A Solar Polar Imager Concept: Observing Solar Activity from a New Perspective

P. C. Liewer[1], D. Alexander[2], T. Appourchaux[3], J. Ayon[1], L. Floyd[4], D. Hassler[5], A. Kosovichev[6], N. Lugaz[7], J. Leibacher[8], N. Murphy[1], M. Velli[1], A. Vourlidas[9]

[1]*Jet Propulsion Laboratory, California Institute of Technology. 4800 Oak Grove Dr., Pasadena, CA 91109*
[2]*Rice University, 6100 Main St, Houston, TX 77005*
[3]*Institut d'Astrophysique Spatiale, UMR8617, Bâtiment 121, 91045 Orsay Cedex, France*
[4]*Interferometrics Inc., 13454 Sunrise Valley Drive, Suite 240, Herndon, VA 20171*
[5]*Southwest Research Institute, 1050 Walnut St, Suite 400 Boulder, CO 80302*
[6]*Stanford University, MC 4085, Stanford, CA 94305*
[7]*Institute for Astronomy, Univ. of Hawaii, Honolulu, HI 96822*
[8]*National Solar Observatory, Tucson, AZ 85719*
[9]*US Naval Research Laboratory, 4555 Overlook Ave., SW Washington, DC 20375*

Abstract

Our current understanding of the Sun, its atmosphere, and the heliosphere is severely limited by the lack of good observations of the polar regions. A potential Solar Polar Imager mission, in a 0.48-AU orbit with an inclination of 75º, would target the unexplored polar regions and enable crucial observations not possible from lower latitude perspectives. The orbit is achieved using a solar sail, a technology now being demonstrated in space by the Japanese IKAROS mission. Observations from a polar vantage point would revolutionize our understanding of the mechanism of solar activity cycles, polar magnetic field reversals, the internal structure and dynamics of the Sun and its atmosphere. Only with extended (many day) observations of the polar regions can the polar flows be determined down to the tachocline where the dynamo is thought to originate. The rapid 4-month polar orbit combined with a suite of *in situ* and remote sensing instrumentation further enables unprecedented studies of the physical connection between the Sun, the solar wind, and solar energetic particles. Moreover, SPI would potentially serve as a pathfinder for a permanent solar polar sentinel for space weather prediction.

I. Introduction

Our understanding of the Sun, its corona and the solar wind has been revolutionized by observations from past spacecraft such as Yohkoh, ACE, Ulysses, TRACE and SOHO and from current spacecraft such as RHESSI, Hinode, STEREO and SDO. Yet as we learn more about the Sun from these missions and the complement of ground-based telescopes, the need for information from the polar perspective only increases. The Solar Polar Imager (SPI) mission concept defined by this study utilizes a solar sail to place a spacecraft in a 0.48 AU circular orbit around the Sun with an inclination of 75º (Figure 1), enabling high latitude studies and extended direct observation of the solar poles. A very similar mission concept POLARIS was submitted to the ESA Cosmic Vision call (Appourchaux et al., 2009). Observing the polar regions of the Sun

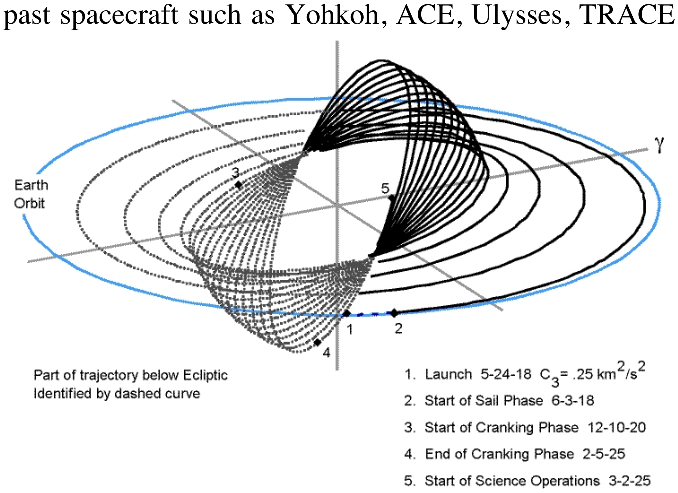


Figure 1 Conceptual SPI trajectory for 2018 launch. The final science orbit at 0.48 AU is in a 3:1 resonance with the Earth at a final heliographic inclination of 75°.

