Magnetic Fields in Stellar Astrophysics

A White Paper Submitted to the Astro-2010 Decadal Survey

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1 Introduction

Building a comprehensive physical picture of stellar structure and evolution is one of the greatest triumphs of 20th century Astrophysics. However, many important aspects of the life cycle of stars are still not understood. They include: the origin and evolution of the stellar magnetic field, including the large-scale field; the sun-spot cycle; the evolution of the stellar rotation; the origin and character of differential rotation; high-energy coronal activity; mass loss in massive stars; and various aspects of binary evolution. Even more critical questions remain open regarding the end of the life of stars and their afterlife as compact objects. These include the mechanisms of core-collapse supernovae (SNe) and gamma-ray bursts (GRBs), the origin of magnetars, the workings of radio-pulsars and pulsar-wind nebulae; and some aspects of accretion disks and jets in binary systems. All these questions are at the forefront of modern Astrophysics. Importantly, many of them unavoidably involve magnetic fields interacting with the plasma. Therefore, they belong to the realm of *Plasma Astrophysics*.

A common theme in plasma astrophysics is the *life cycle of magnetic fields*: How are they produced (dynamo)? How do they interact with the plasma (magnetic braking; magnetocentrifugal wind acceleration; MHD instabilities such as MRI, kink, and Parker)? And how are they destroyed (reconnection)?

In this white paper we outline some of the most outstanding questions and emerging science opportunities related to Magnetic Self-Organization and Plasma Astrophysics. We stress the importance of a well-balanced research program involving four inter-connected components: astronomical observations, analytical theory, computer simulations, and laboratory experiments.

2 The origin of magnetic fields in stellar objects

The origin of magnetic field in stars and compact stellar remnants is an old outstanding problem in Astrophysics. It encompasses young stars, main sequence stars, magnetic white dwarfs, and neutron stars, including magnetars.

2.1 Magnetic Dynamo in low-mass stars

In the Sun and other cool, low-mass stars, vigorous magnetic activity is believed to result from the conversion of convective and rotational mechanical energy into magnetic energy by MHD dynamo. Although the basic ideas are now well established, we still don't really understand many key aspects, such as the differential rotation, the intermittent character of the surface magnetic field distribution (e.g., sunspots), the origin of the solar cycle, the strength of the large-scale (dipole) magnetic field, and the role of the (differential) rotation in the large-scale dynamo. Significant progress on these problems is expected in the next decade due to a confluence of recent advances in analytical theory and numerical simulations, and the advent of new laboratory experiments.

Of particular interest in astrophysics is the origin of large-scale magnetic fields. The kinematic (linear) dynamo theory has been advanced recently with the development of a statistical theory unifying large-scale and small-scale dynamos [14]. In addition, incorporation of magnetic helicity conservation into non-linear large-scale dynamo theory has resulted in the development of a successful saturation model that matches simulations for closed volume [2, 3], as well as for open volume dynamos that can overcome resistive quenching, sustained by helicity flux [1, 22, 19, 23].

Finally, there are now several operating and proposed experiments utilizing *liquid metals* to study MHD dynamo under controlled and well-diagnosed laboratory conditions. In addition, a proposed *plasma* dynamo experiment can offer better diagnostics capabilities and can extend the liquid-metal studies to more astrophysically relevant parameters, e.g., to much higher magnetic Reynolds numbers than in liquid metal experiments. Importantly, it will also allow the viscosity ν to be varied independently of the resistivity η, giving access to a wide range in the magnetic Prandtl number $Pr_m \equiv \nu/\eta$, thought to be a critical parameter for the dynamo onset (in liquid metals Pr_m is fixed by material properties and is usually $\ll 1$). Although the high-β plasmas needed for such experiments have never been studied in the lab, recent advances in permanent magnet technology, plasma source development, and new schemes for driving flow now make it possible. Such an experiment would be a relatively modest investment compared with telescopes and space missions.

