“Understanding Magnetic Eruptions on the Sun and their Interplanetary Consequences”

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I. Introduction

The goal of our MURI project is to develop a state-of-the-art, observationally-tested 3-d numerical modeling system for predicting magnetic eruptions on the Sun and their interplanetary consequences.

This project is motivated by the fact that the Sun drives the most violent space weather events. The mechanisms that trigger and drive these eruptions are the least understood aspects of space weather. A better physical understanding of how magnetic eruptions occur and how these disturbances propagate will surely lead to more accurate and longer range forecasts.

To achieve our goal, a great deal of research is necessary before such a modeling system will work. In particular, careful analysis of existing and future data on the origins of coronal mass ejections is needed. Much of our project is therefore devoted to data analysis and the development of new instrumentation. We must also perform research on understanding the basic physics of what causes magnetic fields on the Sun to erupt. Further, we must develop and test the required numerical models and couple them together. To summarize our approach:

- Perform in-depth, coordinated space and ground based observations of magnetic eruptions and Coronal Mass Ejection (CME) propagation, and develop new instrumentation where needed
- Understand the physics of how magnetic eruptions are triggered and powered
- Develop numerical models for the initiation and propagation of CMEs and the acceleration of Solar Energetic Particles (SEPs)
- Couple together the observationally tested models of the Sun and Heliosphere

Our team is a consortium of about 25 scientists from 9 Universities. In addition to UC Berkeley, our team includes scientists from the University of Hawaii, Stanford University, the NJIT Big-Bear Solar Observatory, UC San Diego, Montana State University, the University of Colorado, Drexel University, and the University of New Hampshire.

![Figure 1](image1.png)

**Figure 1** - The 9 US Universities that are a part of our MURI project.

Our team of multi-disciplinary scientists work on many different aspects of the Sun-Earth system.

![Figure 2](image2.png)

**Figure 2** - Diagram illustrating the Sun-Earth system and its schematic relationship to CMEs.

CMEs and Eruptive Flares are Magnetically Driven

There are typically several CMEs per day, and these are the primary driver of violent space weather. Where does the energy that drives CMEs come from? Terry Forbes, a
member of our team from UNH, has argued convincingly that only the solar magnetic field has enough energy to power these events. The main issue is to understand how this energy is extracted from the magnetic fields into the energy of eruption, and to develop a predictive model that starts from a knowledge of the solar magnetic field and then follows it into an eruption.

The accurate measurement and usage of solar magnetic field data is the key to a Physics-based forecasting model for solar eruptions. Knowledge of the 3-d vector field is essential, since the field is not uniquely specified by line-of-sight measurements. A main focus of our team since the project began has been to develop the machinery needed to use real, time dependent solar magnetic field data as the driver of time-dependent MHD models. We have selected 2 observed events for detailed study and modeling, the May 12 1997 event (also a SHINE event), and the May 1 1996 event. In addition, we have added the Oct 29 2003 event to our cases for detailed study.

This year, in addition to a summary of all of our ongoing work, we report one major milestone -- namely the development of a completely new 3D MHD code, “AMPS”, that we feel is absolutely essential for a physically correct treatment of the interface between the tenuous solar corona and the dense layers of the photosphere and below.

II. Major Milestone: Development of the AMPS code

As part of the ongoing effort to incorporate vector magnetic field data into MHD simulations of the solar atmosphere, Bill Abbett (UCB) has developed a completely new MHD code capable of self consistently simulating the transition layers that couple the sub-surface turbulent convection zone to the low-density corona. The new code, AMPS (Adaptive Magneto-hydrodynamic Parallel Solver) is not only capable of simulating the low-to-high beta transition, but can simulate the energetic transition between the sub-surface, surface, transition region and coronal layers. Briefly, AMPS is a 3D semi-implicit Newton-Krylov solver that uses a high-order CWENO conservative shock capturing scheme to determine numerical fluxes at cell interfaces. The PARAMESH libraries, developed by MURI team member Peter MacNeice at Drexel University, provide the necessary domain decomposition and AMR capability. The semi-implicit treatment of energy source terms (e.g., anisotropic Spitzer thermal conduction and optically thin cooling in the model corona) provide the means necessary to eliminate overly-restrictive timestep constraints, and allow us to more accurately treat the energetic transition between the turbulent photosphere, and the hot corona (see Figures 3-4 for a test example of a combined convection zone, photosphere, chromosphere, and corona Quiet Sun simulation).

Figure 3 - view from above of a photospheric slice of the temperature in a quiet-Sun magneto-convection simulation.

