STELLAR PHYSICS OF THE SOLAR INTERIOR IN THE COMING DECADE

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The Sun provides a nearby stellar laboratory that allows us to investigate important processes occurring in many astrophysical settings. How are heat and momentum transported? How is magnetic field created, circulated, stored, and released? How do magnetic fields interact with plasma? How are various physical regimes in and around a star coupled? What are the mechanisms that determine the opacity of plasma? What drives winds from astrophysical objects?

Understanding of the physics of the solar interior has advanced dramatically during the last decade because of the advent of high-quality and nearly continuous helioseismology observations, with associated innovative analysis techniques, advanced computational capabilities, and more realistic physical modeling. Activity on the far side of the Sun is now routinely detected[1]; the dynamic structure just beneath solar active regions has been resolved[2]; measurements of meridional flow and mapping of the tachocline at the base of the convection zone have placed useful limits on solar-cycle dynamo models[3]; detailed convective models of the outer layers of the star can now reproduce granulation, down flows, and many other characteristics observed in the solar photosphere[4]. Taken together with relevant advances outside solar physics, for example in new opacities determined from atomic physics[5] and newly modeled abundances[6] (progress in fact driven by the solar neutrino puzzle), we have solved significant problems in understanding the solar interior but raised many new issues in modeling the hidden structure of the nearest star. Some of the long-standing questions remain, but they have been sharpened and deepened by new understanding.

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

- Solar dynamos
- Convection immediately below and above the photospheric boundary
- Internal structure and evolution of stellar active regions
- Near-surface excitation and damping, and p-mode coupling to the atmosphere
- Reconciliation of new abundances and stellar interior models

Related areas include:

- Neutrino physics and the solar core
- Solar gravity modes

Solar dynamos -- The Sun's 22-year Hale magnetic cycle and its harmonic, the 11-year activity cycle, dominate the long-term measures of solar variability. Similar stellar cycles in other cool stars are described in another white paper by Schrijver. Details of our star's convective motions, meridional flow, and differential rotation drive the cycle dynamo generally and the formation of individual active regions in particular, but the theory remains incomplete[7]. 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 meridional flow throughout the star and better characterization of non-axisymmetric dynamics, over long intervals, may make possible the development of adequate models to enable prediction. See also the white papers contributed by Kosovichev, by Fan, and by Keil.

Convection immediately below and above the photospheric boundary – This region is where the modes reflect as the acoustic cut-off frequency rapidly rises as the distance to the surface decreases. The immediate sub-photosphere is highly superadiabatic, and the hydrogen ionization zone is a source of convective driving. It is an extremely complex physical environment that can dominate many of the aspects of the waves. Thus lack of knowledge of the physics in the region greatly hampers our interpretation of some helioseismic observations. It is likely that stellar granulation will be revealed as a noise source for asteroseismology. Spectacularly detailed simulations of turbulent convection in the upper layers of the convection zone seem to mimic very faithfully what we observe on the Sun[8]: granulation, supergranulation, intense down flows, as well as 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.

Internal structure and evolution of active regions -- Active regions apparently emerge quickly through the outer several megameters of the convection zone.[9] 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.[10] There is evidence from local helioseismology that the temporal evolution of subsurface helicity below a specific active region may be related to the timing and strength of solar flares.[11]

Over the course of the solar cycle, active region characteristics may change – we already know something about variations in location and orientation, but not yet about helicity, 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 vector magnetic field measurements that 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 fields, mass flows, and other physical conditions affect wave propagation, including the surface effects where the waves reach the solar surface. The Solar Dynamics Observatory (SDO) will help with the issue of spatial resolution, though multiple spacecraft observing from different directions around the heliospheric would be much better for probing more deeply.[12] But it is doubtful whether observations with a single wavelength (i.e. a single height in the atmosphere) can adequately characterize the modes. In addition, recent work[13] 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.

Serious efforts will be required to learn how to interpret the helioseismic observations. One example: how do we model the propagation of waves through sunspots? Two techniques appear to be promising: the numerical modeling of linear waves through background sunspot models[13A] and the simulation of naturally excited waves through realistic radiative MHD simulations of sunspots[13B].

