Annual Report for FY2004: Award No. F49620-01-1-0360

“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 - 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 - 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 1998 event. In addition, we have added the Oct 29 2003 event to our cases for detailed study.

II. Major Milestones of the Past Year

The First Coronal Magnetogram

Coronal magnetic field measurements are essential for testing evolutionary coronal field models and extrapolations from photospheric measurements, such as potential and force-free-field models. The SOLARC infrared fiber bundle spectrograph located at the UH observing site on Haleakala was completed by University of Hawaii team members Haosheng Lin and Jeff Kuhn, and the first coronal magnetogram was obtained from a limb active region. It shows magnetic fields that are in broad agreement with coronal field models from UCB MURI team members. Using the IR FeXIII lines we achieve a flux density sensitivity of better than one gauss over coronal areas of a few arc-seconds. High sensitivity linear polarization measurements in FeXIII yield the field orientation over a large region of the corona. This result has now been published in ApJ Letters.

The First Vector-Magnetogram-Driven MHD Simulation of an Active Region

To drive an MHD simulation from a time sequence of vector magnetograms, one must first infer either a velocity or an electric field at the photosphere to correctly evolve the magnetic field in time. During the past year, our MURI team has published 2 such techniques in the ApJ, the Minimum Energy Fitting (MEF) method, developed by Longcope (MSU) and the Induction plus Local Correlation Tracking (ILCT) technique, developed primarily by Welsch and Fisher (UCB). Details of these techniques were reported in last year’s annual report.

We have now extended these results by developing a 3D kinematic numerical model of the photosphere/chromosphere boundary layer that uses vector magnetic field data (specified along a plane) along with the flows determined by ILCT or MEF to implicitly evolve the 3D vector magnetic field with time. This model is then fully coupled to a 3D MHD model corona, and the entire coupled system evolves in a physically self-consistent manner, in a way that closely follows the observed evolution of the magnetic field at the photosphere. We used vector magnetograms for the May 1 1998 MURI event to perform this study. Abbott presented the initial results of this code coupling at the 2004 SHINE meeting (a ppt presentation is online at:

Figure 3 - An FeXIII IR Zeeman coronal magnetogram of NOAA 10581 superimposed on an EIT FeXV image. Magnetic field contours (thick to thin) correspond to 4, 2, 0, and -2 Gauss fields. Tickmarks show the spatial scale in arcseconds.
Figure 4 - Image showing field line configurations in AR 8210 at the end of the data-driven MHD simulation.

Thus, for the first time, we have performed an MHD simulation of the coronal plasma within an active region that has been driven directly by vector magnetic field data, rather than by idealized interpretations of the data. This capability is an essential step toward a predictive, physics-based model of eruptive solar events.

III. Research Accomplishments Over the Past Year

Magnetic Fields and Flows at the Photosphere and Below

The source of energy that drives almost all solar activity, including eruptive events, must ultimately be the emergence and evolution of the magnetic fields observed at the photosphere, and originating from deep in the solar interior. Thus much of the research in our MURI program is focused on understanding the role of sub-surface and photospheric magnetic fields and flows in coronal magnetic field evolution.

With collaborators Yuhong Fan from HAO UCAR and David Bercik at UCB SSL our MURI group has recently performed a large number of numerical simulations of non-penetrative magnetoconvection in order to understand in detail the apparent net downward transport of signed magnetic flux (e.g., present as a result of a decayed active region magnetic flux rope) that occurs as a result of the characteristic asymmetric flow pattern (broad slow moving upflows punctuated by strong, localized cool downdrafts) present in a stratified, convectively unstable medium.

We find that the rapid net downward transport of signed flux (referred to as "turbulent pumping" in the literature) evident in simulations of penetrative convection (i.e., a model convection zone bounded by a stable layer below) does not manifest itself in a closed domain despite the presence of the strong, vertical flow asymmetries. Instead, for simulations initiated with an initially horizontal flux layer, we find only a weak, transient pumping mechanism that occurs only after the initial field becomes significantly non-uniform, during the time when the distribution of magnetic field relaxes to its equilibrium configuration. Thus, in Abbett et al. 2004, we suggest that the rapid pumping mechanism evident in simulations of penetrative convection is due to the presence of the convective overshoot layer, where flux entrained within the strong downdrafts penetrates into the stable layers where it remains for a timescale far exceeding that of convective turnover.