2.2 Magnetic fields in massive stars

During the past few years, high-resolution spectropolarimetric studies have discovered $\sim$ 1 kG large-scale magnetic fields in early-type (OB) stars with masses up to 50 $M_\odot$ [20]. This important discovery has fundamental implications for our understanding of the observed properties of hot, massive stars, their evolution, and their final stages such as GRB-producing collapsars and the magnetic properties of neutron-star remnants. However, in contrast to magnetic fields in convective low-mass stars, the origin of magnetic fields in massive stars (above $\sim 2M_\odot$) remains poorly understood. Since these stars don't have convective envelopes where a turbulent dynamo may operate, one expects their magnetic fields to be very different from those of low-mass stars. And indeed, observationally, they are structurally simpler, and often stronger, than the fields of cool stars [24], and their characteristics show no clear correlation with stellar age, mass, or rotation [12], suggesting a fundamentally different field origin. In particular, it is now believed that they may be fossil remnants from the stars' formation stage, instead of being actively generated by an internal dynamo, although this is still debated [4]. Distinguishing between these two alternative scenarios will be a central theme for the next decade, and will have a broad impact on massive-star astrophysics. Determining the fields' origins will shed light on their configuration beneath the photosphere. Given that the internal rotation profile of a massive star is a critical factor for determining whether it will produce a GRB, (e.g., [15]), it is clearly important to constrain the structure of the interior fields capable of redistributing angular momentum.

For robust and sensitive field measurements, many line profiles must be observed simultaneously in Stokes IQUV; this necessitates the use of echelle spectropolarimeters, putting high demands on the light collecting power. Therefore, the key to future observational progress will likely lie in the deployment of echelle spectropolarimeters on the new generation of larger, more sensitive telescopes.

2.3 Neutron stars

An important astrophysical application of the large-scale dynamo theory is to newly-born proto-neutron stars (PNS). This topic is important for understanding the magnetic-field distribution of neutron stars and, in particular, explaining why some neutron stars (magnetars) have large-scale magnetic fields of up to 10^{15} G, whereas others have much weaker fields ($\sim 10^{12}$ G). Also, understanding where and when a large-scale PNS magnetic field is generated is needed to to access the dynamical role of magnetic fields in core-collapse SN and GRB explosions.

3 Dynamical Role of Magnetic Fields in Accretion Disks

Magnetic fields are not just passive tracers of the gas motions in various astrophysical systems. Often, they play a decisive dynamical role that may be manifested in a number of, sometimes subtle, ways. This includes situations where a large-scale magnetic field governs the motion of the plasma, e.g., in launching, acceleration, and collimation of outflows , including relativistic jets; magnetically-channeled accretion on neutron stars, white dwarfs, and young stars; and gradual magnetic braking of accretion disks and stars. But dynamical effects of magnetic fields also include the effects of energetically sub-dominant small-scale turbulent magnetic fields in accretion disks and stars on the effective long-time-scale transport of some large-scale quantity, such as angular momentum or large-scale magnetic flux. This often involves a complicated interplay between magnetic fields, large-scale rotation, and turbulence. Perhaps, the most notable recent example is the magneto-rotational instability (MRI) and its role in the angular momentum transport (AMT) in accretion disks.

We also would like to note that MRI is just one example of a general situation where dynamical activity is brought about by some magnetically-induced instability. Other astrophysically important MHD instabilities include the Parker instability and its role in the formation of magnetized coronae of stars and accretion disks, and the kink and its effect on stability and survival of jets. Whereas linear stability analysis is rather straight-forward in most cases, the long-term non-linear behavior of most of these instabilities is much less understood, even though it is usually more relevant for observations.

Importantly, whereas the main focus of accretion disk research in the past decade has been on the AMT problem, plasma turbulence in disks goes far beyond the AMT problem. The focus is shifting towards more refined plasma physics and towards the questions of energy dissipation, thermodynamics, and radiation. Indeed, MRI leads to conversion of gravitational/rotational energy to turbulent kinetic and magnetic energy, but how and where is this energy eventually dissipated into heat and observable radiation? How intermittent is energy dissipation? Does it occur in the collisional (resistive MHD) regime or in collisionless regime requiring more sophisticated plasma physics? Do dissipation events in the disk directly produce non-thermal particles? How much of the accretion energy escapes and is dissipated in the overlying corona, producing the observed high-energy emission? What is the role of coronal magnetic fields in the overall AMT? Also, how does the small-scale MHD turbulence in the disk interact with a large-scale external field of the central star and how is the material transferred from the disk to the star? All these questions will likely dominate the studies of accretion disks in the next decade.

Numerical studies of MRI have seen a resurgence of activity in recent years due to newly emergent concerns about numerical convergence of previous MHD simulations. The ensuing scientific debate has demonstrated that understanding of the nonlinear saturation of MRI and the associated AMT requires very high-resolution simulations, with Reynolds and magnetic Reynolds numbers of many thousands. These simulations are now finally becoming feasible, and one should continue pushing in this direction.

