C. THE HELIOSEISMIC AND MAGNETIC IMAGER INVESTIGATION

The primary goal of the Helioseismic and Magnetic Imager (HMI) investigation is to study the origin of solar variability and to characterize and understand the Sun's interior and the various components of magnetic activity. The HMI investigation is based on measurements obtained with the HMI instrument as part of the Solar Dynamics Observatory (SDO) mission. HMI makes measurements of the motion of the solar photosphere to study solar oscillations and measurements of the polarization in a spectral line to study all three components of the photospheric magnetic field. HMI produces data to determine the interior sources and mechanisms of solar variability and how the physical processes inside the Sun are related to surface magnetic field and activity. It also produces data to enable estimates of the coronal magnetic field for studies of variability in the extended solar atmosphere. HMI observations are crucial for establishing the relationships between the internal dynamics and magnetic activity in order to understand solar variability and its effects, leading to reliable predictive capability, one of the key elements of the Living With a Star (LWS) program. The HMI investigation directly addresses and assists the highest priority science goals of SDO.

The HMI investigation includes the following required seven elements:

1) The HMI instrument provides the observing capabilities required to complete the combined 'HMI' and 'HVMI' objectives as described in the SDO Announcement of Opportunity (AO). HMI is a "suite" as defined by the AO. The instrument has significant heritage from the Solar and Heliospheric Observatory (SOHO) Michelson Doppler Imager (MDI) with enhancements to achieve higher resolution, higher cadence, and the addition of a second channel to provide full Stokes polarization measurements. HMI provides stabilized 1"-resolution full-disk Doppler velocity and line-of-sight magnetic flux images every 45 seconds, and vector-magnetic field maps every 90 seconds. The basic characteristics of the HMI observables and performance of the HMI instrument are summarized in Foldout 1.K. The HMI instrument will be provided by Lockheed-Martin Solar and Astrophysics Laboratory (LMSAL) as part of the Stanford Lockheed Institute for Space Research collaboration.

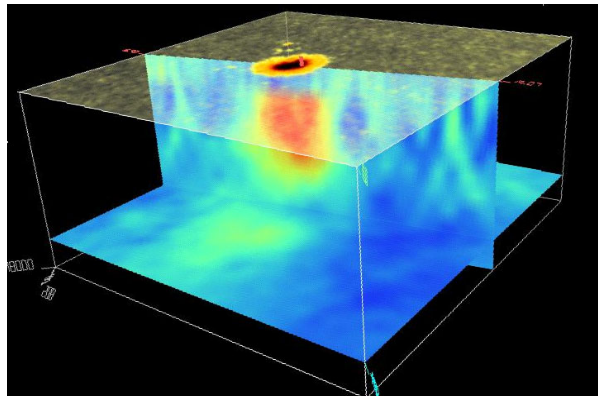

Figure C.1. Sound-speed beneath a sunspot (red –positive and blue negative perturbations) from SOHO/MDI high-resolution data (June 18, 1998).

2) The large data stream from HMI must be analyzed and interpreted with advanced tools that permit interactive investigation of complex solar phenomena. It will be essential to have convenient access to all data products - Dopplergrams, full vector magnetograms, subsurface flow fields and sound-speed maps deduced from helioseismic inversion, as well as coronal field estimates - for any region or event selected for analysis. This investigation will provide a data system for archiving HMI data and derived data products with convenient access to the data by all interested investigators. Sufficient computing capability will be provided to allow the complete investigation of the key HMI science objectives. The principal HMI data products are shown in Foldout 1.L.

3) The HMI investigation includes support of integration of HMI onto SDO, mission planning, HMI operations and receipt and verification of HMI data.

4) Some of the higher level HMI data products are likely to be of great value for monitoring and predicting the state of solar activity. Such products will be identified in Phase-A and produced on a regular basis at a cadence appropriate for each product.

5) HMI will obtain filtergrams in a set of polarizations and spectral line positions at a regular cadence for the duration of the mission. Several processed levels of data products will be produced from the filtergrams. The basic science observables are full-disk Doppler velocity, brightness, line-of-sight magnetic flux, and vector magnetic field. These will be available on request at full resolution and cadence. Of more interest are sampled and averaged products at various resolutions and cadence and sub-image samples tracked with solar rotation. A selection of these will be made available on a regular basis, and other data products will be made available on request. Also of great potential value are derived products such as sub-surface flow maps, far-side activity maps, and coronal and solar wind models that require longer sequences of observations. A selection of these will also be produced in the processing pipeline in near real time. A number of the HMI Co-Investigators (Co-Is) have specific tasks to provide software to enable production of these higher level products.

6) This proposal identifies a broad range of science objectives that can be addressed with HMI observations. HMI provides a unique set of data required for scientific understanding, detailed characterization and advanced warning of the effects of solar disturbances on global changes, space weather, human space exploration and development, and technological systems. HMI also provides important input data required for accomplishing objectives of the other SDO instruments. The HMI investigation will carry out the highest priority studies through to publication of the results and presentation to the scientific community.