Figure 5 – Evolution of a tube (lhs) and a slab (rhs) of magnetic flux in a model of turbulent convection, taken from Abbett et al (2004). Time progresses from top to bottom. Note the formation of thin magnetic flux tube structures as time progresses.

Drs. Welsch, Fisher, and Abbett developed and published (ApJ. v. 610, pp. 1148-1156) a procedure called Inductive Local Correlation Tracking (ILCT) to determine flow fields from time series of magnetograms. This scheme modifies the flows derived by LCT to enforce consistency between the actual magnetic field evolution and the calculated flow fields, via the magnetic induction equation's normal
component. Given vector magnetograms, this technique allows determination of all three components of the flow field in the atmospheric layer where the magnetograms were imaged. This software is available at http://solarmuri.ssl.berkeley.edu/~welsch/public/software.

Dana Longcope developed and implemented the Minimum Energy Fit (MEF) algorithm for inferring a velocity field consistent with observed evolution of the photospheric magnetic field (Longcope, 2004). A new version of the IDL implementation (MEF2.0) was written to include an exact minimization of a discretized energy. This requires the solution of a coupled system of equations to minimize the energy with respect to vertical velocity, even though the Euler-Lagrange equation is actually algebraic. This version was applied to several test cases with satisfactory results. Longcope then proceeded to apply MEF2.0 to IVM data of AR8210, in collaboration with Dr. K. D. Leka. Longcope analyzed numerous pairs of averaged magnetograms (one averaged magnetogram consists of 5 consecutive individual magnetograms) separated by 30 minutes, from times within the period 18:00 - 21:00. Most pairs produced similar flow fields, as did one pair spanning a longer interval. This suggests that the MEF is capable of inferring a reasonable velocity field from actual magnetogram observations. The MEF software was collected into a distribution, along with a test case and brief instructions. The software is available at: http://solarmuri.ssl.berkeley.edu/~dana/team/software/mef2.0/

Stéphane Régnier (Montana), in collaboration with Richard Canfield (Montana), worked on the MURI active region AR 8210, one of our MURI events. They have modeled nonlinear force-free magnetic configurations for AR 8210 in an extended coronal volume. They performed the computation for a 4-hour long time series of IVM vector magnetograms. Then they followed the dynamics of AR8210 during a flaring period (Régnier & Canfield, in preparation). They first studied global quantities. They have compared the evolution of the free energy rate in the corona and the magnetic energy injection rate due to transverse photospheric motions (using MEF technique, Longcope 2004, ApJ, 612, 1181): the injection of magnetic energy into the corona by photospheric motions and magnetic fields was related to the release or storage of magnetic energy in the corona. Therefore the photospheric motions can be considered as precursors of solar eruption and flaring. They have also computed the degree of linkage between magnetic field lines in AR8210. They showed that the self-helicity (twist and writhe of a single flux tube) is small compared to the mutual helicity. They have concluded that the energy storage in AR8210 is not related to twisted flux tubes but is mostly due to the complex topology of the magnetic field configuration. They next followed the local evolution of some important features that appear to be involved in the eruption process, namely a rotating sunspot and an emerging moving parasitic polarity. They find that the photospheric motions allow the storage of energy close to these topological elements and the release of energy is associated with the creation of a current sheet and reconnection. The efficiency of the reconnection depends on the photospheric transverse motions: a slow motion (rotation of few degree per day) is more efficient for storage of energy than a fast motion (0.7 km s\(^{-1}\)).

