PI: Fatima Ebrahimi, Princeton University – DE-SC0012467, **"Global Simulations of Dynamo and Magnetorotational Instability in Madison Plasma Experiments and Astrophysical Disks "**

Objectives: Magnetic fields are observed to exist on all scales in many astrophysical sources such as stars, galaxies, and accretion discs. Understanding the origin of large scale magnetic fields, whereby the field emerges on spatial scales large compared to the fluctuations, has been a particularly long standing challenge. Large scale fields also play important roles in momentum and angular momentum transport in accretion disks and laboratory plasmas. Our physics objective are 1) what are the minimum ingredients for large-scale dynamo growth? 2) could a large-scale magnetic field grow out of turbulence and sustained despite the presence of dissipation? 3) what is the role of large-scale fields in transporting momentum in flow-dominated systems. These questions are fundamental for understanding the large-scale dynamo in both laboratory and astrophysical plasmas. Here, we report major new findings in the area of Large-Scale MHD Dynamo. In particular, Ebrahimi and Pallavi Bhat (postdoc hired by PI:Ebrahimi October 15 2015 - October 15 2016) perform direct numerical simulations to study magnetorotational instability (MRI) dynamo in both global cylindrical geometry and local shearing box.

1 Accomplishments: Radially dependent large-scale dynamos in global cylindrical shear flows and the local Cartesian limit

We have employed the quasilinear analytical calculations to explain the large-scale dynamo growth of radially alternating mean fields (averaged over height and azimuth) observed in the global cylindrical simulations. We have shown from both numerical simulations and semi-analytic quasi-linear theory how radially alternating large-scale toroidal fields can be generated from MHD flow-driven fluctuations.[1] These fields are found in MHD DNS for both zero-net- flux and non-zero-net-flux initial configurations in both the quasi-linear regime and the fully saturated non-linear regime.

(a) Analytical calculations of minimum conditions for radially dependent large scale field growth:

First, we have identified the minimum conditions needed for large scale field growth. Given non-axisymmetric fluctuations (with nonzero vertical and azimuthal perturbations), we calculated the complete form of the quasilinear fluctuation-induced EMFs in both cylindrical and Cartesian coordinates.[1] It is found that large scale dynamo growth in a linear shear flow without rotation can be sustained by shear plus non-axisymmetric fluctuations even if not helical, a previously unidentified distinction. In general, we find a direct relationship between dynamo generating EMFs and differential rotation in the cylindrical model, or linear shear in the local Cartesian model. Comparing cylindrical and local Cartesian models, we find that in each case the fluctuation-induced EMF has separate contributions that depend respectively on 1) non-uniformity of the radially sheared non-axisymmetric perturbations 2) the background differential rotation (cylindrical) or linear shear (Cartesian) 3) the mean angular velocity. These three vertical EMF terms can separately generate a large-scale magnetic field.

Here we present an example of our analytical calculations showing the ingredients required for large-scale growth in flow-dominated systems. In the absence of rotation, a large-scale magnetic field, $\overline{B}_y \sim -\frac{1}{\gamma}\frac{\partial \mathcal{E}_z}{\partial x}$, can directly be generated via a linear flow-shear and a radially uniform non-axisymmetric $(k_y, k_z \neq 0,\, k_x = 0)$ perturbation,

$$\overline{B}_y(x) = \frac{k_y k_z B_0}{(k_y^2 + k_z^2)} \left[\frac{k_y V_y(x)'(k_y V_y(x) - \omega_r)}{(\gamma^2 + \vartheta^2(x))^2} \right]' |\widetilde{V_x}|^2, \tag{1}$$

This is an exact analytical equation for a large-scale azimuthal magnetic field generated via a linear mean shear-flow and any perturbations with nonzero k_y and k_z. The large-scale field given in Eq. (1) is consistent with previous studies of large scale field growth from the combination of linear shear with randomly forced turbulence. However, our calculations explicitly reveal the most minimalist conditions needed for growth in the absence of rotation: a background linear shear and an imposed non-axisymmetric perturbation with nonzero k_y, k_z. The main difference is that helical velocity perturbations are not required.

