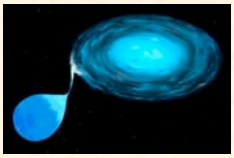
Momentum Transport in Disks.



Eliot has already described the astrophysical context which motivates study of momentum transport in disks.

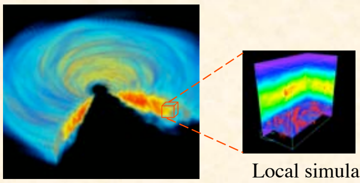
Two most important mechanisms for transport in an accretion disk:

1. Gravitational instability.
2. Magneto-rotational instability (MRI).

Only focus on latter.

Astrophysics goal: to understand accretion disk structure and evolution as thoroughly as we understand stellar structure and evolution (luminosity, spectra, variability, etc.)

MRI is studied with both *global* and *local* "shearing-box" simulations.



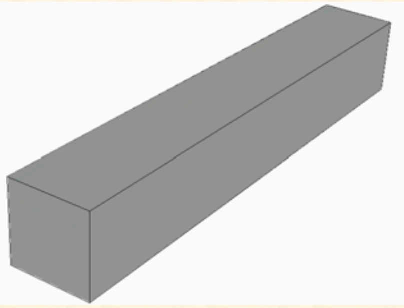
Local simulation

Global simulation

Local simulation: expand MHD equations in a frame orbiting at the local angular velocity Ω_0. Introduces Coriolis force and tidal gravity as source terms.

In 3D, MRI produces sustained turbulence

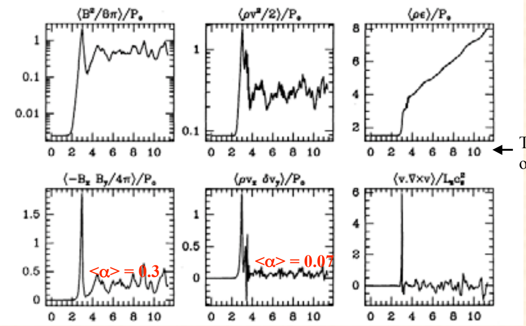
Animation of angular velocity fluctuations: $\delta V_\phi = V_\phi - V_{Kep}$
Initial Field Geometry is Uniform B_y



128 x 256 x 128 Grid
β_{min}= 100, orbits 4-20

Primary importance of MRI is total stress in saturated state.

Time-evolution of volume-averaged quantities:

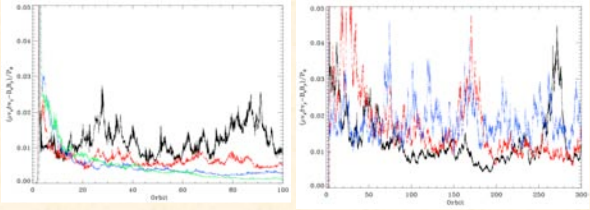


← Time in orbits

Also note: Sustained amplification of B indicates dynamo action.
Maxwell stress with even a small net flux gives a large α

Current Challenge I. MRI and dynamos.

In *unstratified boxes* with *no-net flux* and *no explicit dissipation* MRI drives sustained turbulence = dynamo.



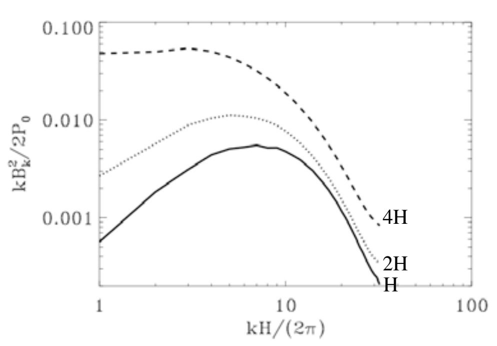
Hx4HxH domain

Hx4Hx2H domain

Black=32/H
Red = 64/H
Blue = 128/H

Saturation amplitude (and numerical convergence) depends on vertical box size.

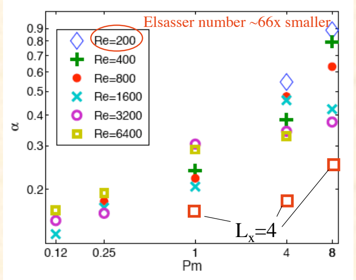
PS show numerical convergence relies on By generated at small k = dynamo.



