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Title:	**Plasma Dynamos: A Comprehensive Program to Understand How and Why the Universe is Magnetized**
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Introduction. Magnetized plasma exists nearly everywhere in the universe and understanding the origin of the magnetic fields may be essential for understanding almost every astrophysical systems. Magnetic fields likely govern accretion, star and planet formation, stellar evolution, cosmic ray acceleration, jet formation, and indeed may even be responsible for life itself by shielding the Earth from radiation and even, possibly, for establishing the chirality of DNA.[1-6]

A magnetic dynamo is a set of mechanisms that converts mechanical energy into magnetic energy, and sustains the magnetic field against dissipation.[7-9] Dynamos produce the ordered, in some cases cyclic, magnetic fields observed in stars, galaxies, accretion disks, and jets, as well as the disordered fields of stellar convection zones, the interstellar medium and in galaxy clusters. In all of the observed cases, magnetic fields have energy densities that are comparable to kinetic-energy density of the plasma motions: this means that (i) they are always dynamically important and so are essential players and that (ii) we are observing some form of saturated state, sustained by the motions, rather than a transient moment in the middle of a long history of continuous amplification. Understanding the origin of these fields, and being able to predict the dependence of their properties on the host system, are necessary to understand important aspects of stellar and galactic structure and evolution, and the nature of accretion. There also is a practical reason to study dynamos: the solar dynamo underlies solar magnetic activity, which drives space weather and affects the Earth's climate.

Astrophysical plasma dynamos are almost always flow-dominated: gravitationally or thermally driven

plasma flow is the main energy reservoir. This is in contrast with most laboratory plasma experiments that are usually magnetically-dominated. In accretion disks, disk galaxies, and some stars, differential rotation is the predominant form of kinetic energy. However, axisymmetric differential rotation is not sufficient for sustaining the field. In most models of dynamos, small-scale turbulence provides additional induction, that allows the large scale magnetic field to regenerate. The source of this turbulence can be due to a host of mechanisms include, convection, supernovae, or essentially non-linear magnetic turbulence in which the magnetic field itself is necessary to create the turbulence that then regenerates the magnetic field.

Astrophysical dynamos are self-organized systems, with multiple processes intertwined at multiple scales governed by geometry, boundary, interfaces and inhomogeneities that define each system. Two examples of important dynamo systems are (1) the Disk-Jet-Lobe System composed of gravitationally bound disk plasma, in which a self-generated magnetic field catalyzes accretion, ultimately expelling angular momentum in the form of magnetized plasma through axial jets that terminating in a diffuse plasma and (2) convection driven stellar dynamos composed of convectively unstable turbulent and differentially rotating stellar plasma, magnetized chromospheres, advection of field by solar wind into Parker spiral.

The scientific challenge is to first use experiment and theory to understand the processes and parts in isolation, including the non-linear couplings between processes, and then stitching the various parts together to discover how new self-organizing phenomena that emerge. We argue that understanding astrophysical dynamos, nothing short of discovering "How magnetic fields are created in the Universe," requires understanding this integration. No question is more compelling in the field of plasma astrophysics.

The ultimate proof of our understanding of dynamos will be whether we can explain and even predict the measurements (laboratory or astronomical) from first principles. Amazingly, at this time, no predictive theory exists which can explain the properties of any astrophysical plasma dynamos. Even the well-known 22 year solar cycle period cannot be theoretically predicted.

Major Scientific Challenges

1. Buildable Kinematic Dynamos. The most basic formulation of the dynamo problem involves finding flows which have a linear, growing magnetic instability. Dynamo onset is understood in terms of a critical magnetic Reynolds number dependent only upon the properties of the flow. Theoretical studies of the past have studied ad hoc flows that are not necessarily solutions to the Navier-Stokes equation. Finding flows that can be realized in both laboratory and astrophysical systems, with the constraints of geometry and boundary conditions is a both a theoretical and experimental frontier.[10-12]
2. The Small-scale or Fluctuation dynamo. Dynamos are often classified, as large-scale or small scale depending upon whether the magnetic field develops on scale similar to or greater than the spatial scale of the driving flows. The mechanism by which magnetic energy at small-scales is generated is believed to be well understood theoretically (chaotic stretching of fields lines), but the understanding of saturation and the material properties (viscosity, thermal conductivity) of resulting magnetic turbulence is a major frontier.[13-15]
3. Large-scale magnetic fields. Small-scale dynamos tend to generate magnetic energy but little net magnetic flux, whereas large-scale dynamos generate both net flux and energy. Discovering how a large-scale field self-organizes from small-scale magnetic and velocity fluctuations in astrophysical systems is a grand challenge for plasma astrophysics. [16-21]
4. Essentially Non-linear Dynamos. In another important class of dynamos, the magnetic field plays a key role structuring the feedback mechanism in the flow. Such subcritical dynamos have no kinematic regime and operate only at finite amplitude of the magnetic field. The magnetorotational instability (MRI) invoked to explain turbulent transport in accretion disks is a notable example.[22,23] The energy