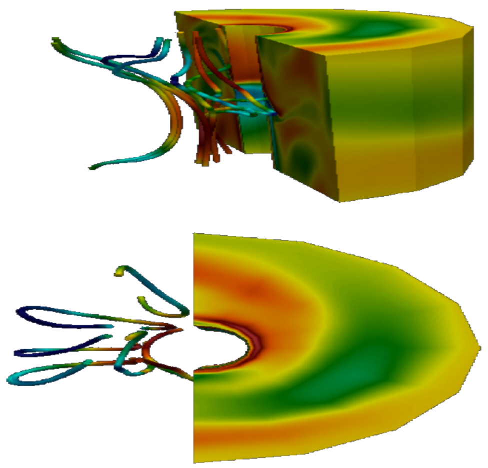

Figure 1: Field line visualizations during non-linear MRI simulations in a 3D cylinder when m = 1 mode perturbation is dominant. Toroidal top view in 3D shows the twisting of the field lines.

(b) Global MHD simulations of shear-flow driven dynamos:
Second, the dynamo growth observed in the MHD simulations is explained by our analytic calculations of a non-axisymmetric fluctuation-induced EMF that is sustained by azimuthal shear of the fluctuating fields. For the MRI case, we express the large-scale dynamo field as a function of differential rotation, and show that the global non-axisymmetric instability itself sources the EMF and the large-scale field grows on the time scale of the modal growth. These analytical calculations have been able to explain the growth of large-scale fields obtained in the global simulations. Our global 3D cylindrical simulations exhibit the MRI and large-scale dynamo growth of radially alternating mean fields, averaged over height and azimuth. The mean fields obtained in the cylindrical system have shown to be as the results of the MRI fluctuations, and the standard 'Ω effect' (shear of the mean field by differential rotation) is unimportant. The resulting radially alternating large-scale fields in the global simulations have implications for angular momentum transport in discs and corona. Figure 1 shows field line visualizations in 3D non-linear MRI simulations, the field lines are stretched and twisted to generate a large-scale toroidal field. Our results suggest that the quasilinear and nonlinear fluctuation-induced EMF may provide fundamental insight into the growth and sustenance of large-scale dynamo in these flow-driven systems.

2 Accomplishments: Large scale dynamo action precedes turbulence in shearing box simulations of the magnetorotational instability

Although the magnetic field evolution in the nonlinear saturation regime of the MRI has been studied in previous simulations, large scale dynamo action in the early MRI growth phase has heretofore not been explored. In contrast to previous MRI dynamo shearing box simulation studies which focus on horizontal averaging to obtain mean fields, we consider separately horizontal and vertical averaging and show the presence of large scale fields in both approaches (Fig. 2). By computing planar averaged fields and power spectra, we find large scale dynamo action in the early MRI growth phase - a previously unidentified feature. Fast growing horizontal low modes and fiducial vertical modes over a narrow range of wave numbers amplify these planar averaged fields in the MRI growth phase, before turbulence sets in. The large scale field growth requires linear fluctuations but not nonlinear turbulence (as defined by mode-mode coupling) and grows as a direct global mode of the MRI. Here, we outline the three main physics highlight of our results:[2]

- **Feedback to vertical mean field in the vertically averaging**: Our two independent planar averaging procedures, horizontal (x-y) averaging commonly performed in previous shearing box MRI studies and vertical (y-z) averaging motivated by the global cylindrical simulations, respectively, would provide a more complete picture for large-scale dynamo action. In particular, y-z averaging leaving variables as function of x (the direction of flow variation) exhibits radially varying mean fields (two top Figs. 2), which compare well with the global cylindrical simulations of EB16 [1]. In addition, only the vertical averaging allows a study of the evolution of large scale vertical field.

