

## COMMISSION 12

## SOLAR RADIATION AND STRUCTURE

*RAYONNEMENT ET STRUCTURE SOLAIRE*

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## TRIENNIAL REPORT 2006 - 2009

### 1. Introduction

Commission 12 encompasses investigations on the internal structure and dynamics of the Sun, mostly accessible through the techniques of local and global helioseismology, the quiet solar atmosphere, solar radiation and its variability, and the nature of relatively stable magnetic structures like sunspots, faculae and the magnetic network. A revision of the progress made in these fields is presented. For some specific topics, the review has counted with the help of experts outside the Commission Organizing Committee that are leading and/or have recently presented relevant works in the respective fields. In this cases the contributor's name is given in parenthesis.

### 2. Irradiance and its variability

#### *2.1. Measurements and models of the Total Solar Irradiance (TSI)*

Measurements of solar irradiance and its variation can only be made from space, and almost thirty years of observation have now established that the total solar irradiance (TSI) varies by only 0.1 to 0.3%, while certain portions of the solar spectrum, the ultra-violet for example, vary by orders of magnitude more. Since November 1978 a set of TSI measurements from space is available, yielding a time series of more than 25 years. The results (PMOD composite) provide reliable TSI measurements for the three solar cycles (Frohlich 2006).

Substantial work had been done to model the observed TSI variations and understand the role of magnetic and quiet Sun regions. A reconstruction of total solar irradiance (TSI) back to 1974, i.e., from the minimum of cycle 21 to the declining phase of cycle 23 based on surface magnetic fields was carried out by using data from the 512-channel Diode Array Magnetograph and the newer spectromagnetograph on Kitt Peak. Their model is

based on the assumption that all irradiance changes on time-scales of a day and longer are entirely due to the variations of the surface distribution of the solar magnetic field. A good correspondence is found with the PMOD TSI composite, with no bias between the three cycles on time-scales longer than the solar rotation period, although the accuracy of the TSI reconstruction is somewhat lower when 512 channel magnetograph data are used. This suggests that the same driver of the irradiance variations, namely the evolution of the magnetic flux at the solar surface, is acting in cycles 21-23 (Wenzler 2006).

Very high-resolution filtergram and magnetogram observations of solar faculae taken at the Swedish 1-meter Solar Telescope (SST) on La Palma were used to investigate the structure of solar faculae, which provide significant contribution to TSI. These data revealed that faculae are not the interiors of small flux tubes – they are granules seen through the transparency caused by groups of magnetic elements or micropores ‘in front of’ the granules. Previous results which show a strong dependency of facular contrast on magnetic flux density were caused by bin-averaging of lower resolution data leading to a mixture of the signal from bright facular walls and the associated intergranular lanes and micropores. The findings are important to studies of total solar irradiance that use facular contrast as a function of disk position and magnetic field in order to model the increase in TSI with increasing sunspot activity (Berger *et al.* 2007).

The TSI variations correlate well with changes in projected area of photospheric magnetic flux tubes associated with dark sunspots and bright faculae in active regions and network. This correlation does not, however, rule out possible TSI contributions from photospheric brightness inhomogeneities located outside flux tubes and spatially correlated with them. Previous reconstructions of TSI report agreement with radiometry that seems to rule out significant ‘extra-flux-tube’ contributions. Using measurements with the Solar Bolometric Imager (SBI) it was shown that these reconstructions are more sensitive to the facular contrasts used than has been generally recognized. Longer term bolometric imaging will be required to determine whether the small but systematic TSI residuals are caused by remaining errors in spot and facular areas and contrasts or by extra-flux-tube brightness structures such as bright rings around sunspots or ‘convective stirring’ around active regions (Foukal & Bernasconi 2008).

An analysis of spatially-resolved measurements of the intensity of the photospheric continuum by the Michelson Doppler Imager (MDI) on the SOHO spacecraft indicated that, while it is possible to account for short-term (weeks to months) variation in TSI by variations in the irradiance contributions of regions with enhanced magnetic fields (larger than ten Gauss as measured by MDI), the longer-term variations are influenced significantly by variations in the brightness of the quiet Sun, defined here as regions with magnetic field magnitudes smaller than ten Gauss. The latter regions cover a substantial fraction of the solar surface, ranging from approximately 90% of the Sun near solar minimum to 70% near solar maximum. The results provide evidence that a substantial fraction, 50% or more, of the longer term ( $\geq$  one year) variation in TSI is due to changes in the brightness of the quiet Sun (Withbroe 2006).