7) SDO investigations, and HMI in particular, have aspects which will be of great interest to the public at large and offer excellent opportunities for developing interesting and timely educational material. A highly leveraged collaborative Education and Public Outreach (E/PO) program is a key part of this investigation.

The Science Objectives presented in Section C.1 and illustrated in Foldout 1 include longstanding problems in solar physics as well as questions that have developed in response to recent progress. The investigation builds on current knowledge of the solar interior, photosphere, and atmosphere, recent space- and ground-based programs, and advances in numerical modeling and theoretical understanding.

The helioseismic and line-of-sight magnetic flux measurements provide data required for the core HMI science program to characterize and understand the Sun's interior and various components of magnetic activity. The capability to measure the vector magnetic field strengthens the LWS program tremendously, in particular, for studying magnetic stresses and current systems associated with impulsive events and evolving magnetic structures.

The HMI science program has evolved from the highly successful programs of MDI, Global Oscillation Network Group (GONG) and Advanced Stokes Polarimeter (ASP). The Co-Investigators include leading experts in helioseismic and magnetic field measurements, experienced instrument developers, observers, mission planners, theorists, and specialists in numerical simulations, data processing and analyses. The HMI investigation benefits from and contributes to other space and ground based programs.

C.1 Scientific Goals and Objectives

C. 1.1 Science Overview

The Sun is a magnetic star. The high-speed solar wind and the sector structure of the heliosphere, coronal holes and mass ejections, flares and their energetic particles, and variable components of irradiance are all linked to the variability of magnetic fields which originate in the solar interior and pervade the atmosphere. Many of these phenomena can have profound impacts on our technological society, so understanding them is a key objective for LWS.

The central question is the origin of solar magnetic fields. Most striking is that the Sun exhibits 22-year cycles of global magnetic activity involving magnetic active region eruptions with very well defined polarity rules[1] resulting in global scale magnetic patterns. Coexisting with these large-scale ordered magnetic structures and concentrated active regions are ephemeral active regions and other compact and intense flux structures that emerge randomly over much of the solar surface forming a 'magnetic carpet'[2, 3]. The extension of these changing fields at all scales into the solar atmosphere creates coronal activity, which in turn is the source of space weather variability.

The HMI science investigation addresses the fundamental problems of solar variability with studies in all interlinked time and space domains, including global scale, active regions, small scale, and coronal connections. One of the prime objectives of the LWS program is to understand how well predictions of evolving space weather can be made. The HMI investigation will examine these questions in parallel with the fundamental science questions of how the Sun varies and how that variability drives global change and space weather.

Helioseismology, which uses solar oscillations to probe flows and structures in the Sun's interior, provides remarkable new perspectives on the complex interactions between highly turbulent convection, rotation and magnetism. It has revealed a region of intense rotational shear[4-6] at the base of the convection zone, called the tachocline[7, 8], which is the likely seat of the global dynamo[9-11]. Convective flows also have a crucial role in advecting and shearing the magnetic fields, twisting the emerging flux tubes and displacing the photospheric footpoints of magnetic structures present in the corona. Flows on all spatial scales influence the evolution of magnetic fields, including how fields generated near the base of the convection zone rise and emerge at the solar surface, and how the magnetic fields already present at the surface are advected and redistributed. Both of these mechanisms contribute to the establishment of magnetic field configurations that may become unstable and lead to eruptions that affect the near-Earth environment.

Methods of local-area helioseismology have begun to reveal the great complexity of rapidly evolving 3-D magnetic structures and flows in the sub-surface shear layer in which the sunspots and active regions are embedded. Most of these techniques were developed by members of the HMI team during analysis of MDI observations. As useful as they are, the limitations of MDI telemetry and the limited field of view at high resolution have prevented the full exploitation of these methods to answer important questions about the origins of solar variability. By using these techniques on continuous, full-disk, high-resolution observations, HMI will enable detailed probing of dynamics and magnetism within the near-surface shear layer, and provide sensitive measures of variations in the tachocline.

Just as existing helioseismology experiments have shown that new techniques can lead to new understanding, methods to measure the full vector magnetic field have been developed and have shown the potential for significantly enhanced understanding of magnetic evolution and connections. What existing and planned ground based programs cannot do, and what Solar-B cannot do, is to observe the full-disk vector field continuously at a cadence sufficient to follow activity development. HMI vector magnetic field measurement capability, in combination with the other SDO instruments and other programs (*e.g.* STEREO, Solar-B, and SOLIS), will provide data crucial to connect variability in the solar interior to variability in the solar atmosphere, and to the propagation of disturbances in the heliosphere.

HMI brightness observations will provide important information about the area of magnetic and convective contributions to irradiance, and also about variations of the solar radius and shape.

C. 1.2 Scientific Objectives

The broad goals described above will be addressed in a coordinated investigation in a number of parallel studies. These segments of the HMI investigation are to observe and understand these interlinked processes:

- **Convection-zone dynamics and the solar dynamo;**
- **Origin and evolution of sunspots, active regions and complexes of activity;**
- **Sources and drivers of solar activity and disturbances;**
- **Links between the internal processes and dynamics of the corona and heliosphere;**
- **Precursors of solar disturbances for space-weather forecasts.**

These goals address long-standing problems that can be studied by a number of immediate tasks. The description of these tasks reflects our current level of understanding and will obviously evolve in the course of the investigation. Some of these tasks are described below.