- **Dynamo action in the absence of turbulence**: The MRI large scale dynamo does not require an underlying turbulent flow to exponentially grow large scale fields on fast dynamical time scales.
- **Direct transfer of energy from large scales to small scales**: The common picture in shearing box simulations has been that large scale dynamo starts with turbulence. Here, we show that large scale fields appear before the small scales.

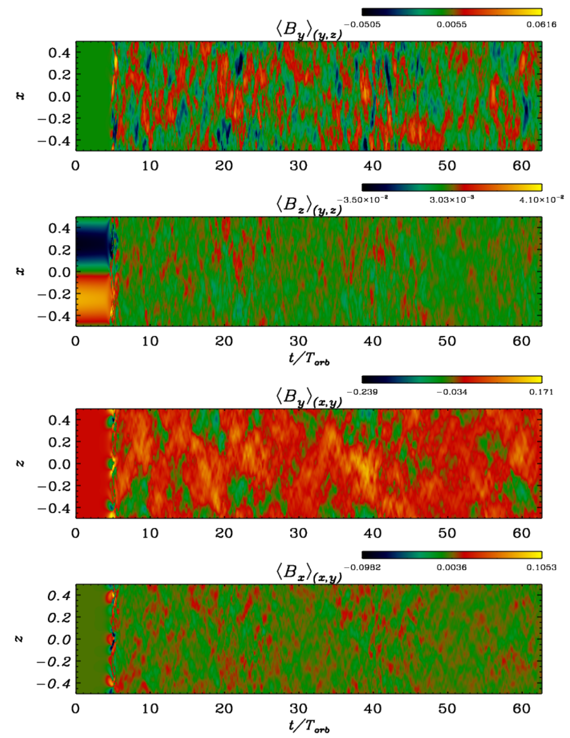

Figure 2: Here y-z and x-y averaged magnetic fields are shown on the left and right respectively. Top: the upper panel is for $\overline{B}_y(x)$ and the lower panel is for $\overline{B}_z(x)$. Bottom: the upper panel is for $\overline{B}_y(z)$ and the lower panel is for $\overline{B}_x(z)$.

To substantiate our findings, we evaluate the individual terms in the mean field equations (components of Eq. 1) for a given type of averaging and show which terms are responsible for the dynamo action in both early growth phase and the turbulent nonlinear regime. We find that in the MRI growth regime, the time derivative of the mean field is well matched by using only the spatial derivative of EMF terms in vertical averaging. Whereas in the case of horizontal averaging, the shear term ($S\overline{B}_x$) for $\overline{B}_y(z)$) also contributes. But in the nonlinear saturation regime, for both cases, the EMF term contributions dominate. We also find that the contribution from the stretching and advection terms involving only mean fields are always negligible. The results of vertical averaging compare well with the global simulations of EB16 [1], where the large scale fields arise entirely from the EMF.

3 Accomplishments: Evolution of the magnetorotational instability on initially tangled magnetic fields

Turbulence is needed to explain the accretion process, the inflow of matter on a central object, in astrophysical disks surrounding black holes and massive stars. Flow-driven magnetorotational instability has long been proposed to explain the transport of angular momentum in accretion disks. However, some initial seed magnetic field is needed to trigger this instability. The initial magnetic field in previous simulations has always been externally imposed, or had a significant system-scale component, even if stochastic. In a recent paper, we have considered the most realistic initial condition ever in the disk-dynamo literature. [3] Starting from a realistic state with velocity and magnetic field fluctuations (with no imposed field), through simulations and analysis we show and explain how self-sustained turbulence can evolve and provide the means for momentum transport and large-scale fields in disks.