## 2.2. Spectral solar irradiance

There have been significant, recent advances in understanding the solar ultraviolet (UV) and X-ray spectral irradiance from several different satellite missions and from new efforts in modeling the variations of the solar spectral irradiance. The recent satellite missions with solar UV and X-ray spectral irradiance observations include the X-ray Sensor (XRS) aboard the series of NOAA *GOES* spacecraft, the *Upper Atmosphere Research Satellite* (*UARS*), the *SOHO* solar EUV Monitor (SEM), the solar XUV Photometers (SXP) on the

*Student Nitric Oxide Explorer (SNOE)*, the solar EUV Experiment (SEE) aboard the *Thermosphere, Ionosphere, Mesosphere, Dynamics, and Energetic (TIMED)* satellite, and the *Solar Radiation and Climate Experiment (SORCE)* satellite. The combination of these measurements is providing new results on the variability of the solar ultraviolet irradiance over a wide range of time scales ranging from years to seconds. The solar UV variations of flares are especially important for space weather applications and upper atmosphere research. The new efforts in modeling these solar UV spectral irradiance variations range from simple empirical models that use solar proxies to more complicated physics-based models that use emission measure techniques. These new models provide better understanding and insight into why the solar UV irradiance varies, and they can be used at times when solar observations are not available for atmospheric studies (Woods 2008).

The International Organization for Standardization (ISO) is preparing a standard that will certify the process of developing ‘reference solar spectra’. However, a few issues remain to be clarified in the current draft standard. In particular, it is not clear what methodology one should use to properly ‘validate’ or assess the performance of a reference composite spectrum primarily based on measured irradiance data. Excellent agreement is found between the latest composite reference spectrum and an experimental irradiance dataset limited to the UV (295–355 nm). Good agreement is also found by comparison with various single-day or average SOLSTICE-UARS spectra over a larger UV region (120–420 nm), even though solar activity interference in this validation attempt appears obvious. Conversely, large differences are noted when comparing the same reference spectrum (as well as other older reference spectra) to spectral data from the SORCE instruments, from 120 to 1600 nm. Furthermore, using the latest version of SORCE data, a comparison between periods of moderate activity and periods of elevated sunspot activity (with low total solar irradiance) suggests that the most part of this loss in total irradiance can be explained by small and smooth spectral changes in the 400–1600 nm waveband, thus confirming that sunspots are dark over all or most of the spectrum (Gueymard 2006).

The SOLAR2000 (S2K) project provides solar spectral irradiances and integrated solar irradiance proxies for space researchers as well as ground- and space-based operational users. The S2K model currently represents empirical solar irradiances and integrated irradiance proxies covering the spectral range from the X-rays through the far infrared. Variability is provided for time frames ranging from 1947 to 2052. The combination of variability through multiple time periods with spectral formats ranging from resolved emission lines through integrated irradiance proxies is a unique feature that provides researchers and operational users the same solar energy for a given day but in formats suitable for their distinctly different applications (Tobiska & Bouwer 2006).

The solar photon output from the Sun, especially true in the wavelengths shorter than 190 nm, varies considerably over time scales from seconds during solar flares to years due to the solar cycle. These variations cause significant deviations in the Earth and space environment on similar time scales, which then affects many things including satellite drag, radio communications, atmospheric densities and composition of particular atoms, molecules, and ions of Earth and other planets, as well as the accuracy in the Global Positioning System (GPS). The Flare Irradiance Spectral Model (FISM) is an empirical model that estimates the solar irradiance at wavelengths from 0.1 to 190 nm at 1 nm resolution with a time cadence of 60 s. This is a high enough temporal resolution to model variations due to solar flares, for which few accurate measurements at these

wavelengths exist. This model also captures variations on the longer time scales of solar rotation (days) and solar cycle (years) (Chamberlin 2008).

