Abstracts for LWS Workshop on Dynamo Frontiers

Session 1: Solar Meridional Circulation and Differential Rotation: Observations

Title: Observational Constraints and New Frontiers for Solar Dynamos

Authors: David H. Hathaway
Affiliations: NASA Ames Research Center

Abstract: Progress toward understanding the Sun's magnetic dynamo has proceeded in fits and starts over the last century. Time after time, observations and new theoretical insights have steered solar dynamo theory in new directions. We are currently faced with new dynamo dilemmas.

Estimates of the kinetic helicity in the bulk of the convection zone, recognition of the buoyancy of magnetic flux tubes, and observations of the differential rotation profile in the convection zone produced the dynamo dilemmas of the 1980s. These dilemmas forced us to push dynamo action to the base of the convection zone. This solution produced its own dilemma – poleward moving dynamo waves at high latitudes that lacked any observational support. This was followed in the 1990s by observations of the poleward meridional flow in the surface layers and the expectation of a slow equatorward flow at the base of the convection zone. Incorporating this meridional circulation in flux transport dynamos helped to solve the dilemma of the poleward moving dynamo wave, and also provided a simpler explanation for the 11-year period of the sunspot cycle. Today, however, observations indicate that the meridional flow turns equatorward at a much shallower depth and may be accompanied by one or more counter cells deeper down. Furthermore, observations of giant cell flows indicate unexpected flow structures and flow speeds. These observations produce new dilemmas for the solar dynamo.

Numerical modeling of the Sun's convection zone has proceeded apace with the observations. Small-scale Radiative-MHD models of granulation and its interactions with magnetic field provide insight into how the magnetic field and the flow field work together to produce magnetic elements, pores, and even sunspots. Meanwhile, the global models now include flows much smaller in scale than supergranules, and have extended their upper boundaries closer and closer to the surface. However, they still have difficulty reproducing the differential rotation profile (with a tachocline at the base of the convection zone and a shear layer at the surface), the meridional circulation (with a single cell from equator to pole and little variation from one rotation to the next), and even the giant cell convection itself (with slow flow speeds and persistent flow structures sheared out in longitude at mid- and high-latitudes).

Observations of the meridional circulation are now accurate enough to reveal its structure in latitude and depth and its slow but systematic changes with solar activity. Observations of giant cell flows in the near surface layers now provide further constraints on the convective motions in the Sun's convection zone. The observations of today now force solar dynamo theory to once again look to new frontiers.

Title: A comprehensive measurement of deep solar meridional flow

Authors: Ruizhu Chen(1,2), Junwei Zhao(2)
AffiliationsInstitutes:
1. Physics, Stanford University, Stanford, CA, United States.
2. HEPL, Stanford University, Stanford, CA, United States.

Abstract: We perform a comprehensive measurement of the deep solar meridional flow using SDO/HMI Doppler-velocity data. Determination of the meridional flow by time-distance helioseismology depends on a precise measurement of the flow-induced travel-time shifts in acoustic waves traveling below the surface. The inference of such travel-time shifts is complicated by the center-to-limb (CtoL) effect dominating the overall travel-time shifts. We develop a measurement strategy that is able to disentangle these two properties. We first track all waves travelling along disk-radial direction. Their inward and outward travel-time shifts for various skip distances, as a function of disk-centric distance and azimuthal angle relative to the equator, are composed of flow-induced travel-time shifts and the CtoL effect, as functions of only latitude and only disk-centric distance respectively. These form an over-determined linear equation set that we then solve for the two properties by regularized least-square method. From the solved meridional-flow-induced travel-time shifts, we finally invert for the meridional flow in the sense of least squares. Here we show the isolated CtoL effect and the inverted results for the meridional flow, and also discuss the isotropy of the CtoL effect.

Title: Meridional Flows from GONG

Author: Jason Jackiewicz

Affiliation: New Mexico State University

Abstract: Estimates of the meridional circulation profile in the outer 25% of the Sun from ground-based helioseismic observations are presented. The results compare reasonably well with space-based data in that the poleward flows cease at about 0.91Rsun. However, a second poleward-moving deeper cell is not observed in GONG data. Tests using mass conservation calculations reveal unusual features that call into question some of the inferred circulation patterns, suggesting much more validation of the helioseismic analysis is needed.

Title: How reliable are the helioseismic measurements of meridional flow in the deep-interior?

Authors: S.P. Rajaguru (1), H.M. Antia (2), and S. Gilda (1,3)
Affiliations:
(1). Indian Institute of Astrophysics, Bangalore, India (2) Tata Institute of Fundamental Research, Mumbai, India (3) Birla Institute of Technology and Science, Pilani, India

Abstract: We present time-distance helioseismic measurements of meridional flow from four years (2010 - 2014) of HMI Doppler observations. We present a critical analysis of noise and systematics in the results and show that the reliability of the results degrades sharply below about 0.9 R_sun. We compare meridional flow inferences from ring-diagram and time-distance analyses for the upper 15 - 20 Mm layers, and assess the contributions from the center-to-limb systematics in both these methods. We also present an analysis of ring-diagram results on temporal variability of near-surface meridional flow for the period 1995 - 2014 (19 years covering solar cycle 23 and part of 24, using MDI/SOHO and HMI/SDO data) and its relationship with the polar magnetic field strength (from Wilcox Solar Observatory).

Title: Results From Improved Analysis of MDI and HMI Global Mode Data

Authors: Jesper Schou (1), Atefeh Barekat (1), Tim Larson (2)
AffiliationsInstitutes: (1) MPS, (2) Stanford

Abstract: We have recently completed a reanalysis of the 15 years of data from MDI and 5 years of data from HMI. This reanalysis has resulted in significantly reduced systematic errors and thus, hopefully, in more reliable inferences about the solar interior. Here we will start by briefly describing the improvements to the analysis and the resulting mode parameters. After that we will show how our inferences about the solar interior are affected, including results about the rotation in near surface shear layer and in the deeper interior.

Title: Helioseismic measurement of meridional circulation and differential rotation from mode eigenfunction perturbations

Authors: Ariane Schad, Markus Roth

Affiliation: Kiepenheuer-Institut für Sonnenphysik, D-79104 Freiburg, Germany

Abstract: I will discuss recent helioseismic measurements of the meridional circulation and solar rotation obtained from analysis of mode eigenfunction perturbations using MDI data. The method is verified using numerical simulations.

Title: Helioseismic Detectability of Solar Meridional Flow

Authors: Martin Woodard(1), Jesper Schou(2)
AffiliationsInstitutes: (1) NorthWest Research associates, Inc., (2) Max-Planck-Institut fur Sonnensystemforschung

Abstract: We describe a theoretical analysis of the noise of helioseismic large-scale meridional-flow measurements, undertaken to assess fundamental detectability limits. The analysis assumes that helioseismic measurement noise is dominated by the stochastic nature of solar wave excitation and furthermore that the excitation process is Gaussian. Calculations were carried out explicitly for mode-coupling ``strengths", which quantify the degree to which the subsurface flow velocity dynamically couples pairs of solar p- and f-mode oscillations. Coupling-strength noise estimates were obtained both for single-vantage-point observations of the Sun (applicable to current near-Earth observations) and for (hypothetical, ideal) multi-vantage-point observations covering the entire photosphere. The main result of the study thus far is that ideal, multi-vantage-point coupling measurements of long-lived ('global') oscillation modes can be much less noisy than current measurements. Global oscillation modes play an important role in probing the deep solar interior and therefore multi-vantage-point observations may provide considerably more information about deep meridional flow than is currently available.

Title: Probing Magnetic Fields at the Base of Solar Convection Zone with Meridional Flows

Authors: Dean-Yi Chou and Zhi-Chao Liang
Affiliation: Dept. of Physics, National Tsing Hua University, Taiwan

Abstract: We use the solar-cycle variations of meridional flow to probe the magnetic field near the base of the convection zone (BCZ). A helioseismic time-distance method is used to measure the travel time difference between opposite directions in meridional planes, which reflects the meridional flow at different depths. Two systematic effects, the surface magnetic effect and the center-to-limb effect, are removed. Using the SOHO/MDI data, we are able to measure the latitudinal distribution of travel time difference for different travel distances, corresponding to meridional flow signals in the solar interior down to 0.54R, over 15 years, including two solar minima and one maximum. The travel time differences at the maximum and the minimum behave differently in three different depth ranges. The travel time difference at the maximum is greater than that at the minimum in the region above the BCZ, while smaller in the region around the BCZ; both are close to zero below the BCZ. The difference in travel time difference between the maximum and the minimum changes about 0.1 sec from the region above the BCZ to the region around the BCZ, corresponding to a change in flow velocity of about 15 m/s around the BCZ. This flow speed change corresponds to an equipartition value of field strength 2,000 gauss at the BCZ. If the change in travel time difference around the BCZ is interpreted as the change in magnetic field around the BCZ, this equipartition value is approximately the lower limit for the change in averaged field strength from the minimum to the maximum around the BCZ, based on an order-of-magnitude estimate.

Session 2: Convection and Magnetism: Observations

Title: Seismic Constraints on Large-Scale Convection in the Sun

Author: Shravan Hanasoge

Affiliation: Tata Institute of Fundamental Research, Bombay, India

Abstract: Helioseismology suggests that transport velocities are substantially smaller than theoretical predictions. Furthermore, it can provide important constraints on the anisotropic Reynolds stresses that control the global dynamics of the solar convection zone. In this talk, I will focus on the latest developments with regards these constraints and discuss future work that will be undertaken in order to address potential sources of error and to improve the methodology.