![Figure 6 - Location in AR 8210 where the effect of sunspot rotation is strong and large velocities are inferred from the MEF inversion method described below. The magnetic configuration is tripolar -- two positive polarities (A and B) and one negative polarity (1). An important topological feature for energy storage is the separatrix surface (simplified to a straight line in this figure). From Regnier et al, in preparation.](image-url)
Yan Li (UCB) has worked on the active region evolution in relation with CMEs, in particular, looking for observational evidence of velocity convergence and shearing motions in the vicinity of the magnetic neutral lines as factors of CME initiation.

We have extended these results by developing a 3D kinematic numerical model of the photosphere/chromosphere boundary layer that uses vector magnetic field boundary data (specified along a plane) along with the flows determined by ILCT to implicitly evolve the 3D vector magnetic field in time. This model is then fully coupled to a 3D MHD model corona, and the entire coupled system evolves in a physically self-consistent manner, in a way that closely follows the observed evolution of the magnetic field at the photosphere. Abbett presented the initial results of this code coupling at the 2004 SHINE meeting (a ppt presentation is online at: http://sprg.ssl.berkeley.edu/~abbett/talks/Shine2004.ppt).

**Prominence Formation**

Understanding filament and prominence structure and prominence formation mechanisms is important because of the strong association between CMEs and erupting filaments and prominences.

In theoretical work simulating filament/prominence formation with Antiochos and Devore at the Naval Research Laboratory, Brian Welsch (UCB) has shown that flux cancellation can reproduce the observed properties of filaments: long, low-lying field lines, paralleling the polarity inversion line (PIL) beneath field lines less parallel to the PIL. In addition, this work has shown that
cancellation-driven reconnection naturally gives rise to field lines that should form X-ray sigmoids as filaments are formed. Such sigmoidal structures have been linked to eruptions. He is working on the first of two manuscripts describing this work.

Piet Martens (Montana) hosted and co-organized the yearly workshop of the PROM (prominences) working group chaired by Sara Martin, at which he presented his work with Paul Wood on filament work through magnetic flux cancellation (Wood and Martens, 2003). The three day meeting took place at MSU at the end of September 2003. Martens, Brian Welsch, and Terry Forbes of our MURI consortium gave invited talks. For on-line proceedings, see: http://solar.physics.montana.edu/martens/PROM-04/web-procs.html

The Breakout CME Eruption Mechanism

One of our team goals has been to understand in detail the physical mechanisms that cause magnetic structures on the Sun to erupt.

Drexel University MURI team members have two distinct but related threads to their research during the past year --- continued exploration of the 'breakout' eruption model using our 2.5D ideal MHD code, and the development of a new method for computing sequences of force-free equilibrium states.

We have been exploring the 'breakout' model for CME initiation using a 2.5D MHD code. Our studies have explored the conditions and requirements for the formation and eruption of the flux-rope in a variety of initial states, and with a range of helicity injection profiles.

Our research focuses on answering three specific questions:
I. Does the breakout model produce fast eruptions?
II. Is the amount of helicity shedding into the heliosphere a useful measure of the likelihood of eruption?
III. Does the breakout process work more or less effectively in less symmetric configurations?

We completed a study of the original case constructed by Antiochos et al. This work will be published in MacNeice et al (Ap.J., vol 614, October 2004). In this paper we detail the evolution of the eruption and study its energetic and magnetic helicity budgets. We also offer evidence to support the hypothesis that the rapid acceleration phase is a consequence of a feedback mechanism in which reconnection at the outer X-line causes erosion of the overlying field, leading the inner sheared field to expand more rapidly, compressing the current sheet and so increasing the reconnection rate. The alternative explanation invoking the 'loss-of-equilibrium' process, after the formation of the inner X-line cannot be completely ruled out, but we believe the timing of events discussed in the paper makes this explanation very unlikely. We have also shown how the approximate conservation of helicity as predicted by Taylor's theorem, can act as an effective error check on the evolution of the magnetic field topology. We have shown how, in this case the helicity conservation is quite sensitive to numerical resolution, and essentially defines a minimum acceptable resolution.

