Helioseismology

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Summary

Virtually all solar phenomena originate in the Sun's interior, thus a full understanding of solar physics requires a comprehensive description of the conditions below the photosphere. This can only be done with helioseismology, which has already provided many significant advances in solar physics. Progress towards current helioseismology science goals would be best accomplished with ground-based multi-wavelength observations, and space-based multi-viewpoint measurements.

Introduction and Goals

All solar phenomena begin with the generation of energy by the fusion reactions in the core of the Sun. During the 10^7-year long journey of a photon from the core to the surface, the energy it carries can be transformed into thermal, kinetic, or magnetic forms. In turn, this energy drives large-scale motions in the convection zone creating differential rotation and generating the magnetic fields that eventually erupt on the solar surface where they cause the solar activity which controls the atmosphere and affects modern society.

The only way that we can probe the solar interior is with helioseismology, the study of the waves that are mainly trapped below the photosphere. These waves are primarily acoustic in nature, and were discovered in 1960. Helioseismology has advanced solar physics in many ways, including

- Demonstrating that the interior was not rotating sufficiently rapidly to call into question predictions of General Relativity.
- Demonstrating that the neutrino flux deficit did not arise from errors in our knowledge of conditions in the solar core
- Substantially validating the standard solar model
- Precisely determining the depth of the solar convection zone
- Mapping the internal solar rotation rate leading to the discovery of the tachocline (Figure 1)
- Detecting activity on the solar far side
- Measuring the surface torsional oscillation deep into the convection zone
- Showing that meridional and zonal flows in the solar convection are linked to activity cycle
- Showing that the oscillation frequencies track the solar cycle
- Determining the structure beneath sunspots
- Discovering that strong subsurface vorticity underlies flare-productive active regions

Scientific Motivation

The Sun is a star, and understanding the solar interior opens up new paths to understanding the interior of all stars. Conversely, understanding other stars places the Sun in astrophysical context and increases our understanding of its likely future evolution. Asteroseismology has become a very active field with the launches of CoRoT and Kepler, and the interplay between helio- and asteroseismology enriches both endeavors.

The most promising research topics for the coming decade for understanding the solar interior are:

- Understanding large-scale flows and constraining solar dynamo models
- Studying convection and rotational shear immediately below the photospheric boundary
- Understanding the near-surface excitation, damping, and *p*-mode coupling to the atmosphere
- Determining the internal structure and evolution of stellar active regions
- Reconciling the new abundances and stellar interior models

- Understanding the physical basis of flare and CME production and the development of space weather predictions

We discuss three of these topics in some more detail.

