1. Dynamos: The Draft

1.1. Introduction

An astrophysical dynamo is a set of mechanisms which convert mechanical energy to magnetic energy, and/or sustain the magnetic field against dissipation. Dynamos can occur in stars, galaxies, galaxy clusters, accretion disks, and jets. Characterizing dynamos theoretically, observationally, and experimentally poses a grand challenge that is linked to other topics in plasma astrophysics.

The study of astrophysical dynamos arose from observation of the 22 year solar magnetic activity cycle and the less regular but also fluctuating geomagnetic field. The behavior of these magnetic fields, which could not be explained by Ohmic dissipation alone, together with early work by Cowling and others disallowing dynamos with a high degree of spatial symmetry, led Parker (1955) to formulate a picture of astrophysical dynamos based on two types of flow: large scale shear (such as differential rotation), and small scale turbulence (such as thermal convection). Shear amplifies the toroidal field by stretching - the ω effect, and imparts kinetic helicity to the turbulence. Turbulence converts toroidal field to poloidal field by twisting - the α effect-, and enhances the dissipation rate over the Ohmic rate- the β effect. The ω and α effects, work on two or more spatial components of the field, allowing it to grow exponentially. The β effect suppresses the growth of magnetic energy at small scales. It, or some other source of fieldline breaking, is also necessary to amplify the field irreversibly.

Parker's treatment was formalized in the 1960's by Krause, Rädler, Steenbeck, and others as a mean field theory. Originally, the theory was kinematic: flows were prescribed and any back reaction of the magnetic field upon them was ignored. Later, various models for reduction of α and β, by magnetic feedback were introduced, allowing the magnetic energy to saturate.

In the 1970s, an α effect was identified in a plasma confinement experiment called a Reversed Field Pinch (RFP). In the RFP, the α effect converts poloidal to toroidal field, and the toroidal field is sustained for longer than a resistive time. Data analysis, theory, and numerical modeling have shown that the α effect in the RFP is produced by a small number of current driven, global instabilities rather than fully developed small scale turbulence. Flux conversion is also seen in Spheromaks, and during sawtooth crashes in Tokamaks, and represents the tendency of the system to relax to a preferred state. Relaxation in the RFP was first explained theoretically by Taylor.

Dedicated laboratory experiments on flow driven dynamos were carried out in liquid metals beginning with an experiment in Riga and continuing with facilities in Cadarache, France, U. Maryland, and U. Wisconsin. These experiments demonstrate the effect of fluid rotation and turbulence in incompressible fluids at low magnetic Reynolds number Rm, and represent an ongoing opportunity to test dynamo theory and numerical modeling.

Serious challenges to mean field dynamo theory arose in the 1990s as a result of observation, theory, and numerical simulations. The solar interior differental rotation was reconstructed using the techniques of helioseismology and found to be constant with radius instead of constant on cylinders, as had been theoretically predicted. The ω-effect associated with the observed rotation profile, used in the mean field dynamo equations, predicts that toroidal flux should migrate away from the equator, the opposite of what is observed in the Sun. On the theoretical side, analysis of the mean field equations themselves and direct numerical simulation predicted that most of the energy in the magnetic field should lie at much smaller scales than observed in stars and galaxies.

The aforementioned challenges and concerns about large scale dynamo theory highlighted both the lack of a theory of nonlinear saturation and the absence of fully nonlinear MHD simulations to test and gauge such theories. But progress toward a nonlinear theory with predictive power has emerged in the past decade via a symbiosis between analytical and numerical work, only a small amount of which can be described here.

One line of development is based on following the flow of magnetic helicity, which describes the linkage of magnetic fieldlines and is conserved in magnetically closed, highly conducting systems. The equations of standard mean field dynamo theory, however, do not properly conserve magnetic helicity. A modified theory, which couples turbulent kinetic helicity and the evolution of small scale magnetic helicity to the evolution of the large scale field is able to predict the growth and saturation of large scale field seen in some numerical simulations. The theory also predicts that unless small scale magnetic helicity can be ejected from the system, the growth of the large scale field becomes very slow. Further work is needed to understand the transition to slow growth and to assess the role of boundaries in real astrophysical systems. The role of kinetic helicity itself, although it is essential to the α effect, remains an open question, as turbulence without kinetic helicity, combined with large scale shear, also appears to be able to generate a large scale magnetic field.

