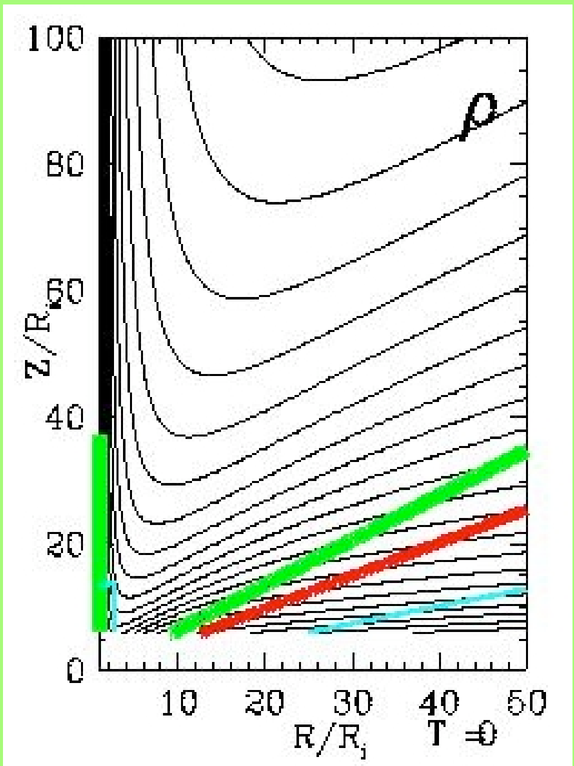
Self-similar initial solutions as i.c.

-Physical variables expressed as a power law of spherical or cylindrical radius along a given direction
-Semi-analytical solution taken as initial & boundary condition
-Initial conditions modified to fill the computational box

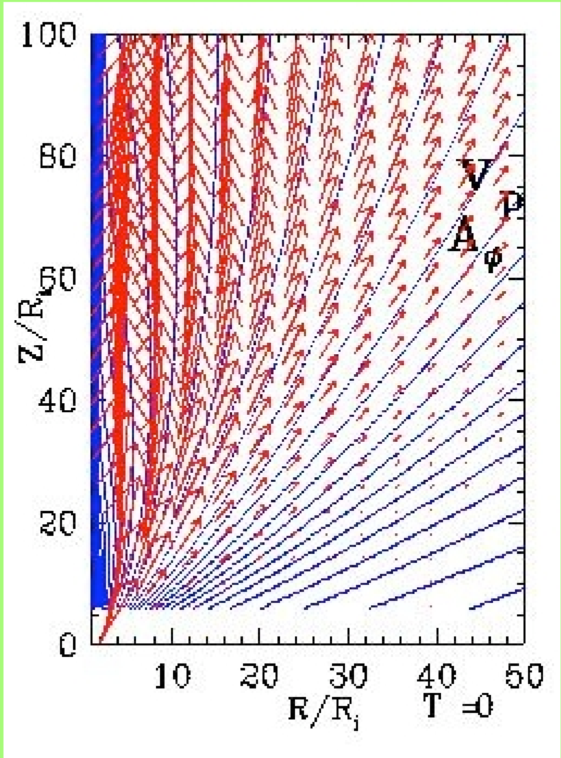
Density



Density & crit. surfaces

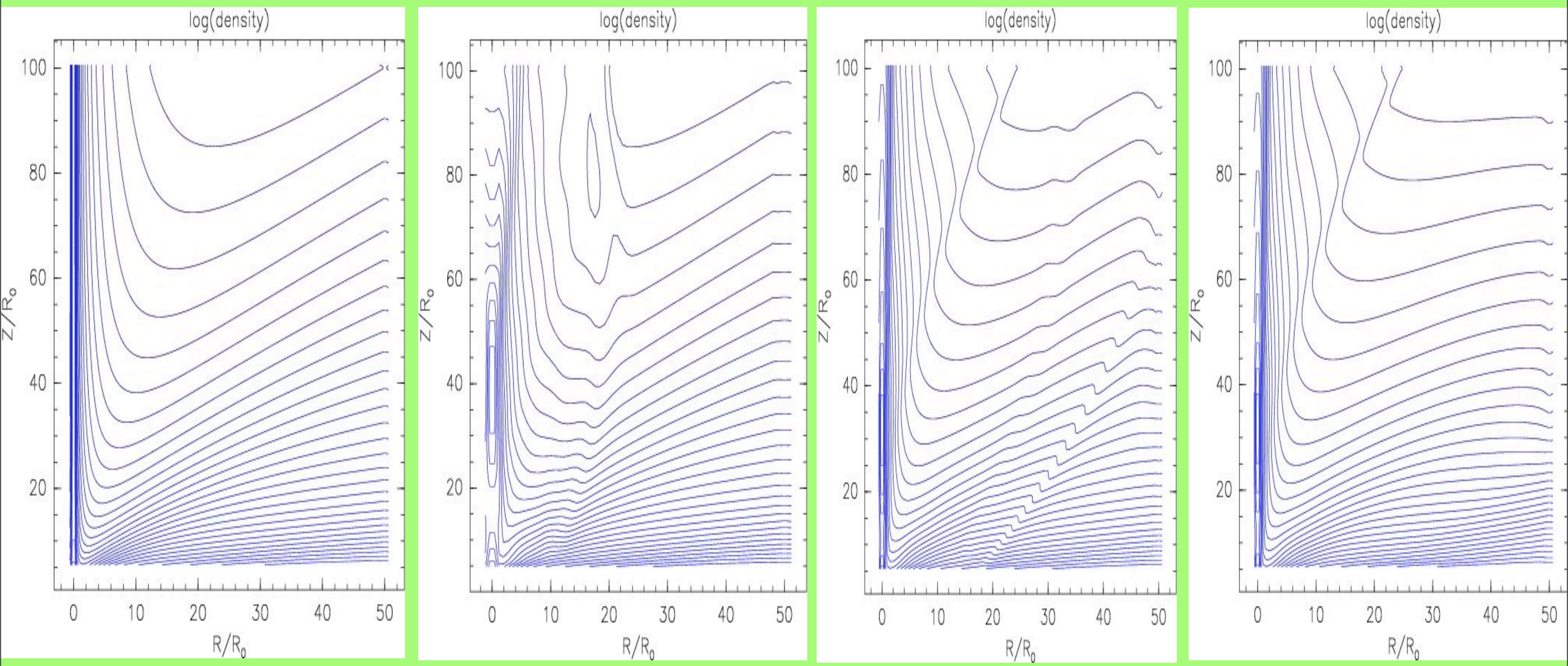


B lines and velocity



Simulations with NIRVANA code

-Density isocontours during one million Courant time-steps
-Relaxation process, towards some new stationary state, similar to i.c.