C. 1.2.1 Convection-zone dynamics and the solar dynamo

Fluid motions inside the Sun generate the solar magnetic field. Complex interactions between turbulent convection, rotation, large-scale flows and magnetic field produce regular patterns of solar activity changing quasi-periodically with the solar cycle. How are variations in the solar cycle related to the internal flows and surface magnetic field? How is the differential rotation produced? What is the structure of the meridional flow and how does it vary? What roles do the torsional oscillation pattern and the variations of the rotation rate in the tachocline play in the solar dynamo?

These issues are usually studied only in zonal averages by global helioseismology[12, 13] but the Sun is longitudinally structured. Local helioseismology has revealed the presence of large-scale flows within the near-surface layers of the solar convection zone.[14-23] These flows possess intricate patterns that change from one day to the next, accompanied by more gradually evolving patterns such as banded zonal flows[24-27] and meridional circulation cells[28-33] (Foldout 1.B,C). These flow structures have been described as Solar Subsurface Weather (SSW).[34] Successive maps of these weather-like flow structures (Foldout 1.F) suggest that solar magnetism strongly modulates flow speeds and directions. Active regions tend to emerge in latitudes with stronger shear.[35] The connections between SSW and active region development are presently unknown.

Structure and dynamics of the tachocline. Observation of the deep roots of solar activity in the tachocline is of primary importance for understanding the long-term variability of the Sun. HMI will use global and local helioseismic techniques to observe and investigate the large-scale character of the convection zone and tachocline. Topics include solar differential rotation, relations between variations of rotation and magnetic fields, longitudinal structure of zonal flows ('torsional oscillations'), relations between the torsional pattern and active regions, subsurface shear and its variations with solar activity, and the origin of the 'extended' solar cycle.

Variations in differential rotation. Differential rotation (Figure C.2) is a crucial component of the solar cycle and is believed to generate the global scale toroidal magnetic field in active regions. Results from MDI and GONG have revealed intriguing 1.3-year quasi-periodic variations of the rotation rate in the tachocline,[37] which may be a key to understanding the solar dynamo.[38] HMI will extend this key series with better near-surface resolution.

Evolution of meridional circulation. Precise knowledge of the meridional circulation in the convection zone is crucial for understanding the long-term variability of the Sun.[39, 40] Helioseismology has found evidence for variation of the internal poleward flow during the solar cycle.[34, 41, 42] To understand the global dynamics we must follow the evolution of the flow. HMI will generate continuous data for detailed, 3-D maps of the evolving patterns of meridional circulation providing information about how flows transport and interact with magnetic fields throughout the solar cycle.

Dynamics in the near surface shear layer. Helioseismology has revealed that significant changes in solar structure over the solar cycle occur in the near-surface shear layer.[32, 33, 43, 44] However, the physics of these variations and their role in irradiance variations are still unknown. HMI will characterize the properties of this shear layer, the interaction between surface magnetism and evolving flow patterns, and the changes in structure and dynamics as the solar cycle advances. It will assess the statistical properties of convective turbulence over the solar cycle, including the kinetic helicity and its relation to magnetic helicity – two intrinsic characteristics of dynamo action.

C. 1.2.2 Origin and evolution of sunspots, active regions and complexes of activity

Observations show that magnetic flux on the Sun does not appear randomly. Once an active region emerges, there is a high probability that additional eruptions of flux will occur nearby (activity nests, active longitudes).[36, 45-49] How

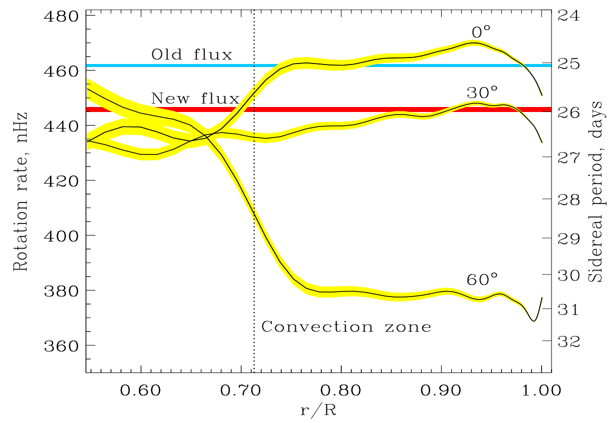

Figure C.2. Solar rotation rate vs. radius at the equator, 30, and 60 degrees latitude in 1997. The blue (red) line shows the surface rotation rate of old cycle (new cycle) emerging magnetic flux in the 1-5 (30) degree latitude range.[36]

is magnetic flux created, concentrated, and transported to the solar surface where it emerges in the form of evolving active regions? To what extent are the appearances of active regions predictable? What roles do local flows play in their evolution?