Essentially nonlinear dynamos, in which the magnetic energy field is always strong enough to affect the flow and contains enough free energy to drive instability, represent another approach to describing the saturated state. A simple, self consistent model based on flow shear and magnetic buoyancy provides an example of how a steady state, cyclic dynamo could operate. Further work is needed to show whether such dynamos can exist when turbulence is present, and how the models can be extended to astrophysical situations.

Finally, a new semianalytic tool for exploring the statistical properties of magnetic fields generated by small scale dynamos in their kinematic stage, for a very wide range of fluid parameters and turbulent spectra, was developed based on the Kazantsev model. Although linear, this method has been useful for interpreting numerical simulations, and is helping to guide both theory and experiment.

The study of astrophysical dynamos today is rife with opportunity. Important ingredients involved in building and sustaining such fields - large scale shear, stratification, or other symmetry breaking effect, small scale turbulence, and efficient mechanisms for field dissipation and transport - have been identified, but much work remains to be done. Some important outstanding problems in astrophysical dynamos are

- What determines the magnetic power spectrum: What allows fields to grow on scales larger than the forcing scale? Are large scale instabilities important in astrophysical dynamos? How is the the magnetic spectrum related to the velocity spectrum at small scales? How do dynamos saturate? What is the role of boundary conditions in the growth and saturation of magnetic fields?
- Most dynamo theory and simulation is based on single fluid magnetohydrodynamics (MHD) with isotropic transport coefficients: how do dynamos operate in collisionless plasmas, such as hot accretion disks and galaxy clusters, or weakly ionized gases such as protostellar disks and much interstellar gas?
- Can we develop a simple successor to, or improved, mean field theory that correctly predicts gross properties of dynamos such as the existence and periods of cycles and the symmetries of the large scale fields?
- Are there essential differences between dynamos in systems with only a seed magnetic field, as was probably the case in the first astronomical objects, and dynamos in systems which have reached a well magnetized steady state such as the Sun?

In the remainder of this report, we briefly characterize a few astrophysical environments and then describe how a combined program of observation, experiment, theory, and simulation, linked to other areas of astrophysics and plasma physics, could lead to progress on these fundamental problems. The essential features of this program are:

- Carry out observing programs on existing and planned facilities to better characterize the solar magnetic field, expand the sample of magnetic fields detected on other stars, produce more detailed, better sampled maps of the Galactic magnetic field, detect magnetic fields in other galaxies over cosmic time, and search for an intergalactic field. Consider proposing new instruments and facilities.

- Develop plasma experiments on dynamos in the flow dominated regime, allowing the effects of rotation, turbulence, compressibility, collisionality, various transport regimes, and boundary conditions to be probed for the first time in the laboratory.
- Study magnetic relaxation and the α effect in magnetically dominated laboratory experiments. Characterize effects beyond MHD, the coupling of relaxation, the α effect, and momentum transport, the role of magnetic stochasticity, and boundary conditions.
- Maximize the impact of observations and experiments by supporting them with theory and simulations. Experiments and simulations can run in similar parameter regimes, offering opportunities to validate the codes and optimize the design of experiments. Use theory and simulation together to understand the extreme parameter regimes encountered in astrophysics, and to distill the results of simulations into simple theories.

We end with brief discussions of the impacts and outcomes of this work, and linkages between dynamo theory and other topics.

1.2. Astrophysical Environments

Dynamos exist in planets, stars, accretion disks, and galaxy clusters; thus astrophysical dynamos span a wide range of physical conditions. Planetary interiors are liquid metal, the other systems are fully to partially ionized gases. Most studies of astrophysical dynamos are based on single fluid magnetohydrodynamics (MHD) with isotropic transport coefficients and magnetic Reynolds number $Rm \gg 1$. Even within this simple framework there are many relevant regimes to be explored: the magnetic Prandtl number Pm (the ratio of viscous to magnetic diffusivity) can be large or small, as can the Rossby number Ro (the ratio of rotation time to flow or convection time).

