Astrophysical Dynamos

Introduction and Current Status

An astrophysical dynamo is a set of mechanisms which convert mechanical energy to magnetic energy, and/or sustain the magnetic field against dissipation. Dynamos produce the ordered, in some cases cyclic magnetic fields observed in stars, galaxies, galaxy clusters, accretion disks, and jets. 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 is also a practical reason to understand dynamos: the solar dynamo underlies solar magnetic activity, which drives space weather and affects the Earth's climate.

Astrophysical dynamos are generally flow dominated: gravitationally or thermally driven flow is the main energy reservoir. In accretion disks, disk galaxies, and some stars, differential rotation is the predominant form of kinetic energy. However, axisymmetric differential rotation alone cannot sustain the field. In most models of dynamos, additional induction is provided by small scale turbulence. Turbulence can also accelerate the decay of the field, which is otherwise well frozen to the plasma.

A description of large scale dynamo action by shear, turbulent induction, and turbulent decay was developed in the 1950s-60s. The theory is known as mean field electrodynamics (MFE) and the dynamo models are sometimes called $\alpha - \omega$ dynamos after their parameterization of turbulent induction (α effect) and rotational shear (ω effect). MFE theory has been applied to interpret observations of solar, stellar, and galactic magnetic fields. Aspects of MFE were also helpful in explaining laboratory experiments, even though such plasmas are magnetically dominated rather than flow dominated. 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. Flux conversion is also seen in Spheromaks, and during sawtooth crashes in Tokamaks, and represents the tendency of these magnetically dominated systems to relax to preferred states.

Serious challenges to MFE arose in the 1990s as a result of observation, theory, and numerical simulations. The solar interior differental rotation measured using helioseismology gives an ω-effect which causes the mean toroidal field to migrate away from the equator, opposite to what is observed in the Sun. On the theoretical side, analysis of the MFE equations themselves, and direct numerical simulation, both predicted that most of the energy in the magnetic field should lie at scales many orders of magnitude below what is observed in stars and galaxies.

Some ideas currently under development may address these problems. One idea is to follow the flow of magnetic helicity, which describes the linkage of magnetic fieldlines, and is conserved in magnetically closed, highly conducting systems. The MFE equations, 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 predicts the growth and saturation of large scale field seen in some numerical simulations. The theory also predicts that unless magnetic helicity can be ejected from the system, the growth of the large scale field becomes very slow. How strong the field becomes with or without helicity ejection is a subject of current research.

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

Key Challenges

Astrophysical dynamos operate under a vast range of physical conditions. Systems with dynamos vary over many orders of magnitude in ratio of magnetic diffusion time to dynamical time (magnetic Reynolds number Rm), ratio of viscous to magnetic diffusivity (magnetic Prandtl number Pm), ratio of rotation period to eddy turnover time (Rossby number Ro), and collisionality, as well as in their dynamics, geometry, and the quality of available observations.

Two key challenges which are essential in applying dynamo theory to astrophysics are:

- How are large scale, possibly cyclic magnetic fields generated?
- How do dynamos operate in systems dominated by non-MHD effects?

Addressing these challenges will require interplay betweem theory, computation, experiment, and observation. The characteristic dimensionless parameters of astrophysical systems are too extreme to realize in either simulations or laboratory experiments (although it is possible in some cases to simulate experiments). Theoretical ideas are necessary to understand what to simulate and how to extrapolate, while observations provide ground truth as well as opportunities to test predictions.

Generation of large scale, cyclic fields Solar, stellar, and galactic magnetic fields are coherent on scales significantly larger than the scales of turbulence in these systems. For example, in galaxies, supernova remnants tens of parsecs in size inject turbulence into the interstellar madium, but the magnetic field is coherent on scales of at least several kiloparsecs. The solar magnetic field, likewise, displays a dipole component and a coherent toroidal field which is antisymmetric about the equator, but the largest scale of turbulent convection is a few tenths $R_\odot$. On the other hand, a significant body of analytical and numerical work suggests that systems with large Rm, the magnetic power spectrum should peak at small scales. The underlying reason is that in order to amplify the field in a system of fixed volume, the fieldlines must lengthen in proportion to their amplification. This tends to produce a highly tangled field.