Experiments aiming to realize MRI in the lab and to study the resulting AMT have begun in the past decade [11]. The high-quality data on the MRI saturation from these experiments will be compared quantitatively to numerical simulations; such one-to-one comparisons should provide much needed physical insights and serve as benchmarks for numerical techniques.

One further development in the MRI and dynamo areas is to consider collisionless plasma effects beyond single-fluid MHD [16, 18, 17]. In collisionless plasmas, e.g., in hot accretion disks, compression of magnetic field lines causes the plasma pressure to become anisotropic, modifying the linear stability of the MRI and shifting the fastest-growing mode to larger scale. In addition, the pressure anisotropy drives various kinetic micro-instabilities (e.g., firehose and mirror), which has a profound effect on the system. New experiments investigating plasma flow-driven instabilities may be an important way to study the microphysics of collisionless MRI, and several such experiments are now under way. Comparisons between liquid-metal and plasma experiments will elucidate these uniquely plasma, non-MHD effects.

3.1 GRBs

Recently, it has be recognized that traditional, purely neutrino-driven models of supernova (SN) and especially GRB explosions may be inadequate. This has lead to a growth of interest in magnetically-driven core-collapse explosions of massive stars, including the application of the magnetic tower concept. Therefore, understanding classical magnetic processes (such as dynamo, MRI, Parker, and kink instabilities, magnetic reconnection, relativistic jet acceleration and collimation) in the exotic environment of collapsing stars is crucial.

Making progress on these issues will require sophisticated numerical simulations. Fortunately, several (general-)relativistic MHD codes incorporating the relevant microphysics (including realistic neutrino transport) are now being developed. These powerful codes will be capable of addressing the above issues and may lead to a breakthrough in GRB (and SN) central engine modeling in the next few years.

In addition, there is also an intriguing possibility that GRB jets may remain magnetically dominated out to large distances [13]. The emitted gamma radiation may then be powered by magnetic reconnection in current sheets produced by kink instabilities [7, 9] or by initial irregularities in the jet. Figuring out how to distinguish observationally this scenario from the classical internal shock model is an important challenge in plasma astrophysics for the next decade.

4 Magnetic Reconnection and Coronal Activity

Whereas magnetic fields are usually created in dense, cold regions by dynamo mechanism, their destruction often takes place in the surrounding hot and rarefied coronal regions, through the process of *magnetic reconnection.* Reconnection is usually defined as a rapid rearrangement of the magnetic field topology, but its importance in astrophysics stems from the associated a violent, explosive release of magnetic free energy and its conversion to the plasma kinetic, thermal, and non-thermal particle energy. Reconnection is believed to power for solar/stellar flares and coronal heating, magnetic storms in planetary magnetospheres, and flares in accretion-disk systems; it has been also invoked as a possible mechanism for giant magnetar flares, for GRBs, and for solving the pulsar-wind σ problem. It may also be an important source of energetic non-thermal particles (cosmic rays). Finally, reconnection may also be crucial for the creation of large-scale ordered fields.

Whereas single-fluid resistive MHD is probably a good description in the dense regions where magnetic fields are generated, it may not be applicable in the overlying tenuous plasmas where reconnection takes place. Thus, the life of magnetic fields is not limited to MHD but goes well beyond, into the "hard-core" plasma physics.

The past decade has witnessed great progress on magnetic reconnection, brought about by the confluence of powerful numerical simulations, dedicated laboratory experiments, and analytical theory. These complementary approaches paint a compelling physical picture emphasizing the critical role of plasma collisionality. This picture can be summed up by stating that there are two regimes of reconnection: a slow reconnection in collisional plasmas where resistive MHD is applicable, and a fast reconnection regime in collisionless plasmas; the latter can be realized by either the two-fluid (e.g., Hall) effects or by anomalous resistivity due to kinetic plasma micro-instabilities.

However, despite its wide acceptance in space and plasma physics communities, this new understanding of reconnection is only now starting to be applied in astrophysics. In particular, it helped elucidate the self-regulatory nature of solar/stellar coronal heating and lead to the formulation of the concept of marginal collisionality of astrophysical coronae (including accretion-disk coronae of black holes [10]). This example illustrates that applying the results of basic plasma physics research, including lab experiments, can be quite fruitful for astrophysics.