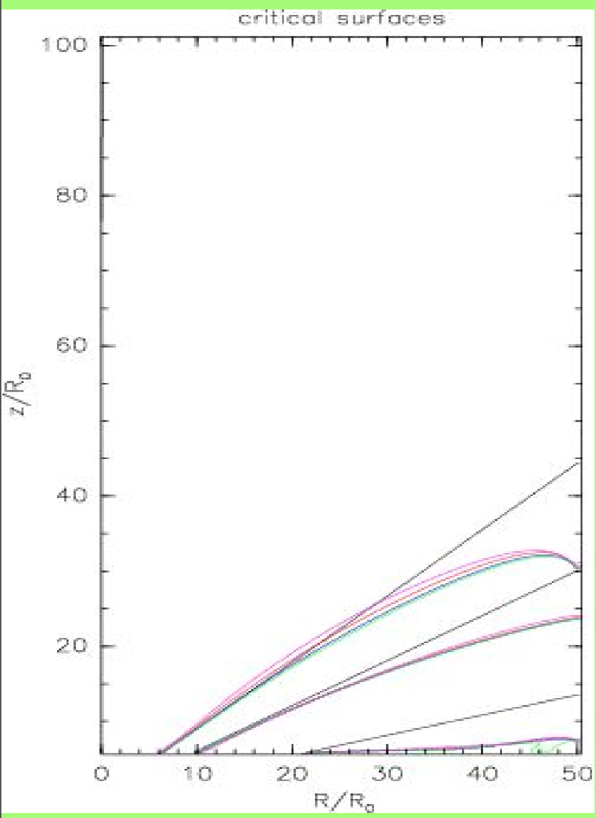


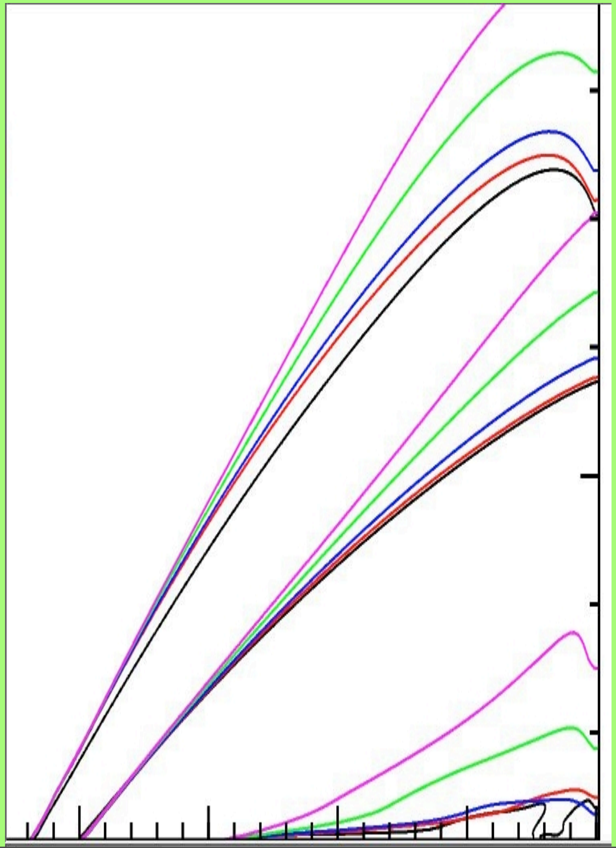
Simulations with NIRVANA code

-Effects of resolution and numerical diffusivity: *Left* panel, eta=0.
-Physical effects of magnetic diffusivity? *Right* panel: Black line is high resolution (512x1024) eta=0 run. Brown, blue, green and magenta are 128x256 runs for eta=0,0.1,0.5,1. There is a clear trend.

eta=0,0.1,0.5,1 ZOOM

eta=0

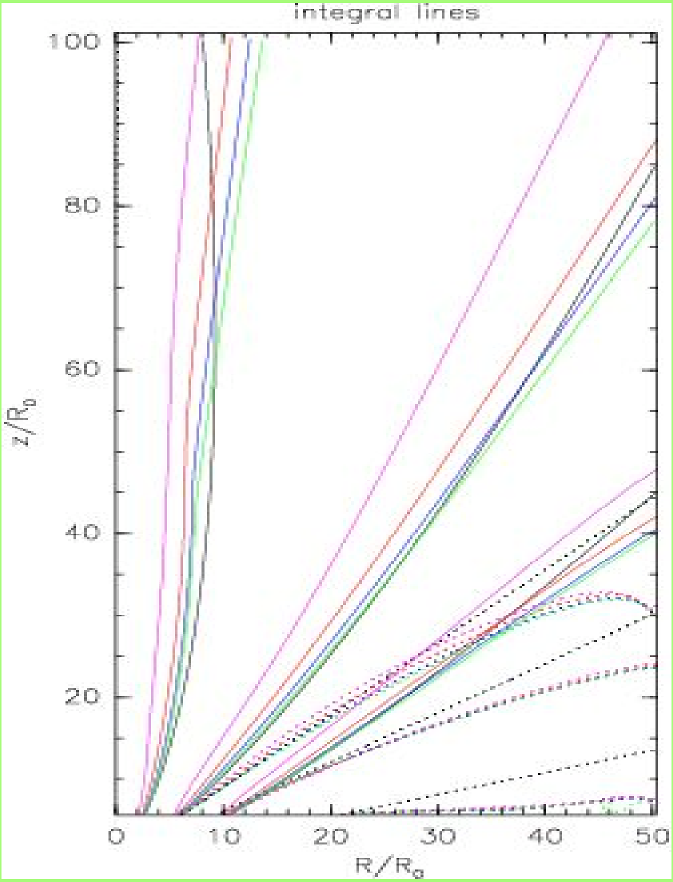




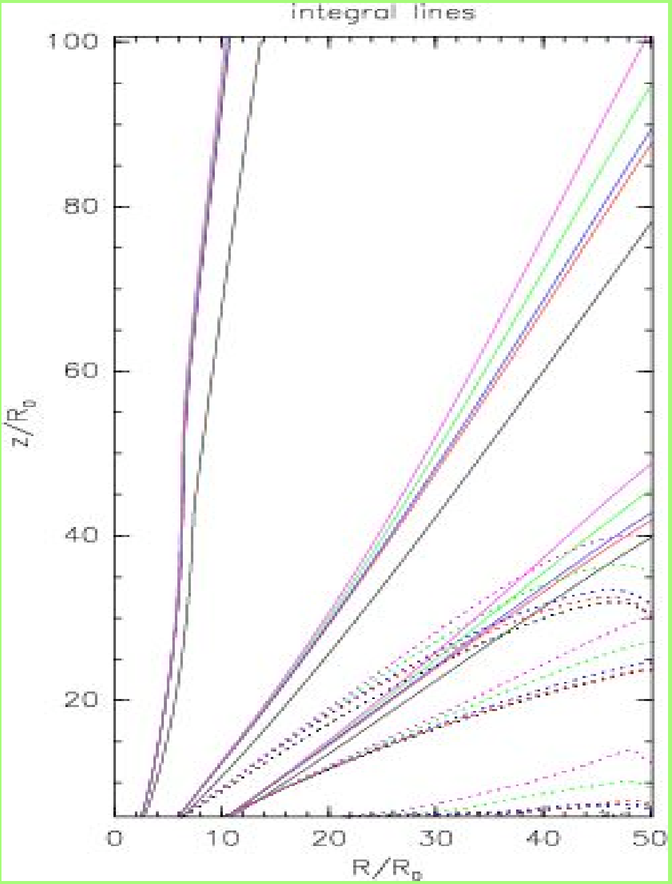
Simulations with NIRVANA code

Integrals along some chosen magnetic field lines show the effects of the numerical (RxZ=64x128,128x256,256x512,512x1024 in magenta,brown,blue,green. Black is i.c. in 512x1024) and physical diffusivity (for 128x256, eta=0,0.1,0.5,1 in brown,blue,green,magenta).