Title: Fast Convective Flows Throughout the Near-Surface Shear Layer
Authors: Benjamin J. Greer, Bradley W. Hindman, Nicholas A.Featherstone, Juri Toomre
AffiliationsInstitutes: JILA, University of Colorado at Boulder

Abstract: We use a new high-resolution implementation of ring-diagram helioseismology to measure convective flows in the near-surface shear layer. This procedure is capable of resolving supergranules near the surface as well as larger scale convection deeper down all in one self-consistent inversion. We find the typical horizontal speed of convective motions to be ~430 m/s near the surface and ~120 m/s at a depth of 30 Mm. We compare these measurements to both existing observational results as well as a host of global convection simulations.

Title: Flows in the Convection Zone with Potential Relevance to the Dynamo.

Authors: Tom Duvall
AffiliationsInstitutes: Max Planck Institute for Solar System Research

Abstract: Recent results on convection zone flows will be examined, including the depth structure of supergranulation, the effect of the Coriolis force on supergranular flows, the amplitude of convection at different depths, and the depth dependence of meridional circulation.

Title: Joy's Law: A Space-Age Update

Authors: A.A. Norton and B.H. McClintock

Affiliation: HEPL, Stanford University, Stanford, CA94305

Abstract: Joy's law has consistently been re-examined as new data allow. Recent papers report on significant variations observed for Joy's law as a function of strong and weak sunspot cycles, North and South hemispheres, and small and large bipolar areas. Tilt-angles determined from magnetograms are larger than those from white-light data and the percentage of anti-Hale spots is higher than previously expected. High-cadence observations of sunspot evolution available in the space-age of solar physics makes it easy to witness the dynamic behavior of tilt angle as a sunspot group emerges and decays. Modeling results from rising flux tubes interacting with convection assist in the interpretation of the large tilt-angle scatter. I present an updated overview of Joy's law while keeping in mind the often-cited causes of tilt angle distributions being dictated by 1) the Coriolis force acting on the rising flux tubes or 2) the inherent orientation of the underlying magnetic field.

Title: Polar Field Reversal and Surface Flux Transport of Cycle 24 Observed by SDO/HMI
Authors: Xudong Sun, Todd Hoeksema, Yang Liu, Junwei Zhao
AffiliationsInstitutes: Stanford University

Abstract: We report the polar magnetic field reversal and the flux transport process of Cycle 24 using five years of data from SDO/HMI. The total flux associated with ARs reached maximum in the north in 2011, more than two years earlier than the south; the maximum is significantly weaker than Cycle 23. The process of polar field reversal is relatively slow, north–south asymmetric, and episodic. We estimate that the global axial dipole changed sign in 2013 October; the northern and southern polar fields reversed in 2012 November and 2014 March, respectively, about 16 months apart. Due to the poleward magnetic surges of the old-cycle polarity and the waning activity, the northern polar field remained close to zero for the past two years. The southern polar field, on the other hand, rapidly recovered to the level of 2010. We show that the surges of the trailing sunspot polarity tend to correspond to normal mean AR tilt, higher total AR flux, or slower mid-latitude near-surface meridional flow, while exceptions occur during low magnetic activity. In particular, the AR flux and the mid-latitude poleward flow speed exhibit a clear anti-correlation. We discuss how these features can be explained in a surface flux transport process that includes a field-dependent converging flow toward the ARs, a characteristic that may contribute to solar cycle variability.

Session 3: Modeling of Convection and Mean Flows

Title: Large-scale flows and dynamo in global large-eddy simulations of the Sun and solar-like stars.

Authors: G. Guerrero (1), P. K. Smolarkiewicz(2), E. M. de Gouveia Dal Pino(3), A. G. Kosovichev(4), N. N. Mansour(5)
AffiliationsInstitutes:

(1) Physics Department, Universidade Federal de Minas Gerais,
(2) European Centre for Medium-Range Weather Forecasts
(3) Astronomy Department, IAG-Universidade de São Paulo
(4) New Jersey Institute of Technology
(5) NASA, Ames Research Center

Abstract: Over the last few years large-eddy simulations have proven to be an important tool in the modeling of MHD processes in stellar interiors. This is related to the fact that sub-grid scale (SGS) models seem to increase the level of turbulence in the simulations and thus capture better the collective contribution of the small scales. In this talk I will present the results of a large set of 3D global simulations of turbulent rotating convection performed with the MHD code EULAG which uses the implicit SGS model MPDATA. Three main results will be presented: 1) The formation of the near-surface shear layer as a consequence of the large Rossby number in the upper fraction of the solar (stellar) convective envelope. 2) Generation of large scale flows and magnetic fields in solar like stars.
These processes will be discussed in terms of the angular momentum transport agents and the mean-field dynamo coefficients, respectively. 3) Finally, I will stress on the importance of the radiative zone and the tacocline in the modeling of the solar dynamo. We have found that when these regions are present in the simulation, the strong magnetic field, developed at the tachocline and stored in the stable zone, controls the evolution and the cycle-period of the dynamo in the entire domain.

Title: Stratified Convection Driven by Internal Radiative Heating: Scaling Laws
Authors: Nicholas A. Featherstone
AffiliationsInstitutes: JILA, University of Colorado, Boulder

Abstract: Deep solar convection serves as the likely source for many interesting phenomena observable at the solar surface and detectable via helioseismology. Under the influence of rotation, helical overturning motions generate, destroy, and rebuild the Sun's magnetic field with striking regularity and also establish a differential rotation throughout the convection zone. The considerable attention devoted to these two phenomena, often in the form of computer programs (i.e., ``simulations''), has yielded results that are both promising and surprising. Numerical algorithms that yield periodic behavior in their magnetic field variables have been one notable source of excitement, providing a potential path toward exploring those physics that contribute to the solar cycle. When applied to other stars, these same approaches hint at the existence of interesting regimes of differential rotation and magnetic field topology, such as the so-called anti-solar differential rotation and ``wreathy'' dynamos. The details of any cyclic behavior, the structure of the differential rotation, and the magnetic field topology realized within a particular star depend on a number of factors, but they are possibly most sensitive to the amplitude of that star's convective motions. At the moment there exists disagreement on the convective amplitudes even for the Sun, and it is thus timely to ask, ``What physics determines a star's convective amplitude?'' In beginning to address this question, I will present results from a suite of spherical 3-D, fully nonlinear, stellar convection zone models. These models are constructed in a manner analogous to the classical Rayleigh B\'{e}nard set up, but possess an internal, radiative heating. The complete series spans roughly five orders of magnitude in Rayleigh number and individual models possess between one and four density scale heights across the shell. Magnetism and rotation have been omitted in this study, which has been designed instead to isolate those effects due to luminosity and background stratification. At sufficiently high Rayleigh number, an asymptotic regime is realized wherein the convective kinetic energy effectively saturates and becomes insensitive to the explicit diffusivities employed in the model. I will discuss the implications of this result, including its bearing on differential rotation.

Title: Transport Properties of Stratified Convection in the High-Rayleigh-Number Regime

Authors: Bradley W. Hindman(1,2), Nicholas A. Featherstone(1)
AffiliationsInstitutes:
(1) JILA, University of Colorado Boulder
(2) Department of Astrophysical and Planetary Sciences, University of Colorado Boulder

Abstract: We have generated a broad range of numerical simulations of solar convection using a spherical global model, called Rayleigh, that solves the anelastic fluid equations. The set of simulations spans almost five decades in Rayleigh number with the most turbulent models achieving an asymptotic regime whereby the kinetic energy within the convection zone is independent of the diffusivities. I will explore the transport properties of these high Rayleigh number simulations, focusing on the transport of heat and momentum. I will discuss the scale separation that is achieved between the small-scale plumes that form in the thermal boundary layer at the model's surface and the large-scale flow cells that span the entire convective domain. The implications of this scale separation on dynamo processes will be explored.

Title: Fanning out of the f-mode in presence of nonuniform magnetic fields and its seismic implications

Authors: Nishant K. Singh (1), Axel Brandenburg (1,2), Matthias Rheinhardt (3)
AffiliationsInstitutes:
(1) Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, SE-10691 Stockholm, Sweden,
(2) Department of Astronomy, Stockholm University, SE-10691 Stockholm, Sweden,
(3) Physics Department, Gustaf Hallstromin katu 2a, PO Box 64, FI-00014 University of Helsinki, Finland

Abstract: We show that in the presence of a magnetic field that is varying harmonically in space, the fundamental or f-mode in a stratified layer is altered in such a way that it fans out in the diagnostic k-omega diagram, with mode power also within the fan. In our simulations, the surface is defined by a temperature and density jump in a piecewise isothermal layer. Unlike our previous work (Singh et al. 2014) where a uniform magnetic field was considered, here we employ a nonuniform magnetic field together with hydromagnetic turbulence at length scales much smaller than those of the magnetic fields. The expansion of the f-mode is stronger for fields confined to the layer below the surface. In some of those cases, the k-omega diagram also reveals a new class of low frequency vertical stripes at multiples of twice the horizontal wavenumber of the background magnetic field. We argue that the study of the f-mode expansion might be a new and sensitive tool to determining subsurface magnetic fields with azimuthal or other horizontal periodicity. Some preliminary results from the analysis of HMI data will also be presented.

Title: Differential Rotation in Solar Convective Dynamo Simulations

Authors: Yuhong Fan(1), Fang Fang(2)
AffiliationsInstitutes: (1) HAO/NCAR, (2) HAO/NCAR

Abstract: We report the results of magneto-hydrodynamic (MHD) simulations of convective dynamo in a model solar convective envelope driven by the solar radiative diffusive heat flux. The convective dynamo produces a large-scale mean magnetic field that exhibits irregular cyclic behavior and polarity reversals. The presence of the magnetic fields is found to play an important role in the self-consistent maintenance of a solar-like differential rotation in the convective dynamo. Without the magnetic fields, the convective flows drive a differential rotation with a faster rotating polar region. We vary the viscosity, magnetic diffusivity and the lower boundary conditions and discuss their effects on the mean flows and the dynamo.