The cyclic nature of at least some magnetic fields is an important part of this challenge. Direct measurement shows that the 22 year solar cycle has existed, with minor interruptions, for millenia. Regular cycles on other stars have also been detected. Understanding how these cycles arise, and how they correlate with the structure of stars, is fundamental to understanding dynamos, and is an aspect of dynamo theory which can be tested observationally.

Dynamos beyond MHD

Although most studies of dynamos are based in resistive MHD, this approximation is inadequate for many astrophysical systems.

Dynamo action in the interiors of solar type stars is well described by single fluid, resistive magnetohydrodynamics (MHD). Flux escape, however, depends on physical processes in the outer atmosphere, which is collisionless. Many processes in interstellar and intergalactic gas, and in hot accretion disks surrounding compact objects, are also collisionless. In a collisionless plasma, stresses and transport coefficients can be anisotropic. This anisotropy is known to affect instabilities in the medium, and to cause new instabilities. The study of dynamos in collisionless plasmas is still in its infancy.

Effects beyond MHD can appear even in collisional systems. In highly luminous stars, and in some accretion disks, radiation pressure is significant, and modifies turbulence. In a weakly ionized media such as cold interstellar gas or protostellar disks, ion-neutral friction leads to nonlinear transport of the magnetic field, can modify magnetic reconnection, and increases the length scale on which ions and electrons decouple, making the Hall effect more relevant. Relativistic cosmic rays, which are coupled to interstellar and intergalactic gas by scattering from small scale fluctuations, provide buoyancy, stresses, heating, and viscosity. Although some of these effects are already included in dynamo models, or in the study of instabilities driven by buoyancy and/or differential rotation which are thought to be relevant to dynamos, no comprehensive treatment of dynamos in these regimes yet exists.

Techniques & Opportunities

Observations

High priority observational programs include using existing and planned facilities to better characterize the solar magnetic field, expanding the sample of magnetic fields detected on other stars, producing more detailed, better sampled maps of the Galactic magnetic field, detecting magnetic fields in other galaxies at earlier cosmic times, and searching for an intergalactic field.

Two new solar observatories, the recently launched Solar Dynamics Observatory and the planned Advanced Technology Solar telescope, will focus on solar activity and on dynamics of the solar convection zone. The Sloan Digital Sky Survey has catalogued large numbers of low mass, active stars, allowing exploration of trends such as age-activity and rotation-activity relationships in stars. These and similar relationships are being followed up with the Kepler mission.

The capability to map galactic magnetic fields would greatly expand with two proposed facilities. The Square Kilometer Array, planned by an international consortium, has made cosmic magnetic fields a high priority. It would be able to detect synchrotron radiation from millions of galaxies and map the magnetic morphology of nearby ones in unprecedented detail. A proposed mission, CMBPol, is designed to detect gravitational waves generated during the Inflation era, but will as a byproduct produce a high resolution, ultrasensitive polarization map of the Galactic magnetic field.

Additional constraints on the strength and structure of galactic and intergalactic magnetic fields are provided by γ rays and ultrahigh energy cosmic rays. Detection of a pervasive intergalactic field would suggest that the Universe was magnetized by a top down process that operated everwhere.

Laboratory experiments

Lab experiments, well supported by theory and simulation, can directly probe dynamo phenomena in a controlled and reproducible way. Such experiments currently lack a funding home at any agency.

Many important issues in dynamo theory could be probed by plasma experiments in the weak magnetic field, flow dominated regime. This regime is nontraditional in the lab, but similar to natural plasmas. It would allow the effects of rotation, turbulence, compressibility, collisionality, various transport regimes, and boundary conditions to be probed for the first time in the laboratory. It would be possible to probe saturation mechanisms and distinguish different operating regimes as well as study basic flow related processes such as buoyancy driven convection and large scale circulation. Construction of one such experiment is already funded.

Studies of magnetic relaxation and the α effect in magnetically dominated laboratory experiments should continue. These experiments allow characterization of effects beyond MHD, the coupling of relaxation, the α effect, and momentum transport, and the role of magnetic stochasticity, and boundary conditions. These experiments, which are often motivated by fusion research, complement dedicated experiments needed to access the flow dominated regime.

Liquid metal experiments complement plasma experiments by accessing the low Pm regime encountered in cold, dense plasmas. These experiments can also probe mechanisms behind the α and β effects, and the conditions necessary to achieve magnetic cycles.

