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An Experimental Plasma Dynamo Program for Investigations of Fundamental Processes in Heliophysics

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Plasma experiments in laboratory settings offer the opportunity to address fundamental aspects of the solar dynamo and magnetism in the solar atmosphere. Experiments are currently under construction that can investigate the self-generation of magnetic fields and related processes in large, weakly magnetized, fast flowing, and hot (conducting) plasmas. These and future experiments will probe questions that are of crucial importance to heliophysics in the solar interior, atmosphere and wind. Uniquely, laboratory plasma experiments coupled with theoretical explorations can serve to calibrate the simulation codes which are being used to understand the solar dynamo, magnetic reconnection and flares in the solar atmosphere, the nature of CMEs, and the interactions between planetary magnetospheres and the solar wind. Laboratory plasma experiments are likely to contribute new understanding complementary to the traditional observational and modeling approach normally used by space physicists.

We argue here that ground-based laboratory experiments have direct connections to NASA based missions and NSF programs, and that a small investment in laboratory heliophysics may have a high payoff. We will use the Madison Plasma Dynamo Experiment (MPDX) as an example, but advocate here for broad involvement in community-scale plasma experiments.

Fundamental plasma processes in heliophysics and connection to NASA missions and NSF programs  The 22-year solar cycle stands out as one of the most remarkable and enigmatic examples of magnetic self-organization in nature. The Sun’s cycles of magnetic activity profoundly affect our modern technological society. Unsurprisingly, solar magnetism is a fundamental focus of current and future NASA missions.

Magnetic fields that emerge at the solar surface as sunspots are built by dynamo action in the solar convection zone. In most solar dynamo models, organized fields are built in the tachocline, an interface layer deep in the Sun at the bottom of the solar convection zone. These magnetic structures then become buoyantly unstable and rise through the turbulent convection to emerge at the surface. After emergence, magnetic reconnection in the solar atmosphere can lead to flares and coronal mass ejections (CMEs) which have substantial impacts on the heliosphere and on Earth’s

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1 This work builds upon excitement in recent years of using liquid metals to study dynamos and will extend these studies to more astrophysically relevant parameters. Use of a plasma for such experiments allows the magnetic Reynolds number (the dimensionless parameter governing self-excitation of magnetic fields) to be approximately a factor of 10 larger than in liquid metal experiments. These experiments will be the first to investigate self-excited dynamos in a plasma, the state of matter that makes up most naturally occurring astrophysical dynamos.
Figure 1: (a) Radial profiles of magnetic diffusivity $\eta$ used in various dynamo models. Shown in grey lines are three representative profiles from 3D convective solar dynamo simulations using the anelastic spherical harmonic (ASH) code [e.g., 1–3]. Also shown is the double-step profiles used in 2D mean-field Babcock-Leighton models that have been used to predict the current solar cycle [4]. The molecular diffusivity for a hydrogen plasma at solar conditions is also shown, multiplied by $10^7$ for display purposes. (b) The Prandtl number $Pr = \nu/\kappa$ (dashed) and magnetic Prandtl number $Pm = \nu/\eta$ (solid) for a hydrogen plasma at solar conditions. Simulations use values of order unity.

magnetosphere in particular. These processes of magnetic flux creation, emergence, and reconnection form many of the driving questions behind the current Solar Dynamics Observatory (SDO), Hinode, the Stereo mission, the very successful Solar and Heliospheric Observatory (SOHO), and the upcoming ground-based NSF Advanced Technology Solar Telescope (ATST). Understanding the origins of the heliospheric magnetic field and the evolution of CMEs in the heliosphere is fundamental to the future Solar Sentinels mission and plays important roles in the future Solar Probe and Interface Region Imaging Spectrograph (IRIS) mission as well. Indeed, the evolution of solar magnetism forms the driving questions behind the Living With a Star (LWS) program at NASA: namely, how and why does the Sun vary, how does the Earth respond, and what are the impacts to humanity?

As a community, we have made significant progress in understanding solar magnetism through a combination of theoretical treatments and observational techniques, but many key components of the solar dynamo remain poorly understood. In particular, the processes behind magnetic buoyancy and the generation of magnetic field through turbulent correlations occur deep in the solar interior and are difficult to constrain with either helioseismic observations or numerical simulations. Magnetic reconnection in the solar atmosphere is likewise poorly understood at present. Our understanding of interactions between the Sun and the Earth have grown tremendously and are greatly facilitated by in situ observations of the solar wind in the near-Earth environment by missions like the Advanced Composition Explorer (ACE) and the Magnetospheric Multi-scale Mission (MMM), but many details of interactions between coherent magnetized plasma structures like CMEs with the Earth’s magnetosphere remain unclear.