The Newton-Krylov implicit solver allows us to filter fast-moving magneto-acoustic waves in the corona, thereby eliminating the temporal disparities inherent in driving coronal simulations with month-long time series of photospheric vector

Figure 4 – vertical slice viewed from the side, showing the magnetic field strength extending from below the photosphere into the tenuous corona.
magnetograms. These temporal disparities are a significant technical challenge - timesteps that are Courant limited by fast-mode waves in the corona necessarily introduce artificial diffusion in the photospheric layers of the model (this numerical diffusion is particularly problematic if the time scales extend of the typical lifetime of a strong active region). Thus, we will evolve the system implicitly until such a time that it is necessary to follow the detailed coronal dynamics (e.g., before an eruptive event), at which time we reduce timesteps to follow evolution occurring at coronal Alfvén speeds. The data assimilation occurs at the photospheric interface of AMPS, and we are currently incorporating ILCT and/or MEF flows into our "active" boundary layer to simulate in a more realistic way (soon over much longer timescales) the coronal evolution of AR-8210.

The testing of AMPS is nearing completion, and a paper describing the code is being prepared for publication. Our first realistic data-driven simulation is forthcoming.

### III. Research Accomplishments Over the Past Year

#### Instrument Development

Developing and improving instrumentation for measuring solar magnetic fields continues to be an important component of our MURI project, as the following work from NJIT/BBSO and UH shows.

The measurement of small-scale and weak-intrinsic magnetic features (known as intranetworks, IN) located inside supergranules, is essential for our understanding of solar magnetism. However, the detection and observation of IN elements are rather scarce due to their smallness and weak magnetic field strength. The Infrared Imaging Magnetograph (IRIM) developed by the Big Bear Solar Observatory (BBSO) has been put into operation. IRIM is one of the first imaging spectro-polarimeter working at the Fe I 1.5649 μm line, the solar deepest photospheric observation, and therefore combines the advantages of the infrared Zeeman sensitivity with the capability of spatial mapping. It makes the measurement of intrinsic magnetic field strength feasible.

The concept of the design has been described by Denker et al. (2003). A three-stage filter system including an interference filter, a bi-refringent Lyot filter and a Fabry-Perot etalon in tandem is used to obtain ~0.1 Å bandpass over a FOV of 145’×145’ in a telescopically configuration. The post-focus instruments include adaptive optics (AO) system, IRIM and its visible counterpart Visible Imaging Magnetograph (VIM). They are arranged on a stable optical table in a constant-temperature Coude room. The detector is a 1024×1024 liquid nitrogen cooled HgCdTe CMOS focal plane array (FRA) with a image sensor chip TCM8600. The quantum efficiency is better than 50% in NIR. Four stacks of calcite module sandwiched between linear polarizers are combined to acquire 2.5 Å bandpass with a diameter of 36 mm. The nematic liquid crystal variable retarders (LCVR) are attached to each stack to tune the bandpass in range of ±100 Å. The polarization optics for measuring the longitudinal magnetic field, as currently constituted, consists of a fixed λ/4 wave plate, a LCVR oriented at 45° to the polarized axis of the Lyot filter and NIR linear polarizers. The left and right circularly polarized Zeeman components are converted to orthogonal states of linear polarizations by the initial fixed λ/4 wave plate. The modulator utilizes Liquid Crystals to electrically switch the central wavelength between 0 and λ/2. The integration time for

![Figure 5 - an IRIM magnetogram compared to the corresponding MDI magnetogram. Clearly the IRIM magnetogram illustrates the features of networks and intranetworks with the unprecedented spatial resolution.](image)
each accumulation and the number of accumulations can be set in accordance with the desired signal-to-noise ratio. On 2005 July 1, IRIM with assistance of the CT and AO system observed NOAA Active Region 10781 at N14E23. The data is over-sampled by a factor of 2.17 of diffraction limitation at 1.5649 μm for the BBSO’s 65 cm solar telescope. The present image scale is 0.15” per pixel. We use 200 msec integration time and 40-frames integration for each image.

The UH MURI effort continues to center on improving magnetic diagnostics of the photosphere and above in order to improve the MHD modelling efforts. The demonstration of a coronal magnetogram during the last reporting period has led to significant instrument improvements that will make coronal B measurements more routine in the future. Foremost has been the completion of a large format IR array camera (2K x 2K pixels) which will be the largest infrared array being used for solar physics. This instrument will be available for use with the coronal magnetometer during the next development cycle.

We (primarily Lin) continue to improve the fiber-based imaging spectrograph technology. The new spectrograph will have an effective spatial sampling of 64 x 64 fibers (8 times larger than the current system) which will allow coronal spatial resolution of about 5 arcseconds and covering 300 arcseconds square. The optical throughput will also be improved by a factor of 2-3 in the new spectrograph optical design.

The Buildup and Storage of Coronal Magnetic Energy

One of the biggest efforts of our MURI project has been developing the techniques to use magnetic field measurements, both line-of-sight and vector magnetic fields, to determine how the coronal magnetic field is energized by the emergence and cancellation of magnetic flux, and by photospheric motions in general. This work is absolutely required by any kind of future physics-based forecasting model of the Sun. Contributions to this research area were made by team members at UH, Montana State, Stanford, and UC Berkeley.