numerical

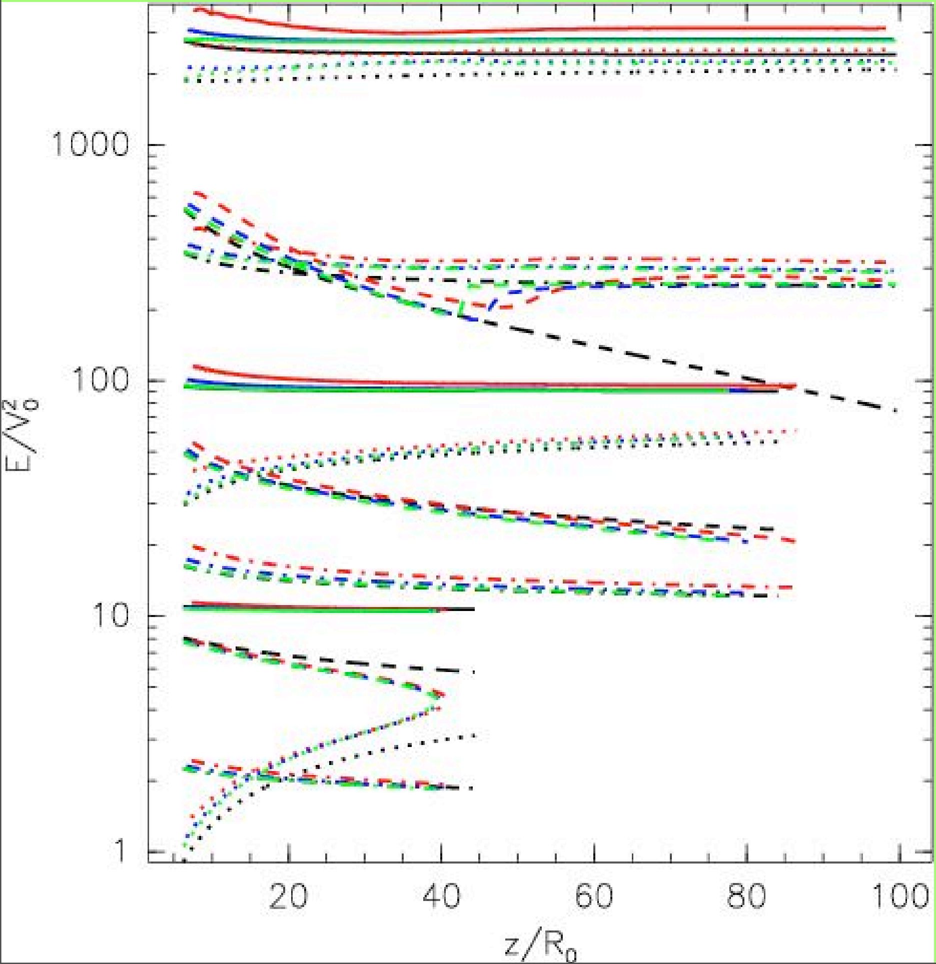


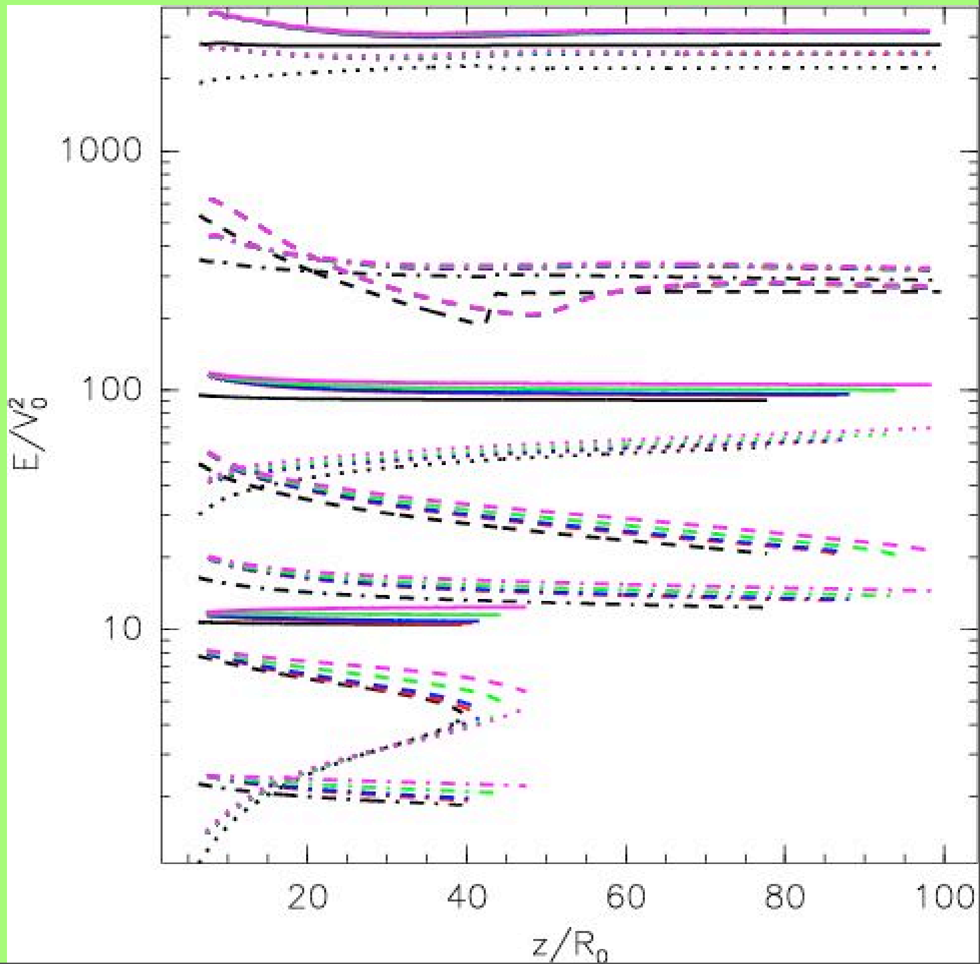
physical



Simulations with NIRVANA code

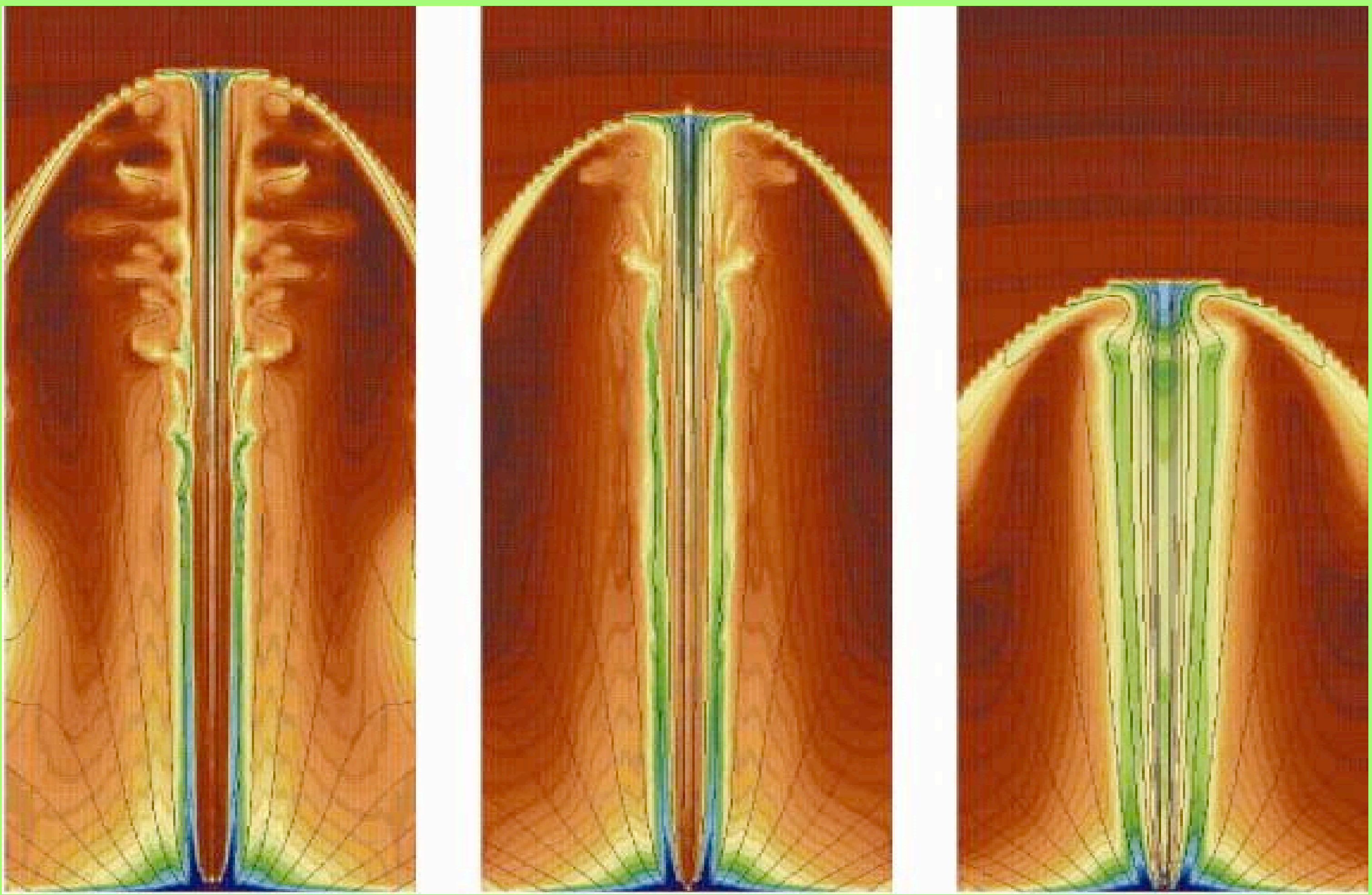
-Effects of resolution and numerical diffusivity on the MHD integrals
-Effects of physical diffusivity on the MHD integrals