HMI will address these questions by providing tracked sub-surface sound-speed and flow maps for individual active regions and complexes under the visible surface of the Sun combined with surface magnetograms. Current thinking suggests that flux emerging in active regions originates in the tachocline. Flux is somehow ejected from the depths in the form of loops that rise through the convection zone and emerge through the surface. Phenomenological flux transport models[50-53] show that the observed photospheric distribution of the flux does not require a long-term connection to flux below the surface. Rather, field motions are described by the observed poleward flows, differential rotation, and surface diffusion acting on emerged flux of active regions. Does the active region magnetic flux really disconnect from the deeper flux ropes after emergence?

Formation and deep structure of magnetic complexes of activity. HMI will explore the nature of long-lived complexes of solar activ-

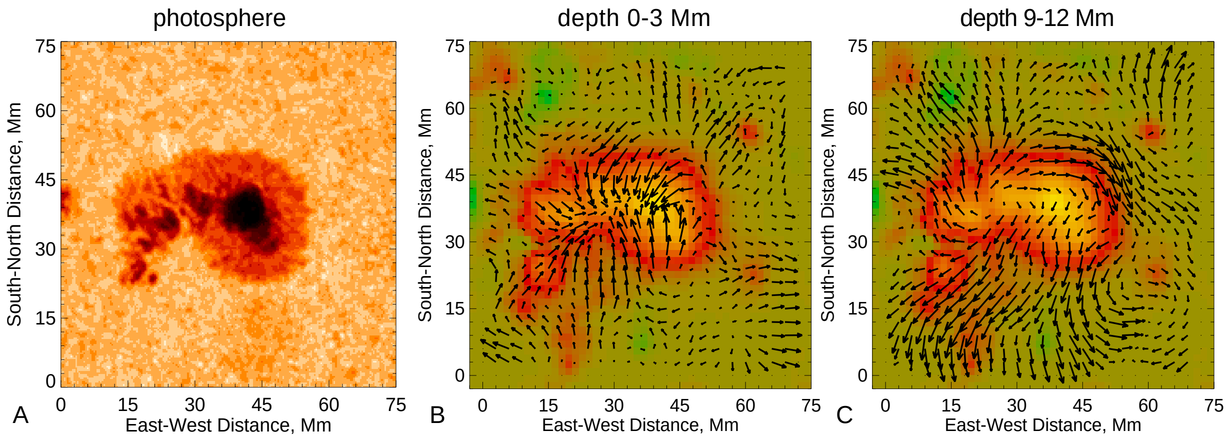

Figure C.3. Vortex flows beneath a twisting sunspot on August 8, 2000. The background color map is the corresponding MDI magnetogram.[60]

ity ('active or preferred longitudes'), the principal sources of solar disturbances. 'Active longitudes' have been a puzzle of solar activity for many decades.[54, 55] They may continue from one cycle to the next, and may be related to variations of solar activity on the scale of 1-2 years and short-term 'impulses' of activity.[56-59] HMI will probe beneath these features to 0.7R, the bottom of the convection zone, to search for correlated flow or thermal structures.

Active region source and evolution. By using acoustic tomography we can image sound speed perturbations that accompany magnetic flux emergence and disconnection that may occur. Vector magnetograms can give evidence on whether flux leaves the surface predominantly as 'bubbles', or whether it is principally the outcome of local annihilation of fields of opposing polarity. With a combination of helioseismic probing and vector field measurements HMI will provide new insight into active region flux emergence and removal.

Magnetic flux concentration in sunspots. Formation of sunspots is one of the longstanding questions of solar physics.[61-63] Recent observations from MDI have revealed complicated flow patterns beneath sunspots (Figure C.3) and indicated that the highly concentrated magnetic flux in spots is accompanied by converging mass flows in the upper 3-4 Mm beneath the surface (Foldout 1.J). The evolution of these flows is not presently known. Detailed maps of subsurface flows in deeper layers, below 4 Mm, combined with surface fields and brightness for up to 9 days during disk passage will allow investigation of the relations between flow dynamics and flux concentration in spots.

Sources and mechanisms of solar irradiance variations. Magnetic features - sunspots, active regions, and network - that alter the temperature and composition of the solar atmosphere are primary sources of irradiance variability.[64] How exactly do these features cause the irradiance variations? HMI together with the SDO Atmospheric Imaging Assembly (AIA) and Spectrometer for Irradiance (SIE), will study physical processes that govern these variations. The relation between interior processes, properties of magnetic field regions and irradiance variations, particularly the UV and EUV components that have a direct and significant effect on Earth's atmosphere will be studied for the first time.