Our MURI workhorse vector magnetometer, the Imaging Vector Magnetograph at UH, is now also measuring fields higher in the solar atmosphere. Most of this effort (primarily Nitta, Mickey, and Li) has been devoted to Sodium resonance line observations -- a tool for revealing the chromospheric field. In combination with a few daily Iron-line survey magnetograms we continue to provide unique vertical-field information to the modelling community. Iron and Na-D vector magnetograms were acquired for all active regions during this period and H-alpha coronagraphy and H-Alpha spectro-heliograms were obtained for Max-Millennium regions. UH Researcher J. Li continues to assist with IVM data reduction and has finished a phenomenological analysis of several flaring regions.

One well-known set of techniques for deriving boundary flow information from both line-of-sight and vector magnetograms is “Local Correlation Tracking”, or LCT, in which changes between 2 consecutive magnetograms is attributed to a flow field, and an inference of the flow field is made from the apparent motion of sub-images. At UCB, we have developed our own LCT technique dubbed “FLCT” (Welsch et al. 2004). During the past year, Fisher & Welsch have worked to improve the speed of FLCT over the original code described in Welsch et al. (2004). We have written new versions in both IDL and C that have improved the execution speed of FLCT by a factor of ~10 over the original version, and have publicly posted the new source code and executables at http://solarmuri.ssl.berkeley.edu:~fisher/publ ic/software/FLCT.

By combining flow velocities from LCT with vector magnetic field measurements, and requiring that the flow fields obey the magnetic induction equation, our MURI team has developed 2 velocity inversion techniques, “ILCT”, and “MEF”. At a recent workshop organized by UCB team member Brian Welsch and held in Sonoma, these and other velocity inversion methods were compared in a hare-and-hounds exercise – in this case there are known flow fields.
associated with a series of synthetic vector magnetograms generated from MHD simulations of magnetoconvection, carried out by Bill Abbett (UCB). Welsch is now preparing a manuscript describing this work, with collaborative help from Drs. Kanya Kusano, Dana W. Longcope, and Manolis Georgoulis.

Longcope (MSU) worked on characterizing helicity injection by photospheric flows. He worked with B. Ravindra, Colin Beveridge and Graham Barnes (NWRA/CoRA) on developing a method to decompose a flow field into braiding helicity and spin helicity contributions. This method was then applied to 48 hours of observations of AR 10486 (2003-10-27). Ravindra calculated local-correlation-tracking flow fields. Barnes and Longcope then generated partitions of the MDI magnetograms and used these to calculate braiding and spin helicities. Using this characterization it is possible to estimate the coronal magnetic energy stored by the motions. The work was presented and further developed at a small workshop hosted by MSSL/UCL. The present status of the AR10486 analysis is summarized on the web site http://solar.physics.montana.edu/dana/ar10486/

Ravindra, working with Longcope, tested the Minimum Energy Fit (MEF) code on the spheromak magnetic field and a sequence of vector magnetograms of AR 8210 and confirmed the results presented in Longcope (2004). He extended this work to the whole available time series of magnetograms with different time steps and with different number of averages of magnetograms. To constrain the velocities in MEF he introduced the horizontal velocities from the Local Correlation Tracking (LCT) method. He then tested this modified code on the active region AR 8210 time series.

Ravindra then applied the modified code to the velocity patterns in active region AR 10486. He and Longcope modified the code to study the change in the magnetic helicity flux close to the time of the flare event in AR 10486 on 28 October 2003. He also extended this work on 29th October and 02nd November 2003 magnetogram data sets.

With collaborators Dr. C. Rick DeVore and Dr. Spiro Antiochos at the Naval Research Lab, Dr. Welsch continued MHD simulations of the prominence formation process. The central result of this research was that convergence of opposing magnetic fluxes at the model photosphere, leading to their annihilation in a process known as cancellation, leads to magnetic reconnection, while shearing the opposing fluxes past each other does not, effectively, lead to reconnection. Dr. Welsch was lead author on a paper summarizing this work, "Magnetic Reconnection Models of Prominence Formation," that has been accepted by the Astrophysical Journal and will be published in November 2005.

A significant result of this work was the observation that the process of flux cancellation led to an increase in free magnetic energy in the simulation volume. Free magnetic energy is the difference between the magnetic field's actual energy, and the field's minimum possible energy, equivalent to the energy of the potential (current free) magnetic field matching the same boundary conditions. The evolution of free energy is of interest because flares and CMEs are, essentially, powered by the release of free magnetic energy. To explain this intriguing result, Dr. Welsch derived an expression for the free energy flux (FEF) into the coronal magnetic field, by first deriving an expression for the change in minimum magnetic energy as a function of time dependent boundary conditions. He then applied this formalism to simple theoretical models of boundary evolution during cancellation, and showed that cancellation can increase the free magnetic energy. He submitted a manuscript describing this work, "Magnetic Flux Cancellation and Coronal Magnetic Energy," to the Astrophysical Journal in June 2005; this manuscript is now in press.