-Total and kinetic energy, enthalpy and Poynting flux, top to bottom, integrals along the chosen lines from previous slide. There is a trend.





Simulations with disk as a boundary

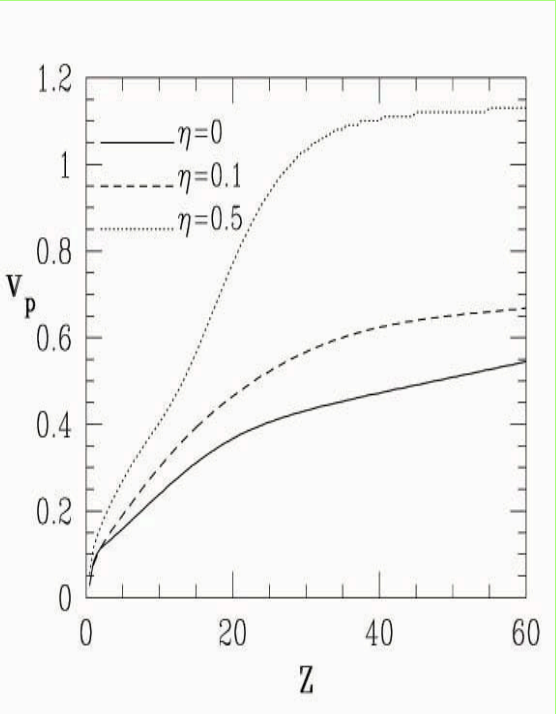
- Diffusive jets have less substructure, bow shock advances slower. T=400 for all three plots. ZEUS code simulations.
- eta= 0 0.01 0.1