Single fluid MHD is invalid for many systems. In hot and/or low density environments, even a weak magnetic field renders transport coefficients anisotropic; the pressure tensor can also be anisotropic. . On scales of order the ion gyroradius (at high plasma β) or the ion skin depth (at low β), the electrons and ions follow different dynamics, and the Hall effect is important. At low ionization, nonlinear transport of the magnetic field can saturate dynamos at the ion-neutral decoupling scale, and ion-neutral friction can effectively increase ion inertia and increase the ion-electron decoupling scale. These factors, as well as the role of boundary conditions, large scale instabilities, and global geometry, are illustrated by the dynamo problem in the Sun, in disk galaxies, and in accretion disks.

1.2.1. The solar dynamo

The solar dynamo allows one to study the cyclic resurgence of magnetic flux in a highly turbulent medium. Single fluid MHD with isotropic transport coefficients suffices throughout the solar interior, but breaks down in the outer atmosphere, where the field is dissipated and flux can escape. Within the interior, $Pm \ll 1$ and $Ro \sim 1$.

The solar dynamo is complex: it involves coupling to the radiative core of the Sun through the tachocline, the dynamics of compressible, ionized fluid in the convection zone (with a link to helioseismology), the transport and emergence of magnetic flux, and further dissipative processes in the corona. It is clear from observations that solar rotation is modulated by the solar cycle and that convection is modified by strong magnetic fields. Thus, the solar dynamo is nonlinear. It is also a laboratory for studying the interplay between small scales and large scales: e.g. the roles of meridional circulation and sunspots, and the interactions between the large scale toroidal flux and magnetic fibrils. And finally, what is the effect of magnetic field escape, and possibly magnetic helicity escape, on the dynamo?

Due to the linkages between solar activity, space weather, and climate, predicting the properties of the solar cycle is of practical as well as astrophysical importance. Because the full complexity of solar dynamics is beyond even the most advanced computing environments, prediction will require a hierarchy of models. An open question is what level of complexity and realism is needed, and what essential features can be captured by simple models. Observations of other stars indicate that dynamo action is common in stars with convection near their surfaces; many such stars show magnetic cycles as well. There are well studied correlations between stellar magnetism, rotation, and age; explaining these relationships tests stellar dynamo theory.

1.2.2. The galactic dynamo

The magnetic field of our Galaxy has both ordered and random components. The coherence length is at least several kiloparsecs, more than an order of magnitude larger than the scale on which supernovae drive turbulence in the Galaxy. The turbulent and magnetic energy densities are similar.

Galaxies, unlike stars, do not show magnetic cycles, and the decay time of galactic magnetic fields exceeds the age of the Universe by many orders of magnitude. The best evidence for galactic dynamos is that the interstellar gas in galaxies is replaced on approximately 10^9 yr timescales due to star formation, stellar outflows and explosions, galactic winds, infall of extragalactic material, and galaxy mergers. Dynamo processes must operate continuously in order to maintain the field in a steady state.

Interstellar gas has $Pm \gg 1$. The electron and ion cyclotron frequencies much exceed the collision frequency, so transport coefficients in the fully ionized regions are highly anisotropic. Both the ion gyroradius and ion skin depth are many orders of magnitude less than global geometric scale, suggesting that the Hall effect is important only in thin layers or at the smallest turbulent scales. Much of the gas is weakly ionized, which affects magnetic flux transport and reconnection. However, the neutral-ion collision rate is not large enough to affect the electron-ion decoupling scale.

Interstellar gas is pervaded by cosmic rays. Cosmic rays are collisionless, but are coupled to the thermal gas by the magnetic field and by scattering from small scale fluctuations. On scales larger than the scattering mean free path (several parsecs), cosmic rays behave as a fluid, and increase the buoyancy of the interstellar medium, possibly contributing to magnetic field excape.

Because of the large Rm of the interstellar medium, the large scale structure of the magnetic field is by far the most difficult property to explain.

1.2.3. Accretion disk dynamos

Accretion disk dynamos play a dual role in astrophysics. Magnetic fields in disks affect the structure of the disk, the nature of accretion, and the formation of coronae and outflows. And, these outflows transport the field in the disk to large scales, seeding the ambient medium with new field.

Accretion disks range from cold, dense protostellar disks which are so weakly ionized in their outer portions that $Rm < 1$ to collisionless disks at MeV temperatures surrounding massive black holes. Accretion disks formed by mass transfer in binary star systems are generally intermediate; highly conducting but collisional. In the inner, conducting regions of protostellar disks, the neutral - ion collision frequency is so high, and the geometric scales are so small, that ion-neutral friction and Hall conductivity are important. In accretion disks around massive black holes, transport coefficients and plasma pressure can be anisotropic, and the electrons and ions can be both thermodynamically and dynamically decoupled.