This FEF formalism can, however, be applied in much more general situations than the special case of cancellation. This technique, combined with velocities derived from time series of vector magnetograms (e.g., ILCT and/or and MEF [Longcope 2004]) can be used to determine the flux of free magnetic energy through the
photosphere. The application of this technique to actual magnetograms is demonstrated for a subregion AR 8210 in the attached images: the left shows the normal magnetic field in grayscale, and the actual (red) and potential (aqua) magnetic fields at the photosphere; the right shows ILCT velocities (Welsch et al. 2004) as blue arrows, and the corresponding free energy flux (grayscale). The fluence of free energy across the full magnetogram area, over the four hour sequence of observations, is approximately $8 \times 10^{30}$ erg, a significant fraction of the energy released in the subsequent flare and CME.

Figure 6 – Left side shows comparison of transverse fields between vector magnetogram msmts (red arrows) and potential field (aqua). Right side shows computed fluence of free energy (grey-scale) and flow velocities (blue arrows).

In another study of magnetic energy evolution, Stanford team member Y. Liu, in collaboration with L. Tian (Rice U.) studied the long-term evolution of an active region lasting 5 solar rotations, in terms of the kink instability.

CME Initiation

Over the past year there were a number of investigations of CME initiation mechanisms, including both observational and theoretical studies, from team members at Berkeley, MSU, Drexel University, and UNH.

At UCB, Yan Li, in collaboration with Janet Luhmann, has been studying the magnetic field topology at CME source regions, especially for quiescent-filament-related CMEs. This study puts current theoretical CME models to the test by comparing with observational data. Two contending CME models, the “Breakout model” and the “flux cancellation model”, require different magnetic field topologies in a CME source region. Our study found both topologies exist on the Sun and are able to initiate CMEs. The “flux cancellation model” topology appears to be more common among 66 cases that we are able to identify during years 1996 to 2004. The “Breakout model” topology is also found each year except for the 1996 solar minimum, and has a much larger number in 2003 (two years after solar maximum) than any other year, but still slightly less than the “flux cancellation” case in that year. Some of our results were presented at 2005 AGU spring/SPD joint assembly and the SHINE workshop 2005. A paper is in preparation for a journal publication.

At MSU, Canfield worked with REU student Ji Son and Loren Acton to study the internal structure of erupting sigmoids from SXT and TRACE data. The work produced evidence that the kink instability, which requires a systematic relationship between kink and writhe of erupting flux systems, is not the dominant mechanism for solar eruptions. He finalized a paper with Stephane Regnier on AR 8210, in which the flow of magnetic energy and helicity through the photosphere and the occurrence of flares are documented. The basic conclusion of the work is that the magnetic helicity content is dominated not by self helicity, but by mutual helicity, which arises from the complex topology of the region.

At Drexel University, Peter MacNeice and his colleagues have concentrated on exploring the breakout process in an asymmetric configuration. They have experimented with shearing the central flux system and each of the side flux systems, and have also performed high resolution simulations with a view to exploring the shock structures produced in the neighborhood of the ‘flare’ reconnection. The analysis of these calculations is still in the preliminary stages, but they have already found evidence to suggest that, (a) the asymmetric case behaves in a similar way to the symmetric case in all essential respects, (b) the rapid acceleration phase may well be the result of the loss of equilibrium, (c) there is evidence of a complex time series of shock structures in the region of the flare reconnection which may play a role in making the flare hard X-
ray emission bursty, as is observed, (d) they have studied the reconnection rate during the breakout process in great detail, and can identify different phases associated with the reconnection of sheared flux and later reconnection of unsheared flux, (e) they have studied the re-distribution of helicity during the reconnection and its association with the reconnection rate, (f) shearing of the side flux systems can also produce eruptions, however these are energetically much less favored.

Of these conclusions, the most important are the evidence for loss of equilibrium and the evidence of intermittent shocks in the flare region.

The evolution of the asymmetric eruption appears to be more consistent with the notion that loss of equilibrium leads to the rapid acceleration of the flux rope. In the asymmetric case, they see a more pronounced propagation of radial momentum originating from the flare reconnection site. In addition they observe that the breakout reconnection rate has achieved its maximum value and maintains that value for some time, during which the location of the breakout reconnection shows no sign of any significant acceleration. It is only shortly after the flare reconnection begins that the outer X-point accelerates rapidly. During this phase one sees a strong radial momentum flux radiating out from the flare reconnection site, and the outer X-point does not begin accelerating until this momentum wave arrives.

High cadence movies of the flare reconnection region from our highest resolution runs have been made (Figure 7). These show tantalizing signs of shocks created by accelerated flare plasma driven downward into the closed loop system below. By itself this is not surprising. However the impact of this accelerated material disturbs the lower loop system causing asymmetric Alfvén waves, and presents the prospect that the resulting sequence of shocks which form may vary rapidly back and forth between quasi-parallel to quasi perpendicular. Since these two regimes have very different particle acceleration efficiencies this may be the cause of much of the burstiness of hard X-ray flare emissions. Further high resolution runs are planned in which they hope to better separate the Alfvén and sonic timescales, and demonstrate more obvious shock structure. Understanding filament and prominence structure and prominence formation mechanisms is important because of the strong association between CMEs and erupting filaments and prominences.