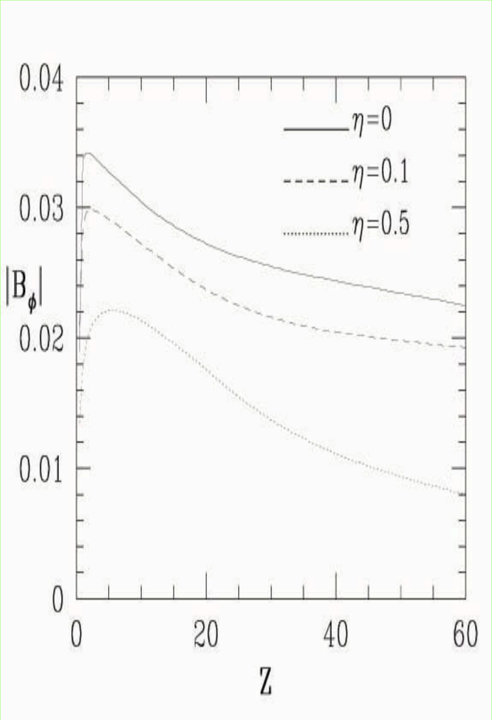


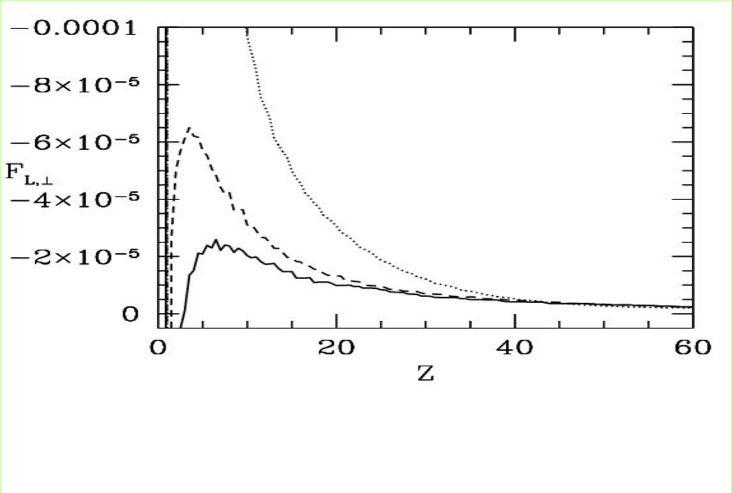
Fendt & Cemeljic, 2002

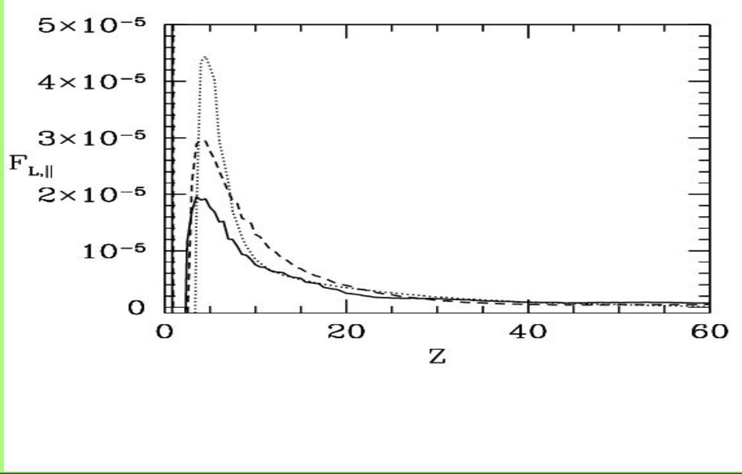
Simulations with disk as a boundary

- Poloidal velocities, toroidal magnetic fields versus diffusivity. Slices in the direction of propagation at R=15 (of 40).
- Velocity increase and magnetic field decrease for increasing diffusivity => axial mass flux decreases for diffusive jet
- Lorentz force-accelerates and collimates (eta=0.0.1,0.5 in solid,dashed,dotted line)



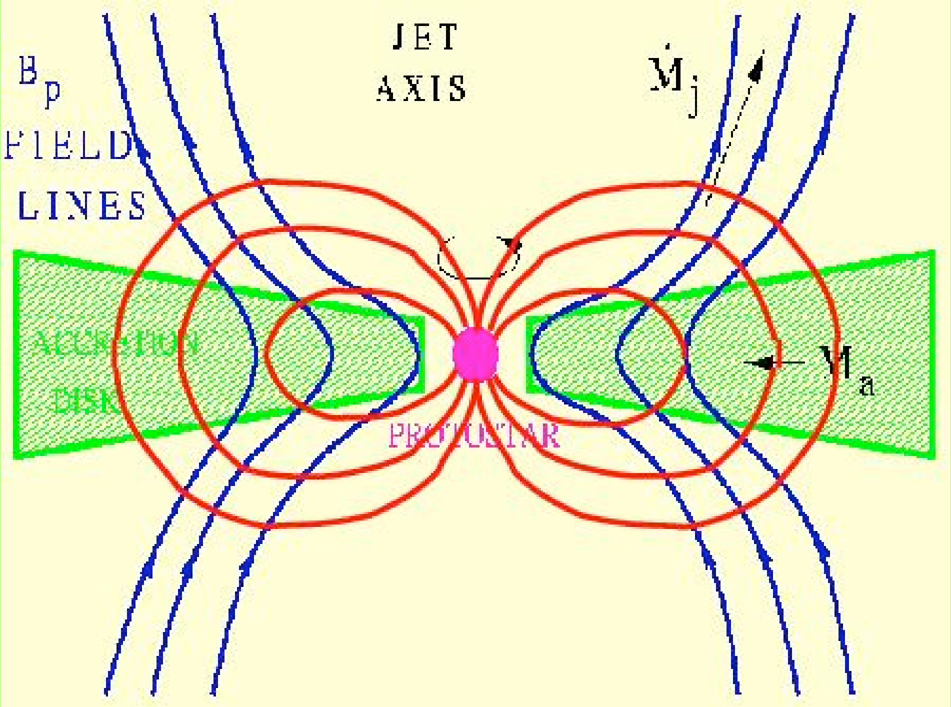






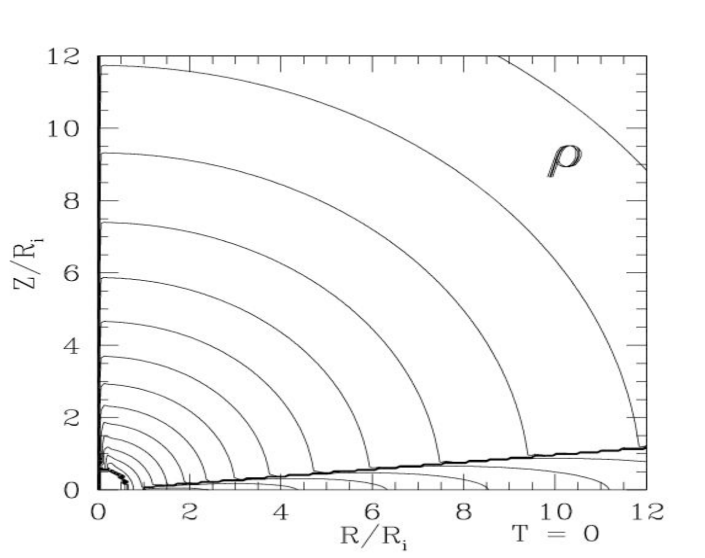
Simulations with the disk included-model

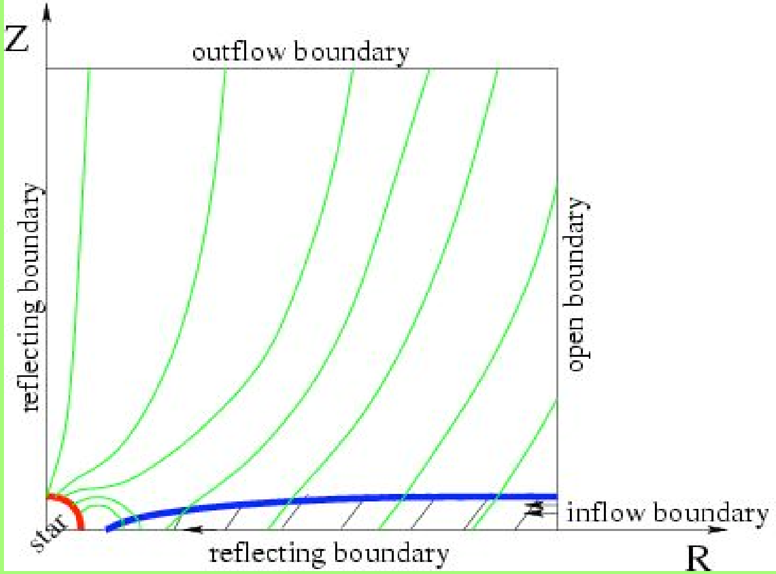
- Disk included in computational box
- Interaction of stellar magnetosphere & disk
- Stellar surface as a boundary