Title: Small- and large-scale dynamo in the solar convection zone
Authors: Hideyuki Hotta(1), Matthias Rempel(1), Takaaki Yokoyama(2)
AffiliationsInstitutes: (1)HAO/NCAR, (2) The University of Tokyo

Abstract: We carry out two series of high-resolution calculations with special focus on the small-scale dynamo in the solar convection zone.

The first series of calculations uses the Cartesian geometry in order to decrease the grid spacing down to 350 km. Using a slope-limited diffusion as well as smaller grid spacing, the effective resolution is significantly increased. In this high resolution calculations, the turbulent magnetic energy increases up to more than 80% of the kinetic energy at the base of the convection zone and the Lorentz feedback on the flow is important. The convection velocity decreases by factor of 2. We also find that the strong small-scale magnetic field increases efficiency of the energy transport.

The second series of calculations uses the spherical geometry in order to investigate the interaction of the small-scale dynamo with the large-scale dynamo. Previous studies indicate that a smaller magnetic diffusivity decreases the amplitude of the large-scale magnetic field (e.g. Nelson et al., 2014). We also find similar results in our "medium" resolution calculations. When the resolution is increased unprecedentedly further, the large-scale magnetic field is recovered. The efficient small-scale dynamo and magnetic field suppresses the small-scale flow, which tends to destruct the large-scale magnetic field.

The results show that the small-scale dynamo, which is insufficiently resolved in most solar global calculations, plays an important role in the solar convection zone.

Title: Self-Organization and Solar-like Differential Rotation Using a Plume Boundary Condition in Global Solar Convection Simulations

Authors: Nicholas Nelson(1), Nicholas Featherstone(2), Mark Miesch(3), Juri Toomre(4)
AffiliationsInstitutes: (1) Los Alamos National Lab, (2) JILA, University of Colorado, (2)HAO/NCAR

Abstract: Global 3D simulations of solar giant-cell convection have provided amazing insight into the processes which yield the Sun's observed differential rotation and cyclic dynamo action. However, as we move to higher resolution simulations capable of exploring the formation of proto-active regions and the near-surface shear layer, a variety of codes have encountered what has been termed the convective conundrum. As these simulations increase in resolution, they tend to produce weak or even anti-solar differential rotation patterns associated with a weak rotational influence (low Rossby number). One potential culprit for this convective conundrum is the upper boundary condition applied in most simulations which is generally impenetrable. In order to transport the solar luminosity, an unphysical diffusive boundary layer is formed near the top of the domain which can dominate the convective driving. I will present simulations using an alternative stochastic plume boundary condition which imposes small-scale convective plumes designed to mimic near-surface convective downflows, thus allowing convection to carry the vast majority of the outward solar energy flux. The use of a plume boundary condition leads to significant changes in the convective patterns throughout the simulated convection zone, allowing models with solar values of the rotation rate and luminosity to maintain solar-like differential rotation at resolutions where otherwise identical impenetrable boundary simulations yield anti-solar differential rotation profiles. I will explore how the plumes imposed at the boundary self-organize into larger, slower convective cells, leading to low Rossby number giant cell convection.

Session 4: Advances in Dynamo Modeling: Convective Dynamos

Title: Simulating and understanding large-scale dynamos

Author: Axel Brandenburg

Affiliation: Nordita, KTH Royal Institute of Technology and Stockholm University, Stockholm, Sweden

Abstract: Large-scale dynamos produce magnetic fields on global scales. Over the last few decades there have been many numerical simulations of turbulent flows that do produce large-scale fields. Understanding them with hand-waving arguments can be difficult. I will argue that a proper understanding implies that one is able to reproduce the obtained behavior with a corresponding mean-field model. I will discuss a few examples: the equatorial dipole magnetic field in the presence of rapid rotation, the alpha-squared dynamo in non-rotating spherical wedges, and various realizations of alpha-Omega dynamos.

Prominent large-scale magnetic fields appear preferentially in the nonlinear regime. This regime is often characterized by bihelical magnetic fields with opposite magnetic helicities at large and small scales. In rotating spherical shells, nonlinearly saturated magnetic fields can also affect the differential rotation, which can be either solar-like (fast equator) or anti-solar (slow equator), depending on Coriolis number. However, most of them do not reproduce the near-surface shear layer, and I will discuss possible reasons for that.

Title: Organization of Coherent Magnetic Fields in Turbulent Thermal Convections

Author: Youhei Masada

Affiliation: Department of Physics and Astronomy, Aichi University of Education

Abstract: The solar magnetism is intimately linked with a large-scale dynamo operating in its interior. Our ultimate goal is to reproduce observed spatiotemporal properties of the solar magnetic field, such as cyclic polarity reversals and butterfly-shaped migrations, in the framework of magnetohydrodynamics. Our understanding on the solar magnetism has been accelerated over the past decade in response to the broadening, deepening and refining of numerical MHD dynamo models. However, it is still unclear what dynamo mode is excited in the solar interior and how it regulates the magnetic cycle.

In this talk, we discuss the possible importance of oscillatory \alpha^2 dynamo mode, which would be excited as a natural consequence of rotating stratified convections, in the solar magnetism. The mean-field dynamo theory had predicted that the large-scale dynamo can be operated in the convection zone, even without the \Omega-effect, via the \alpha-effect. The evidence of it was recently found in convective dynamo simulations in plane-parallel geometry by Kapyla et al. (2009, 2013) and then quantitatively confirmed by Masada & Sano (2014a,b).

The \alpha^2 dynamo wave excited by the turbulent convection propagates throughout the convection zone and changes its polarity with the period characterized by turbulent magnetic diffusion time. An essential ingredient for its oscillatory nature is the gradient of the kinetic helicity, which can be developed as a natural consequence of the rotating stratified convection. In the rotating spherical-shell geometry for modeling the actual sun, the kinetic helicity varies not only in the radial direction but also in the latitudinal direction. Hence, as predicted by Mitra et al. (2010) and recently inferred from our global MHD dynamo simulation (Mabuchi, Masada & Kageyama 2015), the inter-hemispheric gradient of the kinetic helicity and its-driven \alpha^2 or \alpha^2-\Omega dynamo wave might be responsible for the solar-like spatiotemporal evolution of the large-scale magnetic field.

Preliminary results of our convective dynamo studies, such as a scaling law for the magnetic cycle of the alpha^2 dynamo obtained in a series of convective dynamo simulations and the large-scale magnetic spot formation in the solar-like strongly-stratified rotating thermal convection, are also reported.

Title: Large-scale field induction in global MHD simulations of solar convection

Author: Jean-Francois Cossette

Affiliation:

Abstract: Various global MHD dynamo models are now capable of producing well-organized large-scale magnetic flux structures undergoing cyclic polarity reversals. Perhaps one of the most remarkable features that emerges from those experiments is the wide disparity in the spatiotemporal patterns characterizing the evolution of the large-scale magnetic fields that they generate, contrasted to the striking similarities in their associated large-scale flows. An analysis in terms of the mean field decomposition of the induction equation suggests that the observed disparity may arise from the competing effect of contributions from the large-scale shear and turbulent electromotive force to the large-scale field induction. In this scenario, subtle variations in parameters such as the rotation rate, grid resolution, treatment of small scales by the numerical algorithm, or the presence/absence of a stable layer beneath the convective envelope modify the character of the delicate balance that exists between those two contributions, from which arises a variety of large-scale field topologies and temporal evolutions.

Title: Competing dynamo modes in spherical wedge simulations of turbulent convection

Author: Petri Käpylä

Affiliation: Department of Physics, University of Helsinki, Finland

Abstract: We review recent results from simulations of turbulent convection and large-scale dynamo action in spherical wedge geometry. We find solar-like equatorward migration of magnetic activity at low latitudes in a limited parameter range where a negative radial gradient of angular velocity appears to play a crucial role. The dominant magnetic cycle near the surface shows equatorward migration with a cycle period of a few years. This cycle is affected by a deeper-lying longer cycle, the reversals of which disturb the dynamo mode near the surface. This is seen at the surface as Maunder minimum-like periods of low activity.

Title: Benchmarking convective dynamos: subgrid-scales modeling effects

Authors: A. Strugarek, P. Beaudoin, and P. Charbonneau

Affiliation: Université de Montréal, C.P. 6128 Succ. Centre-Ville, Montréal, QC H3C-3J7, Canada

Abstract: Global convective dynamo simulations have exhibited in the past decade a rich variety of magnetic self-organization, from small-scale turbulent fields; stable magnetic structures; to periodically reversing large-scale magnetic fields. Without the need to invoke an underlying stable layer nor surface-related mechanisms, numerical simulations have unveiled the possibility for large-scale, cyclic, and emerging magnetic structures to be generated in the bulk of turbulent stellar convection zones. These promising results were obtained using various ways to treat the small, subgrid scales, that are thought to play an important (albeit unclear) role in the large-scale organization of the magnetic field.

We report here on an ongoing effort to characterize the influence of small-scales by benchmarking those interesting dynamo regimes using jointly large eddy simulations (LES) and implicit-LES (ILES) with the ASH and EULAG codes. The goal is to assess the exact effect of the smallest resolved scales on the large-scale organization for each of these methods. We first benchmark those codes in the LES regime on a standard, stellar convective numerical experiment. Comparing with an equivalent ILES simulation obtained with the EULAG code, and with a high-resolution LES solution obtained with the ASH code, we put a particular emphasis on the importance of the non-local energy transfers mediating the built-up of large scale flows through Reynolds stresses. We then compare these numerical methods on a series of dynamo simulations at different stellar rotation rates, exhibiting a transition from a small-scale dynamo to a large-scale reversing dynamo solution.