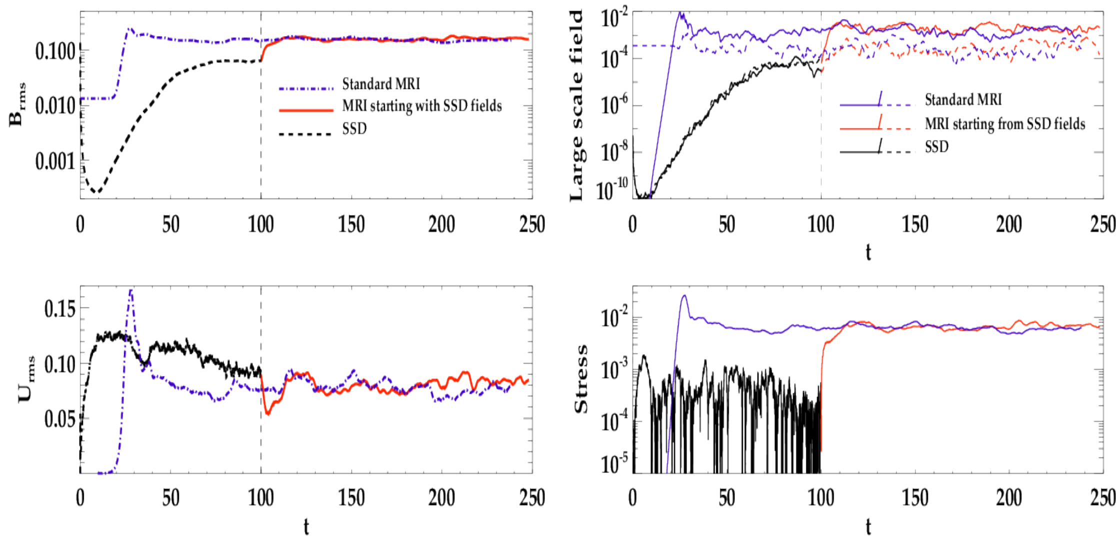

Figure 3: Evolution of $B_{\rm rms}$ and $U_{\rm rms}$ is shown in upper and lower left panels respectively for Run SSD, Run MRI starting with SSD fields (A0) and Run STD. Evolution of energy in large-scale magnetic fields and sum of Maxwell and Reynolds stresses is shown in upper and lower right panels for all three cases. The solid curves refer to x-y averaged fields while the dashed curves refer to y-z averaged fields. The Prandtl number, $\mathrm{Pr_M} = \nu/\eta = 10$, *and magnetic Reynolds number,* $\mathrm{Re_M} = U_{\rm rms}L/\eta = 12000$ *in all the simulations.*

We have shown via direct numerical simulations using Pencil code that the MRI can sustain MHD turbulence even when seeded with an initially random small-scale magnetic and velocity fields supplied by an SSD. In this case, the energy is strongly dominated by fields at small scales, implying that substantial power at low wave modes is not necessary for MRI growth.

There is however, still a minimum strength and coherence required for this growth that is determined by a comparison between the turbulent diffusion time and MRI growth time near the wave number of maximum MRI growth. When the latter time scale is shorter than the former, diffusion wins and the MRI does not grow. If the turbulent velocity forcing scale (a proxy for coherence) of initial fields is decreased or the field magnitude is decreased (by supplying an early unsaturated SSD state as an initial condition) then the fastest growing linear MRI mode moves to smaller scales where it has a harder time competing with diffusion. In short, if the initial coherence scales or strengths are too small, the MRI is quenched.

Simulations are performed in two stages using the shearing box code, the Pencil-Code in a periodic box of 1 : 1 : 1 aspect ratio. First, to obtain the initial condition, we run a simulation of the SSD, without shear or rotation, with an imposed isotropic stochastic forcing in the momentum equation. Second, the velocity and magnetic fields from this small-scale dynamo simulation (either from the kinematic or saturated stage), are introduced into a shearing box simulation as initial condition, with uniform shear $U_y = Sx$ (where S is the shearing rate) and rotation. The transition from SSD (stage 1) to the second stage (when forcing term in SSD is set to zero and shear and rotation are applied) is shown with a vertical dashed line in Fig. 3.