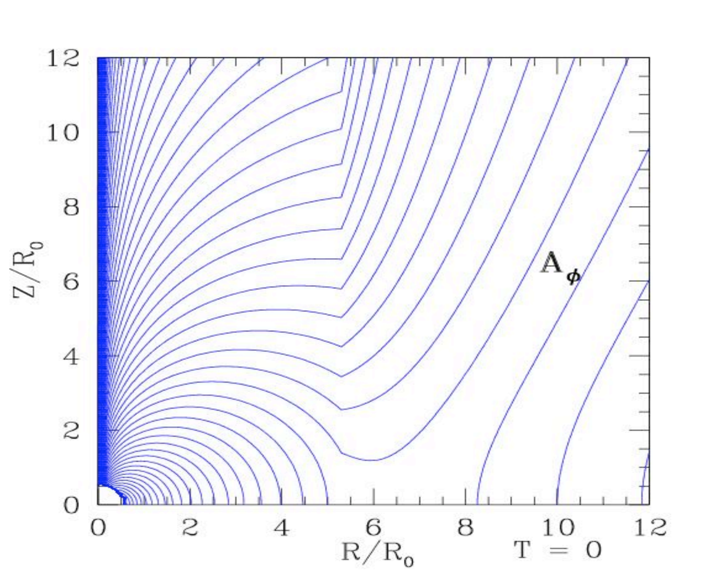


Simulations with the disk included-b.c.&i.c.

- Hydrostatic co-rotating corona above the disk in hydrostatic and magnetic forces balance
- Resistive disk, corona effectively ideal-MHD

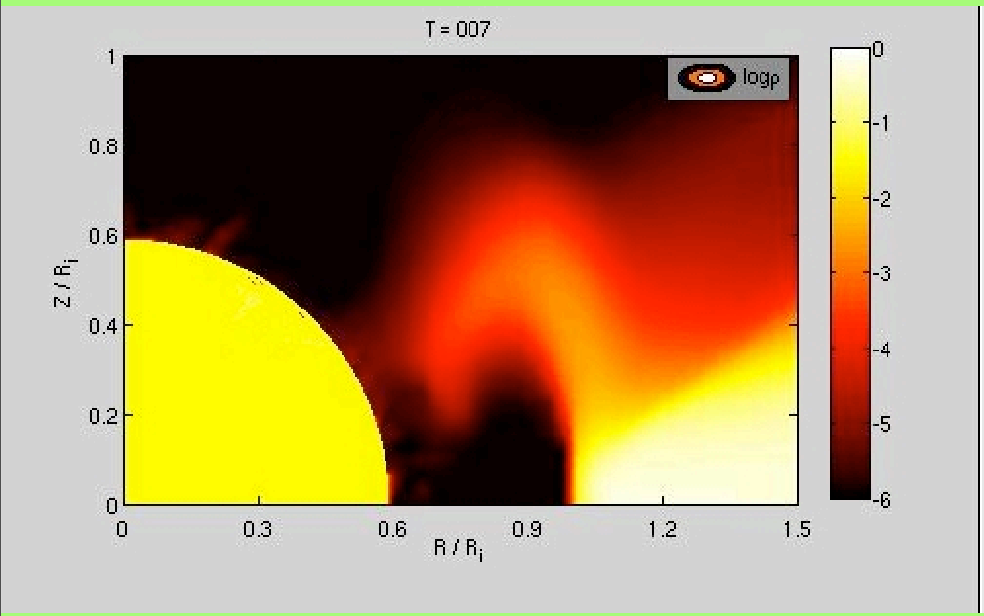


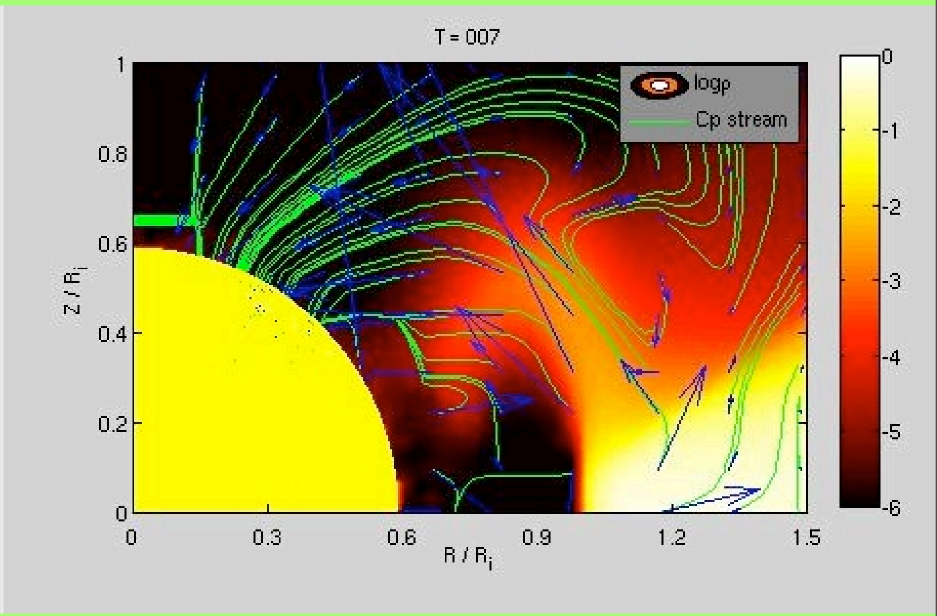




The disk included-stellar dipole field only

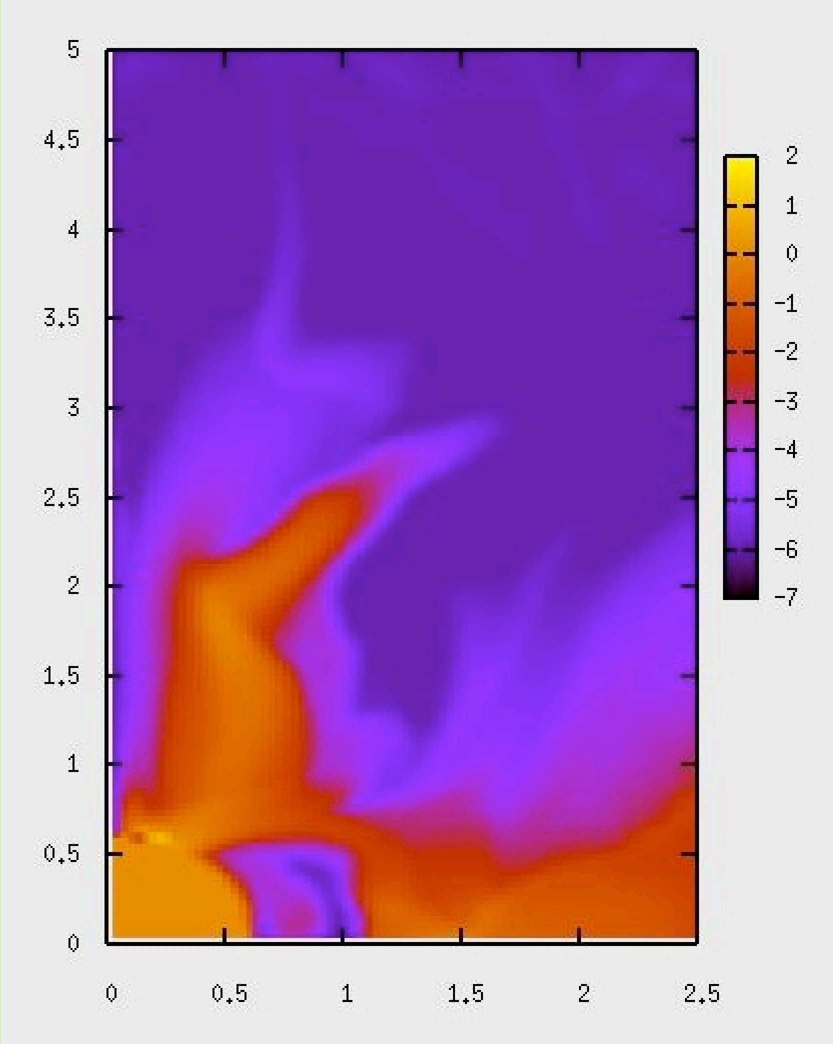
- Interaction of the stellar magnetosphere and the disk
- Funnel onto the star.
- Here is shown initial stage of the funnel buildup