At UNH, Terry Forbes and collaborators, including graduate student Kathy Reeves, have undertaken 2 investigations germane to CME initiation. First, they have developed a new line-tied analytical model of an emerging flux rope based on the model of Titov & Démoulin (1999) which is itself an extension of an earlier 2D model of Forbes & Priest (1995). The magnetic configuration of the Titov and Démoulin model has been used as an initial state for several numerical investigations (e.g. Roussev et al.2004), Török et al.2004), but the model has several important limitations. Unlike the earlier 2D model of Forbes and Priest, the Titov and Démoulin model provides no way to evolve the magnetic field while keeping the normal component of the magnetic field at the photospheric surface fixed. Thus there is no way to evolve it without violating the condition that the magnetic field at the solar surface is line-tied, an essential condition for any flare model. Consequently, the Titov and Démoulin model is also unable to address the conditions needed to trigger an...
eruption. The new model that we have developed during the last year removes this limitation.

Figure 8 Cross sections of the magnitude of the magnetic field for the initial and displaced field configurations of the analytical emerging flux rope model. The white vectors in the right panels show the forces acting on the flux rope when it is displaced from the initial equilibrium. Near the surface the forces always act to restore the flux rope to its initial position, but at greater heights the forces act to push the flux rope upwards, and to twist it out of the plane. Red areas correspond to regions of strong magnetic fields and violet areas to regions of weak magnetic fields.

To incorporate the effects of line-tying, we used the method of images to construct a more general field configuration which allows the position of the flux rope to move while the normal component of the magnetic field at the photospheric boundary remains fixed. The vector potential and field components of the new configuration are expressed explicitly in terms of functions involving incomplete elliptical integrals, and it includes the Titov and Démoulin configuration as a special case.

Preliminary analyses of the equilibrium and stability properties of the new model have already proven useful in interpreting aspects of the recent simulations of Török et al. (2004) and Kliem et al. (2004). In their numerical experiments of the kink instability based on the Titov and Démoulin configuration, they found that their unstable flux ropes were nearly as susceptible to kinking in a downward manner as they were to the usual upward kink. This outcome was unexpected, since the highly conducting surface at the base should repel the flux rope. Our new model explains this result by showing that unstable Titov and Démoulin flux ropes possess stable configurations at lower heights. As discussed in the caption of Figure 8, our analysis also accounts for the aneurism effect. Because of the effects of the line-tying the sections of the flux rope near the surface are more stable then the section at higher altitude. Thus, when an eruption does occur, the sections near the feet of the flux rope do not participate in the eruption. The new model also explains why the flux rope twists out of the plane when it moves upwards.

Forbes and graduate student Kathy Reeves have recently completed a theoretical analysis of the thermal radiation emitted by large, eruptive flares (Reeves and Forbes 2005). The analysis is based on the configuration shown in Figure 9 which consists of an upward moving magnetic flux rope with a vertical current sheet below. Reconnection at the current sheet converts the magnetic energy of the plasma flowing into the sheet into kinetic energy and heat. The analysis assumes that at least half of the Poynting flux into the sheet is channeled along field lines to the chromosphere where it drives an upflow of dense plasma. This process is known as a chromospheric evaporation, and it leads to the formation of a system of thermal flare loops as shown in Figure 9.

The temperatures and densities resulting from chromospheric evaporation were calculated using the simple evaporative cooling model of Cargill et al. (1995). These values were subsequently used to determine theoretical flare light curves for the Transition Region and Coronal Explorer (TRACE), the Soft X-ray Telescope (SXT) on the Yohkoh satellite and the Geostationary Operational Environmental Satellite (GOES). When the background magnetic field strength is weak, the emitted radiation emitted is too faint to constitute a typical flare. The analysis also shows that the correlation between the speed of material ejected as a coronal mass ejection (CME) and any associated flare is not straightforward. For example, it is possible to have two CMEs with nearly the same
trajectories and speeds but for which there is a tenfold difference in the peak intensities of their light curves.

Figure 9 - Predicted temperature distribution and evolution of flare loops obtained from flux rope model of Lin and Forbes (2000) and the chromospheric evaporation model of Cargill et al. (1995). The temperatures range from 30 million K (magenta) to 2 million K (dark blue). The case shown is for a photospheric background field of 50 G. The left panel corresponds to a time of about 200 s after onset and the right panel to a time of about 2600 s after onset.

The magnetic configuration used for the calculation is derived from the eruptive model of Lin and Forbes (2000). This model is based on a loss of global, ideal-MHD equilibrium in a flux rope which is suspended in the corona by a balance between magnetic tension and compression. Equilibrium is lost when the magnetic boundary condition at the photosphere is slowly evolved to a critical point where a balance between compression and tension is no longer possible. When this point is reached, the flux rope erupts outwards to form a vertical current sheet as shown in Figure 9.

