Preface

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This volume contains a collection of articles on the topic of *Solar Dynamics and Magnetism from the Interior to the Atmosphere* stimulated by the LWS/SDO-3/SOHO-26/GONG-2011 workshop of the same name, which was held 31 October–4 November 2011, at Stanford, California, USA.

The goal of the workshop was to discuss recent advances and new problems in the exploration of the Sun's interior structure, solar dynamics and dynamo, mechanisms of sunspot and active regions formation, sources of solar irradiance variations, links between the sub-surface dynamics, and flaring and CME activity. NASA's *Solar Dynamics Observatory*

Solar Dynamics and Magnetism from the Interior to the Atmosphere
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(SDO) mission has been providing a large amount of new data on solar dynamics and magnetic activities during the rising phase of the highly unusual Solar Cycle 24. These data are complemented by the *Solar and Heliospheric Observatory* (SOHO) mission and by ground-based observatories, which include the *Global Oscillation Network Group* (GONG) helioseismology network and the *New Solar Telescope* (NST). In addition, these observations are supported by realistic numerical simulations on high-end computers. This unprecedented amount of data provides a unique opportunity for multi-instrument investigations that address fundamental problems of the origin of solar magnetic activity at various spatial and temporal scales. The data are being used to develop new methods for forecasting solar cycles, emergence and evolution of active regions, and their flaring and CME activity.

This volume represents an attempt to develop a synergy among investigations of the solar interior by helioseismology, surface magnetism, and the atmospheric dynamics, by using both state-of-the-art observations and numerical simulations. The articles are organized in six chapters:

- i) Local and Global Helioseismology.
- ii) Sources of Solar Shape and Irradiance Variations.
- iii) Large-Scale Dynamics, Magnetism, and Dynamo.
- iv) Emerging Magnetic Flux and Subsurface Dynamics.
- v) Formation, Structure, and Evolution of Sunspots and Active Regions.
- vi) Magnetic Topology and Dynamics of the Solar Atmosphere.

Some articles fit in more than one topic, and in such cases the classification is not well-defined, and we recommend that readers consult the whole table of contents. Some of the articles are written as Invited Reviews, but all contain new results and ideas that reflect the current status of the field, new challenges, and future perspectives.

In recent years, our understanding of the solar interior has advanced substantially thanks to the development of helioseismology techniques and continuous observations of solar oscillations by the *Helioseismic and Magnetic Imager* (HMI) onboard SDO and by GONG. High-precision measurements of oscillation frequencies have provided the radial sound-speed profile and the distribution of the angular velocity through the whole interior, except perhaps the very inner core of the Sun. These measurements provided a test of stellar-evolution theory and the standard solar model. However, the discrepancy between the abundance of heavy elements determined spectroscopically on the solar surface and the abundance deduced from solar modeling and global helioseismology data provides a strong indication that our understanding of the basic physics of the solar interior is still incomplete. In particular, there are fundamental issues related to modeling of non-ideal properties of the solar plasma, and the equation of state, which directly affect the accuracy of the estimate for the heavy element abundance by helioseismology. In addition, there are indirect effects due to the uncertainty of the solar age and magnetic-field effects. Therefore, it is important to develop a synergy of more accurate frequency inversion methods and detailed description of the micro-physics in order to resolve the heavy element abundance problem. Also, it becomes increasingly important to investigate the global dynamics of the Sun. In addition to the traditional methods of global helioseismology, based on inversion of rotational frequency splitting, new methods of local helioseismology, which measure the meridional circulation and large-scale flows in the quiet-Sun and active regions, are being actively developed. In particular, the very long time series of solar oscillations observed by the *Michelson Doppler Imager* onboard the SOHO spacecraft and GONG during the whole solar cycle from 1995–2008, provided new measurements of the solar differential rotation down to 0.2 solar radii. However, while the results of these measurements are consistent with the hypothesis of a

uniformly rotating core, they cannot rule out that the energy-generating core rotates faster or slower than the outer radiative zone. This is also a problem of fundamental importance for understanding the formation and evolution of the Sun.