A fundamental limitation facing theoretical explorations of heliophysically relevant plasma processes is the vast separation in parameter space between the natural phenomena and the capabilities of even the largest super computers. As one example, cutting edge global-scale solar dynamo simulations run as part of the NASA High-End Computing (HEC) program and as part of the NSF

\(^2\)using for example the Pleiades and Columbia supercomputers
Partnerships in Advanced Computing Infrastructure Teragrid program typically employ turbulent diffusivities which are more than ten orders of magnitude larger than the molecular diffusivities of the solar plasma (Figure 1a). This also applies to the mean-field models which have been used in attempts to predict amplitude and timing of the current solar cycle [e.g., 4, 5]. Yet these simulations still require substantial computational resources and represent a significant investment by NASA HEC and the NSF Teragrid.

It is deeply impractical to consider simulating global-scale dynamo action in the Sun using molecular diffusivities and doing so would likely require a century of further growth in computational resources. Instead, it is vital to formulate better estimates and models of the turbulent transport processes that occur in a plasma under solar conditions. As an example, even the ratio between how quickly magnetic fields are transported and mixed by turbulence compared to the transport of momentum by the same is poorly constrained. Molecular values of this magnetic Prandtl number $P_m$ are of order $10^{-1}$–$10^{-5}$ (Fig. 1b); turbulent values are thought to be of order unity, but this has not been adequately explored for real turbulent transport in a stratified plasma. These problems are not unique to the solar interior, but are true for simulations of photospheric convection that couple to the chromosphere and corona [e.g., 6], and simulations that capture the interactions between the solar wind, CMEs and planet magnetospheres throughout the heliosphere and to the boundary with interstellar space itself.

The growth of computational resources has made it feasible to directly simulate the plasma regime explored by experiments like MPDX. A program of laboratory experimentation that is tightly coupled with significant numerical simulation efforts will lead to new insights into key plasma processes. In particular, these laboratory plasma experiments will likely achieve self-sustaining dynamo action, will explore the dynamics of magnetic buoyancy in a stratified plasma atmosphere, and will explore the interactions between an Earth-like magnetosphere and magnetotail with a solar-wind like plasma flow. In addition to revealing the fundamental underlying plasma processes at work in these systems, these experiments can anchor the computationally intensive simulations which are used to model the solar dynamo, the buoyant rise and emergence of magnetic structures in the solar interior, and interactions of the solar wind and CMEs with the Earth’s magnetosphere.

**The importance of simulations coupled to experiments**  Just as we cannot directly simulate the turbulent conditions of solar convection, we cannot construct laboratory experiments that capture the vast spectrum of scales present in the Sun. Some important physical ingredients acting in solar convection are very difficult to reproduce in experiments: in particular, it is very difficult to produce conditions that mimic the radial self-gravity of systems like the Sun, and experiments that do must generally be conducted at great cost in low-g environments [e.g., 7].

Laboratory experiments provide great opportunities for exploring key physical processes occurring in plasmas under solar conditions, but they cannot capture the integrated global-scale picture. Global-scale couplings between convection, magnetism and rotation are likely crucial to fully understanding the solar cycle as a whole and may be important for understanding eruptive flares and CMEs as well. At present, simulations are the only option for exploring the coupled global-scale system. Simulations can offer insight into processes that are difficult or impossible to directly measure in the laboratory (e.g., the full 3-D velocity field and magnetic field at all points in a volume at all instances in time) and can suggest profitable avenues for additional experimental exploration. But this is not a one-way process: the laboratory experiments validate the codes and inform those

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3using supercomputers at Pittsburg Supercomputing Center (PSC), San Diego Supercomputer Center (SDSC), Texas Advanced Computing Center (TACC), National Institute for Computational Science (NICS), at the National Center for Supercomputing Applications (NCSA), and others
simulations in how to correctly capture processes that currently elude simple theoretical explanation, including turbulent transport, magnetic buoyancy instabilities, and the non-linear couplings that arise between flows and magnetism.

Ultimately, theoretical explorations, numerical simulations and laboratory experiments must work together in a tightly coupled fashion to achieve optimal results. But this is feasible and can yield large and rapid payoffs. In the MPDX experiment for example, this work has begun already for modeling of the dynamo and magneto-rotational instability scenarios using the NIMROD code, which solves the MHD equations with a number of two-fluid extensions. These simulations have indicated that sustained dynamo action is possible and in which parameter regimes this is most achievable. New simulations are exploring the possibility of buoyancy instabilities, including magnetic buoyancy, and suggest that these may be experimentally achievable. Direct comparisons between the numerical simulations and pathfinder prototype experiments are completing the code validation loop even before construction finishes on the main experiment (MPDX). Theoretical explorations of the simulations and the experiment are in turn providing the ultimate link to the plasma astrophysics.