Near-surface excitation and damping, and the coupling of p modes to the atmosphere -- The deceptively bland term "mode physics" belies the importance of understanding how solar oscillations gain and lose energy which in turn provides important constraints on the turbulence generating the waves. Better mode physics enables the proper interpretation of helioseismic data.[14] The frequency and temporal evolution of every mode is affected by the near-surface conditions where the reflection occurs, just as the physical conditions along the path of propagation affect the wave. To first order the effect is small and linear, but precise interpretation requires more sophisticated analysis, particularly in regions where the magnetic field is strong and particularly on small scales where various inhomogeneities in the plasma are not completely averaged out.[15] The key observational requirement is to combine high-resolution measurements of physical conditions where the modes reflect with theory of how the modes propagate. Understanding how the modes couple to the photospheric plasma and how energy is transferred to the overlying atmosphere also impacts understanding of the energetics and dynamics of the chromosphere and low corona. Understanding of the helioseismology observations will require applying the general insights about mode properties to specific sites where active regions and transient activity occur. This will require simultaneous observations at multiple heights in the atmosphere under many conditions and over large regions of the solar surface.

Reconciliation of new abundances and stellar interior models -- Relatively recent revisions to line profile calculations imply new lower values for the heavy element abundances in the solar interior.[5] Corresponding adjustments required of the standard (and not so standard) stellar models to then match the basic observed solar parameters significantly worsen the match with sound speed and other physical parameters inferred from helioseismology for the Sun's interior. While further progress will be made, initial attempts to reinterpret the measurements or adjust the models have not been successful.[16] If constraints from helioseismology cannot be accommodated for the Sun, significant problems exist for all models of stellar structure. This fundamental mismatch requires 1) strong support for development of basic solar and stellar models, 2) additional investigations of the methods for determining opacities and inferring abundances, 3) renewed emphasis on interpretation of global solar mode analysis and data collection, 4) continuation of the current imaging helioseismology programs to further increase frequency resolution and reduce noise, and 5) new measurements of stellar oscillations through something like the ground-based Stellar Observations Network Group (SONG) network[17] and analysis of other asteroseismology data from CoRoT, Kepler and other sources. See also the white paper on asteroseismology by Giampapa.

Neutrino physics and the solar core -- The deficit of observed solar neutrinos over several decades for some time cast doubt on models of stellar interiors. But helioseismic validation of solar interior structure models demanded another solution of the solar neutrino puzzle[17A]. This led to a radically new understanding of neutrino physics. While currently suggestive rather than conclusive, analysis of continued measurements with Super-Kamiokande indicates there may be some modulation of the solar neutrino flux associated with rotation of the solar core.[18] Continued measurements of solar neutrinos are important and have potential to unveil the conditions currently existing in the core. Better understanding of neutrinos has deep implication for a variety of extreme astrophysical processes.

Solar gravity modes -- Long-sought solar g modes would reveal much about the structure and dynamics of the deep solar core that is effectively invisible to solar p modes. These internal gravity waves, trapped in the radiative zone, decay rapidly in the overlying convective zone. G modes are visible on other types of stars, but despite many attempts to unambiguously detect them, they have thus far proved elusive, with an upper limit of 3 mm/s.[18a] The next generation direct detection instrument, GOLF-NG, has been prototyped and data analysis is underway for assessing its performance.[19] Solar g modes may be observed with space based gravitational wave experiments.[20]