Local helioseismology based on measurements and inversion of frequency shifts and acoustic travel times is capable of providing the 3D structure and dynamics of the convection zone. The interpretation of these measurements and inversions is a subject of hot debate. The debate has been substantially improved with the development of realistic numerical simulations of randomly excited acoustic waves in 3D models of the Sun that include background flows and magnetic fields. The approach based on a synergy of a time–distance helioseismology method and numerical simulations provided new estimates of the subsurface flow structure of supergranulation, which led to a surprising result that strong upflows may be hidden 2 Mm beneath the surface supergranulation pattern dominated by outflows. In addition, local-helioseismology measurements based on unique multi-wavelength data from SDO provide new knowledge about wave propagation in magnetic regions of the solar atmosphere, and wave transformation and scattering. These new results challenge the existing simple models of MHD wave propagation and point to the need for further development of numerical simulations of waves in realistic conditions of turbulent and radiating plasma of magnetic regions. It becomes more and more clear that MHD waves excited by turbulent convection play a fundamental role in the dynamics and energetics of the solar atmosphere.

Variations of the solar diameter, shape, and irradiance are of particular interest because of the long and rich history of these investigations, their role in solar evolution, and global changes of the Earth's radiation and space environment. The high-precision measurements onboard SDO open new perspectives for improving our knowledge of solar variability on wide temporal and spatial scales, and advancing our understanding of the underlying physical mechanisms. In particular, these measurements encourage revisiting of old questions about solar oblateness, the relationship between oblateness changes and solar cycles, the constraints on relativistic celestial mechanics and alternative theories of gravitation. At the high-frequency end of the irradiance spectrum, accurate measurements from the *Extreme Ultraviolet Variability Experiment* (EVE) onboard SDO led to the detection of the global five-minute oscillations in the corona, and their modal structure, which corresponds to the global modes observed in the photosphere. If this surprising link between the interior and corona is confirmed by further observations, it will have important implications on theories of wave propagation on the Sun and mechanisms of coronal heating.

Helioseismology provides critical information for developing dynamo models of the solar magnetic cycle. After the discovery of the tachocline, a narrow rotational-shear layer at the bottom of the convection zone, dynamo theories assumed that the toroidal magnetic fields, which are the primary source of sunspot regions, are generated and stored in the tachocline. In order to explain the sunspot “butterfly” diagram, these theories assumed that the internal meridional circulation transports the toroidal field in the tachocline towards the Equator in the course of the solar cycle, and that this toroidal field emerges locally in the form of compact Ω -shaped magnetic loops and forms sunspot regions. However, there are serious, unsatisfactory aspects of such an advection-dominated dynamo because the strength of the return meridional flow is largely unknown, and because the required eddy diffusivity is about one order of magnitude greater than is predicted by standard mixing-length theory. One possible alternative to the “flux-transport” theory is a dynamo model that takes into account effects of the near-surface rotational-shear layer, also discovered by helioseismology. In the new theory, the magnetic field is generated in the bulk of the convection zone and forms the butterfly pattern in the subsurface-shear layer. This theory represents a paradigm shift in our understanding of the solar dynamo and cycles, and requires further detailed investigation. It is quite intriguing that after this workshop new local-helioseismology results

provided evidence that the meridional circulation may consist of two radial cells, making the flux-transport theory even more problematic. Ultimately, the issue will be resolved by improving the accuracy of the helioseismology measurements, and new approaches are being actively developed. In addition, important information is provided from synoptic analysis of magnetic patterns on the solar surface such as rotation of sunspot groups, and their inclination relative to the Equator (Joy's law). Future dynamo theories will have to explain these patterns.