Theory and simulation

Theory and simulation can be used together to understand the extreme parameter regimes encountered in astrophysics, and to distill the results of simulations, observations, and experiments into simple theories. The impact of observations and experiments is maximized when supported by theory and simulations. Experiments and simulations can run in similar parameter regimes, offering opportunities to validate the codes and optimize the design of experiments. Extracting the maximum benefit from the observational programs described here, from the Sun to the intergalactic medium, will require extensive theoretical modeling and simulation. Much needs to be done numerically and theoretically to explore the vast parameter space of astrophysical dynamos.

Basic studies of magnetic field evolution in geometrically simple systems and studies of dynamos in global models of disks, stars, and galaxies are both useful. 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. Global models include the correct geometry and much of the important physics, but at a coarsely resolved level. Such models 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.

Challenges for the Next 5 Years

Certain aspects of the key challenges in understanding dynamos should yield to progress in the next five years. There will be large bodies of data from the Solar Dynamics Observatory that better constrain magnetic fields and flows on the Sun, and data from Kepler and other satellites that constrain the parameter space of stellar dynamos. First results from the plasma dynamo experiment should be in hand. It will be time to put together detailed observing programs for cosmic magnetic fields, based on exsiting observations and on modeling.

The time is right for **a major thrust in dynamo modeling, requiring significantly expanded computational resources**. Such a program would be similar in scope to efforts in climate modeling, and would include both global models and local models with the high degrees of spatial and temporal resolution necessary to resolve many decades of a turbulent spectrum. The most extensive models should be MHD because of the relative maturity of MHD dynamo theory, and the choice of models should be informed by theory and by smaller simulations. We also recommend committing significant resources to collisionless models that combine correct microscopic physics with the large scale features of astrophysical systems, such as rotational shear and gravitational stratification. The program should be a community effort, with benchmarking studies to assess agreement between codes, and the computational output should be available to the community. Such a program is necessary to address the two major challenges of the subject, generation of large scale, possibly cyclic magnetic fields (regular, like the Sun, or chaotic, like the Earth), and how dynamos operate in environments not described by simple MHD. A desirable outcome of these studies would be simple theories, or low order dynamical models, that predict the main features of astrophysical magnetic fields. This goal is not necessarily achievable within the next 5 years, but it should remain within our sights.

Experimental progress demands **Development of a plasma dynamo experimental program**. There are many steps to take in order to fully realize the potential of laboratory dynamo experiments: development of advanced, fusion research grade, noninvasive diagnostics, development of techniques to achieve buoyancy (a critical factor in many natural dynamos), and development of technologies for driving flow in ways that best replicate astrophysical conditions. Simulation and modeling should be integrated with technological innovation to make the most efficient use of resources. The next generation of plasma dynamo experiments, informed by current and planned experiments, including possible upgrades to these experiments, could also be considered under the auspices of such a program. As the subject matures, a large experiment, operated as a user facility, could be a resource for the whole community.

Astrophysical Impact

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. Because magnetic fields are a major constituent of the interstellar medium in galaxies and play a key role in angular momentum transport in stars and accretion disks, and because their origin in the Universe is an unsolved cosmological problem, dynmao theory is fundamental to astrophysics. A few examples of problems where dynamo theory could have an impact are:

- Do interior dynamos directly drive coronal emission?
- Do accretion disks generate large scale magnetic fields that significantly affect their angular momentum evolution and structure their jets and winds?
- How do magnetic fields affect star formation, including efficency, multiplicity, and initial mass function?
- How do stars, beginning with the protostellar phase, spin down?
- How is energy apportioned between magnetic fields, thermal gas, and cosmic rays in galaxies and galaxy clusters?

Connections to Other Problems in Plasma Astrophysics

The study of dynamos is closely bound up with other topics in plasma astrophysics, and there is natural synergism between them. There is a parallel synergism with other experiments through common needs for advanced diagnostics and other aspects of technology.

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. The flows established by the RFP dynamo may have an analog in flux conversion processes in astrophysics, such as launching jets by rotational shear. The structure of magnetic fields in accretion disks is fundamental to how they transport angular momentum.

Large scale instabilities may place a role in the growth and evolution of large scale magnetic fields. The structure of small scale turbulence is also fundamental to dynamos, and turbulence is affected by dynamos.