with a combination of a Doppler-magnetograph and coronal imagers yields opportunities for major new science. Local helioseismology measurements of polar supergranulation flows, differential rotation and meridional circulation, and magnetograms would allow us to understand the mechanisms of the polar field reversals and also the factors determining the amount of the magnetic flux accumulating in the polar regions, which is a primary precursor of the future sunspot cycles. Correlation between measurements of the Doppler signals in the polar regions with disk center measurements from the ground or from near-Earth spacecraft, such as SDO, should enable the determination of flows deep within the Sun. When Doppler and magnetograph observations are coupled to total solar irradiance monitoring, UV spectroscopic observations and *in-situ* particle and field measurements, the conceptual SPI mission would substantially enhance our knowledge of the root causes of solar variability. While Solar Orbiter will provide a glimpse of the polar regions, it does not have sufficient viewing of the polar regions to achieve the major scientific objectives defined for a potential SPI.

Unique remote sensing and *in situ* observations made possible by this orbit (Figure 1) include

- Measurements of the time-varying flows, differential rotation and meridional circulation in the polar regions of the Sun down to the tachocline
- Measurements of the polar magnetic field and its temporal evolution
- Monitoring of Earth-directed coronal mass ejections from high latitudes
- Observations of active regions over a significant fraction of their lifetimes
- Measurements of the variation in the total solar irradiance with latitude
- Measurements of chromospheric and low coronal outflow velocities as a function of structure and latitude
- Measurements of the variation in the magnetic fields, solar wind and solar energetic particles (SEPs) with latitude at constant distance from the Sun

2. Mission Concept

In order to determine the polar flows down to the tachocline, long (many days) nearly continuous observations of the polar regions are required. ***This is the driving requirement for defining a mission with an orbit inclination of 75°.*** The conceptual SPI mission would use a solar sail to reach this nearly polar solar orbit. By first spiraling in towards the Sun, the radiation pressure is increased so that "cranking" to higher inclination is more efficient. The final radius is chosen to be 0.48 AU because (a) its orbital period is exactly 1/3 of Earth's (3:1 resonance) allowing an unobstructed Earth-spacecraft line for telecommunications and (b) interpretation of solar wind data is simplified closer to the Sun because of shorter interaction time and smaller velocity dispersion.

The SPI Visions Mission concept, as defined in the NASA-funded Vision Mission Study (Liewer et al., 2009) requires a characteristic acceleration of 0.34 mm/s^2 to achieve the 3:1 resonant science orbit at 0.48 AU. Given the leading technology concepts under development for solar sails, this results in a sail of approximately 8.5-14 g/m^2 with physical edge lengths of about 150-180 m. The material used for the sail "sheets" was assumed to be an aluminum-coated polyimide or aluminum-coated Kevlar-reinforced kapton. The mission concept summarized in this paper represents the baseline concept developed for the SPI Vision Mission study that has been fully documented in a report to NASA. Since that study, there have been major advances in the technologies for solar sailing, demonstrated in the laboratory and now also in deep space by JAXA's recent IKAROS mission. The advances in the development of solar sail technology is the subject of separate white paper entitled "Solar Sail Propulsion: Enabling New Capabilities for Heliophysics" submitted by Johnson, et. al. The cost of the baseline mission in the NASA Vision Mission study, inflated to FY10 dollars, is $800-$900M, including launch vehicle.

3. Science Goals

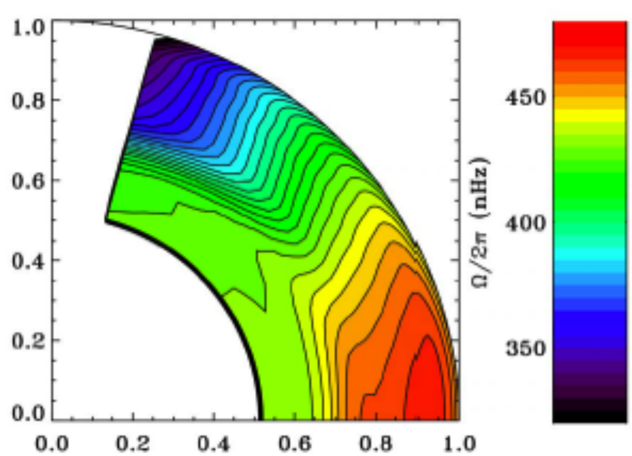
In the study, a refined set of mission science objectives were developed that can only be achieved because of the observations enabled by an SPI short period, highly inclined polar orbit. The primary scientific questions to be answered by the mission are:

1. *What is the relationship between the magnetism and dynamics of the Sun's polar regions and the solar cycle? More specifically, what is the mechanism of the polar magnetic field reversals, and why does the polar field determines the strength of the future solar activity cycle?*
2. *What is the 3D global structure of the solar corona and how is this influenced by solar activity and coronal mass ejections?*
3. *How are variations in the solar wind linked to the Sun at all latitudes?*
4. *How are solar energetic particles accelerated and transported in radius and latitude?*
5. *How does the total solar irradiance vary with latitude?*
6. *What advantages does the polar perspective provide for space weather prediction?*

These mission objectives address every aspect of the first challenge and first key questions of the NRC Decadal Report on Solar and Space Physics: *"Understand the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona."* It may also contribute to the fifth challenge: *"Developing a near-real time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun…"* (SPI goal 6). The mission also address many of the objectives in NASA's 2009 Heliophysics Roadmap: F2) Particle acceleration and transport; F4) Creation and variability of magnetic dynamos; H1) Causes and evolution of solar activity; J2) Capability to predict the origin, onset, and level of solar activity; and 3) Capability to predict the propagation and evolution of solar disturbances.

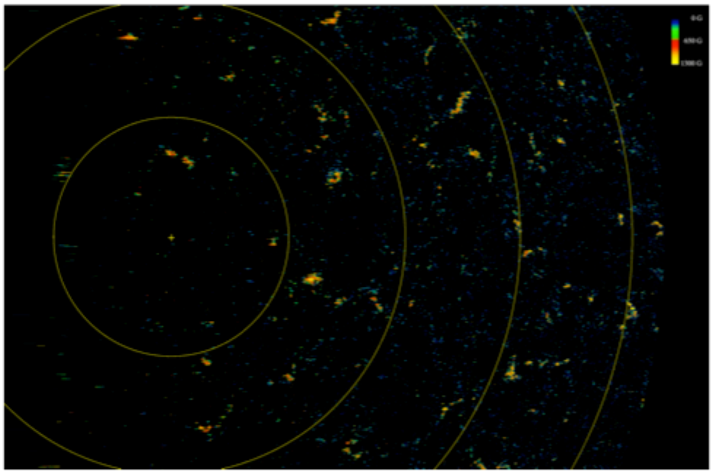
The proposed SPI mission defined here would also contribute to important "multi-viewpoint" science objectives and would complement near-Earth remote sensing and *in-situ* measurements (e.g. SDO, Solar Orbiter and Solar Probe Plus). However, we have limited the primary objectives to those that **require** the viewing geometry provided by the conceptual SPI orbit. Science objectives that could be addressed by a similarly instrumented spacecraft in a low latitude orbit separated from Earth primarily in longitude only should be considered "bonus" science.

Figure 2 Solar rotation rate ($\Omega/2\pi$ nHz) versus depth (solar surface is at 1.0). The white polar and deep regions where the rotation rate is currently unknown would be filled in using the proposed SPI mission (Based on Schou 1998).



The primary goal of the proposed SPI mission is to provide local and full-Sun helioseismology and to characterize the behavior of the solar magnetic field at the poles and its evolution with the solar cycle. Knowledge of the high-latitude convection, meridional circulation and differential rotation is crucial for understanding magnetic flux transport, polar field reversals, the solar dynamo,

Figure 3 Hinode observations of solar landscape showing presence of strong horizontal and vertical magnetic fields (0 G is Blue; 1300 G is Yellow)



solar cycle models and predictions. Understanding these flows would significantly further our understanding of the solar dynamo. Doppler data from the Michelson-Doppler-Imager (MDI) on SOHO and the ground-based Global Oscillation Network Group (GONG) have revolutionized our views of the structure and dynamics of the convective region and the solar dynamo. Figure 2 shows measurements of the differential rotation as a function of depth from SOHO/MDI data. A region of large velocity shear can be seen at about 0.7 R_{Sun}; it is this shear, at the base of the convection zone (tachocline) that is now thought to drive the large-scale solar dynamo. Observations from the Solar Optical Telescope on Hinode during the periods of the highest inclination of the solar axis to the ecliptic have shown that the polar regions are populated by small-scale kilogauss magnetic fields (see Figure 3 from Tsuneta et al, 2008) and that supergranulation forms curious alignment patterns in the near-polar regions (Nagashima et al, 2010). However, the Hinode observations gave us only a glimpse of the structure and dynamics of the near-polar region. Missing are systematic measurements of the flows and magnetic fields in the polar regions. The current ecliptic-viewpoint observations do not provide measurements of sufficient accuracy for helioseismic inversion of the solar structure and rotation in the polar regions. In addition, the proposed SPI would enable measurements of the deep interior using a new technique called stereoscopic helioseismology based on time–distance helioseismology. This technique is to use observations from helioseismic instruments placed at least 120° from each other: one aboard the spacecraft and one ground-based instrument such as GONG, or space-based instrument such as HMI aboard SDO. The observation of the propagation of waves in the core of the Sun from both sides would enable the recovery of the structure of the deep convection zone, tachocline and the energy-generating core.