NRLEUV model represents an independent approach to modeling the Sun's EUV irradiance and its variability. Instead of relying on existing irradiance observations, this model utilizes differential emission measure distributions derived from spatially and spectrally resolved solar observations, full-disk solar images, and a database of atomic physics parameters to calculate the solar EUV irradiance. Recent updates to the model include the calculation of a new quiet Sun differential emission measure distribution using data from the CDS and SUMER spectrometers on *SOHO* and the use of a more extensive database of atomic physics parameters. Although there are many areas of agreement between the modeled spectrum and the observations, there are still some major disagreements. For instance, the computed spectra cannot reproduce the observed irradiances at wavelengths below about 160Å. Also, the observed irradiances appear to overstate the magnitude of the EUV continua. Thus, more work needs to be done to develop reliable irradiance models (Warren 2006).

### 2.3. Solar variability, solar forcing and climate

Total solar irradiance changes by about 0.1% between solar activity maximum and minimum. Accurate measurements of this quantity are only available since 1978 and do not provide information on longer-term secular trends. The total solar irradiance is reconstructed from the end of the Maunder minimum to the present based on variations of the surface distribution of the solar magnetic field (Krivova *et al.* 2007). The latter is calculated from the historical record of the sunspot number using a simple but consistent physical model. The model successfully reproduces three independent data sets: total solar irradiance measurements available since 1978, total photospheric magnetic flux since 1974 and the open magnetic flux since 1868 empirically reconstructed using the geomagnetic aa-index. The model predicts an increase in the solar total irradiance since the Maunder minimum of  $1.3 + 0.2 / - 0.4 \text{ Wm}^{-2}$ . This result is consistent with an independent analysis of Tapping *et al.* 2007.

The climate response to changes in radiative forcing depends crucially on climate feedback processes, with the consequence that solar and greenhouse gas forcing have both similar response patterns in the troposphere. This circumstance complicates significantly the attribution of the causes of climate change. Additionally, the climate system displays a high level of unforced intrinsic variability, and significant variations in the climate of many parts of the world are due to internal processes. Such internal modes contribute significantly to the variability of climate system on various time scales, and thus compete with external forcing in explaining the origin of past climate extremes. This highlights the need for independent observations of solar forcing including long-term consistent observational records of the total and spectrally resolved solar irradiance (Bengtsson 2006).

Cosmogenic isotopes are frequently used as proxy indicators of past variations in solar irradiance on centennial and millennial timescales. These isotopes are spallation products of galactic cosmic rays (GCRs) impacting Earth's atmosphere, which are deposited and stored in terrestrial reservoirs such as ice sheets, ocean sediments and tree trunks. On timescales shorter than the variations in the geomagnetic field, they are modulated by the heliosphere and thus they are, strictly speaking, an index of heliospheric variability rather than one of solar variability. Strong evidence of climate variations associated with the production (as opposed to the deposition) of these isotopes is emerging. This raises a vital question: do cosmic rays have a direct influence on climate or are they a good proxy

indicator for another factor that does (such as the total or spectral solar irradiance)? The former possibility raises further questions about the possible growth of air ions generated by cosmic rays into cloud condensation nuclei and/or the modulation of the global thunderstorm electric circuit. The latter possibility requires new understanding about the required relationship between the heliospheric magnetic fields that scatter cosmic rays and the photospheric magnetic fields which modulate solar irradiance (Beer *et al.* 2006; Lockwood 2006).

It has been proposed that solar cycle irradiance variations may affect the whole planet's climate via the stratosphere, the Quasi-Biennial Oscillation (QBO) and Arctic Oscillation (AO). This hypothesis was tested by examining causal links between time series of sunspot number and indices of QBO, AO and ENSO activity. Various methods were employed in this study: wavelet coherence, average mutual information, and mean phase coherence to study the phase dynamics of weakly interacting oscillating systems. All methods clearly showed a cause and effect link between Southern Oscillation Index (SOI) and AO, but no link between AO and QBO or solar cycle over all scales from biannual to decadal. It is concluded that the 11-year cycle sometimes seen in climate proxy records is unlikely to be driven by solar forcing, and most likely reflects other natural cycles of the climate system such as the 14-year cycle, or a harmonic combination of multi-year cycles (Moore *et al.* 2006).