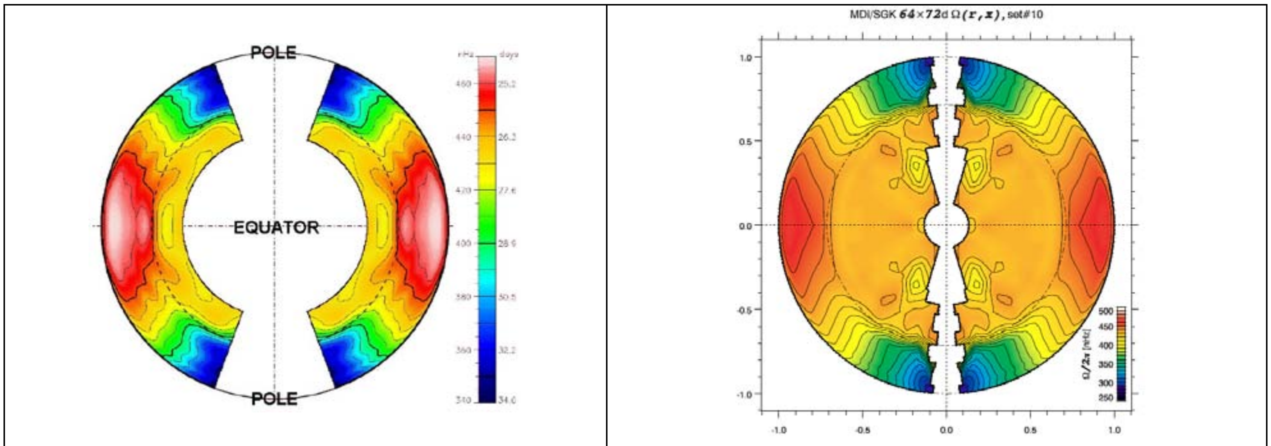

Figure 1: A color contour plot of the solar internal rotation as obtained by helioseismology. On the left is a plot using a few months of data obtained in the early 1990s; the right panel shows a modern inversion from S. Korzennik using 12.6 years of data, demonstrating the improvement obtained with long data sets. These observations revealed that the surface differential rotation extends downward completely through the convection zone, below which it is replaced with solid body rotation. The transition region from differential to solid-body rotation at the base of the convection zone (indicated by the dashed line in the plot) is known as the tachocline. This observation was in contradiction to the then-current dynamo theories of solar activity, which required that the internal rotation be constant on cylinders parallel to the solar rotation axis.

Solar dynamo — The Sun's 22-year Hale magnetic cycle dominate the long-term measures of solar variability. Essential aspects of our star's convective motions, meridional and zonal flow, and differential rotation that drive the cycle dynamo and the formation of individual active regions are still unknown. These motions are intimately connected with the solar cycle as shown by the recent discovery of the correlations between the speed of the meridional flow, the strength of the polar magnetic field and the amplitude of the subsequent solar cycle, as well as between the torsional oscillation migration rate and the temporal length of the recent deep and extended minimum.

Surface measurements of velocities and magnetic fields combined with helioseismic measurements of differential rotation and discovery of the tachocline and near-surface shear layer have provided important constraints on dynamo theories. However, even increasingly realistic models fall far short of adequate treatment of the basic physical processes, relying on parameterization of the widely varying physical and temporal regimes involved. Accurate measurements of the meridional flows throughout the Sun along with better characterization of non-axisymmetric dynamics over long intervals are essential ingredients for the development of adequate models to enable prediction of the solar cycles and long-term activity. In particular, the following key problems need to be addressed during the next decade:

- Determine the structure of the meridional flow at high latitudes and in the deep interior, and characterize the return meridional flow

- Determine the structure and dynamics of supergranulation in the polar regions, the role of supergranular diffusion in the magnetic flux transport, and search for large-scale organization of the supergranular convection (giant cells)
- Determine solar-cycle variations of the deep convection zone, tachocline and the nature of the possible 1.3- and 2-year periodicities
- Determine the 3D structure of the zonal flows ("torsional oscillation") and large-scale converging flows around active regions ("solar subsurface weather") including the relationship to surface flows; investigate the relationship between these flows and the formation of active regions and complexes of activity.

To solve these problems it is necessary to:

- Maintain the existing helioseismic observations provided by GONG and SDO
- Develop new capabilities for out-of-ecliptic observations of the polar dynamics and 3D stereo-type helioseismology for the reconstruction of the global 3D structure and dynamics of the Sun; these capabilities include proposed space missions: Solar Orbiter, Solar-C (Plan A), and Solar Polar Imager (SPI);
- Develop new methods of local and global helioseismology (supported by realistic numerical simulations), and a synergy of these methods, for determining the 3D structure and dynamics of the whole Sun.
- Maintain existing systems that measure surface velocities and magnetic fields.

Internal structure and evolution of active regions — Active regions apparently emerge quickly through the outer several megameters of the convection zone. Current state-of-the-art local-area helioseismology analysis with sufficient precision to resolve their subsurface characteristics requires observations collected over several hours, comparable to the emergence time. Once a sunspot complex has emerged, accurately measuring its characteristics requires the same precise knowledge to resolve what happens on the time scale of its evolution. There is good evidence from local helioseismology that the temporal evolution of subsurface helicity below a specific active region is related to the timing and strength of solar flares, thus local helioseismic techniques should be able to provide useful predictions of space weather. Over the course of the solar cycle, active region characteristics may change – we already know something about variations in location, orientation, and helicity, but not yet about complexity and ultimate source. In order to determine these variations, a large number of regions over the course of a cycle at various depths and ages must be observed, preferably with surface vector magnetic field measurements which provide the best estimates of the field characteristics. More sensitive and more deeply probing measurements require sufficient spatial resolution over a large part of the solar disk and better understanding of how magnetic, velocity and other physical conditions along the ray paths traveled by the sound waves affect their propagation. That includes the surface effects where the waves reach the solar surface. The Solar Dynamics Observatory (SDO) will help with the issue of spatial resolution, although multiple spacecraft observing from different directions around the heliosphere would be much better for probing more deeply. But it is doubtful whether observations with a single wavelength (i.e. a single height in the atmosphere) can completely characterize the modes. In addition, recent work that indicates the inclination of the magnetic field plays a vital role in determining the energy transport of the acoustic waves has opened up a new line of enquiry that will require nearly-continual vector magnetograms in addition to helioseismic observations.