Observations and modeling of the emergence of the dynamo-generated magnetic flux are of primary importance in heliophysics for two main reasons: First, the emerging flux is directly linked to the dynamo process and carries information about the dynamo; second, the emerging flux can trigger flares and CMEs, and thus is important for forecasting space weather and solar storms. Helioseismology made a substantial breakthrough in this topic by detecting acoustic travel-time variations associated with the emerging flux in the deep convection zone (at a depth of 45–70 Mm) 24–48 hours before the magnetic field becomes visible on the surface. The nature of the travel-time variations is not yet understood. These are probably related to scattering of acoustic waves on the emerging flux inhomogeneities. Solving this problem requires modeling of the flux emergence in realistic turbulent conditions of the convection zone. Simulations are being actively developed, and used for understanding links between the dynamo characteristics and properties of the emerging flux.

After emergence at the surface, the magnetic flux is a mixture of small elements of opposite polarity. However, very quickly, elements of each polarity merge and form compact and stable sunspot structures. After the formation, the sunspot magnetic fields continue to evolve, interact with magnetic fields of the opposite polarity, and form unstable magnetic configurations resulting in plasma eruptions. It seems that the magnetic-field dynamics observed on the surface is controlled by subsurface flows. Interaction of these flows, driven by the convective-energy flux, with magnetic fields is a key to understanding the solar activity, but the physics of this interaction is extremely complicated. Currently, only the first steps are being made by local time–distance helioseismology to map the sub-surface flow patterns and link these to the surface magnetic field dynamics. New results from the HMI instrument onboard SDO, obtained for a shallow 500 km deep region, which was previously inaccessible due to low spatial resolution of previous instruments, reveal converging plasma flows in the sunspot umbra area, surrounded by diverging flows. These measurements, supported by results of correlation tracking of the surface field, represent a significant challenge for some recent MHD simulations of sunspots, which predicted only diverging flow patterns. Another local-helioseismology technique, ring-diagram analysis, shows that the subsurface structure of sunspots is characterized by a shallow layer of reduced wave speed and a deeper layer of higher sound speed. Qualitatively, this is consistent with the previous time–distance helioseismology results. However, the depth estimates of these layers are significantly different. This difference may be related to differences in the spatial resolution, but ultimately will be resolved when large-scale realistic MHD simulations of sunspots will become available. So far, only relatively small, pore-like structures were modeled in the simulations self-consistently without specifying artificial boundary conditions to prevent the structure's decay. In these self-consistent simulations, the magnetic structures are maintained by converging downdrafts driven by surface cooling. An alternative model suggests that sunspot-like structure can form because of the suppression of turbulent pressure by the magnetic field. This suppression called “negative effective magnetic pressure instability” also results in converging downdrafts. In addition, the instability leads to a redistribution of turbulent intensity and gas pressure that could provide direct observational signatures.

The structure and dynamics of the atmosphere and corona is governed by magnetic fields generated by a dynamo in the deep convection zone and emerging on the solar

surface. Recent high-resolution observations from the NST of the Big Bear Solar Observatory led to a surprising discovery of ultra-fine structure of magnetic fields extending from the surface to the corona. Analysis of these ultra-fine magnetic fields suggest that they can serve as channels of the energy and mass flow from the interior to the corona and contribute to the coronal heating. The origin of the fine-scale structures and their dynamics are being investigated using new infrared and visible light spectro-polarimeters. The ultimate goal is to obtain high-resolution spectro-polarimetric data for diagnostics of solar dynamics and magnetism from the low photosphere to high chromosphere. Higher up in the corona, the magnetic fields cannot be measured by spectro-polarimetry. Therefore, the challenge is to infer the magnetic-field properties using EUV observations of the coronal magnetic loops from the SDO and the *Solar TERrestrial RELations Observatory* (STEREO) missions, and photospheric magnetograms. New algorithms of nonlinear force-free reconstruction have been developed and provide estimates of free magnetic energy, using only line-of-sight magnetic-field data. These are very important achievements for predicting flare and CME energy-release events.

In summary, recent high-resolution observations from ground and space, as well as realistic supercomputer simulations, have led to substantial progress in our understanding of solar dynamics and magnetism from the interior to the atmosphere. This collection of articles demonstrates that the synergy of high-resolution multi-wavelength observations and simulations is a key to uncovering long-standing puzzles of solar magnetism and dynamics.

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Preface

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