White Paper for *Frontiers of Plasma Science Panel*

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Title:	**Magnetic Self-Organization in Multi-Scale Astrophysical Plasmas**
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1. The Need to Move Beyond Ideal Magnetohydrodynamic Descriptions of Astrophysical Plasmas

Just as much of the progress in theoretical astrophysics from the last three decades was facilitated by a growing appreciation for the dynamical consequences of cosmic magnetism, the great successes of the next three decades will result from a detailed understanding of multi-scale plasma dynamics. Historically, the astrophysical community has invested much effort in understanding the role that meso- and macro-scale phenomena play in shaping the contents of the Universe. Just as magnetic fields were once considered a nuisance to be dealt with as a scalar addendum to hydrodynamics, the effects of plasma processes on the *microphysics* of the Universe are more often than not subsumed into multiplicative scalars that only slightly augment the well-known fluid equations. *It is becoming increasingly clear that these gross simplifications are often not even qualitatively correct; in these days of modern astrophysics, they obfuscate what is otherwise a scientifically rich phenomenology of microphysical plasma behavior.* This white paper leverages recent advances in our understanding of multi-scale astrophysical plasmas to motivate and support a call for investment in code development, supercomputing facilities, and inter-mediate-scale laboratory experiments focused on basic plasma physics relevant to astrophysical systems.

Let us be more specific. Some of the most important astrophysical systems — protoplanetary disks, the intracluster medium (ICM) of galaxy clusters, radiatively inefficient black-hole accretion flows — are characterized by densities, temperatures, and degrees of ionization that place them well outside the ideal magnetohydrodynamic (MHD) limit:

- The gas in protoplanetary disks ~10 au away from the central protostar is characterized by densities ~10^{12} cm^{-3}, temperatures ~100 K, magnetic-field strengths ~0.1 G, and degrees of ionization ~10^{-10}; this

allows non-ideal processes — Ohmic dissipation, ambipolar diffusion, and the Hall effect — to impact the disk dynamics by decoupling the bulk fluid from the magnetic field on a range of scales.

- The temperature in the diffuse ($n \sim 0.005$ cm^{-3}) ionized ICM is measured in keV, which, when coupled with observed magnetic-field strengths ~1 μG, gives an ion Larmor radius ~10^{12} times smaller than the collisional mean free path; this renders the transport properties of the ICM highly anisotropic with respect to the magnetic-field direction and, in doing so, significantly impacts the stability of the ICM.
- The collisional mean free path of the ~keV gas orbiting the ~10^6 solar-mass black hole at the center of our Galaxy is comparable to the accretion radius; this allows for non-Maxwellian distribution functions, whose associated viscous stresses can contribute a significant fraction of the angular-momentum transport required to drive mass accretion.

Despite their wide range of characteristics, these systems have one essential thing in common — they are all *multi-scale plasmas, whose micro-scale properties play a vital role in dictating what macro-scale dynamics is allowed*. The frontier of plasma astrophysics is to treat them as such. To do so requires an investment in new tools and resources to elucidate and analyze this multi-scale behavior.

In what follows, we describe some recent progress related to magnetic self-organization in multi-scale astrophysical plasmas, garnered from adopting the philosophy espoused above, and use these results to motivate which investments we believe are necessary to advance the field.

2. Recent Advances and New Frontiers in Understanding Multi-Scale Astrophysical Plasmas, or How Macro-Scales Adapt to Accommodate Micro-Scale Constraints

Astrophysical plasmas are subject to a wide range of instabilities, which generically lead to sustained turbulence. This is because gravity has a way of setting up and maintaining free-energy gradients in the face of diffusive transport, whether molecular or turbulent. In some situations, however, the plasma finds a way to shut off its access to the source of free energy, usually by re-organizing its magnetic field in some clever way. Here we offer three examples of how this plays out.

We first consider protoplanetary disks, which are dense, cold, and poorly ionized. The latter property casts doubt upon whether the most promising mechanism for enhanced angular-momentum transport in accretion disks, the magnetorotational instability (MRI; [1]), is capable of driving the observationally inferred mass-accretion rates in these systems [2]. Not only are the most potent sources of ionization (e.g., cosmic rays, stellar X-rays, UV radiation) shielded over significant portions of these disks, but also the presence of dust grains is anticipated to remove an appreciable fraction of the charge from the gas phase [3, 4]. Much of the work on this topic has thus focused on assessing whether such disks are magnetically coupled across their full radial and vertical extents at the level required to sustain magnetorotational turbulence [5, 6], the generic outcome of the linear magnetorotational instability [6].