The high-latitude viewing would provide a unique opportunity to study the dynamics of meridional flows and rotation in the polar regions and search for deep longitudinal structures in the tachocline. Figure 4 shows the sound wave ray paths (dashed lines) that would enable us to measure the subsurface meridional flows (solid lines) using a potential SPI's high latitude viewpoints. Long periods of nearly continuous high latitude (above |60°|) viewing of the polar regions are required for determination of the meridional flows, supergranulation, and their rapid changes (on the scale of days) in the polar regions using local techniques. This is because these large-scale flow patterns have small velocities compared to the fluctuating velocities of the turbulent convective zone, and thus long periods are need to average over the fluctuations to determine the mean flows. Uninterrupted polar region observations lasting at least 8-24 hours are required for determination of the surface and sub-surface flows; determination of the polar flows throughout the convection zone down to the tachocline (depth 200 Mm) requires long (many day) continuous observations of the polar regions. ***This is the driving requirement for defining a mission with an orbit inclination of 75°, replacing the 60° inclination recommended in the 2003 SEC Roadmap study.*** An orbit with 60° inclination would allow determination of the flows in the polar regions in the upper convection zone, but not down to the bottom of the convection zone. For the conceptual SPI science orbit, the spacecraft is at high latitude (more than |60°|) for 29% of the time. The orbit provides 36 days at >35° latitude, 28 days continuous viewing of >45°, and 17 days at >60°.

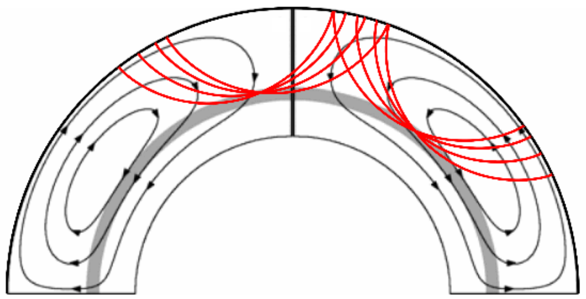


Figure 4 Closed circulation lines: Possible stream-lines of meridional flow. Red lines: Sound wave (p-mode) ray paths that can be used to measure the subsurface meridional flows from high latitude.

Along with the Dopplergrams, magnetograms would be taken every 5 minutes to observe the response of the magnetic field to the surface, sub-surface and interior flows. Together, these observations would be used to study phenomena such as the evolution of active regions, flux transport and the solar cycle field reversal. A potential SPI, complemented by near-Earth magnetograph observations, would enable us to follow the evolution of active regions for much longer than the half-solar rotation now possible. With only observations from Earth, each longitude and latitude is visible 50% of the time; with observations from both Earth and a potential SPI, this increases to nearly 80% for all longitudes and latitudes. This allows improved studies of the evolution of active regions in response to the flows determined by helioseismology as well as to improved "synoptic" magnetograms.

Another key aspect of understanding solar variability is the ability to link variations in the heliosphere to solar surface conditions. *In-situ* measurements of the solar wind plasma, the heliospheric magnetic field, energetic particles and isotopic and elemental composition are required to fully address this issue. The high latitude operations, rapid latitude scans (~4 months) at fixed radius, and the low solar distance of the proposed SPI orbit allows the study of the evolution of the solar wind from its source to the spacecraft nearly free of the effects of stream-stream interactions. This, along with improved magnetic field extrapolations using the multi-viewpoint synoptic magnetograms, provides an unprecedented opportunity to determine the source regions of the solar wind.

The polar perspective of a potential SPI has distinct advantages for space weather prediction. STEREO has shown the advantage of a second viewpoint for predicting the arrival time of Earth-directed CMEs. The proposed SPI coronagraph would be able to observe Earth-directed CMEs from the high-latitude perspective. For events that are "halos" as viewed from Earth, this would give far better speed estimates so that even the very fast CMEs, which are closely associated with the largest and most hazardous solar energetic particle events, can be tracked.