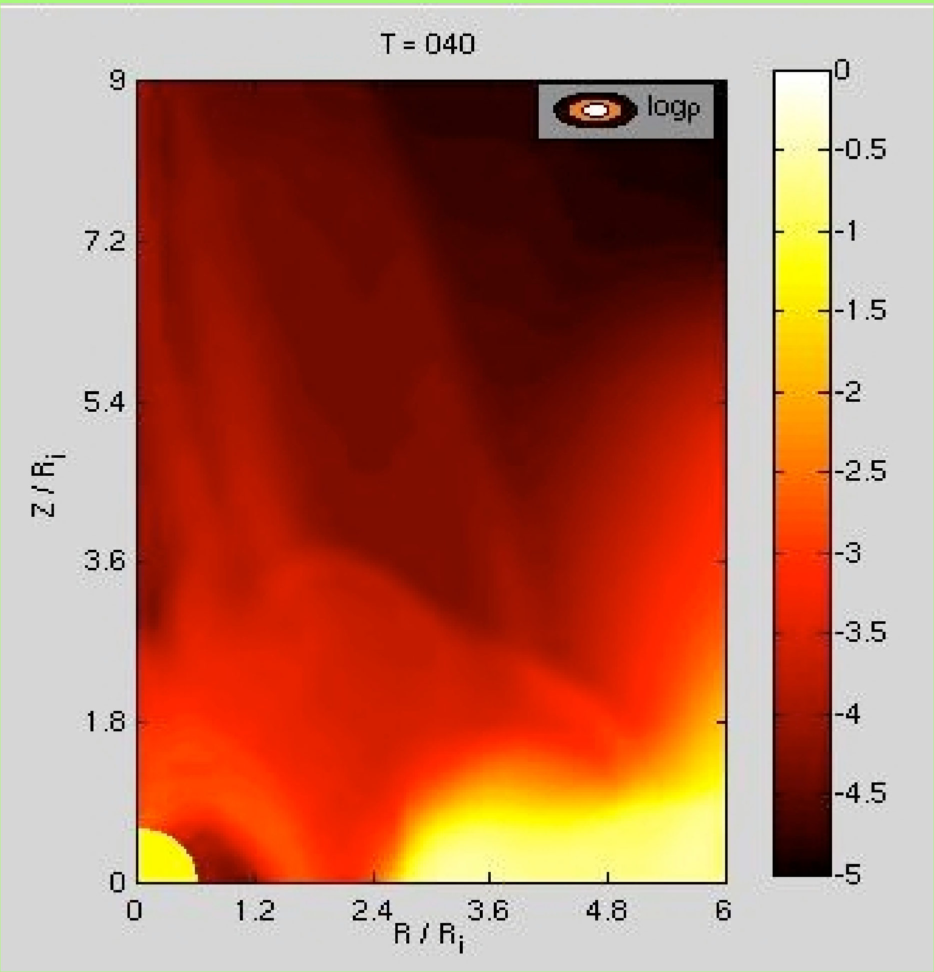
The disk included-stellar dipole field only

- Larger view, when funnel is present. So close to the star outflow will probably not be driven, but further out, flow could be collimated and accelerated by Lorentz force. Here is T<10 solution.



The disk included-stellar dipole field only

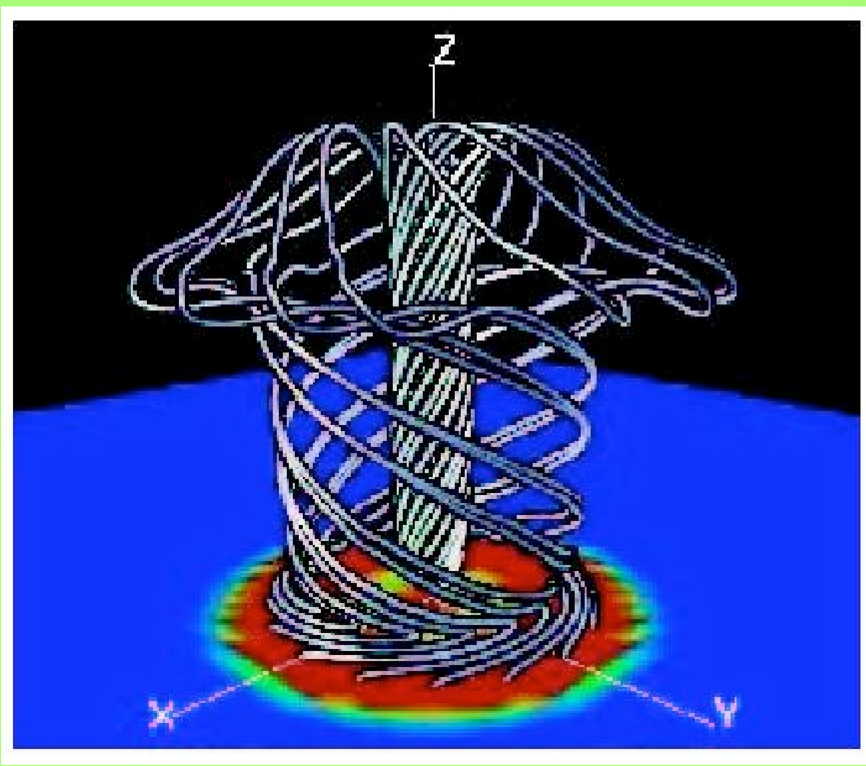
- Larger computational box, after T=40.
- Stellar dipole B*~1kG