It is plausible that angular momentum transport in many disks occurs primarily through Reynolds and Maxwell stresses exerted by small scale turbulence excited by magnetorotational instability (MRI). The MRI is a robust instability that operates for a wide range of magnetic geometries and physical conditions, including weakly ionized gases, collisionless plasmas, and plasmas in which the magnetic field is so weak that particles are not well magnetized. There is numerical evidence that in single fluid MHD, with isotropic transport coefficients, the MRI also acts as a dynamo which can generate a large scale, oscillatory field.

1.3. Opportunities

1.3.1. Observations

The quality and quantity of observations of astrophysical dynamos at all scales is growing dramatically, and is poised to grow even faster with the ongoing deployment of new facilities. Some of these new facilities have elucidating astrophysical magnetism as their primary goal, and many will contribute to our broader knowledge of astrophysical dynamos.

Two new solar observatories are focussed on solar activity. The solar magnetic field and its effect on the solar atmosphere will be observed with unprecedented sensitivity and spatial and temporal resolution with the orbiting Solar Dynamics Observatory (SDO), scheduled for launch in early 2010. SDO will produce full vector magnetograms of the solar photosphere, at one arcsecond resolution, about once every 90 seconds. The magnetograms will be combined with observations of the solar atmosphere to give a detailed picture of the relationships between magnetic field evolution and solar variability. Simultaneous helioseismic measurements will reveal the coupling between subsurface flow and surface magnetism. A new 4m telescope, the Advanced Technology Solar Telescope (ATST), to be deployed in Hawaii, will resolve magnetic flux tubes and through a combined Zeeman and Doppler measurements is expected to measure magnetic and kinetic helicity fluxes on small scale with unprecedented spation and temporal resolution.

Detailed observations of the Sun itself are complemented by observations of magnetic activity on other stars. The large numbers of low mass stars cataloged by the Sloan Digital Sky Survey have been used to explore the decrease in stellar activity with age. Followup observations are probing the rotation - activity relation. These relationships, along with other properties of stellar rotation and activity, are being elucidated at higher sensitivity with the Kepler mission for a large sample of stars.

Galaxies, unlike stars, are transparent to electromagnetic radiation at the long wavelengths at which interstellar magnetic fields are primarily measured. Three complementary types of observation: polarized radio synchrotron radiation, Faraday rotation of point sources and the continuum, and polarized thermal emission from magnetically aligned dust grains, can be used to trace fieldlines and measure fieldstrength. Major advances in these three techniques may occur over the next decade due to two new large projects: the Square Kilometer Array (SKA) and the proposed NASA CMBPol mission.

Probing galactic and intergalactic magnetic fields over cosmic time is one of the top few science goals of the SKA. The SKA will be able to observe synchrotron radiation from tens of millions of galaxies. It will be possible to map the magnetic morphology of nearby external galaxies, and resolve the overall large scale field geometry of tens of thousands of others. The bulk of those galaxies, however, will act as background sources that illuminate the Galactic magnetic field, allowing it to be mapped in unprecedented detail. The sensitivity of the SKA will also permit detection of polarized emission at moderate redshift, tracing back the origin and evolution of magnetic fields in recently formed galaxies.

The primary goal of CMBPol is to detect the imprint on the Cosmic Background Radiation of gravitational waves generated during the inflation era. As a byproduct, CMBPol will provide an arcminute-resolution ultra-sensitive dust emission polarimetry map of the entire sky. This will probe the line of sight averaged orientation of the plane of sky magnetic field in dense interstellar gas throughout the Galaxy.

Additional constraints on the strength and structure of galactic and intergalactic magnetic fields are provided by γ-rays and ultra-high energy cosmic rays. Gamma ray burst photons are diffused and delayed due to $e^{\pm}$ pair creation and subsequent annihilation after spiraling in the intergalactic field. Ultra-high energy cosmic rays, which are intergalactic in origin, are also constrained in their propagation by ambient magnetic fields. Discovery of a pervasive intergalactic field would be evidence that the universe was magnetized by a top down process that operated everywhere.