Title: Understanding the equatorward migration of the Sun’s magnetic field

Authors: Jörn Warnecke(1), Petri J. Käpylä(2,3), Maarit J. Käpylä(3) and Axel Brandenburg(4,5)
AffiliationsInstitutes: (1) Max-Planck-Institute for Solar System Research, (2) Helsinki University, (3) Aalto University, (4) NORDITA, (5) Stockholm University

Abstract: At the beginning of the cycle sunspots appear at high latitude, whereas at the end they appear close to the equator. This is associated with an underlying strong toroidal field which migrates equatorward. Since a few years this behavior has been reproduced in global convective dynamo simulations. I will present results from our simulations of global convective dynamos. All of these simulations produce cyclic and migrating mean magnetic fields. Through detailed comparisons, we show that the migration direction can be clearly explained by an alpha-Omega dynamo wave following the Parker-Yoshimura rule. This lead to the conclusion, that the equatorward migration in this and other work is due to a positive (negative) alpha-effect in the northern (southern) hemisphere and a negative radial gradient of rotation outside the inner tangent cylinder of these models. Furthermore, I will present results of transport coefficients: alpha, the turbulent pumping and the turbulent magnetic diffusivity obtained with the test-field method of dynamo simulations with equatorward and poleward migration. It turns out, that alpha can be indeed approximated with formulation related to kinetic helicity.

Session 5: Advances in Dynamo Modeling: Flux-Transport Dynamos and Heliospheric Coupling

Title: Magnetically controlled stellar differential rotation near the transition from solar to anti-solar profiles

Authors: B. B. Karak, P. J Kapyla, M. J. Kapyla, A. Brandenburg, N. Olspert, & J. Pelt
AffiliationsInstitutes: NORDITA

Abstract: We have studied the behaviour of solar differential rotations near the transition from solar to anti-solar profiles using global compressible MHD simulations in spherical geometry. By taking different radiative conductivities, the convective velocities and hence the rotational influence on the convection is varied in a set of simulations. When we decrease the Coriolis number, differential rotation changes from solar-like to anti-solar. We find that the magnetic field helps to produce solar-like differential rotation. In our simulations we do not find any evidence of the bistable states of differential rotation which has been previously observed in hydrodynamic simulations. In anti-solar differential rotation cases we get coherent single cell meridional circulations, whereas in solar-like rotation we get multi-cellular circulations. In all cases, the poleward propagating speed near the surface is close to the observed value. The large-scale flows show significant temporal variations which are also in observational ranges.

Title: Modelling Active Region Emergence in 3D Flux-Transport Dynamos

Authors: Andrés Muñoz-Jaramillo(1) and Anthony Yeates(2)
1. Montana State University
2. Durham University

Abstract: The importance of bipolar magnetic regions (BMRs) for understanding the solar cycle and its impact on the heliosphere is hard to over-stress. On the one hand, their emergence and decay is believed to form the large-scale poloidal field that ensures the propagation and continuation of the cycle. On the other hand, the complexity and energy contained in their magnetic fields makes them essential drivers of heliospheric variability. Because of this, an accurate simulation of BMR emergence and decay is critical for the development of flux-transport dynamos that can both assimilate observations and interface with other heliospheric models. We will begin this talk by discussing observational evidence that BMRs are critical for the propagation of the cycle. Then, we will discuss how the kinematic formulation of flux-transport dynamos can be used to model BMR emergence in a way that is consistent with detailed simulations of flux-tube emergence. Finally, we will discuss how this can be used to both assimilate BMR observations, and drive heliospheric models.

Title: The importance of the surface magnetic fields to the solar dynamo
Authors: Robert Cameron, Manfred Schuessler
AffiliationsInstitutes: Max-Planck-Institut fur Sonnensystemforschung

Abstract: The large-scale surface magnetic field of the Sun during times of activity minima is highly ordered. It is dominated by the polar fields, which switch polarity every cycle. Application of Stoke's theorem to the induction equation demonstrates that the only way to change the net flux through the solar surface in each hemisphere is to carry magnetic flux across the equator at the photosphere. Since this happens at the equator it is easily observable and the result is that this flux (across the equator) is dominated by the transport of magnetic field associated with the (tilted) active regions.

The structure of the toroidal field at solar activity maxima can only be inferred from the emergence of bipolar magnetic regions. The larger regions in each hemisphere during a cycle mostly (95%) emerge with the same E-W orientation (Hale's law). This suggests that the large-scale toroidal field is highly structured during solar maxima. Stokes theorem can again be applied to show that the generation of net toroidal flux in each hemisphere is dominated by the winding up of field lines which thread the convection zone -- mainly the polar fields. The net amount of toroidal field present in each hemisphere at any time is about the same as the large-scale radial flux at the solar surface.

These two results, together with the strong correlation between the polar fields (and open flux) at minima and the strength of the following cycles, argues very strongly in favor of a Babcock-Leighton dynamo.

Title: Is a Deep One-Cell Meridional Circulation Essential for the Flux Transport Solar Dynamo?

Authors: Gopal Hazra(1), Bidya Binay Karak(2), Arnab Rai Choudhuri(3)
AffiliationsInstitutes: (1) Indian Institute of Science, (2) Indian Institute of Astrophysics, (3) Nordita

Abstract: The most extensively studied theoretical model for solar activity cycle is the flux transport dynamo model, which usually assumes a single cell meridional circulation with equatorward return flow at the bottom of the convection zone. In view of the recent claims that the return flow occurs at a much shallower depth and there might be double cell meridional structure in solar convection zone, we explore whether a meridional circulation with such a flow can still retain the attractive features of the flux transport dynamo. We find that we can retain most of the attractive features of the flux transport dynamo model if there is an equatorward flow in low latitudes at the bottom of the convection zone, even with a complicated multi-cell structure.

Title: Dynamo Models with Double-Cell Meridional Circulation
Authors: A.G. Kosovichev(1,2), and V.V. Pipin(2-4)
AffiliationsInstitutes: (1)NJIT, (2)NASA/Ames, (3)UCLA, (4)ISTP

Abstract: Helioseismology and numerical simulations show that in each solar hemisphere meridional circulation may form more than one cell along the radius in the convection zone. Using the mean-field theory approach we investigate properties of the solar dynamo with such double-cell meridional circulation. The dynamo models include the realistic profile of the solar differential rotation with the tachocline and the near-surface shear layer, and take into account effects of turbulent pumping, anisotropic turbulent diffusivity, and conservation of magnetic helicity. Contrary to previous simplified flux-transport dynamo models, we find that our dynamo model can robustly reproduce the basic properties of the solar magnetic cycles for a wide range of model parameters and circulation speeds. The best agreement with observations is achieved when the surface meridional circulation speed is about 12 m/s. For this circulation speed, the simulated sunspot activity shows good synchronization with the polar magnetic fields. Such synchronization was indeed observed during previous sunspot Cycles 21 and 22. However, the model does not explain the sudden drop in the Sun's magnetic activity in Cycle 23. We discuss possible reasons, and also further directions in the mean-field dynamo modeling.

Title: A 2X2D Babcock-Leighton dynamo model

Authors: Alexandre Lemerle(1) Paul Charbonneau(2)
AffiliationsInstitutes:
(1) Université de Montréal, Montréal, QC, Canada
(2) Collège de Bois-de-Boulogne, Montréal, QC, Canada

Abstract: The Babcock-Leighton mechanism suggests that the emergence and transport of magnetic flux at the surface of the Sun can act alone as a poloidal source term to the global dynamo that drives the activity cycle. We are building such a model by coupling an axisymmetric kinematic dynamo simulation of the solar interior, with a two-dimensional surface flux transport simulation.

One part of the process consists in allowing new surface flux to emerge from deep toroidal field. This emerged synthetic surface flux distribution can be compared with observed emergences for each cycle, and serve as an independent mean to optimize the dynamo parameter regime. On the other hand, surface flux evolution can be matched with observed synoptic magnetograms to optimize the surface flux transport parameters. In both cases the optimization is carried out using a genetic algorithm.

The combination of those two optimized simulations now provides us with a new, inherently solar-like, fluctuating dynamo model, in which surface flux emergence can either be purely synthetic or include partial or total assimilation of observed sunspot emergences. This also provides us with a useful tool for forecasting surface magnetic activity.

A reference dynamo solution will be presented, and its pattern of amplitude fluctuations in response to stochasticity of flux emergence will be shown to present many solar-like characteristics.

Title: Magnetic Flux Tubes in the Turbulent Solar Interior: Toward Linking Fibril Magnetic Fields with Active Regions

Authors: Maria Weber (1), Yuhong Fan (2), Mark Miesch (2)
AffiliationsInstitutes: (1) University of Exeter, (2) High Altitude Observatory

Abstract: Active regions are observable manifestations of solar magnetic fields, thus providing a photospheric link to the deep-seated dynamo mechanism. However, the manner by which magnetic fields traverse the convection zone to eventual emergence at the solar surface is not well understood. We study the dynamic journey of active region progenitors by embedding thin magnetic flux tubes in a rotating spherical shell of turbulent solar-like convection. By utilizing the thin flux tube approximation, we are able to track the evolution of an effectively 1D flux tube while circumventing the problem of artificial diffusion suffered by 3D MHD models, thereby preserving the flux tube's fibril nature. Furthermore, the ability to prescribe flux tube initial conditions allows us to sample the possible parameter regime of solar active region progenitors. We discuss the dynamic journey of our ensemble of flux tubes through the turbulent convection zone, and comment on their ability to reproduce active region observables on both local and global scales, namely tilt angles in accordance with Joy's Law and the active longitude phenomenon. Although idealized, our simulations compliment 3D state-of-the-art solar-like convective dynamo simulations while requiring minimal computational resources. In addition, we briefly comment on the applicability of our model to other stars with convective interiors and the potential of our model to further address some outstanding problems in solar physics.

