Turbulence and order in magnetized flowing plasmas

White paper for APS-DPP-CPP

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Continued observational discoveries of high energy emission and large scale jets from compact accretion flows, including those from black hole engines, highlight the fundamental role of magnetized plasma in explaining many of the most luminous sources in the universe. The engines of these high energy astrophysical accretors, along with stars and galaxies, also commonly show evidence for the contemporaneous presence of both turbulence and magnetic fields ordered on spatial or temporal scales larger than those of the fluctuations. Explaining this dichotomy has been a long standing challenge in basic plasma astrophysics across a range of sources. [1, 2] How such fields grow, given the presence of fluctuations, what are the relative dynamical influences of large vs. small scale fields, what are the best analysis methods, and what minimum ingredients for growth are needed [3, 4, 5, 6, 7, 8, 9, 10], and the role of magnetic helicity transport [11, 12, 13, 14] are all topics of active investigation.

Figure 1: Several types of physical dynamics, including instabilities and nonlinear coupling, could link the large scales to small scales. Fields themselves are all coupled at all scales, as plasma motions and flows make magnetic fields, and magnetic field annihilation through reconnection in disk coronae. The underlying physical mechanisms for generation of large-scale fields in disks, and the radial and vertical momentum transport, are interlinked. The magnetic stress spectrum produced in the disk can directly influence the fraction of energy dissipated within the disk (typically thermal) vs. above the disk (typically non-thermal).

Starting with any seed field, the generation and amplification of fields above some suitably defined forcing scale typical constitutes a "large-scale dynamo (LSD)." The turbulent amplification of fields at or below the forcing scales is referred to as "small scale" or "fluctuation" dynamo (SSD)

Large-scale ordered fields seem to be coupled with large-scale momentum transfer (in the form of jets and coronae) in the otherwise likely turbulent plasmas of astrophysical accretion disks. Small and large scale magnetic fields in astrophysical disks facilitate both the dynamics of angular momentum in disks via magnetorotational instability, as well as the formation and collimation of jets, and creation of flux ropes and particle energization by reconnection in disk coronae. The underlying physical mechanisms for generation of large-scale fields in disks, and the radial and vertical momentum transport, are interlinked. The magnetic stress spectrum produced in the disk can directly influence the fraction of energy dissipated within the disk (typically thermal) vs. above the disk (typically non-thermal).
and can be contemporaneous with the LSD.

**Turbulent small-scale vs large-scale dynamos:** Small-scale (turbulent) dynamo is usually driven due to random stretching of the magnetic field by the turbulent motions. This results in the generation of folded, intermittent (but not volume filling) structures (see Fig. 2). The SSD is likely to be important for the early generation of magnetic fields in stars and galaxies/interstellar medium (ISM). Such SSD generated fields would then be present in the plasma from stars or the ISM that could source accretion disks. LSDs however require special conditions in the underlying flow turbulence to be operational. The turbulence needs to break mirror symmetry for large scale dynamo action which can be accomplished by randomly forced helical turbulence, or large-scale shear flow with non-axisymmetric perturbation is needed.

In magnetically dominated flows of the laboratory, large-scale magnetic relaxation dynamos are directly triggered by a 3-D instability whereby small scale helical fields relax to large scale helical fields. A similar instability-driven onset of LSD also can occur in flow driven systems, and the MRI dynamo is such an example. Ordered fields resulting from LSDs are known to cause or contribute to the saturation of flow-driven turbulent transport in MRI unstable shearing sheet flows. The direct dynamo action due the MRI non-axisymmetric mode itself was first shown through quasilinear and computational calculations, and was demonstrated in 3-D global cylindrical simulations, as well as the exponential growth of LS fields in the early phase of local shearing box simulations with explicit resistivity was also revealed. This direct MRI LSD action has more recently been confirmed in simulations with a different code.

**Turbulent vs. ordered zonal flows:** Similar to the turbulent and ordered magnetic field structures, in flow-dominated plasmas, the flow itself could exhibit and develop structures and correlated transport properties (such as helicity) over a range of scales. In particular, nonuniform flows are ubiquitous both in nature and in the laboratory: they occur in atmospheres, oceans, stars, galaxies, pipe flows, and magnetically confined plasmas, etc. The problem of the onset and self-sustenance of turbulence in spectrally stable nonuniform/shear flows is a challenge for fluid/plasma dynamics research. In such flows, perturbations (of certain spatial characteristics) undergo only linear transient growth leading to short perturbation lifetime. The imperfect linear growth must be compensated by nonlinear positive feedback to repopulate transiently growing perturbations.
Subtle interplay of the linear transient and nonlinear processes can self-organize (chaotic or coherent) perturbations and ensure their self-sustenance. In short, the dynamical interaction of all scales, through the properties of turbulent cascades \[29, 30, 31\], as well as the generated ordered flows \[32, 33, 34, 35\] are essential for understanding the structures and properties of turbulent flows.

A variety of computational techniques and a hierarchy of physics models are needed to understand turbulence and the growth of ordered fields in flow-dominated astrophysical plasmas. Although the validity of physical models (collisional vs. collisionless) depends on the astrophysical context, there remains a need to compare basic physics models with converged numerical simulations in order to better inform practical models of e.g. accretion disks that can be used to compare with observations.

Due to the multi-scale nature of most flow-dominated astrophysical settings, a hierarchy of approaches is necessary and often beneficial. However, it is also possible to get locked into the limitations of a given tool which can bias or limit our understanding. For example, focusing on specifically "local" disk models has one set of limitations whilst fully "global" simulations has another. The same applies to specifically "multi-fluid" plasma models vs. say "gyro-kinetic" models.

For discovery through theory and computations, code-code comparison, physics model comparisons (for example varying ion Larmor radius in kinetic models and two-fluid models to find an overlap for these two models) should therefore be strongly encouraged. Below we discuss several examples where diverse computational approaches can be fruitful.

1- **Global vs. local computational models:** Much of the existing theoretical and numerical studies of the saturation mechanism of flow-driven turbulent media (and dynamo) are based on either (1) simple local approximations, such as shearing-box simulations, or (2) global simulations aimed toward real astrophysical systems. But intermediate complementary numerical approaches (without the complexity of full global simulations or the limitation of the shearing-box model) can be essential. The effect of boundaries (periodic vs. free or impenetrating boundaries) and simulation sizes (box size, for example), can be investigated. Such studies would help to identify the underlying physics and any possible dependence of physics results on the numerical method/domain.

2- **The need for hierarchy of physics models:** The enormous scale separation in astrophysics, as well as wide range of physical parameters (for example magnetic Reynolds number) necessitates a hierarchy of physical treatments for astrophysical settings. Basic models ranging from collisional to collisionless models, including single and two-fluid, particle, hybrid, and continuum Vlasov-Maxwell (and with including atomic and molecular, radiation, general relativity) should all be investigated. To assess the validity of the results, physics models should be validated against observational and experimental data. The correctness of the complex models should also be verified with reduced analytical models. Basic theory, code-code comparison, and validation against existing observational and experimental data, are the key to uncover the underlying physics in complex and multi-scale flow-dominated systems.
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