Tightly linked programs of laboratory experimentation and numerical simulation, backed by significant theoretical analysis to understand both systems, offer opportunities for rapid advancement in our understandings of solar plasma physics.

**Status of MPDX and future plasma experiments** Compared to space missions, ground based laboratory experiments can be quite affordable and can be built on rapid timescales. As an example, the MPDX experiment has been funded for construction through the NSF Major Research Instrumentation program with at total device cost of $2.5M (part of which was $750k in cost-sharing from the UW). In 2009 a Plasma Dynamo Kick-Off Meeting, sponsored by the NSF Center
for Magnetic Self-Organization[4] was held to help formulate the scientific program and to provide feedback on the design of the experiment. Funding began in 2009, and the 3 year project is on schedule: 2010 was spent on design and lab remodeling, in 2011 the machine will be assembled, and in 2012 the experiment should be ready for initial operations. An illustration of the experimental apparatus and the Plasma Dynamo Laboratory built around it is shown in Figure 2.

There are significant barriers to running such programs on a community scale. Using MPDX as an example again, after construction there is not yet a program in place to operate this experiment. This experiment is larger than a typical single-investigator NSF experiment and might be considered a medium-scale basic plasma or laboratory plasma astrophysics experiment as called for in the recent Plasma 2010 report from the National Research Council. The operations of such an experiment and the diagnostic requirements are similar in scale to university-scale experiments in fusion research, yet there is no mechanism for funding the operation of a community-based facility such as this. A major challenge is adequately funding the operations of such experiments and also the significant theoretical explorations and numerical simulation efforts which are vital to maximizing the scientific returns of such facilities.

**Heliophysically relevant plasma experiments** Future plasma experiments could directly address many plasma processes that are directly relevant to heliophysics and NASA. Most experimental plasma facilities at present are focused on other science, with substantial investments in exploring basic plasma processes and the application to fusion energy generation. Plasma experiments can now directly address several key components of the solar dynamo and of eruptive events in the solar atmosphere.

A variety of laboratory experiments are feasible in the near future that are clearly heliophysically relevant:

1. large-scale dynamo experiments (generation of the large scale solar magnetic field),
2. small-scale turbulent dynamo experiments (small scale structure of the solar dynamo and surface magnetism),
3. buoyancy driven stratified convection (solar convection zone and surface),
4. magnetic buoyancy instabilities in a stratified atmosphere (sunspot emergence and solar tachocline physics),
5. flow driven plasma turbulence in near-equipartition (solar wind),
6. flow driven plasma turbulence impacting a model magnetosphere (space weather, sun-earth connection),
7. magnetic field line stretching with potentially explosive, flow-driven reconnection (magnetotail, solar flares),
8. plasma instabilities at high $\beta$ and low collisionality (solar wind spectrum).

A program of heliophysically relevant laboratory plasma experiments can provide important insight into these problems. Such a program will surely suggest additional unexpected avenues for research, as expertise is gained in experimental techniques, and in the theoretical and numerical explorations of such experiments.

[4][http://cmso.info/html/meetings/wi_dec09.htm]
The proposed plasma experiments transcend the scope of single user facilities and instead require substantial community-based facilities. Such experiments should be supported at a larger scale than can be undertaken by individual universities and research groups. This support must extend past the mere construction of experimental facilities: instead, significant advances can be achieved by ongoing support for operations, for theoretical explorations, and for tightly coupled numerical simulations. These synergistic efforts are likely to maximize scientific output and may rapidly advance our understanding of plasma processes occurring in the solar interior, atmosphere and wind, whereas isolated efforts must continue to wrestle with intractable limitations. In summary, we advocate that heliophysics could greatly benefit from the support of community-scale, heliophysically relevant plasma experiments.

References

[1] Brun A S, Miesch M S and Toomre J 2004 ApJ 614 1073–1098
[2] Brown B P, Miesch M S, Browning M K, Brun A S and Toomre J 2010 ApJ submitted
[3] Miesch M S, Brown B P, Browning M K, Brun A S and Toomre J 2010 Preprint 1009.6184
[4] Dikpati M and Gilman P A 2006 ApJ 649 498–514
[5] Charbonneau P 2010 Living Reviews in Solar Physics 7 3:1–91
[6] Nordlund Å, Stein R F and Asplund M 2009 Living Reviews in Solar Physics 6 2:1–116
[7] Hart, J E, Toomre, J, Deane, A E, Hurlburt, N E, Glatzmaier, G A, Fichtl, G H, Leslie, F, Fowlis, W W and Gilman, P A 1986, Science 234 61