Session 6: Data Assimilation in Dynamo Models

Title: Data assimilation with 3D models of the Earth's dynamo

Authors: Alexandre Fournier (1) Julien Aubert (1) Lars Nerger (2) Sabrina Sanchez (1)
AffiliationsInstitutes:
(1) Institut de Physique du Globe de Paris, Paris, France
(2) Alfred Wegener Institute, Bremerhaven, Germany

Abstract: Assimilating geomagnetic data into numerical models of Earth's core dynamics is a challenging problem, since the information contained in the geomagnetic record is intrinsically restricted to the large scales of the poloidal geomagnetic field at the core-mantle boundary, about 3000 km deep in Earth's interior. After a general introduction on the observation of Earth's magnetic field and data assimilation techniques, I will report more specifically on recent efforts carried out to investigate the feasibility of resorting to three-dimensional, buoyancy-driven, numerical models of Earth's dynamo for geomagnetic data assimilation practice using ensemble methods.

Title: A Few Basics about Data Assimilation: Principles and Methods

Author: Olivier Talagrand

Affiliation: Laboratoire de Météorologie Dynamique, IPSL, École Normale Supérieure, Paris, France

Abstract: Data Assimilation, in the form in which it is gradually propagating to more and more different fields of application, originated from the need of defining initial conditions for numerical weather forecasts. It aims at reconstructing as accurately as possible the state of an evolving system, from observations that are distributed in time, incomplete at any time, and of varying nature and accuracy.

Data Assimilation is probably best described as a problem in Bayesian estimation: determine the probability distribution for the state of the observed system, conditioned by the available data. These data consist of the observations proper on the one hand, and of the physical laws that govern the evolution of the system, available in general in the form of a discretized numerical model, on the other. An important aspect is the control of the dynamical instabilities which may develop in the course of the assimilation.

Two main classes of algorithms are widely used at present. Variational Assimilation globally adjusts a numerical model to observations distributed over a time interval. The required numerical minimization can be achieved, in systems with large dimension, through the use of the adjoint of the assimilating model. Kalman Filter constantly updates with new observations the latest estimate of the state of the system. It is most commonly used in the form of Ensemble Kalman Filter, which produces an explicit sample of possible system states. Ensemble Kalman Smoothers, which, like Variational Assimilation, allow propagation of information in both directions with respect to time, are being developed.

These methods are all empirical extensions to nonlinear and non-Gaussian situations of algorithms which achieve exact Bayesian estimation in linear and Gaussian cases. Particle Filters, which are independent of any hypothesis of linearity or Gaussianity, are actively studied, although not used at present in large dimension systems.

These various algorithms will be described and discussed, and their properties illustrated on a number of examples.

Title: Variational data assimilation as a tool to better understand the solar magnetism

Authors: C.P.Hung(1), L. Jouve(2), A.S. Brun(1), A. Fournier(3)
AffiliationsInstitutes:
(1): AIM, CEA Saclay, France
(2): IRAP, Observatoire Midi-Pyrénées, France
(3): IPG, Paris, France

Abstract: We present recent studies which aim at implementing variational data assimilation into mean-field solar dynamo models. The main goal of such studies is to prove that the variational approach is a powerful tool to better determine some key ingredients of such models, as for instance the source of poloidal magnetic field or the mean meridional flow. We will present the first work of Jouve et al (2011) in which a classical alpha-Omega model is used to produce the observations with a particular set of parameters. The so-called twin experiments performed in this work enable to reconstruct the alpha function which was used to produce the observations, by minimizing a well-chosen misfit between data and outputs of the model. The second study which will be presented is a more realistic flux-transport dynamo model in spherical geometry (Hung et al, in prep) in which we intend to infer the meridional flow profile from synthetic observations of the magnetic field. We will then discuss how such data assimilation techniques may improve our ability to forecast the solar magnetic activity.

Title: Estimating the Global Solar Photospheric Magnetic Field Distribution Using the ADAPT Model

Authors: C. Nick Arge1, Carl J. Henney1, Kyle Hickmann2, & Humberto C. Godinez2

Affiliation:

1. AFRL/Space Vehicles Directorate, Kirtland AFB, NM, USA

2. Los Alamos National Laboratory, Los Alamos, NM, USA

Abstract: As the primary input to nearly all coronal models, reliable estimates of the global solar photospheric magnetic field distribution are critical for accurate modeling and understanding of solar and heliospheric magnetic fields. Over the last several years AFRL, in collaboration with Los Alamos National Laboratory (LANL) and the National Solar Observatory (NSO), has been developing a model that produces much more realistic estimates of the instantaneous global photospheric magnetic field distribution than that provided by traditional photospheric field synoptic maps. The Air Force Data Assimilative Photospheric flux Transport (ADAPT) model evolves the observed solar magnetic flux using relatively well understood transport processes when measurements are not available and then updates the modeled flux with new observations (available from both the Earth and the farside of the Sun) using data assimilation methods that rigorously take into account model and observational uncertainties. This talk provides an overview of how the ADAPT model is being used to improve coronal and solar wind modeling, as well as forecasting additional space weather parameters.

Title: Data Assimilation Approach for Prediction of the Solar Activity Cycles

Authors: I.N. Kitiashvili
AffiliationsInstitutes: NASA Ames Research Center

Abstract: Prediction of the solar cycles is one of most interesting problems closely linked to dynamo processes on the Sun. Numerous attempts to predict future solar cycles are mostly based on empirical relations derived from observations of previous cycles, and provide a wide range of predicted strength and duration of the cycles. The current dynamo models also have not been able to make reliable predictions. The origin of these uncertainties is in limitations of the observational data, and also in our insufficient understanding of the complex turbulent dynamics of the solar interior. Data assimilation is a relatively new approach to develop physics-based predictions and estimate their uncertainties in the situations when physical properties of a system are not well-known, and when the available observational data are uncertain, and do not constrain the model parameters. I will present an application of this approach for modeling and prediction of the solar cycles by using a relatively simple non-linear dynamo model, which nevertheless can describe essential general properties of the cycles, and the observed sunspot number series. Despite the simplicity of this model the data assimilation approach provides reasonable estimations for the strength of the following solar cycles. In particular, the prediction of Cycle 24 calculated and published in 2008 is holding so far quite well. Our plan for further development of this approach includes assimilation of synoptic observations of solar magnetic fields into more sophisticated dynamo models.

Title: Helicity observations as a constrain on solar dynamo models

Authors: Mei Zhang
AffiliationsInstitutes: National Astronomical Observatories, Chinese Academy of Sciences, Beijing100012, China

Abstract: We present observations on current and subsurface kinetic helicities that might put constrains on solar dynamo models. We show that the hemispheric helicity sign rule presents clearly in the current helicity observations but this rule shows a solar-cycle variation with strong and weak magnetic fields show opposite helicity signs. We also show that no solar-cycle variation on subsurface kinetic helicity presents in local helioseismology observations and this poses a question on how could a solar-cycle-independent kinetic helicity produce a solar-cycle-dependent current helicity. Finally, we present some preliminary results on how to understand these observations using MHD dynamo simulations such as Fan & Fang (2014).

Session 7: The Solar-Stellar Connection

Title: Magnetic activity of intermediate and low mass stars
Authors: Moira Jardine
AffiliationsInstitutes: University of St Andrews

Abstract: The basic physical processes that govern the generation of the Sun's magnetic field and the coupling between the interior and Heliosphere are all present in other solar-like stars. They are, however, modified by variations in internal structure, differential rotation and rotation rate. The large-scale surface magnetic fields of some 100 stars have now been mapped, some over many epochs, revealing trends in the field geometries produced by stars of a range of masses and rotation rates. The tachocline is (perhaps unsurprisingly) a key element in determining field geometries, but more puzzling is the nature of the highly non-potential surface fields on many stars. The enhanced surface shear observed on more massive stars may drive a more rapid coronal evolution than is seen on the Sun, while the exciting possibility has also arisen of using exoplanets as probes of the structure and evolution of (otherwise hard to observe) stellar winds. In the course of this talk I will review these recent developments in the light of our improving understanding of the solar magnetic field.

Invited Talks

Title: Inferences on the solar-stellar connection and stellar activity from space-based photometry

Author: Bill Chaplin

Affiliation: School of Physics and Astronomy, University of Birmingham, England, UK

Abstract: In this talk I will consider how ultra-precise space-based photometry collected by the NASA Kepler Mission are revolutionizing the observational study of stars, providing important data for helping to constrain our understanding of stellar activity and the solar-stellar connection. I will discuss how these observations -- when combined with other data -- can help to build a detailed picture of the activity of the stars, including the internal structure and dynamics courtesy of asteroseismology. I will also address briefly the use of data from the re-purposed Kepler Mission, K2, and also look to the future and prospects for using photometric data from the NASA TESS and ESA PLATO missions.

Title: Rotation and differential rotation in the Kepler era
Authors: Timo Reinhold
AffiliationsInstitutes: Institut für Astrophysik Göttingen

Abstract: Surface differential rotation (DR) is a crucial ingredient of the solar alpha-Omega dynamo, and likely responsible for magnetic field generation in stars other than the Sun. We show how DR depends on effective temperature and rotation period. Our measurements are in close agreement with previous observations and theoretical predictions. Moreover, we discuss an empirical activity-age relation using the light curve variability as activity indicator, and ages inferred from gyrochronology relations.