1.3.2. Experiments

As mentioned in the Introduction, RFP plasmas, and other magnetically dominated laboratory plasmas, undergo flux conversion during relaxation events. In addition, there is clear evidence that flow is driven, and momentum is transported, during relaxation.

The α effect in the RFP is due to a small number of resistive tearing modes. Although MHD descriptions of these modes provide a model of the α effect to zero order, additional physics is needed to explain the α effect completely: magnetic stochasticity, thermal fluctuations, and two-fluid effects may all come into play, offering an opportunity to study how the α effect could be modified in collisionless systems where these effects are important. The role of magnetic helicity injection and transport could be explored, through manipulation of the plasma - boundary interface and through ac helicity injection.

The role of large scale instabilities in flux conversion and sustainment of the large scale toroidal field in the RFP suggests that global instabilities and a relaxation or self-organization principle could be important in flow driven astrophysical dynamos. The instabilities themselves are more likely to be driven by buoyancy, or by shear flow, than by the current. Likewise, in the MHD description of the RFP, the preferred state is the Taylor-Woltjer state, which is a force free equilibrium with the minimum possible energy at fixed magnetic helicity. Although the force free field is only an appropriate final state for a magnetically dominated system, there may be other preferred states appropriate for flow driven astrophysical systems.

A compelling new area for experimental study is the weak field regime of large plasma β and large Alfvén Mach number, together with large Rm. This is the parameter regime to which astrophysical dynamos belong, and few plasma experiments have operated in this regime. In such circumstances, one might hope to observe a dynamo in the laboratory.

One major challenge that could be taken on in such an experiment is understanding the growth and saturation of small scale fields. Conventional wisdom has it that a weak magnetic field in a turbulent, conducting fluid is amplified up to equipartition with the turbulence, but many details of the saturation mechanism, the final structure, and their dependence on the driving of turbulence and the intrinsic parameters of the medium are missing. Studying small scale dynamos under collisional and collisionless conditions, at large or small Pm, would add critical components to our picture of astrophysical dynamos.

Likewise, experimental studies of the growth of large scale fields should be attempted. It is possible that this is an essentially nonlinear process: simulations of the strong field branch of the geodynamo, recent modeling of liquid metal dynamo experiments, certain simulations of MRI dynamos, and simple toy models have all provided clear examples of subcritical dynamo transitions: dynamos which require a finite amplitude magnetic field to operate, and have no linear growth phase. Such dynamos may be relevant in the contemporary Universe, where magnetic fields are already ubiquitous. More generally, one can ask whether the energy in large scale magnetic structures is derived primarily from the energy in large scale flows or from small scale, turbulent energy through an inverse cascade, and how saturation of the dynamo affects the large and small scale flows. Implementing a variety of boundary conditions, including injection and escape of magnetic helicity, could address longstanding issues in dynamo theory.

Such an experiment would also offer the opportunity to study effects beyond MHD at high β. The Hall effect and kinetic effects such as temperature anisotropies and tensor viscosity could all be studied in such a plasma.

1.3.3. Simulation and Theory

Extracting the maximum benefit from the observational programs described here, from the Sun to the intergalactic medium, will require extensive theoretical modeling and simulation. Whether the problem is modeling the radiative signatures of starspots, predicting the helioseismic signatures of magnetic flux tubes in the solar convection zone, or developing models of the magnetized interstellar medium that can be subtracted from the cosmological signal or used to interpret Faraday rotation measurements, developing robust physical interpretations of the data and confronting theory with observation will require substantial work which must probably be funded independently of the observations themselves.

In the same way, laboratory experiments on dynamos require theoretical and computational support. However, there is an important difference between simulating astrophysical systems and simulating experiments: in the latter, it is becoming possible to work in the same parameter regime as the experiment, while in astrophysics it is generally not possible. Thus numerical modeling of lab experiments is important for validating numerical codes.