We identify the following key problems for understanding the mechanisms of the formation of active regions and their flaring and CME activity, and for developing space weather forecasts based on helioseismic diagnostics:

- Investigate the evolution of subsurface flows and seismic sound-speed perturbations during the life-cycle of active regions for large samples during different phases of the solar cycle
- Develop methods of detecting active regions in the interior prior their emergence
- Determine the relationship between the subsurface dynamics and growth and decay of active regions for predicting their evolution
- Determine the formation and subsurface dynamics of large long-living complexes of activity and methods of their early detection
- Investigate the mechanism of the formation of sunspots, and their subsurface magnetic and thermodynamics structure and dynamics;
- Determine characteristics of subsurface flows (e.g. helicity, shear velocity) related to the flare and CME activity of active regions.

The required capabilities include the following:

- Maintain the continuous helioseismic observations of active regions during the full solar cycle from SDO and GONG
- Multi-viewpoint helioseismic and magnetic field observations of active regions using space missions, Solar Orbiter, Solar-C (Plan-A), SPI
- Multi-wavelength observations of individual active regions and sunspots from SDO, GONG, Hinode/SOT, MOTH and Mt. Wilson
- Substantial improvement of local helioseismology methods for diagnostics of magnetic regions
- Large-scale radiative MHD simulations of sunspots and active regions for understanding effects of turbulent magnetic fields on wave excitation and propagation and to test methods of local helioseismology

Subsurface turbulent magneto-convection, wave excitation, and the coupling to the atmosphere — The immediate sub-photosphere is highly superadiabatic, and the hydrogen ionization zone is a source of convective driving. It is an extremely complex turbulent physical environment that can dominate many of the aspects of the waves. Thus lack of knowledge of the physics in this region greatly hampers our interpretation of some helioseismic observations. Spectacularly detailed simulations of turbulent convection in the upper layers of the convection zone seem to mimic very faithfully what we observe on the surface of the Sun: granulation, intense downflows, and the creation, transport, and destruction of small magnetic flux elements. However these models are limited in two important ways: Current observations of subsurface conditions are not good enough to validate many of the features seen in the models. The models, which need to span the huge range of spatial and temporal scales in order to adequately sample and calculate the scale heights, densities, temperatures, pressures, and magnetic fields, cannot be computed with today's computers. The importance of understanding how solar oscillations gain and lose energy provides important constraints on the turbulence generating the waves. Better oscillation physics in turn enables the proper interpretation of helioseismic data and understanding of subsurface dynamics.

The key requirement is to combine high-resolution measurements with theory of physical conditions where the solar waves are excited and propagate. Understanding how the modes couple to the photospheric plasma and how energy is transferred to the overlying magnetized atmosphere also impacts understanding of the energetics and dynamics of the chromosphere and low corona. This will require simultaneous observations at multiple heights in the atmosphere under many conditions and over large regions of the solar surface. Multi-line measurements may also help reduce the background noise in the oscillation spectra.

The key problems that need to be addressed during the next decade are:

- Understanding of the wave excitation mechanism in the quiet Sun and magnetic regions
- Investigation of wave interaction with magnetized turbulence
- Determination of wave propagation and transformation properties in strong magnetic field regions of sunspots
- Investigation of wave leakage into the atmosphere and the role of waves in the energetic and dynamics of the chromosphere

These problems require the following capabilities:

- Coordinated multi-wavelength high-resolution Doppler and spectro-polarimetric observations of the solar photosphere from space missions and ground-based observatories (SDO, Hinode, Solar Orbiter, GONG, MOTH, NST, ATST, SOLIS, Mt. Wilson, BiSON)
- Coordinated high-resolution imaging and spectroscopic observations of the chromosphere (NST, ATST, IRIS, Gregor)
- Large-scale high-resolution radiative MHD simulations of the plasma dynamics from the subphotosphere to the chromosphere and corona
- Development of accurate and efficient sub-grid scale turbulence models of the magnetized plasma

Critical capabilities needed for future helioseismology studies of the solar interior