Title: Superequipartition Convective Dynamos in Massive Stars

Author: Kyle Augustson

Affiliation:

Abstract: Observations have revealed the presence and topology of magnetic fields on the surfaces of some main sequence massive stars. These stars possess a convective core that supports strong dynamo action. This core is linked to the dynamics of the rest of the star through overshooting convection and magnetic fields and may influence the surface magnetism. Such effects are captured through 3-D MHD simulations of a 10 $M_{\odot}$ B-type star, using the anelastic spherical harmonic (ASH) code. These simulations capture the inner 65% of the star by radius, encompassing the convective core and an extensive portion of the radiative exterior. Vigorous dynamo action is achieved in the convective core with self-consistent super-equipartition (SE) states sustained over a range of rotation rates. Indeed, the ratio of magnetic to convective kinetic energy shows a distinct scaling with Elsasser and Coriolis number. The impact of this dynamo action upon the differential rotation of the core is assessed by contrasting hydrodynamic and MHD simulations. The processes that permit the maintenance of such SE states are examined.

Title: Meridional Circulation and Flux Transport Dynamos
Authors: Dibyendu Nandy, Soumitra Hazra
AffiliationsInstitutes: Center of Excellence in Space Sciences India, IISER Kolkata

Abstract: While a fully self-consistent theoretical model of the solar cycle remains elusive, significant progress has been made based on convection simulations and kinematic, flux transport dynamo modelling of the solar interior. The success of these flux transport dynamo models is largely dependent upon a single-cell meridional circulation with a deep equatorward component at the base of the Sun's convection zone. However, recent observations suggest that the meridional flow may be very shallow (confined to the top 10% of the Sun) and more complex than previously thought. Taken together these observations are a challenge to the current paradigm of flux transport dynamo models. By accounting for the turbulent pumping of magnetic flux as evidenced in magnetohydrodynamic simulations of solar convection, we demonstrate that flux transport dynamo models can generate solar-like magnetic cycles even if the meridional flow is shallow, or altogether absent. I will discuss the plausible implications of these results (and other independent studies) on flux transport dynamics in stellar interiors and solar cycle forecasting.

Title: Non-kinematic alpha2omega mean-field dynamo model
Authors: Corinne Simard(1), Paul Charbonneau(2)
AffiliationsInstitutes: (1) Université de Montréal,(2) Université de Montréal

Abstract: The recent progress in the development of global MHD simulations of solar convection has significantly improved our understaning of the solar dynamo. A few years ago, we implement a 3D-MHD global simulation of the convection zone, call EULAG-MHD, producing regular large-scale magnetic field [Ghizaru 2010, Smolarkiewicz & Charbonneau 2013]. Several analyses of this simulation have been performed [Passos 2014, Beaudoin 2013, Cossette 2013, Racine 2011, Dube 2014] in order to disentangle the underlying dynamo mechanisms. Unfortunately, those kind of models remains complex to analyse and costly in computation time. In this context, we construct a kinematic mean-field alpha2omega model incorporating the turbulent EMF [Racine 2010] and the differential rotation extract from EULAG and show that we can reproduce many features of its mean magnetic field [Simard 2013]. The next step to better study dynamical effects is to introduce the backreaction of the Lorentz force. This new non-kinematic axisymmetric mean field dynamo model covers a full meridional plane and also includes the complete 9-components alpha-tensor coming from Eulag-MHD. The resulting dynamo models support a wide range of magnetic solution where parity modulation, grand minima and double dynamo behavior can be seen. I will present solutions showing some of those features along with its corresponding torsional oscillation.

Title: Magnetic field generation in fully convective stars

Author: Matt Browning

Affiliation:

Abstract: In stars like the Sun, the tachocline of shear at the base of the convective envelope has been widely thought to play a crucial role in generating organized, cyclical magnetic fields. But sufficiently low-mass stars (as well as pre-main sequence and sub-stellar objects) are convective throughout their interiors, and so presumably do not possess an interface akin to the tachocline. A generic theoretical expectation has therefore been that such stars should harbor magnetic dynamos very different from those in solar-like stars. I will discuss how this expectation has been partly borne out, but partly confounded, by recent observations and theoretical modeling of dynamos in fully convective stars. In particular, I will review 3-D MHD simulations of convection and magnetism in such stars, and highlight how the dynamo process in these models depends on rotation rate and stellar mass. Finally, I will also describe some of the impact the dynamo-generated magnetism has on flows and heat transport, and ask what insights into Solar magnetism (if any) might be gleaned from the study of these low-mass stars.

Title: Double dynamo signatures in a global MHD simulation and mean-field dynamos
Authors: Patrice Beaudoin (1), Corinne Simard (2), Jean-François Cossette (3), Paul Charbonneau (4)
AffiliationsInstitutes: Université de Montréal

Abstract: The 11-yr solar activity cycle is the most prominent periodic manifestation of the magnetohydrodynamical (MHD) large-scale dynamo operating in the solar interior, yet (quasi-)periodicities longer and shorter are also present. The so-called "quasi-biennial" signal appearing in many proxies of solar activity is gaining increasing attention since its detection in p-mode frequency shifts, which suggest a subphotospheric origin. A number of candidate mechanisms have been proposed, including beating between co-existing global dynamo modes, dual-dynamos operating in spatially segregated regions of the solar interior, and Rossby waves driving short-period oscillations in the large-scale solar magnetic field produced by the 11-yr activity cycle. In this article, we analyze a global MHD simulation of solar convection producing regular large-scale magnetic cycles, and detect and characterize shorter periodicities developing therein. By constructing kinematic mean-field alpha^2 Omega dynamo models incorporating the turbulent electromotive force (emf) extracted from that same simulation, we find that dual dynamo behavior materializes in fairly wide regions of the model's parameters space. This suggests that the origin of the similar behavior detected in the MHD simulation lies with the joint complexity of the turbulent emf and differential rotation profile, rather that with dynamical interactions such as mediated by Rossby waves. Analysis of the simulation also reveals that the the dual-dynamo operating therein leaves a double-period signature in the temperature field, in turn indicating that a dual-period helioseismic signature should also be present. Taken jointly, our results support the hypothesis that the solar quasi-biennial oscillations are associated with a secondary dynamo process operating in the outer reaches of the solar convection zone.

Title: Convectively-driven dynamo action in the quiet Sun

Authors: Paul Bushby(1), Benjamin Favier(2)
AffiliationsInstitutes: (1) Newcastle University, UK, (2) IRPHE, Aix-Marseille University, France

Abstract: Regions of quiet Sun exhibit a complex distribution of small-scale magnetic field structures, which interact with the near-surface turbulent convective motions. It is probable that some of these magnetic fields are generated locally by a convective dynamo mechanism. Using a wide Cartesian domain to represent a localised region of quiet Sun, we investigate this system by considering convection in a compressible layer of electrically-conducting fluid. In a model with idealised boundary conditions, we find that purely hydrodynamic convection exhibits both granulation and mesogranulation (the existence of which is controversial in the Sun). Furthermore, the mesogranular peak in the kinetic energy spectrum becomes more pronounced at higher Reynolds numbers. Introducing a seed magnetic field into this system, we explore the dependence of the resultant dynamo growth rate upon the magnetic Reynolds number and the magnetic Prandtl number (confirming that the critical magnetic Reynolds number for dynamo action tends to be higher in systems with a lower magnetic Prandtl number, at least for computationally accessible values of this parameter). In the nonlinear regime, the magnetic field distribution compares very favourably to observations, both in terms of the spatial distribution and the measured field strengths. Finally, we will compare results from this model with the results from more recent calculations, in which more realistic boundary conditions have been adopted.

Session 8: Perspectives and Outlook

Invited Talks

Title: The future of dynamo modeling
Authors: Matthias Rempel
AffiliationsInstitutes: HAO/NCAR

Abstract: Sixty years have past since Parker's groundbreaking turbulent dynamo paper in 1955 and almost fifty years have past since the formulation of meanfield theory by Steenbeck Krause & Raedler in 1966. 3D convective dynamo simulations have a history of more than 30 years since the groundbreaking work of Gilman & Glatzmaier in the early eighties. Dynamo theory has been a success story in the sense that it provided a wealth of dynamo scenarios that are in principle possible in astrophysical systems, however it has been less successful in pinpointing the detailed mechanism at work in the sun and other stars.
The approach of the past has been a combination of 3D MHD simulations and meanfield models -- where do we go from here? While I cannot answer that question I will attempt a synthesis of results at the meeting and an outlook by highlighting a few key issues that need to be addressed in order to make progress.

Title: Perspectives in Helioseismology

Author: Laurent Gizon

Affiliation: Max Planck Institute for Solar System Research and University of Göttingen, 37077 Göttingen, Germany

Abstract: Today helioseismology faces a number of challenges and progress is not as fast as it used to be. Current problems are hard: meridional circulation, active region emergence, properties of convection. While observations of solar oscillations are of extremely high quality, their interpretation requires a lot of care. I will discuss developments in data analysis and modeling that may help produce more reliable and accurate inferences. I will also mention future projects, such as the Solar Orbiter mission to be launched in 2018.

Posters

Title: interaction of solar wind with cometary plasma
Authors: Zahida Ehsan
Affiliations/Institutes: COMSATS IIT Lahore, Pakistan

Abstract: A kinetic instability of dust-acoustic mode exists when two plasmas interact. The instability threshold is affected when such (quasineutral) plasma permeates through another static plasma. Such case is of interest when the solar wind is streaming through the cometary plasma in the presence of interstellar dust. In the limits of phase velocity of the waves larger and smaller than the thermal velocity of dust particles, the dispersion properties and growth rate of dust-acoustic mode are investigated analytically with validation via numerical analysis.