Recent work has shown that, at radii ~1-10 au in typical protoplanetary disks where the Hall effect is the dominant non-ideal process, the MRI saturates not in fully developed turbulence but in a relatively quiescent state exhibiting large-scale, long-lived, axisymmetric ("zonal") structures in the magnetic and velocity fields [7; Fig. 1]. Their emergence — a result of the anti-diffusive nature of the Hall effect when the Maxwell stress increases with magnetic-field strength — reduces the turbulent transport by at least two orders of magnitude from extrapolations based upon resistive MHD, a result that calls into question contemporary models of layered accretion [8]. Simply put, the new degrees of freedom engendered by the Hall effect allow the magnetic field to self-organize and thereby access a different saturation channel.

Our second example concerns the "cool cores" of galaxy clusters, in which the observed temperature decreases in the direction of gravity due to strong Bremsstrahlung cooling [9]. Such inverted temperature profiles have been shown to be buoyantly unstable when the magnetic-field lines that thread it conduct heat down the temperature gradient [10, 11]. However, rather than drive vigorous convective turbulence, this heat-flux-driven buoyancy instability saturates by reorienting the conducting magnetic-field lines perpendicular to the gradient, insulating the plasma from the available source of free energy [12-15].

Third, and finally, we turn to radiatively inefficient black-hole accretion flows, the canonical example being that around our Galactic center, Sgr A*. The MRI is expected to drive turbulence and its consequent enhanced angular-momentum transport in this environment, despite the collisionless conditions. In fact, the MRI can even be strengthened by the departures from velocity-space isotropy that are allowed in such

a plasma [16, 17]. This is because the observationally inferred magnetic field of ~1 mG is more than sufficient to magnetize the plasma, thereby introducing a directional bias in these departures that leads to anisotropic "viscous" stresses [18]. These macro-scale stresses are, however, limited by micro-scale kinetic processes — firehose, mirror, and the like — which place stringent constraints on the allowed departures from velocity-space isotropy in the plasma distribution function [19, 20]. These constraints, dependent upon the plasma beta parameter (estimated to be ~10 in this particular system), can be satisfied in one of two ways: (1) the plasma produces electromagnetic fluctuations at scales comparable to the gyroradii of the particles, leading to wave-particle interactions that work to "scatter" the distribution function back to a stable configuration [21]; and/or (2) the magnetic field reorganizes itself so as to minimize the production of velocity-space anisotropy [22-24]. Both processes, having recently been identified in dedicated kinetic numerical simulations [25, 26], have implications for the growth and structure of large- and small-scale magnetic fields in the Universe [27].

All three examples given here necessitate an understanding of multi-scale plasma physics and the interplay between MHD and kinetic scales that currently lies at the forefront of theoretical astrophysics.

3. Tools of the Trade and What is Needed to Advance the Frontier

It is generally the case in the study of astrophysical fluid dynamics that, with a few notable exceptions, physical insight and analytical calculations precede numerical simulations. This is understandable — developing suitable, stable, and accurate numerical integration algorithms and finding large supercomputing facilities on which to run them tends to be more time-consuming and much more expensive than any pencil-and-paper calculation. But this is true only to a point.

Right now, the astrophysical fluid dynamics community has found itself without precise knowledge of what equations to actually solve in modeling many of the aforementioned systems. This stems from the usual closure problem, exacerbated in these systems by the wide range of physical processes occurring below, at, and above kinetic scales. To make progress, the most straightforward solution would be to leverage the powerful electromagnetic particle-in-cell (PIC) codes [28] that are becoming more prevalent nowadays to conduct first-principles simulations and thus guide theoretical progress by numerical means. The advantage of such codes, of course, is that they rigorously solve for everything: Debye-scale plasma oscillations, Larmor-scale physics, electromagnetic wave propagation, collective macro-scale dynamics, etc. But this is also a disadvantage. The expense entailed in capturing all of these processes more often than not demands a reduced speed of light and/or a depressed ion-to-electron mass ratio, corrupting the scale hierarchy and entangling physics that ought to be spatially and temporally well-separated. A hybrid-kinetic approach, in which the electrons are treated as a fluid while the ions are handled kinetically, obviates many of these sacrifices and is thus often employed [29-31], but is ignorant of electron-scale physics that is crucial for determining, e.g., the differential heating of ions and electrons that is of fundamental importance to interpreting the emission from astrophysical objects.