A concrete manifestation of the short-term variability of the Sun is the production of energetic particles that can reach several hundred MeV/nucleon. At 0.48 AU the velocity dispersion effects are greatly reduced and the magnetic field lines can be more readily traced back to the source regions on the Sun. This makes it possible to relate flare-accelerated particles to their sources and to identify the time and altitude at which CME-driven shock acceleration begins near the Sun with much greater precision. The fast latitude scans of the conceptual SPI orbit permit frequent snapshots of the latitudinal gradients in the intensity of anomalous and galactic cosmic rays which can be used to determine the diffusion coefficients for particle transport both parallel and perpendicular to the magnetic field. Measurements from ACE and the two STEREO spacecraft at large longitudinal separations show that the energetic particles accelerated in solar flare events rapidly spread over a broad range of heliolongitudes, contrary to expectations for a point-like release of particles. The longitudinal transport mechanism remains to be established. The proposed SPI would be able to determine how energetic particles are transported in latitude and allow the study of how coronal hole boundaries influence particle transport.

Measurements of the variation of the total solar irradiance (TSI) is fundamental to our understanding both the Sun-Earth Connection and the Sun as a star. The conceptual SPI orbit is ideal for determining the latitudinal variation in TSI; the rapid changes in solar latitude enable a complete 360° sweep every 4 months with polar and equatorial observations separated by only ~30 days. Through comparisons of the high latitude observations with simultaneous in-ecliptic observations from instruments on other platforms, a true measure of the latitudinal variation of TSI can be determined. With parallel modeling efforts, polar brightness contributions and those caused by magnetic activity could be better characterized. Moreover, measurements of the TSI from the different perspectives provided by the proposed SPI mission would help with the interpretation of observations of sun-like stars whose rotation axis orientations must be deduced. This should help to decide the still open question as to whether the Sun's brightness variations are substantially lower than other Sun-like stars.

4. Instrument payload

To meet the science goals of the proposed SPI mission an instrument package has been designed to optimize the science return while economizing in mass, power and cost. Table 1 summarizes the instrument suite on board the conceptual SPI. The coronagraph pointing control is driven by the inner field of view cutoff. The pointing knowledge for the EUV Imager is determined by pointing control requirement of the coronagraph while the EUV Imager pointing stability assumes 2.5 arcs pixels and a 1024×1024 CCD with exposure times from 15s to 30s and jitter amplitude <1 pixel. The power requirements are upper limits. Power savings of almost a factor of 10 would be possible by replacing the CCD detectors with CMOS Active Pixel Sensors currently developed for Solar Orbiter.

Table 1. Instrument Payload

	Remote Sensing Instrument Package					*In-situ Instrument Package*		
	Doppler Magneto-graph	**Coronagraph**	**EUV Imager**	**TSI Monitor**	**UV Spectrograph**	**Magneto-meter**	**Solar Wind Ion Composition & Electron Spectrometer**	**Energetic Particles (20 keV/nuc – 100 MeV/nuc)**
Mass (kg)	5	8.25	7.6	7	6	1.5	4	4
Average Power (W)	4	10.4 for both Cor & EUV		10	6	2	6.5	3.1
Pointing Control (3σ)	0.5°	0.1°	0.5°	0.5°	30″	0	2°	n/a
Pointing Knowledge (3 σ)	0.5°	0.1°	0.5°	0.1°	15″	0.1°	0.5°	2°
Pointing Stability	0.2" in 10s (3σ)	7-10 arc-s/s (3σ)	1.5 arc-s for 4s (3σ)	0.1°/s (3σ)	0	0	0.1°/s	n/a
Avg. Data Rate (kbps)	75	41	41	0.3	10	0.6	0.2	0.5
Field of View	1.5°x1.5°	8° half-angle 1.5-15 R_s	2.5° half-angle	2.5°	10″ x 1.4° (instantaneous FOV of slit)	n/a	Ion sensor: 10°x90° Sunward e^-: 20°x90° Backward e^-: 20°x160°	LEPT: 120°x20° SIT: 20°x20° SEP: 45° cone

The helioseismology science objectives discussed briefly above require an instrument capable of producing Doppler images as well as line-of-sight magnetograms. The baseline instrument considered consists of conventional polarization analyzers and a magneto-optical filter (MOF) type of optical resonance filter. The MOF-based DIMAG design has been successfully employed in ground-based applications and extensively studied for spaceflight applications. The combination of intrinsic stability and imaging capability allows the MOF based instrument to address a wide range of science objectives, with an optimal use of on-board resources.

