White Paper for *Frontiers of Plasma Science Panel*

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	"X"
Oral	
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Title:	Large Scale Dynamos and Transport: Bridging the conceptual gap between magnetically dominated and flow dominated plasmas
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

Magnetic fields are observed to exist in astrophysical sources on all scales in the universe and explaining their origin comprises a set of long standing questions in basic plasma astrophysics. In particular the origin of large-scale magnetic fields, whereby the field emerges on temporal or spatial scales large compared to turbulent fluctuations has been a particularly engaging enterprise. While the interiors of astrophysical rotators are flow-dominated and much astrophysical dynamo theory has focused on these interior regions, the coronae of astrophysical rotators are magnetically dominated like laboratory fusion plasmas. The generation of large scale magnetic fields inside flow dominated rotators and the evolution of fields to larger scales in magnetically dominated coronae and in laboratory plasmas are all examples of magnetic field organization. All of these can also be classified as large scale dynamos when we define such as the amplification or sustenance of magnetic energy against exponential decay in a specified range of scales, independent of the source of energy.

All large scale dynamos in astrophysics and in fusion plasmas are conceptually linked through the importance of a turbulent electromotive force and via magnetic helicity evolution [1a]. Despite these unifying concepts, there has been a large gap between the fusion and astrophysical communities working on similar problems. Bridging the gap will foster progress in both communities.

Among the broad class of astrophysical rotators that show evidence for large scale magnetic fields are galaxies, stars, and accretion disks, the latter of which often possess collimated jets and x-ray

emitting coronae both likely the result of large scale fields [1b]. The source of large-scale magnetic fields could be the combination of a fossil field (from interstellar media) and field generated through dynamo action. There has been an extensive study of models in which large-scale magnetic fields are generated in situ from turbulence and sustained in the presence of dissipation (i.e. the alpha dynamo effect [1a,1b,2]). Tracking the topological properties of the magnetic field such as magnetic helicity, have shown promise toward helping to understand the large scale dynamo.

Large scale fields also play important roles in momentum and angular momentum transport. The need for enhanced angular-momentum transport has been a long-standing problem in accretion disks and laboratory plasmas. In velocity shear-driven flow systems, the magnetic field can trigger turbulence via the magneto-rotational instability (MRI)[3,4], which supplies Maxwell stress favorable to outward angular momentum transport in Keplerian flows. In magnetically driven systems, the field itself or the turbulence arising from current-driven reconnection (tearing modes) can transport momentum.[5] In either flow-driven or magnetically driven cases, the critical question arises as to how the turbulence driven by an instability (MRI or tearing mode) generates the measured large-scale fields. There is strong evidence from magnetically-dominated laboratory plasmas of RFP type [6], as well as simulations [7], that tearing instabilities play an important role in the relaxation process through the alpha dynamo effect. The measured alpha effect in these plasmas has been shown to convert one type of magnetic flux into another while a turbulent plasma relaxes to a state of minimum energy, subject to the conservation of total magnetic helicity [6 , 8]. As shown in these experimental studies, the magnetic helicity as a rugged invariant [9] has an important role on the dynamo effect.[10] The role of magnetic-helicity flux on the alpha effect has also been extensively studied in different dynamo studies.[11-14]

The fundamental direction we are advocating in this white paper is to foster the study of the dynamo problem from a unified perspective in both magnetically and flow dominated self-organized systems. We believe the community could strive for better understanding of the large scale dynamo mechanism by bridging efforts across laboratory and astrophysical contexts.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Magnetically dominated vs. flow dominated dynamos:

For both magnetically- and flow-dominated self-organized systems, the common questions are; What is the role of magnetic helicity as non-helical structures cannot produce dynamo? What is the primary mechanism for field amplification? What is the role of magnetic helicity fluxes in amplification? Could magnetic helicity fluxes sustain large-scale fields? What is the form of magnetic helicity fluxes in all these systems?

Examples of laboratory experiments: There is quite a good understanding of the MHD dynamo mechanism in magnetically dominated laboratory plasmas, such as the RFP, as stated above. However, a frontier is, to investigate the dynamo in the two-fluid regime. The astrophysically-relevant plasma laboratory experiments MPDX and PCX have been constructed to study dynamo and momentum transport from MRI and similar flow-driven MHD processes in a hot, weakly magnetized and fast-flowing plasma. These experiments offer unique opportunities for two-fluid and collisionless numerical studies of the MRI and flow-driven dynamos. [15-16] Global simulations in the Hall and MHD regimes have provided guidance and been necessary to obtain quantitatively reliable predictions for PCX, and in general for MRI plasma experiments. It was found that (a) the Hall effect is predicted to play a critical role for the onset of MRI in PCX, (b) two-fluid physics also significantly changes the nonlinear evolution and saturation of the axisymmetric MRI.

There are common characteristics between the two examples of tearing and flow-driven MRI dynamos. In both, 1) momentum is transported through fluid stresses, 2) the alpha effect was shown to have an important role in the self-organization, but is still under debate for the flow-driven case, and 3) effects beyond MHD are important in both but less studied. There are numerous problems for the flow-driven MRI dynamo not well understood, but more established for the tearing case. For example, 1) the saturation of flow-driven MRI, [17-19] the saturation in the tearing dynamo is through current relaxation, 2) the nature and the underlying dynamo mechanism is less understood in the simulations of flow-driven MRI.

Global vs. local treatment in the simulations

Despite recent progress in the study of flow-driven large scale dynamos in MRI simulations, we lack an explanation of the large scale dynamo mechanism in this context. Most of the existing theoretical and numerical studies of MRI-driven turbulence and large scale dynamo are based on the local approximation. [20-22] The simulation domain of the so-called shearing box consists of a local co-rotating patch of accretion disk, small enough to expand the MHD equations into Cartesian coordinates and ignore curvature terms. This simple model may provide insights into the mechanism that determines angular momentum transport in disks and the local approximation also has the advantage of requiring less computational resources compared to the global treatment. However, there are several important issues, such boundary conditions, the computational box size (limited scale), that have been raised by many authors over the validity of the shearing-box approximation for astrophysical disks. In addition, there is actually little evidence from these simulations that the MRI transport is dominated by small scales [1b,23]. It is therefore important to extend our understanding of the MRI turbulence by using also a global treatment as a complement. The averaging process may also be affecting the dynamo analysis in both local and global simulations and this should be further studied.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

Large scale dynamos comprise a set of cross-cutting problems in, plasma physics and astrophysics and understanding how they work is essential for understanding the origin of magnetic fields inside the flow dominated regions of astrophysical rotators as well as in the magnetically dominated coronae of these rotators. They are also essential for understanding the mechanisms and saturations of angular momentum transport in accretion disks. Large scale dynamos are also the key to understanding magnetic relaxation of laboratory plasmas in fusion devices.

The large scale dynamo problem is less studied in the regimes beyond MHD in both magnetically-dominated and flow-dominated plasmas. Since the flow-driven large scale dynamo has yet to be demonstrated in a plasma experiment, theoretical and numerical studies of this regime will be essential for progress. Theory and simulations that make predictions are necessary for both the understanding and the success of dynamo experiments.

While there have been conceptual advances in dynamo theory and simulations, there remain may frontiers, in particular, while tracking magnetic helicity evolution is now known to be an important principle for understanding how large scale dynamos evolve and saturate, the specific effects in a given context (i.e. their dependence on boundary conditions, initial conditions, flow profile of a given application) remains to be understood.

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