equipartition between magnetic fields and kinetic turbulence in galaxies and clusters suggests that these dynamos have reached nonlinear saturation.

5. Heterogeneous Dynamos and Flux Transport. Real dynamos (as opposed to idealized mathematical models) are always spatially heterogeneous and the specific mechanism of field self-generation may rely upon poorly understood interactions between disparate parts. For example in the solar dynamo, toroidal flux is likely generated near the tachochline through shear of a poloidal field, while the regenerated poloidal field may be occurring in the convection zone or even at the solar surface.[24-27]
6. Boundary Conditions and Interfaces. Dynamos in Nature interact with the surrounding media in profound and poorly understood ways. These interactions may govern the process by which self-generation occurs. Several examples include the ejection of magnetic helicity at solar or disk surfaces through flares[28-30]; the small scale dynamo heating of the solar corona and launching of stellar wind; the launching of magnetized solar wind and jets, which carry away angular momentum from the central dynamo.[31,32]
7. Plasma Dynamos. Diffuse plasmas (such as disk or cluster plasmas) that are sufficiently collisionless will exhibit important plasma effects not described by standard MHD treatments, including two fluid effects (Hall), pressure anisotropies that govern viscosity and heat transport, compressibility effect. Such plasma is often subject to neutral interactions which affect the dynamics as well. It is likely that there are new mechanisms for magnetic field generation uniquely associated with plasmas when beta>1 and when the plasma is collisionless and anisotropic pressure can develop. [33-38]
8. Exotic Dynamos. Dynamos also exist in more extreme astrophysical environments,[39] like those found in newly born neutron stars,[40] generally believed to be produced by an MHD dynamo, but driven by neutrino-powered convection during the first few seconds of the star's birth although magnetorotational turbulence dynamos are also a possible explanation. How these processes work under the extreme conditions of baryonic matter at nuclear densities combined with relativistically hot photo-leptonic (electron-positron pairs and photons in thermodynamic equilibrium) is very poorly understood. One of the most important challenges is to explaining the great dynamic range of magnetic field strengths observed in neutron stars: from a mere 10^9-Gauss fields inferred in old, recycled millisecond pulsars, to 10^{12} Gauss in "normal" neutron, to mind-boggling 10^{15} Gauss magnetic fields in so-called magnetars.[41] Interestingly, magnetic fields in magnetars exceed the critical quantum magnetic field $B_Q \sim 4\times10^{13}$ Gauss; if this is the case, quantum effects must the included in the equation of motion of the fluid. *Quantum turbulence* in presence of magnetic fields is basically unexplored.[42]

Approach. The scope of this problem is extremely broad and, perhaps, the most important unsolved problem in plasma astrophysics. Moreover, plasma physics as a discipline has the foundations and the sophistication to address the critical issues holding up a complete understanding, ranging from deep understanding of MHD, two fluid, kinetic, and the necessity of addressing system physics (all experiments are systems)---indeed many plasma physicists are already working in this area. We believe the importance of this problem and the skill-set match to plasma physics, justifies an ambitious multi-institutional program of theory, observation and experiment to bring this to understand how magnetic fields are created in the Universe.

Observations. Astrophysical observations are now providing unprecedented measurements of the 3D magnetic and velocity fields that make up astrophysical dynamos and this makes up a Frontier if astronomy. During the next decade upgraded and new facilities [LoFAR, JVLA, ALMA, NG-VLA, SKA] will provide unprecedented information via polarization (angle and percentage) and Faraday rotation on the magnetic field structures in galactic disks,[43] jets/lobes, and even even the magnetic fields of the intercluster medium plasma.[44-47] These new observations will be producing more detailed maps of galactic fields and will be used to detect galactic magnetic fields from earlier cosmic times. Interactions between magnetic fields plasma flow and cosmic ray are also now being probed.