From our analysis we have found that the fraction of the released magnetic energy that goes into thermal energy depends strongly on the reconnection rate at the current sheet. As a measure of the reconnection rate we use $M_A$, the Alfvén Mach number at the midpoint of the edge of the sheet. For $M_A$ near unity only about 15% of the total magnetic energy in the configuration is converted into the thermal energy of the flame. The remaining 85% is channeled into the kinetic energy of the ejected mass. However, as the reconnection is made more difficult (e.g. by reducing the electrical resistivity of the plasma), the percentage of the total magnetic energy which is thermalized increases. For $M_A = 0.01$, about 80% of the energy is thermal and only about 20% is transferred to the kinetic energy of the ejecta. These variations reflect the fact that as the reconnection rate decreases the current sheet becomes longer, so that even though the rate at which magnetic energy flows into the sheet decreases, the net Poynting flux into the current sheet increases. As $M_A$ tends to zero, the thermal energy eventually goes to zero in the absence of any reconnection.

Figure 10 - Left Panel: Initial configuration of the three-dimensional analytical model developed by T.G. Forbes and P.A. Isenberg. Right Panel: Plot of the normal magnetic field component at the surface corresponding to the photosphere (lower surface of the box in panel at left). During the upward displacement of the configuration, this field component does not change because of the effects of inertial line-tying.

The Global Solar Corona

Studies of the large scale corona were undertaken by team members at Stanford and UC Berkeley.

The Stanford group has developed a new method for generating MDI high-resolution synoptic maps of the solar magnetic field.

As adaptive grids are being adopted in various dynamic coronal models in space weather research, it becomes necessary to provide, simultaneously, the whole surface distribution of the photospheric magnetic field; one that contains the real metastable field configuration plus the newly emerging magnetic features at the time of interest. MDI synoptic frames with high spatial resolution provide such a proxy of the
instantaneous global surface distribution of the photospheric field.

Synoptic frames consist of a magnetogram observed at the time of interest inserted into the synoptic charts around the specific time. We both improve the MDI synoptic charts around the time of interest and also eliminate the effect of the differential rotation in the merged synoptic frame at the specific. We recently found that the zonal polar field of each high resolution MDI synoptic chart between September 1996 and March 2003 varies as \((\sin(\text{latitude}))^8\), consistent with the finding from low-resolution WSO magnetograms in the 1970’s. Based on this result, we fill the data gap in the polar regions for MDI synoptic charts. The success rate of the prediction of the heliospheric current sheet crossing using 107 MDI synoptic charts between June 1996 and June 2004 reaches 86%, higher than that using WSO or KPNO synoptic charts (Zhao, Hoeksema, Liu, and Scherrer, 2005).

The effect of the advection of magnetic features on synoptic frames has been estimated and for the time interval ranging from 4 to 14 days the effect of the differential rotation of magnetic features accounts for most of the surface transport of photospheric magnetic fields. We show that the locations of the neutral line and of footpoints around the time of interest calculated using the synoptic frame with the effect of differential rotation eliminated are somewhat improved (Zhao, Hoeksema, and Scherrer, 2004).

Our Stanford team members have also been working on global-scale coronal MHD models. The reconstruction of the three-dimensional MHD coronal structure is one of the important approaches for studying the solar corona, solar wind and space weather predictions. This approach utilizes the observable quantities of the Sun, such as the magnetic field at the solar surface and the plasma at the base of the solar corona, to determine the unobservable three-dimensional features of the solar wind and solar corona.

Because the solar corona is sub-Alfvenic, it is necessary to perform time-dependent MHD simulations to retrieve the whole coronal structure. In addition, it is quite important to develop an adequate treatment of the computational boundary at the sub-Alfvenic solar surface region in order to fully utilize the data of the solar coronal observation.

In this context, we have developed an MHD simulation code that is based on:
1) the TVD-MUSCL method, which is one of the standard methods for MHD simulation and is also widely used in various field of computational fluid dynamics (CFD), and
2) the projected normal characteristics method, which can deal with the sub-Alfvenic boundary on the basis of mathematics and physics. Because the available solar observations cannot fully determine the physical conditions required to start the simulation, we currently imposed a mass flux limitation on the solar surface. A new equation system has been established with this reasonable assumption. The details of our new efforts are described in Hayashi, Ap.J.Supp., 2005.

The violent solar eruptions of October and November 2003 can be considered as extreme events in terms of both their occurrence and heliospheric consequences. Hoeksema and Liu (Stanford) have investigated how these storms changed the global-scale coronal magnetic field. Hoeksema (2004) investigated the causes and effects of the super-storms associated with the magnetic field in the corona and the heliosphere, and explored how the strong active regions that produced the events affected the solar cycle evolution of coronal structure and the location of the heliospheric current sheet. Gopalswamy et al. (2005) determined the extreme characteristics of these events, in terms of the CMEs being much faster, wider, and more energetic with a much higher rate of halo occurrence; they were highly geo-effective, and associated with large solar energetic particle events. Liu (2005) investigated the large scale magnetic fields associated with the active regions and their effects for the associated events.