Current Challenge II. Pm dependence of stress.

With net-flux, stress in saturated state depends on Pm. However, these results are at low R_M, not the fully turbulent high-R_M regime.

Variation of stress with P_m from Lesur & Longaretti (2007)

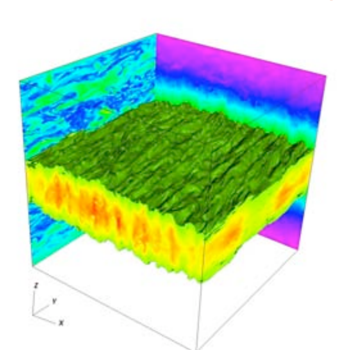


But LL used L_x=1, which Pessah & Goodman (2009) have argued suppresses parasitic instabilities.

Simulations with Re=800 but L_x=4 show much smaller saturation amplitude.

Remaining Pm dependence may be because $\lambda_{max}/L_z < 1$ for $P_m \sim 1$

Current Challenge III. Saturation amplitude of MRI in stratified and global disk models.



No-net vertical flux.
$\beta = 2P_0/B_0^2 = 100$

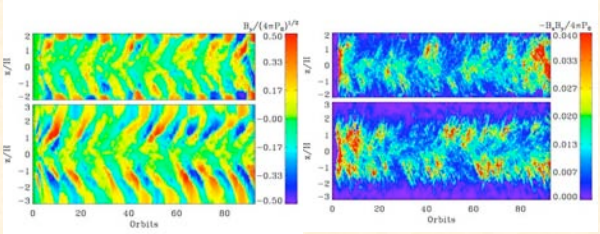
Domain size either:
H x 4H x 4H
or 4H x 4H x 4H
Resolution 32/H to 128/H

Periodic BC in z.

Density isosurface, slices of density and B^2 at 100 orbits.

Spacetime plots reveal periodic emergence of By.

Comparison of domains with +/- 2H and +/- 3 H

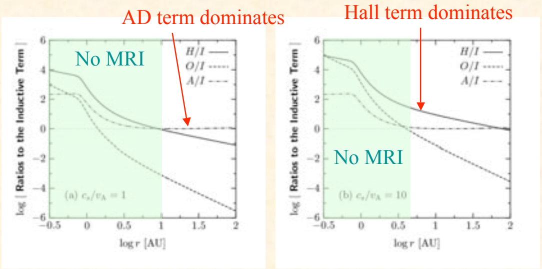


Appears to be a cyclic dynamo.

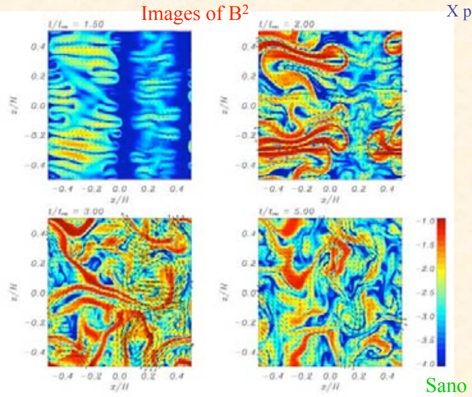
Issues: How does stratification affect saturation?
Where and how is energy dissipated (is there a corona)?

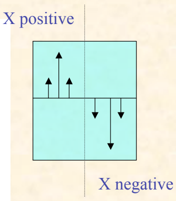
Current Challenge IV. Non-ideal MHD.

Models of proto-planetary disks indicate the inner regions are stable to MRI, outer regions dominated by AD or Hall effect



2-D simulation with initially sinusoidal field ($B_z = B_0 \sin x$) dramatically demonstrates properties of Hall effect:

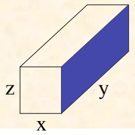


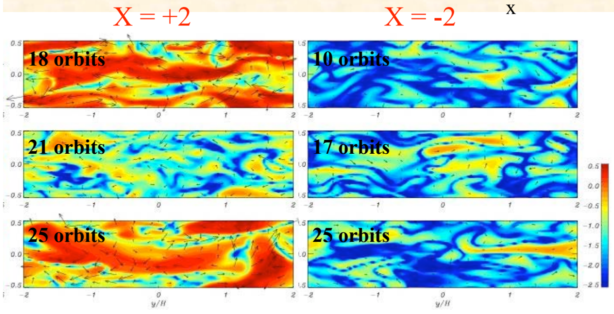


At late times, fully developed turbulence with $X_{eff} \sim 0$

Sano & Stone 2002

In 3D, snapshots of magnetic pressure show temporal fluctuations, higher amplitude for X > 0

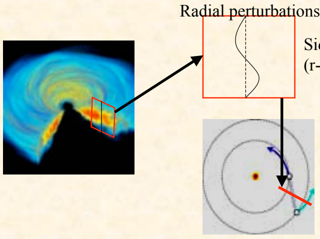




Current Challenge V. Kinetic MRI.