#### 2.4. Measurements of solar irradiance on new space missions

LYRA is the solar UV radiometer that will embark in 2009 onboard *Proba2*, a technologically oriented ESA micro-mission. LYRA is designed and manufactured by a Belgian Swiss German consortium (ROB, PMOD/WRC, IMOMEC, CSL, MPS and BISA) with additional international collaborations. It will monitor the solar irradiance in four UV passbands. The SWAP EUV imaging telescope will operate next to LYRA on *Proba2*. Together, they will establish a high performance solar monitor for operational space weather nowcasting and research. LYRA will also demonstrate technologies important for future missions such as the ESA *Solar Orbiter* (Hochedez *et al.* 2006).

The solar payload of the ESA *Columbus* laboratory, which was launched to the International Space Station on 7 February 2008 with Space Shuttle Atlantis, has three solar irradiance instruments complementing each other to allow measurements of the solar spectral irradiance throughout virtually the whole electromagnetic spectrum – from 17 nm to 100  $\mu\text{m}$ , in which 99% of the solar energy is emitted. *SOVIM* (Solar Variable and Irradiance Monitor), which covers near-UV, visible and thermal regions of the spectrum (200 nm–100  $\mu\text{m}$ ) is developed by PMOD/WRC (Davos, Switzerland) with one of the instrument's radiometers provided by IRM (Brussels, Belgium). *SOLSPEC* (Solar SPECTral irradiance measurements) covers the 180 nm–3000 nm range. *SOLSPEC* is developed by CNRS (Verreries-le-Buisson, France) in partnership with IASB/BIRA (Belgium) and LSW (Germany). Very accurate irradiance measurements are expected in terms of relative standard uncertainties (RSU) ranging from 5% to 3% depending on the wavelength range (Schmidtke *et al.* 2006a; Schmidtke *et al.* 2006a).

*PICARD* is a new space mission dedicated to simultaneous measurements of the solar diameter, spectral, and total solar irradiance. It is presently in development for launch in 2009 on board of a microsatellite under the responsibility of Centre National d'Etudes Spatiales (France). The payload will consist of an imaging telescope, three filter radiometers with in total twelve channels, and two independent absolute radiometers (Dewitte *et al.* 2006).

The Atmospheric Imaging Assembly (AIA) on the *Solar Dynamics Observatory* (SDO) will provide revolutionary coverage of the entire visible solar hemisphere observed from photospheric to coronal temperatures at 1-arcsecond resolution with a characteristic cadence of 10 seconds for each channel. The AIA comprises four dual normal-incidence telescopes that enable it to cycle through a set of EUV channels centered on strong emission lines of iron ranging from Fe IX through XXIII and helium 304 Å plus two UV channels near 1600 Å and a broad band visible channel. Combined with the vector-magnetic imagery from the SDO Helioseismic and Magnetic Imager (HMI) the AIA observations will significantly further our understanding of the dynamics of the magnetic field in the solar atmosphere and heliosphere both in quiescent and eruptive stages. The comprehensive thermal coverage of the corona will open new avenues of study for coronal energetics and seismology which will benefit from the excellent calibration against the SDO-EVE spectral irradiance measurements (Title *et al.* 2006).

The Extreme ultraviolet Variability Experiment (EVE) on board the NASA *Solar Dynamics Observatory* (SDO) will measure the solar EUV irradiance from 0.1 to 105 nm with unprecedented spectral resolution (0.1 nm), temporal cadence (10 sec), and accuracy (20%). The EVE program will provide solar EUV irradiance data for NASA's *Living With A Star* (LWS) program, including near real-time data products for use in operational atmospheric models that specify the space environment and to assist in forecasting space weather operations. The EVE program will advance understanding of the physics of the solar EUV irradiance variations on time scales from flares to the solar cycle (Woods *et al.* 2006).