Ledvina (UCB) has been performing global synoptic map driven MHD simulations with Zeus3D of the pre-eruptive magnetic field configurations of Carrington rotations 1922
and 1935, corresponding to the May 12 1997 and May 1 1998 MURI events. In the figure below we show the simulations of the coronal magnetic field near the sun and the corresponding heliospheric current sheet for CR1922 (right) and CR1935 (left). We are validating these results against simulations performed with the SAIC MAS code available at the CCMC. Future simulations will investigate what magnetic configuration the corona relaxes to after the eruption of the CMEs (based on the updated synoptic maps). We will perform further MHD simulation of other Carrington rotations in order to try to understand how sensitive the large-scale magnetic topology of the solar corona is to active regions and low latitude coronal holes.

Figure 11 – Structure of the global solar corona and heliospheric current sheet for Carrington rotations 1935 (left), and 1922 (right), corresponding to the May 1 1998 and May 12, 1997 MURI events, respectively.

CME Propagation in the Heliosphere

University of Colorado MURI team member Dusan Odstrcil continued his simulation of heliospheric events with the numerical 3-D MHD code ENLIL driven by SAIC (Pete Riley, SAIC) and WSA (Nick Arge, AFRL) coronal models of ambient solar wind and fitted CME parameters by the cone model (Xuepu Zhao and Yang Liu, Stanford). In contrast to quite remarkable match with in-situ spacecraft observations of the isolated, well-observed 12 May 1997 CME, we achieved in the previous year, the heliospheric modeling of 1-2 May 1998 CMEs is much more challenging. This is among other caused by a necessity to simulate multiple transient phenomena. The right panel in Fig.1 shows that the May 2 and May 1 CMEs merge before they reach the Earth and that this structure propagates into the solar wind disturbed by the preceding April 29 CME. The top panel in Fig. 12 shows that April 19 CME propagates into solar wind disturbed by the preceding April 27 event. Thus to accurately simulate propagation of May 2, 1998 CME one has to simulate at least three preceding CMEs as well. Of course, inaccuracy in modeling of one event enhances inaccuracy in modeling of subsequent events.

Figure 12 - Results of MHD simulations of the heliospheric response to the April 27 and 29, 1998 CMEs (top panel) and April 29, May 1, and May 2, 1998 CMEs (bottom panel) CME after few days of evolution. Left part of both panels show the solar wind flow velocity on the equatorial plane up to 2 AU. Positions of planets are shown by black dots. The solid black line shows an interplanetary magnetic field line passing through the Earth. Right part on both panels show the radial profiles of the solar wind flow velocity and particle density along the Sun-through-Earth line on top and bottom plots, respectively. The dotted lines show profiles of undisturbed solar wind. The solid lines show profiles of solar wind disturbed by four consecutive CMEs.

While simulation of global solar wind structures including magnetic clouds and interplanetary shocks can be realized on uniform or non-uniform computational grids, resolution of detail structures and geospace applications require much higher resolution
that is however beyond computational capabilities of current supercomputers. The multi-grid technique provides an efficient way to achieve high resolution as shown in Fig. 13. An advantage of this approach is that interplanetary shocks steepen during their propagation and thus they become relatively thin structures when approaching the geospace environment.

Figure 13 - Application of the multi-grid technique to simulation of an interplanetary shock. Eight panels show the same distribution of the solar wind velocity on twice finer zoom. Computational blocks (cells) are shown by thick (light) blue lines on plots with twice finer zoom. White diamond shows the L1-point and white box shows a possible magnetospheric simulation box 100x40 Earth radii wide.

Our UCSD team members are now able to use their 3D reconstruction technique to analyze SMEI data in preliminary form and provide density in the interplanetary medium at low resolution. These analyses are currently being compared with LASCO coronagraph data and with interplanetary scintillation data for selected time intervals (late May, 2003 and late October 2003). Figure 1 shows the October 28, 2003 CME reconstruction, and its comparison with interplanetary scintillation g-level observations obtained during the same time interval. Notable in both reconstructions is that the mass derived from these two techniques gives approximately the same value and that this mass is in approximately the same location in spite of the extremely fast shock that preceded the CME and that has at this time reached the Earth. Past studies have indicated that shocked plasma may contain more small-scale (~200km) turbulence by as much as an order of magnitude than other interplanetary regions. If this were the case IPS-derived masses would be highly unreliable so this would negate the idea that the scintillation process could be used to determine reliable bulk densities. Although more complete analyses with other events are expected to refine this study, the clear indication for this very large event is that the differences between the IPS and white light density measurements are minimal. The masses using the SMEI data in the figure caption give an interesting comparison with LASCO coronagraph observations since LASCO observed the upper portion of the CME to have \( \sim 2 \times 10^{16} \) g out-of-the-sky-plane excess mass, and the southern portion to have \( \sim 4 \times 10^{16} \) g out-of-the-sky-plane excess mass.