Helioseismic observations of the polar regions – Determination of the differential rotation and the meridional circulation in the polar regions will provide unprecedented insights into the dynamics of the convection zone and the operation of the solar dynamo. Helioseismic determinations of the solar internal rotation profile rely primarily on global acoustic oscillations. Current observations of global modes are insensitive to the polar regions because of the difficulty of viewing these regions from the ecliptic. Thus, the differential rotation of the polar regions is currently unknown (See Figure 1). Existing helioseismic measurements suggest sharp spatial and temporal variations, including the possibility of a polar jet, but these measurements can only be confirmed by observing the polar regions directly, from an out-of-ecliptic orbit, and by applying methods of local helioseismology. Observations of the polar regions is a key to understanding the basic mechanisms of solar magnetic activity and predicting sunspot cycles. Recent observations of the polar regions from Hinode, during the periods of the highest inclination of the solar axis, have provided evidence for concentration of the Sun's dipolar field into compact kilogauss structures and for alignment of the supergranulation pattern. However, detailed investigations of the magnetism and dynamics are only possible from out-of-ecliptic space missions. Solar Orbiter, SPI and Solar-C (Plan-A) are among the potential missions that may be developed during the next decade to provide this capability.

Multi-viewpoint helioseismology – Current helioseismology observations allow us to determine the axisymmetric structure and dynamics of the Sun by the methods of global helioseismology, and also to obtain maps of 3D flows and sound-speed perturbations in a relatively shallow subsurface layer on the front side of the Sun. They also allow detecting large active regions on the far side. However, stereo-type multi-viewpoint observations are necessary for the reconstruction the global 3D structure and dynamics of the interior. These observations will enable stereo-helioseismology based on long-base time-distance cross-correlation analysis of solar oscillations observed from the Earth orbit and a remote spacecraft. These observations will provide more accurate diagnostics of the tachocline and the deeper interior, including estimates of the spatial large-scale inhomogeneity of the solar core, and measurements of the core rotation. They will allow us to investigate the lifecycle of active regions by following their evolution for longer periods, and also investigate the nature of long-living complexes of activity ("active longitudes").

***Multi-wavelength observations of solar oscillations* –** The critical data missing from all existing programs to improve this are observations at multiple heights in the solar atmosphere. These are required for adequate understanding of mode physics and interpretation of the mode characteristics to reveal what is really happening beneath the surface. In addition, high spatial, spectral, and temporal resolution observations over small areas will also provide information on the unresolved small-scale processes that may be important. Finally, nearly continuous long-term observations of the surface vector magnetic field will be needed to fold the magnetic field inclination into the analysis. Limited modern multi-spectral helioseismic observations with the MOTH instrument in Antarctica have been used to study *p*-mode characteristics in the presence of magnetic fields, and led to a discovery that the regions of inclined magnetic field can serve as "magnetic portals" through which acoustic energy can leak into the chromosphere. In the future, GONG could be a unique tool for probing the solar interior with improved instrumentation, multi-wavelength diagnostics and automated data analysis. The solar interior changes continuously, from cycle to cycle; there is evidence for long-term trends in solar magnetism and irradiance. Advances in our understanding of stellar interiors require long-term observations of the conditions inside the Sun.

To meet these needs, substantial modification of the GONG network would be necessary. Preliminary discussions of an upgraded GONG network concept contain the following elements:

- Simultaneous Doppler and magnetic field observations in 4 to 16 different spectral lines. Possible instrument concepts include a Fabry-Perot (e.g. the Göttingen Fabry Perot Interferometer), fiber-fed multi-scanning spectrograph (e.g. FIRS), magneto-optical filter (e.g. MOTH), and Michelson interferometer (e.g. SIAMOIS).
- Images with a format of either 2k × 2k or 4k × 4k. This would require an entrance aperture of 20 or 40 cm to replace the current 10-cm diameter unit.
- The higher-resolution images would also require some type of image correction in order to achieve the full spatial resolution below the terrestrial atmosphere. Since the small aperture precludes adaptive optics, the image correction system might consist of a tip-tilt mirror and high-speed computing to perform differential destretching of the data as it is collected.

