White Paper for *Frontiers of Plasma Science Panel*

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Title:	**Understanding Magnetic Self-Organization**
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1. Study of Magnetic Self-Organization in Collaboration with Solar Physics Research

When an external force is applied to plasma, the magnetic configuration gradually changes to a new equilibrium while the plasma parameters slowly adjust. If at any point this new state becomes unstable, the plasma rapidly reorganizes itself to a new MHD equilibrium state by forming current sheets, driving magnetic reconnection, and changing magnetic topology. Excess magnetic energy is converted to plasma kinetic energy, and the plasma magnetically relaxes or self-organizes to a lower energy state. One can say magnetic self-organization takes place when there is a need for magnetic field to release its excessive energy stored on global scales. These global magnetic reconnection phenomena have been an important subject to study, including their causes, dynamics, and consequences, being applied to almost all cases of self-organization in magnetic fusion plasmas, magnetospheric plasmas, solar plasmas, and some more distant astrophysical plasmas.

Coronal mass ejections (CMEs)—solar eruptive events that generate hazardous space weather—are typical magnetic self-organization phenomena [Kunow 2006]. A wide variety of scenarios have been proposed for the triggering of CMEs [e.g., Chen 1989, Forbes and Isenberg 1991, Low 1996, Antiochos et al. 1999, Kliem and Török 2006]. Though the details of these models vary, they each share at least one common feature: the existence of a sheared or twisted magnetic field configuration that stores magnetic energy in the corona prior to the eruption. This configuration eventually destabilizes, triggering ideal

instabilities and/or magnetic reconnection events that drive the eruption. A fundamental magnetic configuration that is frequently invoked to explain CMEs is the line-tied magnetic flux rope [Kuperus and Raadu 1974, Titov and Démoulin 1999, Amari et al. 2014]. This is a coherent magnetic structure tied at either end to a fixed boundary such as the solar surface. To help solve key questions regarding the equilibrium and stability of flux ropes in the solar corona, flux ropes and their self-organization have also been studied in the laboratory. In particular, a number of arched flux rope [Bellan et al. 1998, Tripathi and Gekelman 2010, Oz et al. 2011] and linear flux rope [Bergerson et al. 2006, Furno et al. 2006, Lawrence and Gekelman 2009, Stensonand et al. 2012] experiments have been conducted in recent years. These experiments have studied such phenomena as plasma instabilities including the kink instability [Bergerson et al. 2006, Oz et al. 2011] and the formation of current sheets in 3D at so-called quasi-separatrix layers (QSLs) [Lawrence and Gekelman 2009]. Two very recent experiments [Brookhart et al. 2015, Myers 2015] have underscored the prominent role of self-organization and 3D reconnection in modifying the current profiles and force balance in line-tied magnetic flux ropes.

In low-q pinch discharges in laboratory fusion devices such as the spheromak and the RFP (reversed-field-pinch), we observe self-organization events which consist of a slow flux build-up phase followed by a fast magnetic reconnection. One of our objectives is to find a common physics base between magnetic self-organization phenomena in solar corona and laboratory fusion plasmas.

2. Major Scientific Challenges and Opportunities

Despite significant progress in the past decades, there exist a number of outstanding major scientific challenges to be addressed for a better understanding of magnetic self-organization phenomena in solar and laboratory plasmas:

Space observations

CMEs and other solar phenomena are typically studied using a combination of remote observations and numerical modeling. This combination is necessary because, while it is well established that the coronal magnetic field is the dominant force driving CMEs and other coronal activity, the magnetic field cannot be directly measured from remote observations. As such, modeling techniques such as nonlinear force-free field (NLFFF) reconstructions [e.g., Schrijver et al. 2008, Wiegelmann et al. 2008, Savcheva et al. 2012] and magnetohydrodynamic simulations [e.g., Fan 2007, Aulanier 2010] of coronal flux ropes have become essential tools in the study of solar eruptions. Given the prominence of these numerical modeling techniques and the inability of remote observations to adequately constrain the results, a significant opportunity exists to collaborate with the solar community to benchmark modeling results against carefully designed laboratory experiments (see below).

Laboratory experiments

Laboratory experiments provide two unique advantages when studying a remote astrophysical system such as the sun: (1) the plasma parameters can be independently modified; and (2) *in situ* diagnostics such as magnetic probes can be used to directly measure the internal structure of the plasma. As one example, these advantages have recently been applied to study the torus instability as an eruption mechanism in the laboratory [Myers 2015]. The specifics questions being studied are: How does the decay index of the "strapping" field (analogous to the vertical field in a tokamak) affects flux rope eruptions? How the kink instability criteria work in solar coronal flux ropes? A specially designed experiment as used to vary parameters such as the strapping field decay index and identify the stability boundaries. In the initial study

[Myers 2015], the decay index threshold calculated by Kliem and Török has been found to be not a sufficient condition for eruption. Instead, a magnetic tension force due to the self-organized "guide" magnetic field that runs along the flux rope axis plays a central role in determining whether the flux rope erupts. The tension force and its interaction with the guide magnetic field are characterized as a self-organization event that dynamically changes the force balance in the plasma as the flux rope relaxes to a lower energy state. Using this study as a guide, we propose collaborative research opportunities for investigating the dynamics of flux rope eruptions by setting up a laboratory condition in which magnetic flux ropes are generated and carefully studied.

	Parameter	Symbol	Solar	Laboratory
(a)	Driving (buildup) time/Alfvén time	τ_D/τ_A	100–10^4	50–500
	Driving (buildup) time/Resistive diffusion time	τ_D/τ_R	10^{-7}	~ 0.1
(b)	Ion gyroradius/Minor radius	ρ_i/a	10^{-6}	5×10^{-2}
	Electron mean free path/plasma length	λ_{ei}/L	10^{-2}	10^{-3}–10^{-2}
(c)	Lundquist number	S	10^4–10^{12}	$(0.2$–$2.5) \times 10^3$

Table 1: Dimensionless parameters of a typical flux rope in the solar corona and in the laboratory.

Supporting numerical simulations:

Large-scale MHD models have recently been implemented to study eruptive mechanisms such as the torus instability. Additionally, nonlinear force free field (NLFFF) models have been widely used to describe coronal flux ropes. As techniques such as these become increasingly prevalent, their interpretation should be subject to comparison to relevant physical systems such as the laboratory flux ropes described here.

Summary: In order to maximize the value of laboratory plasma research to the solar and broader astrophysical communities, it is desirable to produce quantitative results that can be communicated to those working with relevant solar observations and/or theories. We understand that it is not sufficient to simply report on experimental phenomena that are qualitatively similar to observations of the solar corona. To this end, we should identify a series of scientific deliverables that will solidify the impact of the proposed research: For example, 1. Quantify in detail the criteria (such as the potential field index) that are required to achieve a solar eruption. Furthermore, we will identify the physical mechanisms that are behind the eruptions. The laboratory results will be compared directly to the existing body of theory, simulation, and observational results. 2. Investigation of solar-relevant phenomena that accompany the observed coronal dynamics. We will also investigate and determine how much the magnetic energy is converted to particles during magnetic self-organization events.

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