### 3. Solar abundances: status (H. Socas-Navarro)

The solar chemical composition is under question. Recent works by Asplund *et al.* (see references in Bogdan *et al.* 2005) using a 3D hydrodynamical model of the photosphere yield abundances that are considerably lower than those obtained traditionally with 1D semiempirical models. Particularly important is the revision proposed for O, the third most abundant chemical element in the Universe after H and He and one of the largest contributors to the opacity in the solar interior. With the proposed revision (Asplund *et al.* 2004 recommend  $lg\epsilon_O = 8.66 \pm 0.05$ , versus  $8.83 \pm 0.06$  of Grevesse & Sauval 1998), the excellent agreement existing between helioseismical data and theoretical predictions from stellar structure models breaks down. The far-reaching implications of a revision in the solar composition and the doubts it would cast on stellar structure and evolution models have stirred controversy in the community, to the extent that this problem is often referred to in the literature as 'the solar Oxygen crisis'. The implications of this revision for global helioseismology are discussed below.

Due to its volatility, the O abundance cannot be directly determined from meteorites and we are forced to rely solely on the photospheric abundance. Unfortunately, very few O lines exist in the visible spectrum and they are not straightforward to interpret as they are either extremely weak forbidden lines, exhibit NLTE effects and/or are strongly blended. The normal procedure to infer abundances involves using a model of the solar photosphere to synthesize the lines and then adjusting the abundance to fit the observed data. One thing that the solar crisis has bluntly put forward is how strongly model-dependent this process is and how uncertain our atmospheric models are (or, perhaps more precisely, how important the little model uncertainties are). On the one hand, a 3D model is to be preferred over a 1D model. However, when the 1D model is semiempirical, meaning that it has been derived by fitting observations (and therefore may have adjustments

folded in to accurately reproduce the data) whereas the 3D model is a theoretical *ab initio* convection model, then there are advantages in using the semiempirical one. To make things more complicated, a recent work using a different 3D convection simulation produced abundances that are in the intermediate range ( $8.73 \pm 0.07$ , Caffau *et al.* 2008).

At the moment, most of the argumentation in the literature has to do with the validation of the various atmospheric models employed (e.g., Ayres *et al.* 2006; Koesterke *et al.* 2008) since the issue of the solar abundances seems to be so critically model-dependent. An alternative approach has recently been published (Centeno & Socas-Navarro 2008) in which the authors make use of a new procedure that is nearly model-independent. This procedure is based on spectro-polarimetric observations of a sunspot and it allows for a very robust determination of the abundance ratio of O to Ni, resulting in a value that is consistent with the intermediate/high abundances ( $8.86 \pm 0.07$ ). It remains to be seen if this claim can be independently verified by other groups and if the new procedure is indeed robust enough. If so, the controversy would be settled in a way that would restore confidence in results obtained from seismology and stellar interior models, thus preserving the current order of things.

## 4. Helioseismology

### 4.1. Solar interior

Global helioseismology, based on analysis of mode frequencies, has provided accurate inferences of the solar internal structure, particularly the sound speed Christensen-Dalsgaard(2002). Standard solar models have been reasonably successful in reproducing the solar sound speed determined from helioseismology, although the remaining very significant discrepancies have raised questions, e.g., about possible mixing beneath the convection zone (e.g. Brun *et al.* 2002). However, this state of affairs was shattered by a redetermination of the solar surface composition (for a review, see Asplund 2005). The new determinations took the three-dimensional, time dependent nature of the solar atmosphere into account and in addition included departures from local thermodynamical equilibrium. This caused a very substantial reduction in the inferred abundances of oxygen, nitrogen and carbon, such that the overall abundance  $Z$  by mass of heavy elements was reduced from 0.018 to 0.012. When used in solar modelling, the result was a significant reduction in the sound speed beneath the convection zone, such that the maximum departure between the solar and model sound speed increased from 0.3 per cent to 1.5 per cent (see, e.g., Turck-Chièze *et al.* 2004, Bahcall *et al.* 2005). Also, the values of the depth of the convection zone and the envelope helium abundance in the model showed very substantial differences from the helioseismically inferred values, and substantial departures were found in the properties of the solar core, as inferred from frequencies of low-degree modes. These issues were reviewed by Basu & Antia(2008).