The notion that CMEs are required by the Sun so it can shed concentrations of magnetic helicity has been discussed in the literature in recent years. The obvious implication for CME forecasting implied in this paradigm is that magnetic helicity buildup would be a good indicator of the likelihood of eruption. While this may be true in general we have performed a variant of our original simulation that suggests that this indicator may be very difficult to apply in practice. We modified our original simulation so that the shear stressing of the magnetic field at the inner boundary injected no net magnetic helicity into the corona. Then by verifying that the modified stressing does produce an eruption, and by showing that this eruption is almost identical in most ways to the original case, we have established that (1) net helicity shedding from the region of the eruption is not a requirement for eruption, and (2) subtle
differences in shear stressing profiles can greatly modify the amount of helicity shed but may have only the subtlest of signatures imposed on the subsequent eruption. This work is being prepared for submission to ApJ Letters.

The simulations described above used an initial topology with a symmetry plane about the equator. We broke this symmetry by siting the inner flux system at 30 degrees north, and found that the model still produces an eruption.

Finally, we have continued our support and development of the PARAMESH adaptive mesh refinement package, which is being used by a number of MURI-funded researchers. In addition we have supported the installation of the ENLIL code, developed by University of Colorado team member Dusan Odstroil, at the Community Co-ordinated Modeling Center (CCMC).

**Modeling Pre-Eruptive Magnetic and Thermodynamic Structure in the AR8210 event on May 1, 1998**

To determine initial conditions for MHD simulations of active regions such as AR8210, an active region that the
on vector magnetograms, and have then solved the energy equation for several thousand coronal loops within the active region to compute the 3-D thermodynamic structure within the active region. The previous figure shows a map of Alfvén wave resonant frequencies of the active region.

**The Solar Corona in the 1997 May 12 Event**

The 1997 May 12 event is a typical flare-CME-associated case, demonstrating every phenomenon thought to link these two kinds of transients: A C1.3/1N flare, with a duration of more than 8 hours, was reported to occur at 04:42 UT on 12 May 1997 in the active region AR8038 at N21W08. Associated with this flare were a complete halo CME and an eruption of a filament. A magnetic cloud was observed to associate with this CME (Webb et al. 2000). The projected speed of this CME is measured to be 250 km/s (Plunkett et al., 1998), and the true speed was estimated, based on a cone model, to be about 650 km/s (Zhao et al. 2002). In addition, an EIT wave and double dimmings seen in EIT images were also reported (Thompson et al. 1998). Also, it is worth--while to mention that this event occurred during solar minimum when solar, heliospheric and geoelectric background conditions are relatively simple. This makes the modeling of this event easier. Therefore, this event was selected by many programs, including the MURI program at Berkeley, CISM, and the SHINE group.

Supported partly by the UCB MURI, Stanford team member Yang Liu has been performing research on configuration of the magnetic fields in the event, and its relation to the event (Liu 2004; Liu & Forbes 2003). By analyzing the observational data obtained by various instruments, we have presented evidence of changes in both small-scale and large-scale magnetic fields during the 1997 May 12 flare/CME. The small-scale changes are detected in the photospheric fields of the active region. The large-scale changes are inferred from a modeled coronal magnetic field, computed from the observed photospheric magnetic field. The latter result implies that the magnetic fields calculated from field observations can reflect transient-related variations. This study suggests that observation-based force-free-field models of the active region fields, and potential field models of the large scale fields, may provide the necessary configurations to initiate or drive realistic MHD models of flares and CMEs.