After the MRI takes over from the SSD supplied initial conditions, the saturated state of the magnetic and velocity fields in our simulations is essentially indistinguishable from that of the more commonly studied case of initial vertical fields of zero net flux (Standard MRI case shown in Fig. 4). In particular the saturated amplitudes of the total magnetic and velocity fields (magnetic field being dominant), the accretion stresses, ratio of Maxwell to Reynolds stress, and the magnetic and kinetic power spectra are all very similar for the two aforementioned initial conditions (Fig. 3). The azimuthal (B_y) component of magnetic fields from all three runs in Fig. 3 are also shown in Fig. 4. For Run SSD, most of the box is orange indicating weaker small-scale fields. The

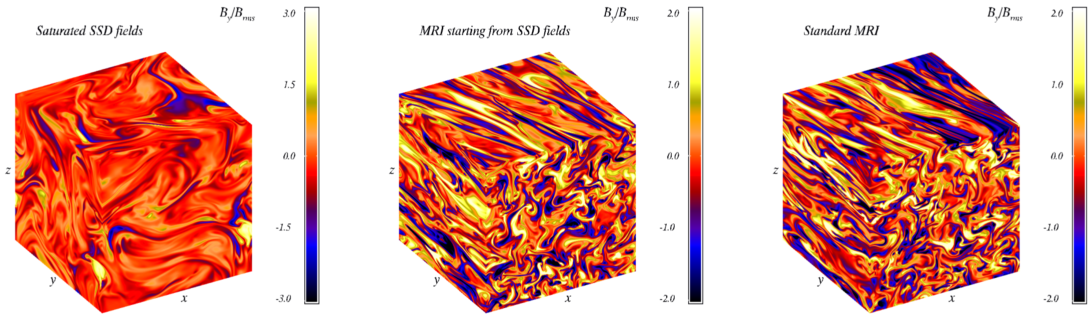

Figure 4: The azimuthal or B_y component of the magnetic fields are plotted for Run SSD, Run A0 and Run STD at high resolution of 512^3 *in left, middle and right panels, from the saturated regimes.*

scattered appearance of yellow or blue regions (both indicating higher magnitude fields) is due to the intermittency of the SSD. For the two MRI triggered runs, there are longer more coherent structures, particularly in the azimuthal direction, indicating the presence of large-scale fields. Also there are stronger small-scale fields as well, indicating higher contributions to Maxwell stresses compared to Run SSD. Note the characteristic vertical loopy structures (an MRI signature) in the x-z plane in both Run A0 and Run STD. Thus Run A0 and Run STD compare well **indicating that such simulations (with zero net flux) are independent of the respective initial conditions.**

Published articles in refereed journals supported by this grant:

[1] F. Ebrahimi and E. Blackman, "Radially dependent large-scale dynamos in global cylindrical shear flows and the local cartesian limit", MNRAS 459, (1422-1431) 2016.

[2] P. Bhat, F. Ebrahimi, and E. G. Blackman,"Large-scale dynamo action precedes tur- bulence in shearing box simulations of the magnetorotational instability" Mon. Not. R. Astron. Soc. 462, 818 (2016).

[3] P. Bhat, F. Ebrahimi, and E. G. Blackman, and K. Subramanian,"Evolution of the magnetorotational instability on initially tangled magnetic fields", Mon. Not. R. Astron. Soc. 472, 2569-2574 (2017).

Presentations at the conferences/workshops supported by this grant:

[1] P. Bhat et al. "The growth of Large-Scale Dynamo in shearing box simulations of the magnetorotational instability" presented at the APS-DPP San Jose, California (2016)

[2] F. Ebrahimi, Invited talk, "Shear-driven dynamos without the standard omega effect", invited talk at Dynamo Workshop at Princeton Center for Theoretical Science, Princeton, Dec. 7-9, (2015)

[3] F. Ebrahimi, How magnetic field is annihilated while being generated?", Invited speaker and the workshop leader at the APS Conference for Undergraduate Women in Physics, Princeton, Jan 14, (2017)

[4] P. Bhat, Invited talk,‘Large scale dynami in MRI simulations”at the Max-Planck-Princeton Center for Plasma Physics, Dec. 5-8 (2016)

[5] P. Bhat, Invited talk, “Large scale MRI dynamo” at the expanding universe of plasma physics May 2-12 (2017) in Les Houches (France)