These practicalities taken into consideration, we recommend the following. First, **code development**. Flexible numerical codes should be developed that allow the user to switch between different physical treatments — e.g., kinetic ions and fluid, drift-kinetic, or gyrokinetic electrons; MHD fluid plus kinetic energetic species; etc. Such codes ought to be made publicly available, so as to reduce duplication of effort and maximize output, and should leverage the investments that national supercomputing institutions have made in co-processors to speed up computations intensive in floating-point operations (e.g., PIC codes). Second, **supercomputing facilities**. Current annual allocations on most national machines (e.g. those facilitated by XSEDE) are measured in millions of CPU-hrs. The exception is NASA's INCITE program, for which typical allocations are ~100M CPU-hrs. What is notably absent from the domestic program are mid-level allocations (~10-50M CPU-hrs); current small-scale allocations may be enough for routine fluid simulations, but not for kinetic ones. Finally, **intermediate-scale laboratory experiments** focused on basic plasma physics relevant to astrophysical systems are badly needed. There is no substitute for being able to create a plasma in a lab, subject it to stirring, differential rotation, magnetic fields, and measure its response. Laboratory plasma experiments in poorly ionized plasmas or weakly collisional (i.e. ion Larmor radius < machine size) plasmas with ß > 1 would be particularly useful. Universities are a natural venue for these sorts of experiments [33], which are larger than a typical single-PI experiment but do not require a major national facility. A program for continued funding operations of these facilities should also be instituted, with accompanying university training of plasma students borne in mind.

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Figures (maximum 1 page)

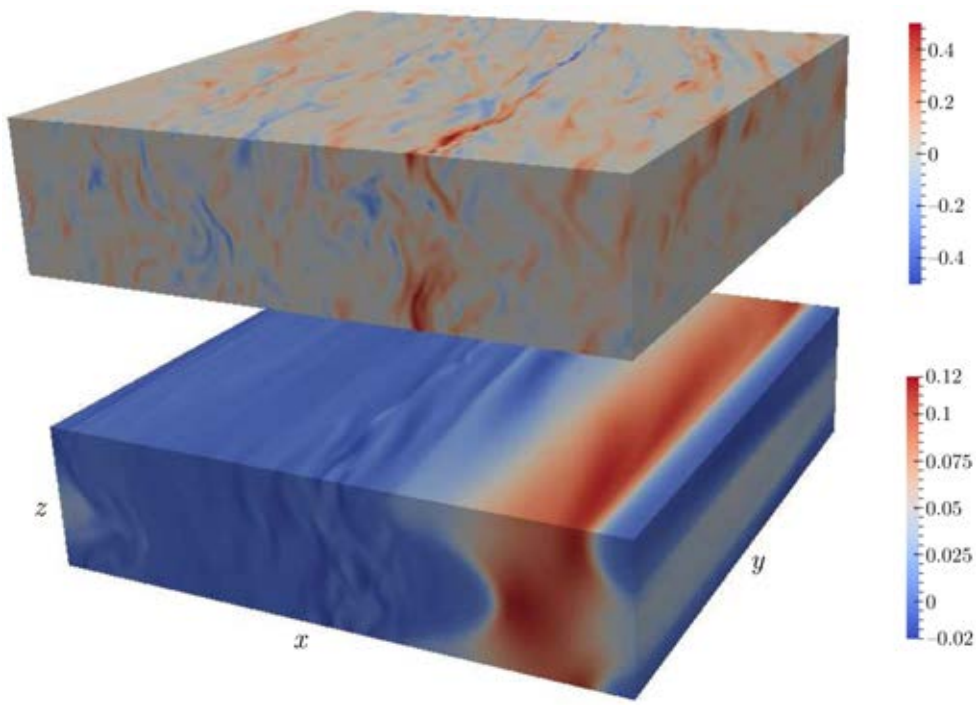

Fig 1. Snapshots of the vertical magnetic field field in the saturated state of the magnetorotational instability in (*top*) ideal MHD and (*bottom*) Hall-MHD [8]. The *x*, *y*, and *z* axes correspond, respectively, to the radial, azimuthal, and vertical dimensions in a local co-rotating patch of a protoplanetary disk.