![Figure 11](image)

**Figure 11** - Top panels are synoptic frames of photospheric magnetic field. This kind of synoptic map is generated using a full disk magnetogram taken at the time of interest and the associated Carrington synoptic charts. In this way the new chart can represent, approximately, the entire-surface magnetic field at that instant. The maps shown in the top panels generated, using the traditional synoptic charts and the 03:12UT magnetogram (top left panel), the 04:52UT magnetogram (top middle panel), and the 06.28UT magnetogram (top right), can roughly represent magnetic field at solar surface before, during, and after the event. The plots below are the radial magnetic field at 1.2 solar radii (second row), 1.7 solar radii (third row), and 2.5 solar radii (bottom row), computed respectively from the synoptic maps shown in the top row, based on a Potential Field Source Surface model. The source surface for these computations is set at 2.5 solar radii. The thick white contours denote the magnetic neutral lines. The computed magnetic fields show differences at low height at the vicinity of AR8038 during the flare, which is marked by ‘A’ in the middle panel of the second row. However, it appears no changes at the source surface during the event.

Based on observations, we also modeled a flux rope presumed in this event. Liu and Forbes’ calculation shows that the twist in this rope is only 0.87π, much less
than the theoretical limit for a kink instability for a straight tube (Hood and Priest, 1981), and also less than the one measured from eruptive prominences (Vrsnak, Ruzdjak, and Rompolt, 1991). The background magnetic field, however, appears to gradually decrease before the flare by a factor of 12.7%. This suggests that relief of constraint of background field on the flux rope might be the reason causing this event.

**Simulations of Heliospheric CME/ICME propagation and Transport**

We simulated the 12 May 1997 interplanetary CME event with a numerical 3-D MHD code in the last year. Although we reproduced with some fidelity the arrival of the shock and ICME at Earth, detail analysis of the simulations showed discrepancies in the stand-off distance between the shock and the ejecta and in inclination of the shock front with respect to the Sun-Earth line. In 2004, we investigated these problems in more detail. First, we assessed the effects of using synoptic coronal maps that differ in method of preparation. We compared transient disturbances that propagate in two different ambient solar wind structures, one derived from full-rotation maps computed by SAIC coronal model and the other computed from WSA coronal model. Second, we investigated how differences in the presumed temporal evolution of the coronal stream structure affect the propagation of the disturbance.

We found that heliospheric simulations with the SAIC and WSA full-rotation models provide qualitatively similar parameters of the background solar wind and transient disturbances at Earth. Improved agreement with the observations is achieved by artificially modified maps that simulate the rapid displacement of the coronal hole boundary after the CME eruption. We have also considered how multi-point temporal profiles of solar wind parameters and multi-perspective synthetic white-light images (emulating upcoming STEREO spacecraft observations) might be used to differentiate between different event scenarios.

The 21 April 2002 and 24 August 2002 events have been selected by the SHINE scientific community as events No. 3 and 4, respectively. These events are especially interesting for the investigation of energetic particles since the solar flares and CMEs had similar parameters, while the energetic particle properties were quite different. We were invited to present heliospheric simulations of these events at the SHINE 2004 Workshop. The Figure below illustrates that while the ICME propagates east of the Sun-Earth line in both cases, the differing ambient solar wind structure ahead of the two ICMEs produce different connectivities of the interplanetary magnetic field (IMF) line from the Earth to the interplanetary shock. Thus different parameters at the shock and different inclinations of the shock to the IMF lines provide different conditions for particle acceleration. Work is ongoing to study the effect of the ambient solar wind obtained by different coronal maps and to incorporate preceding transient events.

**Figure 12 - Results of MHD simulations of the heliospheric response to the 21 April 2002 (left) and 24 August 2002 (right) CME after 2 days of evolution. The solar wind radial velocity is show on the equatorial plane (translucent) and on the iso-surface of the traced injected material using color scale. This velocity is also shown on the equatorial plane by black contour lines. The purple tube shows the IMF lines passing through the Earth which is identified by a small blue box.**

**Analyzing Observations of ICMEs, Interplanetary Clouds, and Other Heliospheric Structures**

Richard Canfield (Montana) worked with Robert Leamon, Alexei Pevtsov, and three undergraduate students to relate the magnetic and topological parameters of twelve interplanetary magnetic clouds to associated solar active regions (Leamon et al., 2004). They used a cylindrically symmetric constant-alpha force-free model to derive field line twist, total current, and total magnetic flux from in situ observations of magnetic clouds. They compared these
properties with those of the associated solar active regions, which they inferred from solar vector magnetograms. The relationships between fluxes, currents, and twists in magnetic clouds and associated active regions strongly imply that that magnetic clouds associated with active region eruptions are formed by magnetic reconnection between these regions and their larger-scale surroundings, rather than simple eruption of pre-existing structures in the corona or chromosphere.