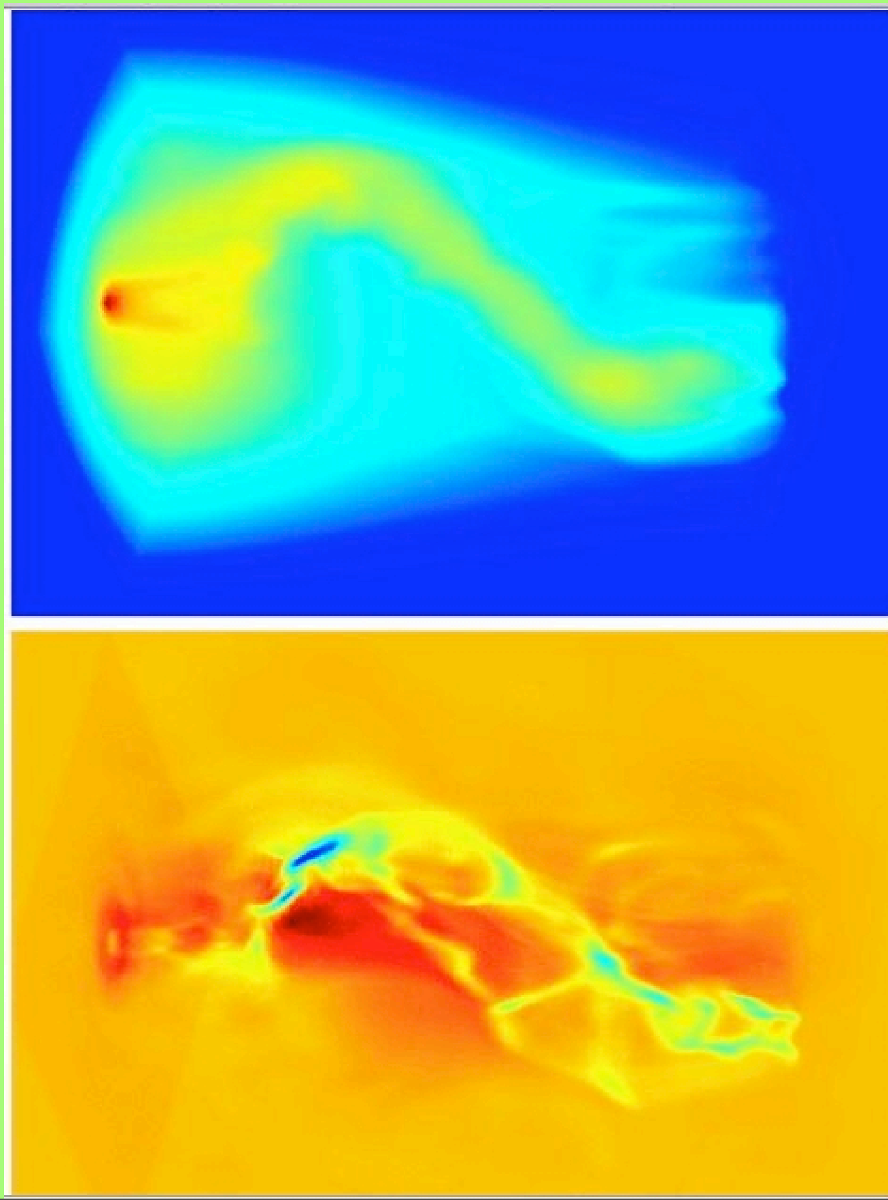
Full 3D, why do we need it?

Ouyed et al., 2003

-Disk as a b.c., left side.
-Instability-but ”backbone” of the jet preserved => single helix, ”corkscrew” jet



Kato et al., 2004 – magnetic tower

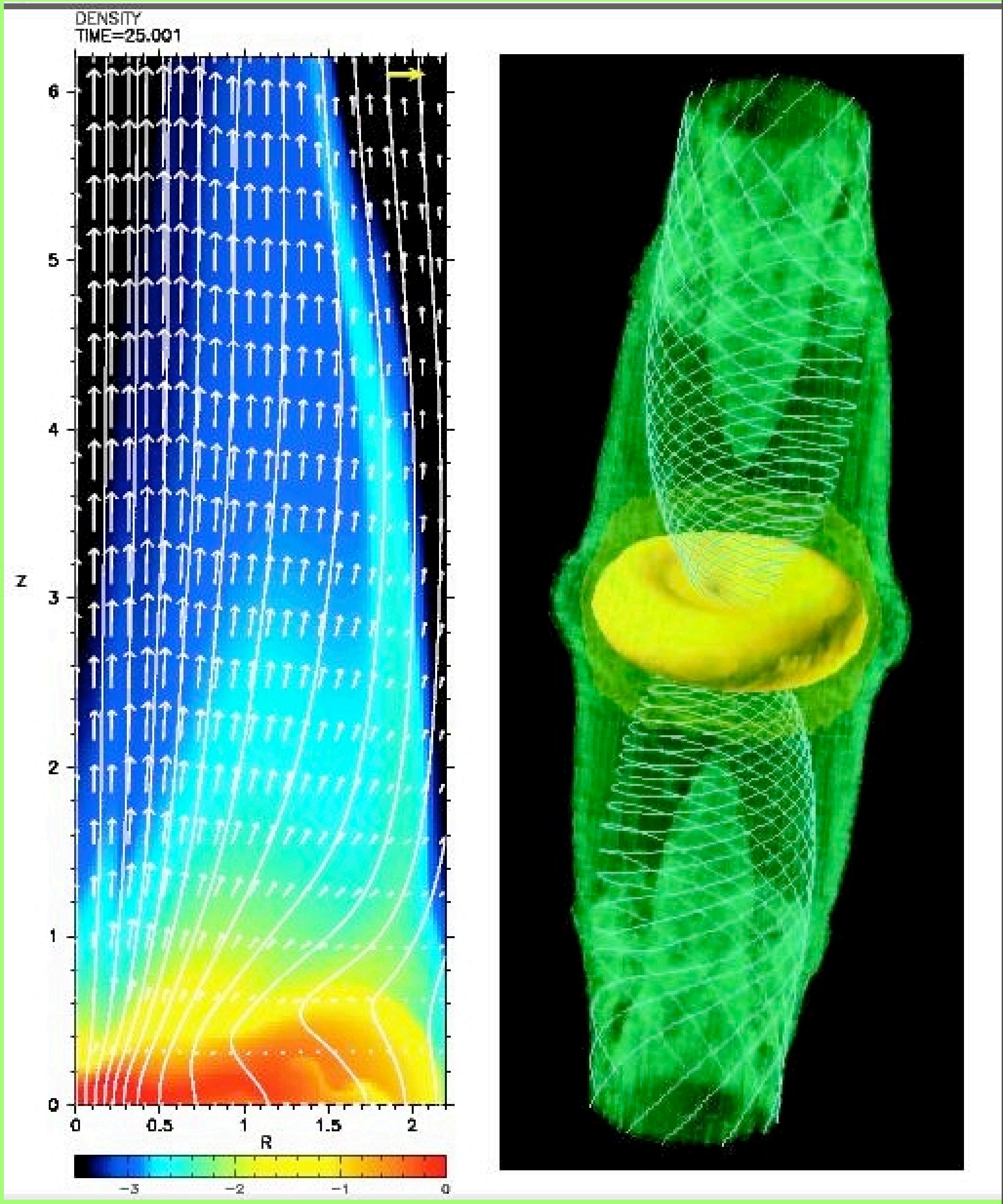


Full 3D, why do we need it?

-Approximations in 2D

-Numerical schemes

-Intrinsic 3D instabilities



Kuwabara et al., 2005

Overview

- Magnetic diffusivity - anomalous
- Numerical simulations: analytical i.c., disk as a boundary, disk included – in 2.5D
- Close vicinity of the star-there is “machine”
- Full 3D simulations. **STABILITY**