1 Laboratory Simulations of Eruptive Solar Phenomena

A powerful new technique for investigating the fundamental mechanisms underlying eruptive solar phenomena has recently been developed at Caltech by team member Bellan. This technique uses a pulsed, high power laboratory plasma arranged to have the same boundary conditions as the solar phenomena, and operated in a physics regime governed by the same equations. Because of this equivalence in both physics and geometry, the dynamical behavior and the topological evolution of the lab plasma closely mimics eruptive solar phenomena. Figure (BELLANFIRSTFIGURE.tif) shows a typical photo of one of these laboratory plasmas. Since the lab plasma is quite reproducible and can be diagnosed fairly completely, it is possible to make quantitative comparisons with theoretical models and so validate or invalidate these models. It is also possible to reproduce many of the peculiar phenomena seen in observations (e.g., sigmoids, filamentation, complex topology) and then study these in a controlled setting. This experiment gives a "hands-on" tool for investigating the underlying topological and dynamical essence of eruptive solar phenomena such as CME's, erupting filaments, and flares.

Figure 1: Typical example of laboratory plasma simulating eruptive solar prominence (filament). Distance between footpoints is 8 cm, nominal magnetic field strength is 3-5 kG, plasma current is 30 kA, lifetime is 10 μs. The plasma β, topology, and dynamics are similar to what is observed on the sun.

1.1 Methodology

The technique for making these laboratory simulations of coronal structures is s-ketched in Figure 5(BELLANSECONDFIGURE.ps). A magnetic bipole (horse-shoe magnet) mounted on the wall of a large vacuum chamber creates an initial quasi-stationary, arch-shaped, potential magnetic field of a few kilogauss which protrudes into the vacuum chamber. A plasma is formed via electrical discharge in the region between the magnet poles and then a current is driven from one magnet pole to the other by a high energy capacitor bank. Initially, when the current is small, it simply follows the arched potential field lines [cf. Fig. 5(b)], but as it increases to 10's of kiloamps, it self-pinches, causing its cross-section to become uniform along its length, just like an erupting solar filament. The self-field also causes the current channel to twist and writhe [cf. Fig. 5(c)], again like a solar filament. Finally, for very large currents the upward current on one leg of the prominence and the downward current on the other leg mutually repel leading to a bulging of the major radius of the current channel [cf. Fig. 5(d)]. This bulging stretches the original potential field and, if sufficiently strong, leads to eruption.

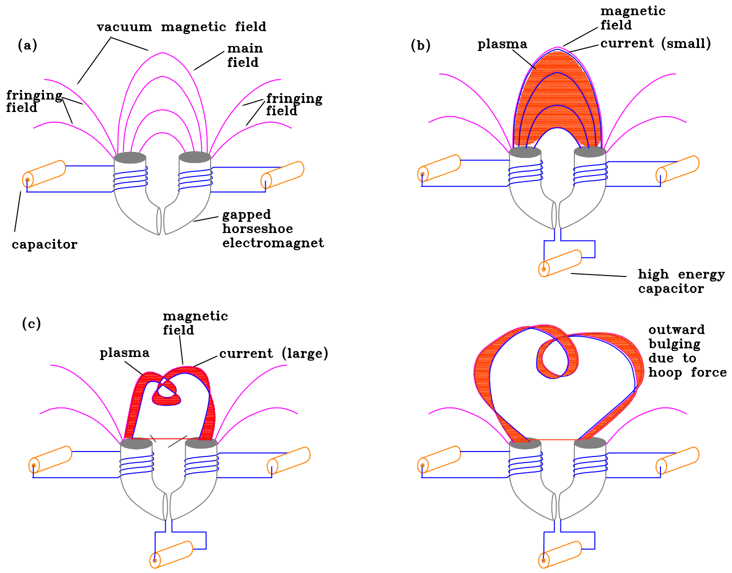

Figure 2: Experimental method: (a) initial vacuum field from gapped horseshoe magnet, (b) small plasma current follows initial arched field lines, (c) large plasma curent causes field lines to pinch and twist, (d) very large current causes arched field lines to bulge outwards.

Besides manifesting the fundamental magnetohydrodynamic forces believed to govern eruptive solar phenomena, the experiments so far have reproduced many important details. In particular, the lab plasmas display sigmoidal shapes (when viewed from above), and develop smaller braided filamentary structures which are both twisted and interwoven. The most recent set of experiments have demonstrated that an over-arching arcade field can inhibit eruption and quantitative measurements indicate that the required strength of this larger scale arcade field is in good agreement with the predictions of a three-dimensional MHD force-balance model.

1.2 Research plan

Both theories of eruptive solar phenomena and these experiments show that the behavior of complex coronal structures such as CME's, flares, and filaments is primarily determined by two independent types of boundary conditions on the solar surface, namely (i) the magnetic field normal to the surface $\mathbf{B}_n$ and (ii) the plasma velocity tangential to the surface, $\mathbf{U}_{\tan}$. By itself, the normal magnetic field produces static, arched potential fields. The addition of cyclonic tangential velocities twists up these arched fields leading to bulging, sigmoidal shapes, and finally eruption. Both the normal magnetic field and the tangential plasma velocity are independently adjustable in the lab experiment. The normal field can be adjusted by using different electromagnet arrangements (e.g., four magnet poles instead of two, different spacings between poles, different symmetries, strengths, geometrical extents, or complexities). The tangential plasma velocity can be adjusted by changing the surface distribution of the electrostatic potential $\phi(x,y)$ imposed by the capacitor bank. This is because the tangential velocity at the surface is just $\mathbf{U}_{\tan} = -\nabla\phi(x,y) \times \mathbf{B}_n(x,y)/B_n^2$ so that local maxima or minima of potential (such as are produced by electrodes) create cyclonic plasma velocities in the plane of the surface. The effect of changing the normal magnetic field has been clearly demonstrated by using several different magnet configurations. Control of the tangential velocity $\mathbf{U}_{\tan}(x,y)$ has also been demonstrated by using different shapes of ground plane electrodes (solar surface). The chirality (handedness) of the twist has been changed by reversing the polarity of $\mathbf{B}_n$.

Systematic studies of various topological configurations will be undertaken and the relationship of topology to eruption will be elucidated. Erupting filaments have been produced in the experiments to date. By careful control of the surface velocity shear profile, it is planned to reproduce the more complicated situation of a CME overlying a filament. Precursors for eruption will be examined, for example the degree of sigmoidal behavior prior to an eruption.

The experiments have also shown that the visual appearance of a simulated prominence (filament) depends strongly on the angle from which it is viewed. This is because, as with solar plasmas, the simulated prominence is optically thin and so the optical depth of what is being viewed strongly affects the observed brightness and hence the perceived image. This important perception issue will be investigated in detail by photographing various structures from different points of view and by making 3D images using an existing high-speed stereo camera system.

As an additional part of this activity, the lab plasma setup will be upgraded to produce a direct simulation of the Sun-Earth connection. An expanding, propagating lab prominence will play the role of a helicity-laden magnetic cloud propagating through interplanetary space. By placing a small dipole magnet in the path of the expanding helical flux tube, a situation analogous to the Sun-Earth connection will be established. The interaction between the large propagating helical field and the much smaller static dipole field will be studied. This experiment will show how magnetic clouds shed from the sun by an eruptive solar event affect Earth's magnetosphere.

The lab experiments will be both highly visual and quantitative and so will have a strong connection to both solar observations and the various theoretical models attempting to describe these observations. The experiments are expected to provide compelling, quantitative insight into the fundamental physics governing CME's and filament eruptions and also the topological issues relating to these phenomena.