Figure 14 - SMEI and IPS scintillation level reconstruction of the October 28, 2003 CME on October 29 at ~03 UT. The CME is reconstructed and viewed from a vantage point 30˚ above the ecliptic plane and approximately 45˚ west of the Sun-Earth line. a) SMEI data analysis showing a loop-like shape of dense material that has reached ~0.5 AU. The loop is comprised of a northern dense structure and a more southerly blob that is partly comprised of material associated with a prominence. The northern portion of the ejection contains \( \sim 7 \times 10^{16} \) g of excess mass, the southern portion \( \sim 4 \times 10^{16} \) g excess. b) CME reconstruction (Tokumaru et al., 2005) of the northern portion same CME using a conversion from IPS scintillation-level to density. Tentative mass estimates give a value of \( \sim 4 \times 10^{16} \) g excess for this event which relates closely with the northern portion observed in Thomson-scattered white light. The lower portion of the event is not observed in the IPS analysis because of the lack of radio sources to the south at this time.
Acceleration and Transport of Solar Energetic Particles

A new calculation of the proton-excited wave intensity upstream of a stationary planar shock has been carried out by M.A. Lee at UNH. The new calculation relaxes the assumption made in the previous analysis (see Lee 2005 in the list of publications) that the growth rate of a given wave with wave number $k$ is dominated by the resonant protons with the lowest possible energy. Although this assumption is reasonable close to the shock, it is not so reasonable farther upstream because the upstream region is increasingly dominated by higher energy particles which can more easily escape from the region near the shock. The new calculation reveals that the wave intensity, which is $\propto k^{\beta-6}$ at small $k$, transitions to being $\propto k^{-2}$ at large $k$ with a transition wave number $k_0(z)$ which decreases as an inverse power of increasing distance from the shock. Here $\beta = 3X/(X-1)$ is the standard power-law spectral index for a stationary planar shock, where $X$ is the shock compression ratio. This form has important consequences for the variation of ion composition throughout the event including the ions which arrive promptly at the observer with high streaming anisotropy. The low-$k$ power law, $\propto k^{\beta-6}$, which resonates with higher energy ions, leads to enhancement of the heavy ions (larger $A/Q$) with increasing distance upstream of the shock. However, the large-$k$ power law, $\propto k^{-2}$, which resonates with lower energy ions, does not fractionate between species with different $A/Q$. The resulting compositional variation seems to account for that observed in many events. A paper presenting this calculation is published in the proceedings of the IGPP International Astrophysics Conference and is listed below (Lee, 2005b).

In collaboration with A.J. Tylka, D.V. Reames and C.K. Ng, we have investigated the origin of the large variations in the Fe/O ratio at high energies observed between different solar energetic particle (SEP) events. The origin appears to arise from the magnetic obliquity of the shock. The ion seed population for injection at the shock consists of both solar wind ions and ambient energetic particles. Quasi-parallel shocks (with upstream magnetic field primarily parallel to the shock normal) have a lower energy threshold for ion injection than do quasi-perpendicular shocks. Thus, quasi-parallel shocks accelerate predominantly solar wind ions, whereas quasi-perpendicular shocks accelerate predominantly ambient energetic ions, which include material from earlier impulsive events rich in heavy ions. This feature of shock acceleration appears to account for the extreme compositional variations often observed between events at high energies. A paper describing this work (Tylka et al., 2005) has been published in the Astrophysical Journal.

Of course, an individual event can exhibit a range of obliquities on the observer’s magnetic field line throughout the event. The event fluence contains contributions from all values. A paper is in preparation which shows that a reasonable integration over shock obliquity, assuming a range of ratios of solar wind to ambient energetic seed ions, can account quantitatively for the observed range of variation of Fe/O with energy.

This work establishes the important role of the energetic ion seed population in understanding the composition of gradual SEP events. The seed population will also affect the energy spectrum of the accelerated particles at weak shocks, for which the standard power-law index of shock acceleration is greater (softer) than that of the ambient seed population.

At the Solar Wind 11 Conference, M.A. Lee reported on preliminary calculations which, for the first time, include both ambient energetic ions in the seed population in addition to the solar wind, and an enhanced upstream wave intensity excited by the energetic protons. The calculations also included the effect of magnetic focusing in the diverging solar wind by including an effective “free escape” boundary upstream of the shock. This combination of features appears to yield a very promising analytical model which can account for the essential features of gradual SEP events.
IV. Publications by members of the UC Berkeley MURI: May 2001- July 2005. New publications since last year marked with an asterisk (*).


*Hesse, M., T.G. Forbes, and J. Birn, On the relation between reconnected magnetic


Li, Y., Luhmann, J.G. Hoeksema, J. T., Zhao, X. P. and Arge, C. N., Visualizing CMEs and predicting geomagnetic storms


Moon, Y.-J., Wang, H., Spirock, T., Goode, P. R., Park, Y. D. New method for resolving 180 degree ambiguity in solar vector


Tian, Lirong, Y. Liu, and J. Yang, Magnetic properties of four active regions with the largest proton events in the 23rd cycle, *Advances in Space Research*, accepted, 2003.


*Xu, Y., Cao, W., Ma, J., Hartkorn, K., Jing, J., Denker, C., Wang, H., Properties of

*Yu, Y., Hick, P.P., and Jackson, B.V.,