Remote observations of solar and stellar magnetic fields are also coming into a new era. NASA's Solar Dynamics Observatory (SDO) in 2010 is providing high-resolution, high-cadence data on the structure and evolution of magnetic fields in the solar photosphere and corona.[48] The DKIST telescope now being built in Hawaii will be capable of even higher spatial resolution, and provide data on the coupling between small and large-scale dynamo action. These magnetic observations complement ongoing ground-based and space-based monitoring of solar internal dynamics by means of helioseismology, [the GONG network of telescopes]. Asteroseismic (Kepler) and spectropolarimetry is also being applied to investigate the strength and topology of magnetic fields in other stars, greatly enriching our understanding of how dynamo processes depend on stellar type and rotation rate[49-51] and new telescopes are being developed in this area [SPIRou]. Finally, NASA's upcoming Solar Probe plus mission will probe the Alfvén radius interface region of our own sun and will provide the first ever measurements of the region where the flow-dominated solar wind meets the magnetically dominated solar corona.

Theory and Numerical Simulations. Two major modeling efforts make up a Frontier that could see major progress during the next decade: ***System and multi-scale, multi-physics modeling*** and ***kinetic modeling of plasma dynamos.*** A key component of this modeling effort could be a serious validation effort comparing experiment to simulations, especially with regards to sub-grid models and interface dynamics.

Stellar Dynamo Systems. The solar dynamo is perhaps the most familiar and the most closely scrutinized example we have of magnetically self-organizing system on an astronomical scale. Photospheric observations clearly reveal the turbulent, chaotic nature of solar convection and small-scale magnetism as well as the striking regularity of the 11-year solar magnetic activity cycle. Yet, despite ongoing scrutiny, the fundamental physical mechanisms that establish and sustain the periodic solar activity cycle of its large scale field are still not well understood. We believe that a major computational frontier during the next decade will involve multi-scale modeling (such as LES) that couple the disparate physics of the radiative zone (including inward diffusion of both magnetic field and rotation), the tachocline (where large scale toroidal fields believed to be generated), the convection zone, flux emergence into the photosphere and ultimately angular momentum loss to the solar wind. [27,52,53]

Galactic dynamo systems pose a unique set of challenges. There is observational evidence for coherent magnetic fields on scales of several thousand light years, but kinetic forcing occurs on scales of tens of light years. [2,54] Material is constantly added to and removed from galactic disks, and is distributed extremely inhomogeneously, with densities ranging from $10^{-3} - 10^{5}$ cm^{-3} and temperatures ranging from $10 - 10^{6}$K.[55] Relativistic cosmic ray particles provide pressure comparable to thermal pressure, and there is evidence for density and velocity fluctuations on spatial scales down to the proton gyroradius. Most of the kinetic energy is in differential rotation. Understanding the mechanisms responsible for generating, removing, and organizing galactic magnetic fields–and accomplishing this before the Universe had reached a tenth of its present age–will require integration of basic dynamo theory with the special features of galaxy geometry and gas content.

An astrophysical *disk-jet-lobe (DJL) system* [powered by, for example, a supermassive black hole (SMBH)] is the final example of large-scale dynamo process that requires the system and multi-scale modeling. The multi-scale and multi-physics nature of DJL systems has rendered system-level integration necessary. Gravitational energy of matter falling into the SMBH is converted to kinetic energy of flows inside the accretion disk, some of which is then converted via dynamo to magnetic energy that facilitates both the accretion of plasmas unto SMBH via turbulent angular momentum transport and the formation of large-scale, organized magnetic fields. The dynamo then leads to the formation of powerful magnetized jets, which stay undisrupted for up to $\sim 10^{6}$ light-year (but develop dynamical instabilities). Magnetic

energy carried by jets is further converted to accelerate plasmas to extraordinary energies, likely via both magnetic reconnection and shocks. We believe that substantial progress can be made if we will view DJL systems as a sequence of linkages of several components, e.g., connections between disk and jet, jet and lobe, lobe and wider intergalactic medium, and particle acceleration and radiation, etc., where studies of individual components are initialized and affected by how the previous and subsequent stages evolve. A concerted joint effort among observations, laboratory experiment, theory and numerical simulations can then be combined to address these challenges.