UCSD team members continue work on a SMEI data analysis routine that provides a stable baseline over several weeks, without sacrificing SMEI angular resolution (See the following Figure). This provides a calibrated data set sufficient for high-resolution 3D reconstruction of the heliosphere. The 3D results in turn allow us to refine SMEI images, which can be presented from any desired viewing location; the original sky maps are often contaminated by troublesome backgrounds and portions of these are sometimes further swamped by bright aurora light. A SMEI aurora light removal algorithm now works automatically to remove these troublesome signals. Extrapolating across these regions and removing contaminant signals is best accomplished as we do in IPS sky maps. Here, sky map outages and contaminant signals are modeled away using a realistic 3D solar wind model iteratively fit to the data, both removing the contaminated regions and interpolating across them.

Figure 13 - The relationship between ratios formed from the magnetic fluxes and electrical currents observed in 12 interplanetary magnetic clouds (MC) and the corresponding solar active regions (AR) associated with to their eruption. As the flux ratio grows, so does the current ratio. The relationship is demonstrably real, with a confidence level 99.9%, implying that the magnetic cloud is formed by reconnection of the active region (plausibly the source of the current) with its surroundings.

Figure 14 - SMEI 'fisheye' skymap images of the heliospheric response to the May 28, 2003 CME observed to 'halo' the Sun in LASCO observations and in SMEI observed beyond 45° elongation in the first image set and to have begun to engulf the Earth at 90° elongation in the second at the times indicated. a) and b) Direct SMEI sky map images on 29 May, 2003. Shown are two orbits of data differenced from an 8-orbit average for SMEI cameras 1, 2 and 3. The white regions in the sky maps that extend roughly outward from the center are primarily locations where auroral light is too bright to provide a photometric signal. The data were smoothed using a 1° Gaussian filter. The specks in each image are stellar signals - mostly bright stars that have changed brightness over the observation interval. Brightness is in SMEI camera analog to digital units (ADU). One S10 is approximately 0.55 ADU. A LASCO C3 coronagraph image is inserted in the top right map for scale (b). The approximate same images showing far more features and the halo enhancement surrounding Earth are obtained from time series modeling using SMEI data from cameras 1, 2, and 3. Brightness is given in S10 normalized to an r-2 density falloff relative to the 90° elongation circle.
The views retain only the heliospheric signal in the sky maps. The following figure shows samples of this technique's ability to refine 2D SMEI sky maps, and to view heliospheric structures at a level that is an order of magnitude more sensitive than possible from individual sky maps.

UCSD also now provides a planetary forecast on our Web site that includes real-time velocity, density, and radial and tangential magnetic field updates at all of the inner planets: Mercury through Mars (see the following figure). These and our regular forecasts are found at URL http://cassfios02.ucsd.edu/solar/forecast/index_ss.html. Current analyses on our regular Web site at http://cassfios02.ucsd.edu/solar/forecast/index_v_n.html also include real-time magnetic field data from both NSO and WSO and compares them with ACE in situ measurements.

Figure 15 - North polar projection of the UCSD 3D reconstruction of real-time solar wind density. The images taken from the UCSD Web site front page at 21:00 UT 16/09/2004 depict conditions at the inner planets from the UCSD a) corotating and b) time-dependent solar wind models. Time series measurements forecast velocity, density and two components of the solar wind magnetic field in real time. Models at Earth are compared with ACE data obtained in real time from SEC, Boulder, Colorado on the same Web site.