In a weakly collisional plasma, viscous transport is only along magnetic field lines (Braginskii 1965). Relevant to inner regions of AGN disks.

This leads to the magneto-viscous instability (MVI) in disks (Islam & Balbus 2008). Mechanism is identical to magneto-rotational instability (MRI), except viscosity (rather than Maxwell stress) transports angular momentum! MVI is very weak field limit of kinetic MRI (Quataert et al. 2002, Sharma et al. 2003)

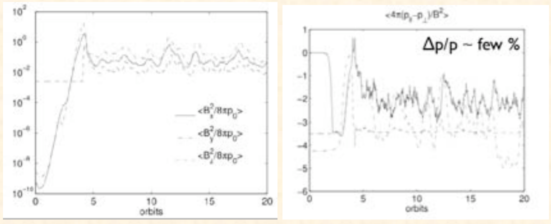


Radial perturbations to vertical B

Side view
(r-z plane)

What are the properties of the saturated state of the MVI?

Kinetic MRI in Landau limit

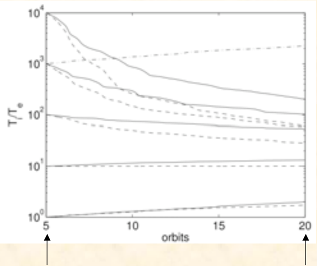


Sharma et al. 2006

Saturation amplitude similar to MHD.
However, significant angular momentum transport by anisotropic pressure; $P_{r\phi} \sim B_r B_\phi$

Results in electron heating in two-fluid kinetic MHD.

Anisotropic P in MRI turbulence drives significant heating of electrons.



Artificially suppress electron heating, large T_i/T_e is maintained.

It seems impossible to support very large T_i/T_e with MRI turbulence.

Start with different T_i/T_e

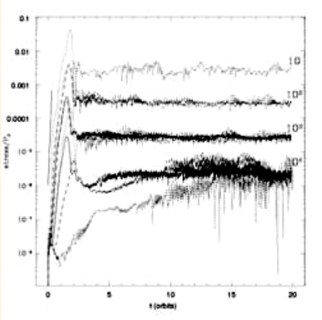
T_i/T_e always relaxes to ~10-100 at late times

With T_i/T_e given by kinetic MRI, $\dot{M}$ in Sgr A* must be small.

3D shearing-box simulations of the MVI.

In nonlinear regime of Braginskii MHD, pure MVI produces turbulence and significant Reynolds stress.

$\beta = 10^{10}$; field is too weak for MRI



Labeled by Re = $C_s^2/\Omega\nu$

H x 4H x H box
Numerical resolution:
dotted = 32/H
dashed = 64/H
solid = 128/H

Summary: Key Challenges.

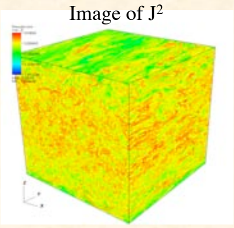
1. Understand mean-field dynamo driven by MRI.
2. Understand effect of Pm on saturation amplitude of MRI in stratified and global disk models.
3. Investigate nonlinear regime of MRI with more physics, such as kinetic MHD and radiation-dominated MHD.
4. Astrophysics: understand non-thermal spectra, temporal variability, and production of jets and outflows on the basis of disk dynamics (MRI).

Key techniques: biggest impact has been from advanced numerical algorithms that scale well on new architectures. PPPL MRI experiment has had an important impact, but not on the study of MRI (yet).

Connections to other groups.

1. Reconnection:

Image of J^2



4H x 4H x 4H

2. Turbulence
3. Dynamos
4. Radiative hydrodynamics
5. Particle acceleration