Title: Collisionless Ion Heating and Acceleration of Solar Wind

Authors: Zahida Ehsan[a] and Raoul. M. G.M Trines[b,c]
Affiiliations/Institufes: a) COMSATS Institute of Information Technology (CIIT), Defence Road, Off Raiwind Road, 54000 Lahore, Pakistan. b) Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot, Oxon, OX11 0QX, UK. c) Lancaster University, Lancaster, LA1 4YW, UK.

Often the heavier ions escape from the Sun are often much hotter and have higher speeds than the ionized hydrogen which dominates the solar wind. Also within a given solar wind stream, different species flowing through one another at speeds of up to several hundreds have also been observed.

Despite a large number of efforts, it has not been resolved how ions are heated and/or accelerated, particularly in a collisionless reconnection layer. For this reason, explanation and understand of this crucial phenomenon of ion acceleration has been a focal point of research among solar and space community.

The solar corona and solar wind are so tenuous that wave-particle interactions can dominate over fluid or collisional processes, resulting in highly nonthermal plasma as seen by spacecraft in interplanetary space. These nonthermal properties can be used to identify the role wave- particle interactions play in heating the corona and solar wind.

If we can understand the underlying physics, we will be able to predict the relative heating of ions and electrons in the solar wind, the corona, and other magnetized plasmas.

Since phenomenon of Landau damping of waves is inherently involved in any kinetic model and is related to the sharing of energy between waves and particles. Here we propose to study the transport of energy through nonlinear Landau damping of circularly polarized electromagnetic (EM) waves or in particular whistler waves which are found ubiquitously in solar atmosphere.

However, a careful analysis is required along with numerical simulations and verifications of model with observational data.

References: M. J. Aschwanden, ApJ, 560, 1035, (2001) and references therein. B. N. Rogers, R. E. Denton, J. F. Drake, and M. A. Shay, Phys. Rev. Lett. 87, 195004 (2001), J. C. Kasper, B. A. Maruca, M. L. Stevens, and A. Zaslavsky, Phys. Rev. Lett. 110, 091102 (2013), Z. Ehsan, N. L. Tsintsadze, J. Vranjes, and S. Poedts, Phys. Plasmas16, 053702 (2009).

Title: Making use of 3D numerical simulations of rising flux tubes to constrain a flux transport dynamo
Authors: Yori Fournier
AffiliationsInstitutes: Leibniz-Institut für Astrophysik Potsdam (AIP)

Abstract: We would like to present an on going work on the use of recent numerical results to constrain a flux transport dynamo. Numerisists usually agree that there are two types of simulations: numerical modeling and numerical experiments. The first one enable a great control on the physical processes acting on the model, but has the great limit that it will always rely on some arbitrary parametrization. The second has the advantage to rely on a strong mathematical descriptions of Nature but one has to be careful in the analysis of the results. That is the reason why it is crucial to make use of both methods if we want to learn from our simulations. In the present poster, we want to present some recent results we obtain from numerical experiments of rising flux tubes and the way we apply them on a flux transport dynamo model in order to constrain the parametrization of the alpha-effect of this model.

Title: Towards a global analytic model of mean solar behavior: the tachocline as a trans-Alfvenic feature

Authors: Lee Gunderson(1), Amitava Bhattacharjee(2)
AffiliationsInstitutes: (1) PPPL, (2) Princeton University

Abstract: While the surface rotation profile of the sun has been known over 100 years, a detailed picture of the sun's internal rotation profile has required the recent advent of helioseismology. Perhaps the most striking feature of the solar rotation profile is the solar tachocline, a thin layer of large shear separating the solid rotation of the stably-stratified interior from the differential rotation of the solar convection zone (SCZ). Observations and simulations suggest that thermal wind balance holds to lowest order in the SCZ, and an analytic model of solar rotation has been developed by further assuming a functional relationship between the entropy and rotation (Balbus et al.). This model yields good fits away from the surface and tachocline, but the validity of its assumptions remain questionable. We seek a global analytic model of solar rotation by starting from the exact solution to axisymmetric ideal MHD, the Grad-Shafranov equation, and thereby including magnetic field and poloidal flow from the onset. By invoking an anelastic ordering, we are able to derive a Balbus-like relation and recover similar rotation profiles. Additionally, we find that a tachocline-like structure naturally arises if the poloidal Alfv´enic Mach number approaches unity near the bottom of the SCZ. While a large poloidal field in the deep solar interior is not a new idea (Gough and McIntyre), we propose the novel conjecture that the tachocline is the result of the necessary transition from super-Alfv´enic flows in the SCZ to sub-Alfv´enic flows in the radiative interior, and that the onset of convective instability provides a natural cusp for this transition to take place.

Title: Magnetically controlled stellar differential rotation near the transition from solar to anti-solar profiles

Authors: B. B. Karak, P. J Kapyla, M. J. Kapyla, A. Brandenburg, N. Olspert, & J. Pelt
AffiliationsInstitutes: NORDITA

Abstract: We have studied the behaviour of solar differential rotations near the transition from solar to anti-solar profiles using global compressible MHD simulations in spherical geometry. By taking different radiative conductivities, the convective velocities and hence the rotational influence on the convection is varied in a set of simulations. When we decrease the Coriolis number, differential rotation changes from solar-like to anti-solar. We find that the magnetic field helps to produce solar-like differential rotation. In our simulations we do not find any evidence of the bistable states of differential rotation which has been previously observed in hydrodynamic simulations. In anti-solar differential rotation cases we get coherent single cell meridional circulations, whereas in solar-like rotation we get multi-cellular circulations. In all cases, the poleward propagating speed near the surface is close to the observed value. The large-scale flows show significant temporal variations which are also in observational ranges.

Title: 3D Modeling of the Local Dynamo Action on the Sun

Authors: I.N. Kitiashvili(1), A.G.Kosovichev(2), N.N. Mansour(1), A.A. Wray(1)
AffiliationsInstitutes: (1) NASA Ames Research Center, (2) New Jersey Institute of Technology

Abstract: Truly understanding of the solar activity is not separable from the `background' state of solar magneticonvection with small-scale magnetic fields distributed and self-organized into large-scale structures. By using 3D radiative MHD numerical simulations we reproduce dynamical and turbulent properties of the solar magnetoconvection with a high degree of realism. We find that these fields result from a local dynamo action in the top layers of the convection zone, where extremely weak `seed' magnetic fields can locally grow above the mean equipartition field forming stronger than 2000 G localized magnetic structures. The simulation results show that the magnetic flux is predominantly generated in regions of small-scale helical downflows. We find that the local dynamo action takes place mostly in a shallow, about 500 km deep, subsurface layer, from which the generated field is transported into the deeper layers by convection downdrafts. We demonstrate that the observed dominance of vertical magnetic fields at the photosphere and horizontal fields above the photosphere can be explained by small-scale magnetic loops produced by the dynamo. We argue that such small-scale loops play an important role in the structure and dynamics of the solar atmosphere, and that their detection in observations is critical for understanding the dynamo action on the Sun.

Title: The variation of subsurface flows during Solar Cycle 23 and 24

Authors: Rudolf Komm^1, Rachel Howe^2, Frank Hill^1

Affiliations: 1. National Solar Observatory; 2. University of Birmingham

Abstract: We study the solar-cycle variation of the zonal and meridional flow in the near-surface layers of the solar convection zone from the surface to a depth of about 16 Mm. We have analyzed Dopplergrams obtained with the Michelson Doppler Imager (MDI) onboard the Solar and Heliospheric Observatory (SOHO), the Global Oscillation Network Group (GONG),and the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO) with a dense-pack ring-diagram analysis. The three data sets combined cover almost two solar cycles. The zonal and meridional flows vary with the solar cycle. Their amplitude variation tracks the mean latitude of activity and appears about three years before magnetic activity is visible in synoptic maps of the solar surface. We focus on the variation of the zonal and meridional flows, including their long-term variation at mid- and low-latitudes using GONG and MDI data and their variation at the high latitudes that are now accessible using HMI data. We will present the latest results.

Title: Multi-scale Flows and Magnetic Field Evolution in Solar Cycle 24

Authors: Alexander Kosovichev(1,2) and Junwei Zhao(3)
AffiliationsInstitutes: (1)NJIT, (2)NASA/Ames, (3)Stanford

Abstract: Local time-distance helioseismology and magnetic field measurements from the HMI instrument on SDO provide unique high-resolution data that allow us to investigate detailed dynamics of the upper convection zone and its relation to the magnetic field evolution during the first five years of the current solar cycle. This study is focused on the understanding the role of the near-surface shear layer (NSSL) in the dynamo process, generation, emergence and transport of the solar magnetic flux. The helioseismology data represent 3D flow maps in the depth range of 0-20 Mm, obtained uninterruptedly every 8 hours for almost the whole solar disk with the spatial sampling of two arcsec. We calculate the flow characteristics (such as divergence, vorticity and kinetic helicity) on different spatio-temporal scales from supergranulation to global-scale zonal and meridional flows, investigate their multi-scale organization (such as inflows into active regions and hemispheric asymmetry), and compare with the evolution of the observed magnetic activity.