C.1.2.3. Sources and drivers of solar activity and disturbances

It is commonly believed that the principal driver of solar disturbances is stressed magnetic field. The stresses are released in the solar corona producing flares and coronal mass ejections (CME). The source of these

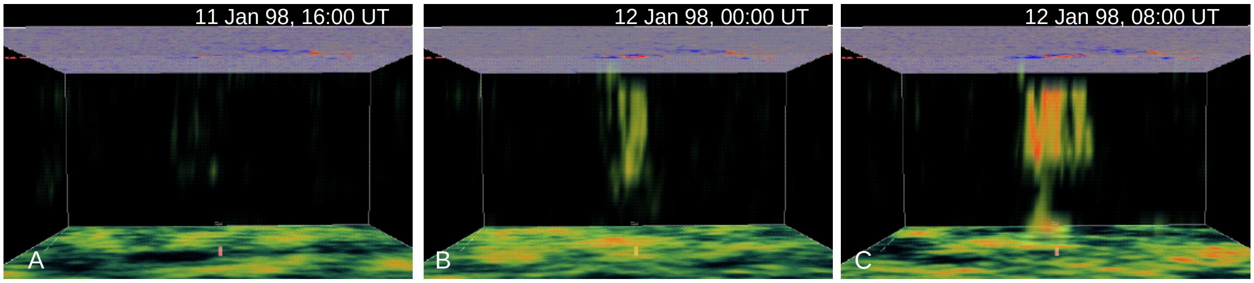

Figure C.4. MDI Images of sound-speed perturbations in an emerging active region obtained by the time-distance method with 8-hour resolution.[76] The horizontal size of the box is 460 Mm, the vertical size is 18 Mm. Magnetograms are shown on the underside of the solar surface**.**

stresses is believed to be in the solar interior.[65, 66] Flares usually occur in areas where the magnetic configuration is complex, with strong shears, high gradients, long and curved neutral lines, etc.[67] This implies that the trigger mechanisms of flares are controlled by critical properties of magnetic field that lead eventually to MHD instabilities. But what kinds of instability actually govern, and under what conditions they are triggered are unknown.[68] With only some theoretical ideas and models, there is no certainty of how magnetic field is stressed or twisted inside the Sun or just what the triggering process is.

Origin and dynamics of magnetic sheared structures and δ-type sunspots. The spots in Figure C.5 contain two umbrae of opposite magnetic polarity within a common penumbra and were the source of powerful flares and CMEs.[69] Such δ-type sunspot regions are thought to inject magnetic flux into the solar atmosphere in a highly twisted state.[70-72] It is important to determine what processes beneath the surface lead to development of these spots and allow them to become flare and CME productive. This investigation will be carried out by analysis of evolving internal mass flows and magnetic field topology of such spots.

Magnetic configuration and mechanisms of solar flares. Vector magnetic field measurements can be used to infer field topology and vertical electric current, both of which are essential to understand the flare process.[73] Observations are required that can continuously track changes in magnetic field and electric current with sufficient spatial resolution to reveal changes of field strength and topology before and after flares.[74, 75] HMI will provide these unique measurements of the vector magnetic field over the whole solar disk with reasonable accuracy and at high cadence.

Emergence of magnetic flux and solar transient events. Emergence of magnetic flux is closely related to solar transient events.[77-79] MDI, GONG, and BBSO data show that there can be impulsive yet long-lived changes to the fields associated with eruptive events. Emergence of magnetic flux within active regions is often associated with flares. Emerging magnetic flux regions near filaments lead to eruption of filaments.[80] CMEs are also found to accompany emerging flux regions. Further, emergence of isolated active regions can proceed without any eruptive events. This suggests that magnetic flux emerging into the atmosphere interacts with pre-existing fields leading to loss of magnetic field stability. Observations of electric current and magnetic topology differences between newly emerging and pre-existing fields will likely lead to the understanding of why emerging flux causes solar transient events.[81] Vector polarimetry provided by HMI will enable these quantitative studies.

Evolution of small-scale structures and magnetic carpet. The quiet Sun is covered with small regions of mixed polarity, termed 'magnetic carpet' (Foldout 1.G), contributing to solar activity on short timescales.[2] As these elements emerge through the photosphere they interact with each other and with larger magnetic structures. They may provide triggers for eruptive events,[82] and their constant interactions may be a source of coronal heating.[83-85] They may also contribute to irradiance variations in the form of enhanced network emission. While HMI will certainly not see all of this flux, it will allow global scale observations of the small-scale element distribution, their interactions, and the resulting transformation of the large-scale field.

C. 1.2.4 Links between the internal processes and dynamics of the corona and heliosphere

The highly structured solar atmosphere is predominately governed by magnetic field emerged from in the solar interior. Magnetic fields and the consequent coronal structures occur on many spatial and temporal scales. Intrinsic connectivity between multi-scale patterns increases coronal structure complexity leading to variability. For example, CMEs apparently interact with to the global-scale magnetic field,[86] but many CMEs, especially fast CMEs, are associated with flares, which are believed to be local phenomena. Model-based reconstruction of 3-D magnetic structure is one way to estimate the field from observations.[87-89] Models using vector field data in active regions provide the best match to the observations. More realistic MHD coronal models[90] based on HMI high-cadence vector-field maps as boundary conditions will greatly enhance our understanding of how the corona responds to evolving, non-potential active regions.