Synergy with realistic numerical simulations – Numerical simulations have become increasingly important for understanding the complex physics of the turbulent magneto-convection, formation and dynamics of sunspots, excitation and propagation of waves, and also provide artificial data for testing helioseismology methods. The helioseismic inversions are necessarily based on simplified wave models. Numerical "forward" modeling of more realistic conditions is absolutely essential for the verification and testing of the helioseismology methods and their improvements. Significant progress has been made for developing MHD simulations of wave propagation in a local 3D domain and in 3D models of the whole Sun , which are used for testing various aspects of helioseismic measurements and inversions, and for understanding the differences and consolidating the inversion results obtained by different techniques. In the coming decade, a substantial role will be played by realistic radiative MHD simulations of solar turbulence and waves, from first principles. Several radiative MHD computer codes (Stein-Nordlund, MURaM, SOLAR_BOX) have been developed and used for modeling magneto-convection, magnetic structures, and oscillations. Currently, the simulations of this type are carried out for relatively small and shallow computational domains. There is a strong need of expanding these simulations for large and deep regions. This will require developing numerical methods, algorithms and codes, which can be used on massive parallel computers, 10^4-10^5 CPUs, which will be soon available (Teragrid and Blue Water systems). This is a substantial effort of critical importance for helioseismology requiring specific support.

Needs

The study of the physics of the solar interior, and its import for the solar atmosphere and corona, has been greatly influenced by the modern imaging helioseismic programs of GONG and SOHO/MDI, now extended by SDO/HMI. The next decade should bring online the ATST, a SOLIS Network, multi-spectral helioseismology, continued operation of GONG, and the beginning of routine multi-viewpoint helioseismology from space.

Top priority should be given to these initiatives:

- Adequate support for analysis of SDO, GONG, Mt. Wilson, BiSON and MOTH data and for development of new helioseismic diagnostics.
- Support for continued long-term operation of GONG to supply highly reliable, comprehensive ground-based synoptic observations of the changing Sun in cooperation with SDO. It is essential to have two systems to cross-calibrate the measurements and to provide long-term continuity of the observations.
- Development of out-of-ecliptic missions for studying the structure and dynamics of the polar regions, and the mechanism of the polar field reversals and their role in the activity cycles.
- Development of multi-view helioseismology missions (Solar Orbiter, SPI, Solar-C/Plan-A) for stereo-type observations of the solar interior, helioseismic reconstruction of the global 3D structure and dynamics of the Sun, and investigation of the lifecycle of active regions and complexes of activity.
- Multi-height/multi-spectral observations of waves propagating in and through the photosphere for understanding the physics of solar oscillations and waves.
- Studies of the links between the turbulent convection zone and energetic and dynamics of the solar chromosphere and corona along with further development of local helioseismlgy methods to forecast space weather.
- A design study for a new-generation ground-based network for multi-spectral helioseismology.
- Substantial computational resources to support realistic MHD simulations of the multi-scale convection, dynamics of emerging magnetic flux, formation of sunspots and active regions, coordinated modeling and helioseismology analysis efforts.
- Joint programs combining helioseismology and dynamo theory to advance understanding of the solar dynamo.

With these initiatives, helioseismology will provide greatly improved observations of the Sun's interior, the seat of all solar phenomena.

ACRONYMS

ATST: Advanced Technology Solar Telescope
BiSON:Birmingham Solar Oscillation Network
CME: Coronal Mass Ejection
CoRoT: **CO**nvection **RO**tation and planetary **T**ransits, European space mission
FIRS: Facility Infrared Spectropolarimeter, located at NSO/Sac Peak
GONG: Global Oscillaton Network Group, gorund-based six-site helioseismology network
MHD: Magnetohydrodynamics
HMI: Helioseismic and Magnetic Imager, an instrument on SDO
MDI: Michelson Doppler Imager, an instrument for helioseismology on SOHO
MOTH: Magneto-Optical Filter at Two Heights
MURaM: The **M**ax-Planck-Institute for Aeronomy/ **U**niversity of Chicago **Ra**diation **M**agneto-hydrodynamics code.
NST: New Solar Telescope, located at Big Bear Solar Observatory
SDO: Solar Dynamics Observator, NASA space mission
SIAMOIS: Seismic Interferometer to Measure Oscillations in the Interiors of Stars
SOHO: Solar and Heliospheric Observatory
SPI: Solar Polar Imager
SOLIS: Synoptic Optical Long-term Investigations of the Sun, an instrument at Kitt Peak to measure vector magnetic fields
SOT: Solar Optical Telescope