The measurement requirements for progress are demanding. Important astrophysical processes on the Sun occur on all time scales and their characteristics evolve over long periods. For example, local area helioseismology requires continuous monitoring of the near five-minute p-mode oscillations over large areas for many hours to resolve slight travel time variations relevant to active region evolution and conditions on the far side of the Sun. It takes months and years to follow changes through the convection zone of the meridional flows and torsional waves related to the 22-year solar activity cycle through the convection zone. Recent work[21] indicates that the measurement of the deep meridional return flow, which is currently thought to set the timing and strength of the solar activity cycle, requires a nearly-continuous observational helioseismic time series of about ten years if the magnitude of the flow is 1 to 2 m/s as estimated from mass conservation. We have only recently obtained time series of that length with the modern imaging helioseismology instrumentation of the Michelson Doppler Imager (MDI) on the ESA/NASA Solar Heliospheric Observatory (SOHO) and NSF's Global Oscillation Network Group (GONG). Since the magnitude of the meridional return flow may be smaller than the estimate, and since noise may dominate the results, it is important that imaging helioseismic observing programs continue for at least one more solar cycle. This will also provide a sampling of the second half of the 22-year Hale magnetic cycle, and ensure that we can study the interior as the Sun undergoes a period of somewhat anomalous behavior as seen by the reduced total solar irradiance[22] and the historic low in solar wind pressure[23]. Finally, longer helioseismic observations reduce the noise in frequency determinations, which thereby increases the sensitivity of the results to very small velocities inside the Sun.

The ***absolutely vital longer term requirement*** is better understanding of what happens at the upper reflection of the normal modes of oscillation. All p modes encounter and indeed spend the bulk of their time near the surface where the sound speed is the lowest. This region is poorly understood and the lack of knowledge degrades our confidence in our estimates of systematic and random errors.

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 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.

Major computational efforts are required in forward modeling of local helioseismology; in the detailed modeling of convection (extending deeper, higher and more globally); in the improved understanding of opacity and reaction rates under conditions appropriate to stellar interiors; and in realistic physical models of the solar dynamos that generate magnetic fields. A coordinated effort is needed to provide more adequate computational and modeling resources.

Near-term plans for obtaining the required new observations and instrumentation include extending the critical synoptic observations of GONG to include H-α images (funded by the US Air Force Weather Agency) and replacing data from SOHO/MDI with the higher spatial and temporal resolution measurements of the Heliospheric and Magnetic Imager (HMI) on SDO, which is currently scheduled for launch later in 2009.

Long-term needs for sufficiently characterizing the p-mode upper turning point region are:

- Continuation of current long-term observational data sets
- Development, deployment and operation of long-term continual multi-spectral helioseismic observations
- Construction of a network for continual vector magnetic field observations
- Solar observations with very high spatial, spectral, and temporal resolution

Currently, the probing of the solar interior is done with the GONG and SOHO/MDI instruments, which have both been operating since 1995/1996. SOHO/MDI is about to be replaced by SDO/HMI, which uses a different spectral line from SOHO/MDI and GONG. This creates a break in the oscillation time series, and requires cross-calibration with SOHO/MDI and GONG.

With the launch of SDO later in 2009 and the cessation of MDI observations, GONG will be the longest operating imaging helioseismology system with highly consistent instrumentation. This is needed to obtain the precision required to detect the deep meridional flow and other extremely-low amplitude subsurface flows. In addition GONG, being a ground-based network, can be maintained, upgraded, and is far more robust than space missions. The design lifetime of SDO is 5 years, and experience suggests it will likely last at least 10 years, but there is no space-borne helioseismology mission after SDO. After the end of the SDO mission all information about the solar interior will come from the ground-based observations.

There is thus an opportunity during the next 3 to 5 years when helioseismology observations will be done simultaneously from the ground and space. This overlap and the resulting cross calibration tests of the instrument, reduction, and analyses are important for gaining confidence in the results, and understanding the changes in the systematic errors. The ground-based network instrumentation, operations and analyses must be properly prepared and cross-calibrated with the space measurements.

Limited modern multi-spectral helioseismic observations[24] have been used to study p-mode characteristics in the presence of magnetic fields, and the technique has been proposed for asteroseismic studies at Dome-C in Antarctica[25]. Thus, instruments for multi-spectral stellar seismology have been produced, and the lessons learned from their development will guide future helioseismic instrumentation. A workshop on the subject is tentatively planned to be held later in 2009.

In the future GONG could be a unique tool for probing the solar interior with improved instrumentation, multiwavelength 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 will be necessary.