Complexity and energetics of the solar corona. Observations from SOHO and TRACE have shown a variety of complex structures and eruptive events in the solar corona. However, categorizing complex structures has not

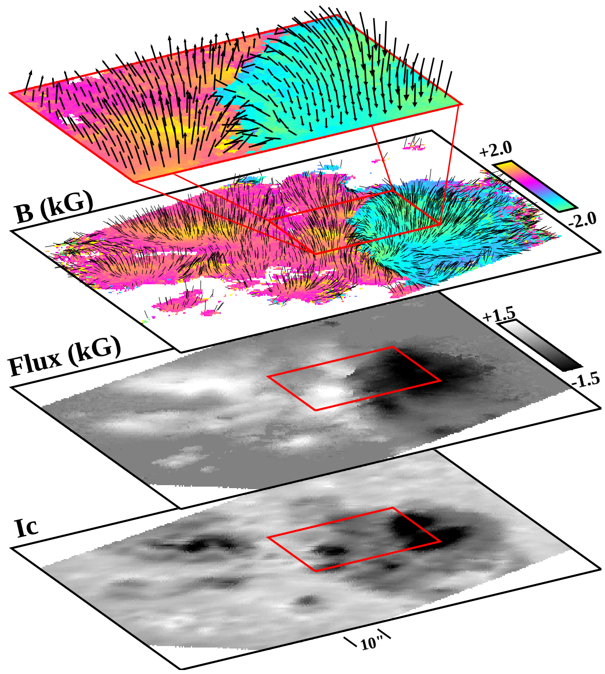

Figure C.5. Vector magnetic fields in the HMI Ni I 6768 Å line, observed with ASP, 2002 March 10, 18:58 UT, NOAA 9866: S9 W65.

revealed the underlying physics of the corona and coronal events.[91] Two mechanisms have been proposed to generate stressed magnetic fields: photospheric shear motions and emerging magnetic flux; and both may, in fact, be at work on the Sun.[92] But which plays the dominant role and how the energy injection is related to eruptive events is unknown. Magnetic helicity is an important characteristic of magnetic complexity and its conservation intrinsically links the generation, evolution, and reconnections of the magnetic field.[93-97] HMI will provide data to allow estimations of injections of energy and helicity into active regions[98, 99]: the vector magnetic field and the velocity field (from helioseismology and correlation tracking). Observations from SDO AIA and White-light Coronagraphic Imager (WCI) will show the subsequent response and propagation of complexity into the corona and heliosphere, relating the build-up of helicity and energy with energetic coronal events such as CME's.

Large-scale coronal field estimates. Models computed from line-of-sight photospheric magnetic maps have been used to reproduce coronal forms that show multi-scale closed field structures as well as the source of open field that starts from coronal holes but spreads to fill interplanetary space.[100] Modeled coronal field demonstrates two types of closed field regions: helmet streamers that form the heliospheric current sheet and a region sandwiched between the like-polarity open field regions. There is evidence that most CMEs are associated with helmet streamers and with newly opened flux.[101, 102] HMI will provide uniform magnetic coverage at a high cadence, and together with simultaneous AIA, WCI and STEREO coronal images will enable the development of coronal field models and study of the relationship between pre-existing patterns, newly opening fields, long distance connectivity, and CMEs.

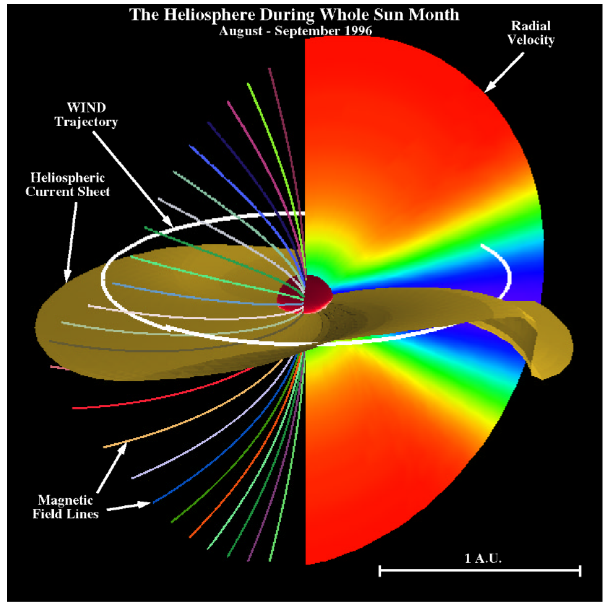

Figure C.6. MHD model of the solar corona and heliosphere driven by the observed line-of-sight photospheric magnetic field[103].

Coronal magnetic structure and solar wind. MHD simulation and current-free coronal field modeling based on magnetograms are two ways to study solar wind properties and their relations with coronal magnetic field structure[103-106] (Figure C.6). These methods have proven effective and promising, showing potential in applications of real-time space weather forecasting. It has been demonstrated that modeling of the solar wind can be significantly improved with increased cadence of the input magnetic data.[107] By providing full-disk vector field data at high cadence, HMI will enable these models to describe the distribution of the solar wind, coronal holes and open field regions, and how magnetic fields in active regions connect with interplanetary magnetic field lines.

C. 1.2.5 Precursors of solar disturbances for space-weather forecasts

Variations in the solar spectral irradiance and total irradiance may have profound effects on life through their potential but poorly understood role in climate changes. The variation from cycle to cycle of the number, strength, and timing of the strongest eruptive events is unpredictable at present. We are far from answering simple questions like 'will the next cycle be larger than the current one?' 'When will the next large eruption occur?' Or even 'when will there be several successive quiet days?' As we learn more about the fundamental processes through studies of internal motions, magnetic flux transport and evolution, relations between active regions, UV irradiance, and solar shape variations we will be vigilant for opportunities to develop prediction tools. Nevertheless, there are several near term practical possibilities to improve the situation with HMI observations.