Title: A Three-Dimensional Babcock-Leighton Solar Dynamo Model

Authors: Mark S. Miesch and Mausumi Dikpati

Affiliation: HAO/NCAR

Abstract: We present a three-dimensional (3D) kinematic solar dynamo model in which poloidal field is generated by the emergence and dispersal of tilted sunspot pairs (more generally bipolar magnetic regions, or BMRs). The axisymmetric component of this model functions similarly to previous 2.5 dimensional (2.5D, axisymmetric) Babcock–Leighton (BL) dynamo models that employ a double-ring prescription for poloidal field generation but we generalize this prescription into a 3D flux emergence algorithm that places BMRs on the surface in response to the dynamo-generated toroidal field. In this way, the model can be regarded as a unification of BL dynamo models (2.5D in radius/latitude) and surface flux transport models (2.5D in latitude/longitude) into a more self-consistent framework that builds on the successes of each while capturing the full 3D structure of the evolving magnetic field. The model reproduces some basic features of the solar cycle including an 11 yr periodicity, equatorward migration of toroidal flux in the deep convection zone, and poleward propagation of poloidal flux at the surface. The poleward-propagating surface flux originates as trailing flux in BMRs, migrates poleward in multiple non- axisymmetric streams (made axisymmetric by differential rotation and turbulent diffusion), and eventually reverses the polar field, thus sustaining the dynamo. In this poster we briefly describe the model, initial results, and future plans.

Title: Sunspot group, tilt angles and surface field reconstruction from historical observations

Authors: V. Senthamizh Pavai, Rainer Arlt

Affiliation: Leibniz Institute for Astrophysics Potsdam (AIP), Potsdam, Germany

Abstract: To understand the nature of the solar cycles, which aids in developing better dynamo models, long term statistical study of sunspot properties is needed. From analyzing historical sunspot drawings, we can obtain (i) solar cycle properties for many earlier cycles and (ii) improvements for empirical relations of sunspot emergence. The tilt angles of sunspot groups is an important property in flux-transport dynamo models in that it provides the source term for the poloidal magnetic field. With the improvement for the sunspot group properties, simulations of the polarfield and openflux are performed.

We have analyzed the sunspot drawings of Samuel Heinrich Schwabe (1825 – 1867), Scheiner (1618, 1621, 1622, 1624 and 1625 – 1627) and Staudacher (1749 – 1796). The positions and umbral areas of sunspots were obtained from drawings. The Staudacher drawings are rough so the area values are not precise. The average tilt angle and Joy's law were obtained. The "magnetic equator" during 1825 1867 was also calculated. The empirical relations with latitude, cycle strength and phase used in sunspot emergence were tested for Schwabe data and it seems to work well. Using the surface flux transport model, the evolution of magnetic field on the surface of the Sun was then derived.

Title: Helioseismology in the Lab

Authors: Ethan Peterson, John Wallace, Mike Clark, Jan Egedal,
Cary Forest, and the MPDX Team
AffiliationsInstitutes: University of Wisconsin - Madison

Abstract: To date, the majority of solar dynamo science has been conducted with highly sophisticated 3D numerical simulations and inferences made through helioseismic inversion. With the recent completion of the novel Madison Plasma Dynamo Experiment (MPDX) at the University of Wisconsin - Madison, a promising new frontier of dynamo studies can be pursued. The hot, flow dominated, spherical, spinning plasmas created in MPDX are ideally suited to studying kinetically driven magnetohydrodynamic instabilities like the dynamo. With its unique, programmable, boundary-driven flow system, MPDX is capable of recreating solar-like boundary flows and studying angular momentum transport throughout a spherical, spinning plasma, much like the Sun. To properly diagnose the dynamo instability in the lab and to study angular momentum transport, excellent velocity and magnetic field diagnostics are required. With the eventual goal of reconstructing global 3D flow profiles in MPDX, acoustic modes are excited in the plasma and observed on the surface by magnetic probes in the confining cusp field of the machine in a fashion akin to helioseismology. Successful excitement of acoustic modes and detection in the magnetic signals has been demonstrated. With the completion of a surface array of magnetic probes, a mathematical inversion will be possible to reconstruct global flow profiles while minimizing disturbance of the plasma.

Title: Pixel Dynamics Analysis of Photospheric Spectral Data

Authors: Anthony Rasca(1,2), James Chen(2), Alexei Pevtsov(3)
AffiliationsInstitutes: (1) National Research Council Postdoctoral Associate, (2) Naval Research Laboratory, (3) National Solar Observatory

Abstract: Recent advances in solar observations have led to higher-resolution surface (photosphere) images that reveal bipolar magnetic features operating near the resolution limit during emerging flux events. Further improvements in resolution are expected to reveal even smaller dynamic features. Such photospheric features provide observable indications of what is happening before, during, and after flux emergence, eruptions in the corona, and other phenomena. Visible changes in photospheric active regions also play a major role in predicting eruptions that are responsible for geomagnetic plasma disturbances. A new method has been developed to extract physical information from photospheric data (e.g., SOLIS Stokes parameters) based on the statistics of pixel-by-pixel variations in spectral (absorption or emission) line quantities such as line profile Doppler shift, width, asymmetry, and flatness. Such properties are determined by the last interaction between detected photons and optically thick photospheric plasmas, and may contain extractable information on local plasma properties at sub-pixel scales. Applying the method to photospheric data with high spectral resolution, our pixel-by-pixel analysis is performed for various regions on the solar disk, ranging from quiet-Sun regions to active regions exhibiting eruptions, characterizing photospheric dynamics using spectral profiles. In particular, the method quantitatively characterizes the time profile of changes in spectral properties in photospheric features and provides improved physical constraints on observed quantities.

Title: Visualization and Analysis of 3D MHD Simulations of Solar Dynamics and Dynamo
Authors: Andrey Stejko(1), Gustavo Guerrero(2), Alexander Kosovichev(1)
AffiliationsInstitutes: (1)NJIT, (2)Universidade Federal de Minas Gerais

Abstract: Recent numerical MHD simulations can reproduce the basic characteristics of solar differential rotation, meridional circulation and dynamo. However, there are still significant differences from solar observations. For a better understanding of the underlying physical process we apply 3D visualization and data analysis tools to results obtained with the EULAG code.

Title: Convection in Oblate Late-Type Stars
Authors: Junfeng Wang, Mark S. Miesch, Chunlei Liang
AffiliationsInstitutes: George Washington University, HAO

Abstract: We investigate the convection, oblateness and differential rotation in rapidly rotating late-type stars with our novel and powerful Compressible High-ORder Unstructured Spectral-difference (CHORUS) code. Recent observations have revealed the drastic effects of rapid rotation on stellar structure, including centrifugal deformation and gravity darkening. The centrifugal force counteracts gravity, causing the equatorial region to expand. Consequently, rapidly rotating stars are oblate and cannot be described by an one-dimensional spherically symmetric model. If convection establishes a substantial differential rotation, as in the envelopes of late-type stars, this can considerably increase the oblateness. We extend our CHORUS code to model rapidly rotating starts. In the CHORUS code, the hydrodynamic equations are discretized by a robust and efficient high-order Spectral Difference Method (SDM) on unstructured grids. For the SD method, in the standard element, two sets of points are defined, namely the solution points and the flux points. The solution and flux values within the element can be computed using Langrangian polynomials. On the cell interfaces, an approximate Riemann solver is used for computing the inviscid flux and an averaging operation is used to compute the viscous flux. The computational stencil of the spectral difference method is compact and advantageous for parallel processing. CHORUS has been verified by comparing it to spherical anelastic convection simulations on benchmark problems. Here we conduct the first gobal simulations of convection in oblate stars. We quantify the influence of the oblateness on the mean flows and the thermal structure of the convection zone and we discuss implications of these results for stellar observations.

Title: Possible signature of solar oblateness in the Sun's oscillation frequency splittings

Authors: Martin Woodard
AffiliationsInstitutes: NorthWest Research Associates, Inc.

Abstract: Departures from spherical symmetry split the frequencies of the Sun's normal oscillation modes. In addition to the well-studied, dominant splitting of the mode frequencies, due to the first-order advection of internal wave motion, a number of second-order effects on the frequency splittings are expected. Whereas the well-observed rotational frequency splittings have an odd dependence on the azimuthal order, m, of the modes, the second-order effects should have an even dependence. Second-order effects of potential interest, whose ultimate cause is solar rotation, include the solar oblateness, the direct effect of rotation on wave motion, pole-equator temperature differences, and anisotropic convection. The biggest, and thus far the only well-studied, second-order effect on splittings, is due to the cyclic variations in magnetic activity near the Sun's surface. A crude analysis of the even mode-frequency splittings, obtained from approximately 15 years of SOHO/MDI spherical-harmonic time series, was recently performed. To extract the small splittings of interest from the dominant, solar-cycle effects, which have a strong mode-frequency dependence, the former were assumed to depend only weakly on mode frequency and to have no time dependence. The observational analysis yielded statistically significant frequency splittings of order ten parts-per-million of the frequencies themselves, roughly consistent with the observed solar oblateness.

Title: Temporal Evolution of Solar Meridional Flow and Large-Scale Structures at High Latitudes

Authors: Junwei Zhao, R. S. Bogart
AffiliationsInstitutes: W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085

Abstract: It was recently reported (Zhao et al. 2014, ApJ Lett) that shallow meridional flow, above the latitude of about 40 degree, showed an anti-correlation relation with the magnetic flux being transported toward the pole during the rising phase of cycle 24. The meridional flow speed was faster (slower) when the following- (leading-) polarity flux was being transported. Using HMI data, we continue to monitor the evolution of the meridional flow and study whether the similar anti-correlation persisted after the solar activity passed its maximum.

Recently, Hathaway et al. (2013, Science) reported the detection of large-scale flow structures at high solar latitudes which may be signatures of giant cells. These structures display anomalous zonal flow speed. By use of HMI time-distance pipeline results, we also identified similar structures. With about 5 years' data available, we monitor the temporal evolution of these structures, and discuss the relation between these large-scale structures and magnetic flux being transported toward the pole.