Theory and simulation of astrophysical dynamos have generally followed two paths. One path is basic studies of magnetic field evolution in geometrically simple systems such as periodic boxes of turbulence, with or without velocity shear, and with or without stratification. Analytic or semi-analytic models can address a large range of dimensionless parameters, and can control the input flow field and turbulent spectrum, but require approximations that need to be tested. Numerical models work within a narrower range of parameters and capture usually less than 4 decades of inertial range turbulence, but can address a wider range of nonlinear aspects of magnetic field evolution. These analytical and numerical studies, combined, have led to many important results on the conditions under which magnetic fields can grow, the statistical properties of these fields, and how they react back on the underlying flow, but many questions remain. We do not yet fully understand how the saturated magnetic energy spectrum depends on the forcing model or on dimensional parameters such as Pm. Isotropically forced simulations seem to predict more energy on small scales than inferred from observations, suggesting that some key ingredient is missing. Most of these studies have used single fluid MHD with isotropic transport coefficients, although there have been some numerical simulations of the Hall dynamo, and dynamos in weakly ionized fluids. It is expected that initial studies of dynamos in collisionless plasmas will use equally simple basic setups.

The other path is the study of dynamos in global models of astrophysical systems such as accretion disks, galaxies, and rotating, convective stars. These models include the correct geometry and much of the important physics, but at a coarsely resolved level - for numerical reasons, the diffusivities used, whether explicit or numerical, always lie far larger than the molecular diffusivities. It is also difficult to run the simulations long enough to properly capture cyclic activity: one 22 yr solar cycle is about 270 rotation periods, whereas simulations may require timesteps as short as 100 s to temporally resolve small scale convection. Nevertheless, such simulations probe what geometric features, such as aspect ratio, are necessary to generate large scale fields, better couple the dynamo process to the physics of the system, and can use natural boundary conditions.

1.4. Impacts and Major Outcomes

The study of astrophysical dynamos as outlined through this combination of observation, experiment, simulation, and theory should be able to predict the overall structure, strength, cyclic behavior if any, and power spectrum of magnetic fields in astrophysical bodies. Many of the observable signatures of such fields are related to their coupling with the ambient medium. This is not necessarily the seat of dynamo activity itself, but we touch on it briefly in the following section. Improved understanding of astrophysical dynamos would lead to better models of star formation through cosmic time, accretion, and the dynamics of interstellar and intergalactic gas.

Dynamo theory as it now exists is a complex subject. State of the art numerical simulations, in particular, are likely to be beyond the resources of most research groups. Ultimately, a desirable outcome for dynamo studies would be simple theories, or low order dynamical models, that predict the main features of astrophysical magnetic fields. Development of such theories should remain within our sights.

1.5. Links to other Topics

The study of dynamos is closely bound up with other topics in plasma astrophysics, and there is natural synergism between them.

Magnetic reconnection, without which there can be no change in magnetic topology, is key to dynamos. Reconnection may suppress growth of the field at small scales and permit the escape of field through open boundaries. Because reconnection is an inherently small scale process, effects beyond MHD may be important in reconnection layers even if not elsewhere in the dynamo medium.

There is interplay between dynamos and momentum transport. The torsional oscillations seen in solar surface rotation vary over the solar cycle and may be produced by magnetic torques. This is a reminder that even when the ratio of magnetic energy to overall flow energy is small, the energy in *differential* rotation may be small enough to be affected by magnetic fields. The flows set up by the RFP dynamo may have an analog in flux conversion processes in astrophysical systems, such as launching of a jet by rotational shear. Of course, MRI turbulence transports momentum as well as amplifying magnetic fields.

All astrophysical systems with dynamos also appear to be turbulent. When the turbulence amplifies the field and when it merely enhances the dissipation rate is an unsolved problem; the answer probably lies in subtle properties of the turbulence. Since turbulence is affected by the underlying mean flow and by the magnetic field, teasing apart the roles of turbulence and mean flow in a nonlinear dynamo is a difficult problem.

We have alluded to the role of large scale instabilities in magnetic field growth and saturation. Buoyancy and shear flow instabilities are the best studied candidates in astrophysics. In magnetically dominated lab plasmas, current driven instabilities are important. Small scale kinetic instabilities in anisotropic plasmas may be important for the energy balance and the growth of small scale field, and may affect the system on large scales by enhancing the viscosity and resistivity.

Finally, there is the coupling of the dynamo to the ambient medium. For example, energy is lost from a stellar interior or an accretion disk through a Poynting flux into the surrounding corona, but the Poynting flux cannot be computed without a model for the coronal field. The same holds for the magnetic helicity flux. Coronae are magnetically dominated systems, not flow dominated systems; their magnetic evolution probably has more in common with relaxation in magnetically dominated lab plasmas than in the dynamo region itself. Moreover the observable radiative signatures of the dynamo will be at or above the transition from flow dominated to magnetically dominated.