Solar Energetic Particle Acceleration and Transport

Forbes and Lee have collaborated with I. Sokolov and I. Roussev of the Michigan MURI team to calculate the proton distribution function produced at a shock, which results from the U. Michigan coronal/heliospheric MHD code. Thus, the shock parameters as functions of time are calculated consistently within MHD theory. The wave intensities required for effective ion scattering adjacent to the shock are not calculated self-consistently, but they are chosen to be representative of intensities predicted analytically under simplifying assumptions. A paper submitted to Astrophysical Journal Letters describing this work is in the process of revision.

One of the outstanding puzzles in observations of SEP events is the variability of abundance ratios within an event or from event to event, particularly at high energies. A popular ratio for these studies is Fe/O involving two species which are easy to measure using instruments on several spacecraft. In some events this ratio increases with energy above a few MeV/nuc, while in others it decreases markedly. And this divergent behavior can be found in events with similar characteristics and heliographic locations.

In collaboration with A. J. Tylka, D. V. Reames and C. K. Ng, Lee has been exploring the possible origin of this variability in the angle $\theta$ that the shock normal makes with the upstream magnetic field. The basic idea is that the seed particle pool for acceleration at the shock consists of solar wind ions, and ambient energetic particles from previous impulsive events that are enriched in heavy ions like Fe. The mix of accelerated ions depends on $\theta$ since the energy threshold for injection at a quasi-perpendicular shock is higher than at a quasi-parallel shock. A consequence of this idea is that quasi-parallel shocks should exhibit solar wind composition, since solar wind dominates the number density in the pool, and quasi-perpendicular shocks should exhibit impulsive event composition. Since quasi-perpendicular shocks tend to accelerate ions above the injection threshold more rapidly than quasi-parallel shocks, a further consequence is that the quasi-perpendicular events should extend to higher energy. But since the remnant impulsive-event pool is smaller in density, these events should be smaller. A paper by Tylka et al., showing that the correlations expected based on this idea are indeed observed in a sample of events, was
submitted to Astrophysical Journal and is in the process of revision.

As an extension of this project we have developed a simple model to predict the family of possible Fe/O ratios as functions of energy depending on the possible admixtures of solar wind and remnant impulsive SEPs in the injection pool. We have simply assumed that in any event the range of $\theta$ realized by a given shock on a given magnetic field line is uniform between 0° and 90° so that the fluence involves an integral over those realizations. With simple assumptions about the high-energy cutoff and the injection rate as functions of $\theta$, the family of curves of Fe/O versus energy appears to cover the range of observed variability. The figure below shows the predicted fluence energy spectra for Fe and O and their ratio for a quasi-perpendicular event and a particular injection pool. Note that the event is dominated by remnant impulsive event material at high energies, but by solar wind material at low energies. This work is particularly timely, since it is relevant to the current controversy concerning the origin of these Fe excesses at high energy in many events: direct injection from the flare site behind the CME or shock-accelerated particles with rigidity-dependent transport. A paper on this topic is in preparation.

![Figure 16 – Fluence of Fe, O (and their ratio) for a quasi-perpendicular event.](image)

**Solar Instrument Development and Observational Data for MURI studies**

The BBSO vector magnetograph provides magnetograms with a spatial resolution of one arcsecond and a field of view of 300 arcsec. The sensitivity is about 10 Gauss for the vertical field for an integration time of about 30 seconds. This instrument has provided numerous results and has reached its final stage of development. The results are posted on a daily bases at http://www.bbso.njit.edu/cgi-bin/LatestImages.

![Figure 17 – Example of the line-of-sight component of the magnetic field measured with the BBSO vector magnetograph.](image)

Yet, the problem of the 180 degree ambiguity for the horizontal magnetic fields common to vector magnetographs remains. Resolving the 180 degree ambiguity is e.g. important for calculating the energy stored in solar magnetic fields. Up to now mainly the force-free field approximation was used to resolve the 180 degree ambiguity. However, there exist more sophisticated methods to resolve this problem. We choose the Mees Solar Observatory magnetic vector ambiguity resolution as a starting point for our own IDL 'library' and we are currently in the testing phase for this project.