It is evident that this increased discrepancy represents a substantial problem for solar, and hence potentially stellar, modelling. Various attempts have been made to modify the models to bring back a more reasonable agreement between the models and the helioseismic inferences, including changes to the diffusion rates or a substantial change to the solar neon abundance; as reviewed by Guzik (2006) these have met by little success. Since the effect of the heavy-element abundances on solar structure is predominantly through their effect on the opacity, it is obvious that the models could be corrected through a change to the intrinsic opacity that compensates for the changed composition e.g., Bahcall *et al.* (2005), Christensen-Dalsgaard *et al.* (2008), although it is not clear whether the required change, up to around 30 per cent, is physically realistic. An independent

verification of the revised composition would clearly be very desirable. In fact, Caffau *et al.* (2008) found a somewhat higher value of the oxygen abundance than did Asplund and his collaborators, using a similar technique. A very interesting possibility is to use the thermodynamic effects of the heavy-element composition on the sound speed in the convection zone as a diagnostics of the abundances, e.g., Antia & Basu (2006), Lin *et al.* (2007), although the effects are subtle.

Helioseismic inferences of solar internal rotation have revealed a nearly uniformly rotating radiative interior and latitudinal differential rotation in the convection zone, with a localized transition between the two regimes in a narrow so-called tachocline at the base of the convection zone for a review, see, Thompson *et al.* (2003). Observations over a full solar cycle have shown variations in the rotation rate extending over much of the solar convection zone, and apparently strongly correlated with the bands of activity, e.g., Howe *et al.* (2006), with diagnostic potential to test dynamo models of the activity cycle. An apparent variation, with a period of around 1.3 yr, in the rotation rate at the base of the convection zone was found to be active between 1996 and 2000 (Howe *et al.* 2000). This appears to have stopped, or at least changed its nature, around 2001 (Howe *et al.* 2007); it remains to be seen whether it will reappear in the corresponding part of the new solar cycle. Solar oscillation frequencies are strongly correlated with the variation in space and time of the magnetic field on the solar surface, e.g., Howe (2007), while evidence for changes in solar structure at greater depth has been elusive. However, Baldner & Basu (2008) found interesting changes between solar minimum and maximum, at a level of 0.01 per cent, in the squared sound speed at the base of the convection zone.

The acoustic modes observed in the five-minute region provide some information about the solar core, although only fairly weak constraints are available for the rotation of the core and the information remains limited about the structure of the central parts of the Sun. Far higher sensitivity would be provided by the observation of g modes in the Sun, and the detection of such modes has been a major goal for asteroseismology since its inception. Interesting recent analyses of the sensitivity of g-mode frequencies to the properties of the solar interior were presented by Mathur *et al.* (2007), Mathur *et al.* (2008) and García *et al.* (2008). Unfortunately, the very low amplitudes of the expected modes, in a frequency region with substantial background solar ‘noise’, makes detection very difficult; a recent analysis obtained an upper detection limit of around  $5 \text{ mm s}^{-1}$  Elsworth *et al.* (2006). However, evidence for dipolar g modes in observations from the GOLF instrument on the SOHO spacecraft was found by García *et al.* (2007), on the basis of the detection of peaks in the power spectrum with the uniform period spacing expected for such modes. Interestingly, the analysis indicated that the inner core of the Sun is rotating substantially faster than the surface. However, it is probably fair to say that independent confirmation of these remarkable results will be essential, including a careful statistical analysis Appourchaux (2008).

#### 4.2. Local helioseismic diagnostics

Methods of local helioseismology (time-distance helioseismology, ring-diagram analysis and acoustic holography) provide unique information about the structure and dynamics of large-scale convection, sunspots and active regions (Zhao 2008). In the past 3 years, most of the efforts was focused in three directions: validation and testing of local helioseismology methods in the turbulent conditions of the upper convection zone (Duvall *et al.* 2006; Birch *et al.* 2007; Braun *et al.* 2007; Georgobiani *et al.* 2007; Zhao *et al.* 2007) and presence of strong magnetic fields (Braun and Birch 2006; Rajaguru *et al.* 2006; Zhao and Kosovichev 2006; Couvidat and Rajaguru 2007; Nigam *et al.* 2007; Cameron *et al.* 2008;