Far-side imaging and activity index. A procedure for solar far-side imaging was developed using data from MDI[108] (Figure C.7), and has led to the routine mapping of the Sun's far-side[109]. Acoustic travel-time perturbations are correlated with strong magnetic fields, providing a view of active regions well before they become visible as rotate onto the disk at the east limb. Synoptic images, which are now able to cover the entire far hemisphere of the Sun[110], will provide the ability to forecast the appearance of large active regions up to 2 weeks in advance and allow the detection of regions which emerge just a few days before rotating into view. HMI's full coverage to the limb will allow lower-noise farside estimates.

Predicting emergence of active regions by helioseismic imaging. Rising magnetic flux tubes in the solar convection zone may produce detectable seismic signatures[76] (Fig. C.4), which would provide warning of their impending emergence. Helioseismic images of the base of the convection zone will employ a similar range of p-modes as those used to construct images of the far side. A goal is to detect and monitor seismic signatures of persistent or recurring solar activity near the tachocline. Success here could lead to long-term forecasts of solar activity.

Determination of magnetic cloud Bs events. Potentially valuable information for geomagnetic forecasts - predictions of magnetic cloud Bs (southward field) events - can be obtained from the vector field measurements. Long intervals of large southward interplanetary magnetic field, Bs events, and high solar wind speed are believed to be the primary cause of intense geomagnetic disturbances with the Bs component the more important quantity[111]. It has been shown that orientation in 'clouds' remains basically unchanged while propagating from the solar surface to Earth's orbit[112]. This provides a plausible chain of related phenomena that should allow prediction to be made from solar observations of the geoeffectiveness of CMEs directed toward Earth. Estimates of embedded Bs will be significantly improved by incorporating frequently updated vector field maps into coronal field projections with the potential addition of coronagraphic observations from AIA, WCI, and STEREO.

C.1.3 Scientific Approach

The investigation described above is a comprehensive broad-based investigation into the sources and mechanisms of solar variability and its impact on the space environment. An investigation with this scope requires dedicated efforts of a diverse team of researchers. HMI investigators are experts in the required disciplines including instrument design and development, data handling and access, instrument calibration, data analysis, theory, modeling, and presentation of results to the broader science community and the public at large. But the opportunity and challenges of LWS, SDO and HMI require a larger effort. The real limit to the scientific return is likely to be the support of people to pursue data analysis and theory development. We will maximize the scientific return by providing convenient access to high-level data products to Guest Investigators (GIs) and other scientists. The members of our research team will also actively participate in the coordinated SDO GI and LWS Theory and Modeling Programs.

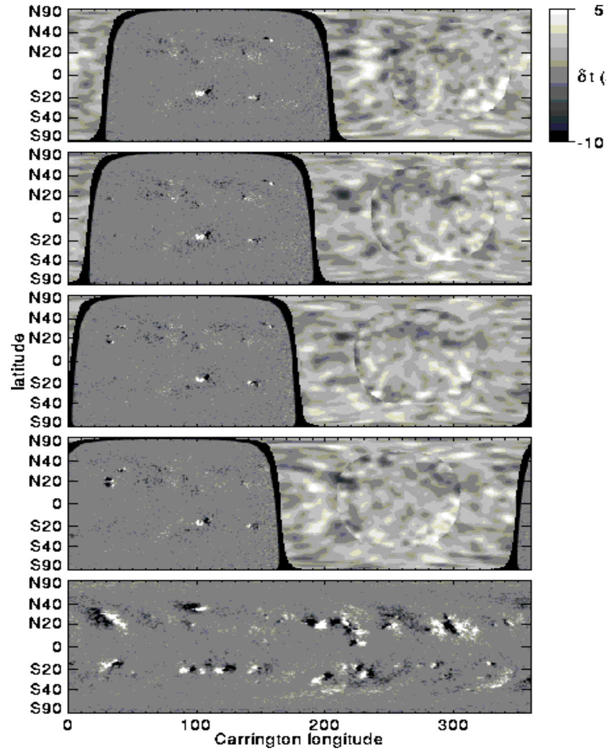

Figure C.7. Composite images of the near-side magnetic flux density (left) and far-side acoustic travel-time perturbations (right) for 1999 April 22-25.[110] The bottom panel shows a synoptic magnetogram for the subsequent Carrington rotation.

HMI data and results will be crucial for the success of the SDO mission by providing necessary key data for the coronal and irradiance instruments, in particular, magnetic field measurements, energetic characteristics of active regions, and flow maps associated with developing active processes. The goal is, in cooperation with the coronal instruments, particularly, with AIA, SIE and WCI, to develop knowledge and understanding of the solar and heliospheric aspects of the Sun-Earth system that directly affect life and society.