The Infrared Imaging Magnetograph (IRIM) is a new two-dimensional spectrometer currently being developed by the Big Bear Solar Observatory. IRIM is designed to record magnetograms in the Fe I 1.5649 micron line. This line enables a precise measurement of solar magnetic fields since the magnitude of the Zeeman splitting increases with the square of the wavelength used. In order to obtain the required spectral resolution, a three-stage filter system is used: The first stage is a simple interference filter with a FWHM of 50 Å. The
second stage is a four element Lyot filter with a FSR of 40 A and a FWHM of 2.5 A. The last stage is a Fabry-Perot Etalon with a FSR of 5.5 A and a FWHM of 80 mA. The total transmission of the combined system will be in the range of 8-10 %. This system is one of the first infrared magnetographs used in solar physics with the IR Lyot filter being the first of its kind. This filter also utilizes Liquid Crystals instead of rotating elements to tune the central wavelength. Therefore extensive test were required to characterize and calibrate the Lyot filter with its Liquid crystal drive voltages and the Fabry-Perot etalon. These test were performed at the Evans facility of the National Solar Observatory, Sacramento Peak. We used the horizontal Coelostat and a spectrograph with a resolution of 200000. The calibration curves of the LC drive voltage vs wavelength for stage 0 are shown in figure 3. From this calibration curves the wavelength shift vs drive voltage can be deduced to line up the four stages and center it on the 1.5648A spectral line. We also characterized the Etalon by measuring its FSR and the scanning step size. The duration of the testing was 10 days and we succeeded to characterize the IRIM components sufficiently to have the commission run in November 2004. IRIM is part of a larger joint effort to improve the high-resolution observational capabilities of the Big Bear Solar Observatory. This effort includes optical and mechanical improvement of the telescope itself and, as an especially important item, the fine-tuning of the newly installed high-order Adaptive Optics system. As far as the post-focus instrumentation is concerned two two-dimensional spectrometers are being developed at BBSO. One spectrometer is IRIM and the other spectrometer is its visible counterpart, the Visible Imaging Magnetograph (VIM). In addition, a real-time speckle reconstruction system is under development that will further improve the spatial resolution of the observations. These developments are also important steps towards the construction of the NST, a 1.6 m solar telescope currently being built by the Big Bear Solar Observatory.

The Imaging Vector Magnetograph at UH continues to make daily vector magnetograms, in the 630.2 nm photospheric line, of all numbered active regions. During the past year the IVM observing plan has been modified to accumulate a significant body of observations of chromospheric active region magnetic fields. First, the daily survey has been repeated in the Na I 589.6 nm line, which is formed higher in the atmosphere, where the force-free field approximation is valid. Following the surveys, the region selected by the RHESSI planners is observed repeatedly for an hour or more. This sequence permits either studies of temporal evolution—albeit over a relatively short period—or averaging to reduce the uncertainty in the magnetic field determination.

The 15-July-2002 flare has been carefully observed using IVM and EUV data to look for temporal magnetic field evolution in work recently submitted to ApJLetts by Dr. Jing Li.

The SOLARC infrared fiber bundle spectrograph was completed and the first coronal magnetogram has been obtained from a limb active region. It shows magnetic fields that are in broad agreement with coronal field models from our UCB MURI collaborators. Using the IR FeXIII lines we achieve a flux density sensitivity of better than one gauss over coronal areas of a few arcseconds. High sensitivity linear polarization measurements in FeXIII yield the field orientation over a large region of the corona.

IV. Publications by members of the UC Berkeley MURI: May 2001- July 2004. New publications since last year marked with an asterisk (*).


*Abbett W. P., Z. Mikic, J.A. Linker, J.M. McTiernan, T. Magara, and G.H. Fisher,


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.


*Tylic, A. J., C. M. S. Cohen, W. F. Dietrich, M. A. Lee, C. G. Macleans, R. A. Mewaldt, C. K. Ng, and D. V. Reames, Shock geometry, seed populations, and the origin of variable elemental composition at high...