Moradi and Cally 2008; Parchevsky and Kosovichev 2008), measurements and modeling of properties of supergranular scale convection (Green and Kosovichev 2006; Woodard 2006; Georgobiani *et al.* 2007; Green and Kosovichev 2007; Jackiewicz *et al.* 2007; Komm *et al.* 2007; Kosovichev 2007b; Woodard 2007; Hirzberger *et al.* 2008; Jackiewicz *et al.* 2008), and measurements of the wave-speed perturbations and mass flows associated with sunspots and emerging active regions (Couvidat *et al.* 2006; Kosovichev and Duvall 2006a; Kosovichev and Duvall 2006b; Zharkov *et al.* 2007; Braun and Birch 2008; Haber 2008; Komm *et al.* 2008; Kosovichev 2008; Kosovichev and Duvall 2008; Zhao 2008). Recent progress in realistic simulations of solar convection (Stein *et al.* 2007a; Stein *et al.* 2007b) has provided an unprecedented opportunity to evaluate the robustness of solar interior structures and dynamics obtained by methods of local helioseismology (Braun *et al.* 2007; Zhao *et al.* 2007). It has been demonstrated that in the numerical simulations properties of acoustic waves (p-modes) and surface gravity waves (f-modes) are similar to the solar conditions, and that these properties can be analyzed by the time-distance technique. The time-distance helioseismology measurements and inversions are tested by calculating acoustic travel times from a sequence of vertical velocities at the photosphere of the simulated data and inferring mean three-dimensional flow fields by performing inversion based on the ray approximation. The inverted horizontal flow fields agree very well with the simulated data in subsurface areas up to 3 Mm deep, but differ in deeper areas. These initial tests provide important validation of time-distance helioseismology measurements of supergranular-scale convection, illustrate limitations of this technique, and provide guidance for future improvements (Zhao *et al.* 2007). Among the improvements of local helioseismology techniques is the implementation of Born approximation-based travel-time sensitivity kernels that take into account finite-wavelength effects and provide more accurate results than the previously employed ray-path kernels, the inclusion of solar noise statistical properties in the inversion procedure through the noise covariance matrix, and the use of the actual variance of the noise in the temporal cross-covariances in the travel-time fitting procedure (Couvidat *et al.* 2006; Birch *et al.* 2007; Jackiewicz *et al.* 2008). Of these three improvements, the most significant is the application of the Born approximation to time-distance helioseismology. This puts the results of this discipline at the same level of confidence as those of global helioseismology based on inversion of normal-mode frequencies. It was showed that both Born and ray-path approximations return a similar two-region structure for sunspots. However, the depth of inverted structures may be offset by 1 or 2 Mm, and the spatial resolution of the results is more accurately estimated with the more realistic Born sensitivity kernels (Couvidat *et al.* 2006). Investigation of the relationship between characteristics of subsurface flows and surface magnetic flux revealed that quiet regions are characterized by weakly divergent horizontal flows and small anticyclonic vorticity (clockwise in the northern hemisphere), while locations of high magnetic activity show convergent horizontal flows combined with cyclonic vorticity (counterclockwise in the northern hemisphere). Divergence and vorticity of horizontal flows are anticorrelated (correlated) in the northern (southern) hemisphere especially at greater depth. These trends show a slight reversal at the highest levels of magnetic flux; the vorticity amplitude decreases at the highest flux levels, while the divergence changes sign at depths greater than about 10 Mm. The product of divergence and vorticity of the horizontal flows, a proxy of the vertical contribution to the kinetic helicity density, is on average negative (positive) in the northern (southern) hemisphere. The helicity proxy values are greater at locations of high magnetic activity than at quiet locations (Komm *et al.* 2007). The initial results of investigations of the magnetic flux emergence and dynamics of active regions (Hindman *et al.* 2006; Kosovichev and Duvall 2006a; Kosovichev and Duvall 2006b; Haber 2008; Komm *et al.* 2008;

Kosovichev and Duvall 2008) reveal many interesting properties. In particular, it is shown that large active regions are formed by repeated magnetic flux emergence from the deep interior, and that their roots are at least 50 Mm deep (Kosovichev and Duvall 2006a). The active regions change the temperature structure and flow dynamics of the upper convection zone, forming large circulation cells of converging flows (Hindman *et al.* 2006; Kosovichev and Duvall 2006a; Haber 2008; Komm *et al.* 2008; Kosovichev and Duvall 2008). The helioseismic observations also indicate that the processes of magnetic energy release, flares and coronal mass ejections, might be associated with strong (1–2 km/s) shearing flows, 4–6 Mm below the surface (Kosovichev and Duvall 2006b).