Even with the above recent advances in the physics of reconnection, many important questions concerning both its fundamental aspects and its astrophysical applications remain unsolved. Here are some of the most outstanding questions that will dominate astrophysical magnetic reconnection research in the next decade:

1. *Impulsiveness:* Reconnection often occurs impulsively.Is there any general criterion why magnetic energy is stored for a long period and then suddenly released? How do anomalous resistivity and/or two-fluid effects produce an impulsive transition to fast reconnection?

Which of them dominates in a given situation and how do they interact with each other?

2. *Energy partitioning and non-thermal particle acceleration:* To understand various astrophysical systems such as stellar and accreting black-hole coronae, it is important to know where the magnetic energy released by reconnection goes, i.e., how it is partitioned among the bulk kinetic energy of the plasma, the electron and ion heating, and non-thermal particle acceleration.

Specifically, non-thermal particles often play an active role in low-density coronal environments. For example, a large fraction of the magnetic energy released in solar flares is believed to go to non-thermal electrons. This raises an intriguing possibility that reconnection may be an important source of cosmic rays. And yet, the efficiency of particle acceleration in reconnection is still not understood. Determining it requires examining the interplay between plasma microturbulence, non-thermal particle acceleration, and various loss mechanisms.

3. *High-Energy-Density Reconnection:* Several important astrophysical phenomena where reconnection has been invoked, namely giant flares in the magnetospheres of magnetars and central engines of gamma-ray bursts, have physical conditions that are very different from those considered in the reconnection research so far. In particular, the energy density in these systems is so high that one needs to take into consideration pair creation, radiation pressure, and radiative cooling. Such high-energy-density reconnection has not been explored so far and represents a new frontier in astrophysical magnetic reconnection.

4. *Non-stationary, turbulent reconnection:* Most classical reconnection models are steady-state and laminar. A new research frontier is time-dependent, turbulent, reconnection (both collisional or collisionless) in very large (especially astrophysical) systems whose global scale is many orders of magnitude larger than the microphysical plasma scales. Modern large-scale simulations (both fluid and PIC) indicate that the nature of reconnection in such systems is going to be profoundly different—they are more prone to virulent secondary instabilities, such as the tearing of a long current sheet, causing it to break up in a chain of multiple plasmoids and probably affecting the reconnection rate scaling. This is a particular example of the interplay between reconnection and turbulence, which is becoming an important theme in reconnection research. It is important for astrophysics because of its relevance for non-thermal particle acceleration [6] and its observable signatures (e.g., radio emission).

Future progress in numerical simulations of reconnection will come both from the expected increases in computer power and from advances in numerical codes. For example, incorporating Coulomb collisions into a PIC code [5] will enable us to bridge the gap between two-fluid simulations, which implicitly assume some degree of collisionality, and purely collisionless PIC studies. These new capabilities will allow us to elucidate the transition between the slow collisional and fast collisionless reconnection regimes.

It is also important to invest resources into developing the analytical theory of reconnection. Indeed, most of the progress in the past decade has been purely numerical and a complete theoretical understanding of reconnection is still lacking. This is important because most astrophysical systems where reconnection takes place are characterized by much greater separation of scales than can be achieved in simulations or in the lab. Although a number of new and promising theoretical ideas, both on the fundamental issues of magnetic reconnection and on its astrophysical applications, have been proposed in recent years, this positive momentum will be lost unless continuously supported.

On the experimental side, we advocate for the next generation, medium-scale laboratory experiments aimed at addressing the above science questions. In particular, a larger size is needed to have better diagnostics that would enable one to address the energy-partitioning problem, including non-thermal particle acceleration. In addition, a larger size will make it possible to reach sufficient scale separation to verify the formation of the so-called Petschek structure, which hasn't been seen in reconnection experiments so far. Also, a longer current sheet is needed to investigate the secondary tearing instability in both collisional (resistive) and collisionless regimes, thus addressing the bursty nature of magnetic reconnection and the associated particle acceleration (which is also one of the key directions of numerical research for the next few years). Finally, the new generation of experiments should enable studies of important global aspects of magnetic self-organization, e.g., the current-sheet formation process and the nonlinear dynamics of multiple current-sheet systems.

Another exciting experimental opportunity in the next decade is the availability of new powerful laser facilities. They will open up the high-energy density (HED) frontier in reconnection research, e.g., by enabling one to study the effects of radiation on HED reconnection, which will have important implications for high-energy astrophysics (e.g., magnetar flares).

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