The magnetic field and helioseismology studies are augmented by a range of imaging observations designed to provide both coupled and stand-alone science. The coronagraph/EUV Imager/UV Spectrograph combination would provide new insight on the evolution of active regions and their response to the magnetic field as well as allowing us to determine the global 3D structure of the corona and inner heliosphere. In addition, the coronal imaging instruments (see Table 1) would yield new observations on the global effect of CMEs on the large-scale corona and help determine the physical characteristics of the source regions of CMEs and Solar Energetic Particles. The coronagraph and EUV Imager instruments are based on heritage from SECCHI coronagraphs and SOHO/EIT, respectively.

The particle characteristics of the solar wind and those resulting transient events are observed by the *in-situ* instrument suite which would enable us to sample the solar wind closer to the Sun and in high latitude regions where the interplanetary field is less wound by solar rotation. To meet the energetic particle objectives it is necessary to measure protons, helium, and heavy-ion composition from C to Fe over a wide energy range. It is also necessary to measure solar electrons, to separate ^{3}He and ^{4}He, and to distinguish sunward and anti-sunward particle flows. These measurements can be accomplished with several small telescopes of standard design, such as those on STEREO. The energetic particle package is based on heritage from LET, HET and SIT instruments on STEREO which have broad coverage, include new low-mass, low-power designs, and were designed for a 3-axis stabilized spacecraft.

A differential electrical substitution radiometer would provide a state-of-the-art TSI measurement at all available solar latitudes. Such an instrument measures the difference in compensating electrical power required to maintain a constant temperature in two cavities: one exposed to the Sun through a known aperture and another, reference cavity having no solar exposure. An example of such a design is the Differentially Balanced Solar Irradiance Monitor (DBSIM), under development at NASA/JPL.

5. Conclusion

The Solar Polar Imager mission uses solar sail propulsion to place a spacecraft in a 0.48 AU circular orbit around the Sun with an inclination of 75º. Observations from such a vantage would revolutionize our understanding of the internal structure and dynamics of the Sun and its atmosphere. The rapid 4 month polar orbit combined with a suite of *in situ* and remote sensing instrumentation further enables unprecedented studies of the physical connection between the Sun, the solar wind, and solar energetic particles. By providing a unique perspective on the global structure and evolution of the Sun and its corona, the proposed SPI mission would significantly advance our knowledge of key solar phenomena, our understanding of the Sun as a star, and our forecasting abilities for the Sun's effects on the space environment. The observations of the polar region are at the heart of understanding one of the fundamental questions in solar physics and astrophysics: how and why does the Sun vary?

A portion of the research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

T. Appourchaux, P. C. Liewer and 20 other authors, "POLAR Investigation of the Sun – POLARIS," Experimental Astronomy **23** (2009) pp.1079-1117.

P. C. Liewer, D. Alexander, J. Ayon, A. Kosovichev, R. Mewaldt, D. Socker, A. Vourlidas, "Solar Polar Imager: Observing Solar Activity from a New Perspective" in *NASA Space Science Vision Missions*, (ed. Marc S. Allen), American Institute of Aeronautics and Astronautics, Progress in Astronautics and Aeronautics **224** (2009) pp. 1-40.

K. Nagashima, J.Zhao, A. G. Kosovichev, and T. Sekii, "Detectio of supergranulation Alignment in Polar Regions ofs the Sun by Helioseismology," (submitted for publication, 2010) arXiv:1011.1025

J. Schou, Antia, H. M., Basu, S., Bogart, R. S., Bush, R. I., Chitre, S. M., Christensen- Dalsgaard, J., di Mauro, M. P., Dziembowski, W. A., Eff-Darwich, A., Gough, D. O., Haber, D. A., Hoeksema, J. T., Howe, R., Korzennik, S. G., Kosovichev, A. G., Larsen, R. M., Pijpers, F. P., Scherrer, P. H., Sekii, T., Tarbell, T. D., Title, A. M., Thompson, M. J., and Toomre, J., "Helioseismic Studies of Differential Rotation in the Solar Envelope by the Solar Oscillations Investigation Using the Michelson Doppler Imager," ApJ **505** (1998) pp. 390–417.

S. Tsuneta, Ichimoto, K.,Katsukawa, Y., Lites, B. W., Matsuzaki, K.,Nagata, S., Orozco Suárez, D., Shimizu, T., Shimojo, M., Shine, R. A., Suematsu, Y.,Suzuki, T. K.,Tarbell, T. D., Title, A. M., "The Magnetic Landscape of the Sun's Polar Region," ApJ **688**, pp. 1374-1381.