The other long-term needs listed above are being addressed by two projects. The National Solar Observatory (NSO) has developed a vector spectromagnetograph (VSM) as part of its SOLIS program[26]. NSO is also proposing to construct a network of VSM instruments to provide full-disk vector magnetograms to the community. This data will be of great utility for understanding the physics of the upper turning point of the acoustic waves. A white paper on the VSM network has been submitted. The Advanced Technology Solar Telescope (ATST)[27] will provide the required observations with very high spatial, spectral, and temporal resolution. This telescope is negotiating the NSF' MREFC process, and should receive construction funding in the near future.

Summary
The study of the stellar physics of the solar interior has been greatly influenced by the modern imaging helioseismic programs of GONG and SOHO/MDI. The next decade will hopefully bring SDO, the ATST, a SOLIS Network, multi-spectral helioseismology, and continued operation of GONG.

Top priority should be given to these initiatives:
- Adequate support for analysis of SDO, GONG and other helioseismology data.
- Support for continued long-term operation and modernization of GONG to supply highly reliable, comprehensive ground-based synoptic observations of the changing Sun.
- Multi-height/multi-spectral observations of waves propagating in and through the photosphere.
- Construction of a SOLIS network
- Construction and operation of the ATST and appropriate instrumentation.
- Significant computational resources to support coordinated modeling and analysis efforts.

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[1]Lindsey & Braun, Science ,287, 1799, 2000; Gonzlaez-Hernandez et al., Proc. GONG2006/SOHO18/HELASI, 3.1, 2006; Zhao, J., ApJ Lett 664, L139, 2007.
[2]Mason et al., Ap.J. 645, 1543, 2006; Kosovichev, Advances in Space Research 38, 876, 2006.
[3]Howe et al., ApJ 649, 1155, 2006.
[4]Stein et al., AIP Conf. Proc. 948, 111, 2007
[5]Asplund et al., A&A 417, 751, 2004.
[6]Fukuda et al, Phys.Rev.Lett. 81, 1562, 1998.
[7]Jouve et al., A&A 483, 949, 2008.
[8]Stein & Nordlund., ApJ 642, 1246, 2006.
[9]Kosovichev & Duvall, ASP Conf. Ser. 383, 59, 2008
[10]Braun & Birch, ApJ Lett 647, L187, 2006.
[11]Komm et al., ESA SP-559, Proc. SOHO 14 / GONG 2004, 158, 2004.
[12]ESA's Solar Orbiter and Japan's Solar-C Plan A.
[13]Schunker & Cally, MNRAS 372, 551, 2006
[13A]Cameron et al., Solar Phys. 251, 291, 2008.
[13B] Rempel et al. ApJ 691, 640, 2009.
[14]Severino et al, ApJ 561, 444, 2001; Barban et al., ApJ 602, 516, 2004; Jacoutot et al., ApJ 682, 1386, 2008.
[15]Couvidat & Rajaguru, ApJ 661, 558, 2007.
[16]Basu & Antia, Physics Reports 457, 217, 2008
[17]Grundahl et al., J. Physics, Conf. Ser. 118, 012041, 2008.
[17A]Fogli et al., Phys. Rev. D., 64, 093007, 2001.
[18]Sturrock, Solar Physics 252, 221, 2008.

[18A]Appourchaux et al., Astronomy and Astrophysics Review, 2009
[19]Turck-Chieze et al., J. Phys. Conf. Ser 118, 012044, 2008
[20]Giampieri et al., Astrophys & Space Science 261, 35, 1998; Burston et al.., J. Phys. Conf. Ser 118, 012043, 2008
[21]Braun & Birch, ApJ 689 L161, 2008
[22]http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant
[23]Ebert et al. JGRA 114, Issue A1, CiteID A01109, 2009
[24]Finsterle et al, Solar Phys. 220, 317, 2004; Jain et al, in "Subsurface and Atmospheric Influences on Solar Activity", ASP Conf Ser 383, 389, 2008
[25]Mosser et al, J. Phys. Conf. Ser 118, 012042, 2008
[26]http://solis.nso.edu/
[27]http://atst.nso.edu/