Important cooperation will be developed with other space missions and ground-based observatories. In particular, to support STEREO data interpretation, HMI magnetic data will provide the basis for modeling the corona and solar wind around CMEs, as well as indications of the causes of these transients. HMI will also provide global context for Solar-B vector measurements that are focused on specific active regions, and also information on coronal holes and solar wind stream structure used in the interpretation of L1 solar wind monitor data from spacecraft such as ACE. In the area of helioseismology cooperation with the GONG+ project will provide some cross-checks of helioseismic inferences.

C.1.4 Theoretical Support and Modeling

Exploiting the full scientific potential of HMI requires access to advanced theoretical 3-D simulations of global-scale turbulent convection interacting with rotation and magnetic fields; local-domain near-surface magneto-convection simulations of granulation, meso-granulation and supergranulation including realistic equations of state, opacities and radiative transfer; local and global dynamo processes variously within the tachocline and the near-surface shear layer; wave excitation and propagation in magnetized plasmas; and upper atmosphere and coronal magnetic field configurations and their evolution, including the response to footpoint displacements and flux emergence. Given rapid developments in massively-parallel supercomputing, major advances are feasible in these theoretical areas in the next five years as HMI is implemented. HMI Co-Is are playing pivotal roles in such theoretical efforts, but will require suitable organized investments from many programs, including the LWS Theory and Modeling program. Theoretical models for inversion of helioseismic and magnetic data are also extremely important for HMI data analyses. This range of the theoretical efforts needed to exploit fully HMI opportunities exceeds the scope of this investigation. However we must directly support integration of analytical methods and models developed elsewhere into the suite of tools available to the broad HMI team.

C.1.5 Scientific Operation Modes and Requirements

The scientific operation modes and data products can be divided into four main areas: global helioseismology, local-area helioseismology, line-of-sight and vector magnetography and continuum intensity studies. The principal data flows and products are summarized in Foldout 1.L. These four primary scientific analyses cover all main HMI objectives, and have the following characteristics:

- *Global Helioseismology: Diagnostics of global changes inside the Sun.* The normal-mode method will be used to obtain large-scale axisymmetrical distributions of sound speed, density and flow velocities throughout the solar interior from the energy-generating core to the near-surface convective boundary layer. These diagnostics will be based on frequencies and frequency splittings of modes of angular degree (l) up to 1000, obtained for intervals of several days each month and up to l=300 for each 2-month interval. These will be used to produce a regular sequence of internal rotation and sound-speed inversions to allow observation of the tachocline and the near-surface shear layer.

• *Local Helioseismology: 3D imaging of the solar interior.* The time-distance technique, ring-diagram analysis and acoustic holography represent powerful tools for investigating physical processes inside the Sun. These methods are based on measuring local properties of acoustic and surface gravity waves, such as travel times, frequency and phase shifts. The targeted high-level regular data products include:

- synoptic maps of mass flows and sound-speed perturbations in the upper convection zone for each Carrington rotation with a 2-degree resolution, from averages of full disk time-distance maps;
- synoptic maps of horizontal flows in the upper convection zone for each Carrington rotation with a 5-degree resolution from ring-diagram analyses;
- higher-resolution maps zoomed on particular active regions, sunspots and other targets, obtained with 4-8-hour resolution for up to 10-day transits;
- deep-focus maps covering the whole convection zone depth, 0-200 Mm, with 10-15 degree resolution;
- farside images of travel-time perturbations associated with large active regions every 12 hours.

These observations require uninterrupted series of Dopplergrams of lengths 8 to 24 hours with the following characteristics: 50-second (or higher) cadence, spatial sampling of 2 Mm for distances up to 75 degrees from the disk center, and the noise level better than 20 m/s.

• *Magnetography. Complete coverage of magnetic processes in the photosphere.* The traditional line-of-sight component of the magnetic flux is produced as a co-product with the Doppler velocity. Several products will be computed with various cadence (up to 10 minutes) and resolution for use as input to coronal field and solar wind models and correlative studies. To accurately model the global fields the zero point accuracy should be better than 0.1G.

•*The vector magnetic field.* This is one of the most important physical observables of the active solar atmosphere. HMI will produce several standard data series of vector fields. A simple 'magnetograph mode' analysis will be computed continuously in real time for large scale coronal modeling and other space weather applications. With help of inversion techniques[113], HMI will also provide tracked and full-disk vector magnetic field, filling factor, and thermodynamic parameters of photospheric plasma within reasonable errors. The data will be used to measure free energy, stresses and helicity of the magnetic field, providing important input to many prime science objectives and tasks of HMI and other SDO investigations. These polarimetric observations require a few minutes temporal cadence, a spatial sampling of 0.5", and a 0.3% polarization precision to yield 5% accuracy of the magnetic field strength, a few tens of degrees in inclination and azimuth in strong fields.

• *Continuum Intensity: Identification of irradiance sources.* The observations of the intensity in the continuum near the HMI spectral line will give a very useful measure of spot, faculae area and other sources of irradiance. This will be important for studying the relationship between the MHD processes in the interior and lower atmosphere and irradiance variations. The continuum data will be also used for limb shape analysis, and for public information and education purposes. These measurements require calibration of system pixel-pixel gain variations to a level 0.1%, as demonstrated with MDI.

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