Plasma dynamo modeling and theory. The multi-scale nature of plasma dynamo presents conceptual challenges that are more serious than the constraints of numerical resolution and analytical tractability that traditionally plague fluid (MHD) dynamo theories. Indeed, at the time of writing, the only known set of equations that are guaranteed to rigorously describe plasma dynamos are the Vlasov-Maxwell set; suitable closure model do not yet exist since which can properly address the range of physical processes occurring below, at, and above kinetic scales. Simultaneously addressing electron and ion scales with full kinetic codes in untractable. The compromise we endorse is the hybrid-kinetic treatment, in which electrons are treated as a fluid while momentum-carrying ions are handled kinetically. Validation efforts would be greatly facilitated if a flexible, publicly available, hybrid-kinetic code (whether Eulerian-grid or particle-in-cell), equipped with particle-particle collisions and geometrical flexibility was available to the astrophysical as well as experimental plasma physics communities.

Experiments. To study dynamos in the lab requires flow-dominated high magnetic Reynolds number flowing plasma (hot, big and fast flowing) that have are quasi-stationary for many resistive decay times,[56-58] This regime is very different than exists in most laboratory plasmas. Flow-dominated plasmas do exist in HEDP experiment, but there are limitations in these experiment that come about due to their intrinsically transient nature.[59-61] During the next 10 years, it appears tractable for plasma experiments (both confined and HEDP based) to address kinematic dynamos,[62] small-scale dynamos and their dependence upon magnetic Pm,[12,63] begin to address how large scale magnetic fields can be created in flows that have both a small scale dynamo and large scale shear. Interfaces between magnetically dominated and flow-dominated plasmas mimicking the centrifugal launching of winds or jets also appear feasible,[64,65] and important information about the role of helicity and its transport across boundaries can be investigated. Plasma experiments in both spherical and disk geometries are now being pursued and will be operational during the next several years.

Facilities are needed that can:

1. To study dynamos requires creating **flow-dominated** ($M_A \equiv V/V_A \gg 1$) plasmas with **large magnetic Reynolds number** ($Rm = \mu_0 \sigma V L \gg 1$). New techniques are required to (1) confine and heat large unmagnetized plasma, (2) to control the large-scale flow (and flow shear), and (3) to inject/control small-scale turbulence. Ideal experiments would long pulse and **quasi-stationary** on the time scale for magnetic field growth. Independent control of Re and Rm would allow both diffuse and dense dynamos to be investigated.
2. **Buoyancy experiments** (either convectively driven, or magnetically driven) with/or without rotation could have a large impact on understanding specific mechanisms in stellar dynamos.
3. **Interface experiments.** New experiments are needed which can investigate how magnetized plasma interacts with its surroundings, and in particular how plasmas transition from magnetically dominated to flow dominated and vice versa. This would include experiments mimicking: **flux ejection** of CMEs into background plasmas; **centrifugally launched winds and jets** where magnetically dominated plasma launch flow-dominated winds and jets; **magnetic lobes** where magnetized plasma is confined by external pressure.

4. **Plasma dynamos**. To study the role of ion pressure anisotropy on magnetic field generation (hot accretion disks and ICM plasmas), a concept is needed that can create a turbulent flow-dominated (M_A>1) with $\beta \geq 1$ with magnetized and collisionless ions (ρ_i<<L, $\nu_{ii} \ll \Omega_i$). In a broader sense, **turbulence experiments near equipartition**, both with and without guide fields are needed.
5. **Exotic Plasmas with Magnetic Fields.** In the next decade, in laboratory experiments will be created where the density of matter in the flow can reach conditions such that the Fermi energy of the electrons/ions become comparable to their thermal energy (e.g. at the National Ignition Laser facility during Mbar capsule compression experiment) comparable to the cores of neutron stars. Similarly, pair-plasmas may also be realizable.

Figures

Figure 1. Astrophysical dynamo systems exist over an enormous range of scales, include both diffuse and dense plasmas, and are always complex systems.

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