#### 4.3. *Imaging of the far-side of the Sun*

It is of great importance to monitor large solar active regions on the far side of the Sun for space weather forecasting, in particular, to predict their appearance before they rotate into our view from the solar east limb. Local helioseismology techniques, including helioseismic holography and time distance, have successfully imaged solar far-side active regions. The possibility of imaging and improving the image quality of solar far-side active regions by use of time-distance helioseismology was explored by (Zhao 2007). In addition to the previously used scheme with four acoustic signal skips, a five-skip scheme is also included in this newly developed technique. The combination of both four- and five-skip far-side images significantly enhances the signal-to-noise ratio in the far-side images and reduces spurious signals. The accuracy and reliability of this method are tested by using numerical simulation (Hartlep *et al.* 2008). Initial results toward a calibration of the far-side helioseismic images of active regions in terms of active region size and magnetic field strength were obtained by comparing the helioseismic maps of large active regions on the far side of the Sun, calculated from Global Oscillation Network Group (GONG) Doppler observations, with magnetic and visible-continuum images of the same active regions on the visible hemisphere before and after their far-side passage (González Hernández *et al.* 2007). The far-side seismic signature is expressed as a phase shift that a far-side active region introduces to waves from the near hemisphere as they are reflected into the solar interior on their way back to the near hemisphere. There is a significant correlation between this far-side signature and both the total area of the active region, as viewed on the near hemisphere, and the area of the sunspots contained in the active region. An approximately logarithmic increase in the seismic phase signature with increasing magnetic field strengths above a critical field of 10 G has been found. This is roughly consistent with similar helioseismic signatures measured on the near solar hemisphere concurrent with associated magnetic fields.

#### 4.4. *Helioseismic effects of solar flares*

The helioseismic waves excited by solar flares ('sunquakes') are observed as circular, expanding waves on the Sun's surface. The first sunquake was observed for a flare on July 9, 1996, by the *Solar and Heliospheric Observatory (SOHO)* space mission. New sunquake events were detected from the SOHO/MDI of during solar flares of 2003–2006 (Besliu-Ionescu *et al.* 2006; Donea *et al.* 2006; Kosovichev 2006; Kosovichev 2007a; Kosovichev 2007c; Moradi *et al.* 2007; Zharkova and Zharkov 2007; Besliu-Ionescu *et al.* 2008; Martinez-Oliveros *et al.* 2008a; Martinez-Oliveros *et al.* 2008b; Zharkova 2008). These observations show a close association between the flare seismic waves and the hard X-ray source, indicating that high-energy particles accelerated during the flare impulsive phase produced strong compression waves in the photosphere, causing the sunquake. The results also reveal new physical properties such as strong anisotropy of the seismic waves, the amplitude of which varies significantly with the direction of propagation (Kosovichev

2006; Kosovichev 2007a). The waves travel through surrounding sunspot regions to large distances, up to 120 Mm, without significant distortion. In addition to the local observations of the sunquake waves it was found that the flares may excite global oscillations of the Sun (Karoff and Kjeldsen 2008). A new type of flare-driven waves was discovered from *Hinode* observation of the December 13, 2006, flare. These waves were detected in the sunspot umbra during the impulsive phase and probably represent a fast MHD mode (Kosovichev and Sekii 2007). The observations and analysis of helioseismic effects of solar flares open new perspectives for helioseismic diagnostics of flaring active regions on the Sun and for understanding the mechanisms of the energy release and transport in solar flares.

#### 4.5. *Helioseismology programs on new space missions*

The great success of helioseismology investigation in recent years was due high quality data from the GONG and BISON networks and from the space mission *SOHO*. First results from initial helioseismic observations by the solar Optical Telescope (SOT) on board the Japan *Hinode* space mission launched in 2006 (Sekii *et al.* 2007) demonstrated that intensity oscillation data from the SOT Broadband Filter Imager can be used for various helioseismic analyses. The  $k$ - $\omega$  power spectra, as well as corresponding time-distance cross-correlation function that promises high-resolution time-distance analysis below 6-Mm travelling distance, were obtained for G-band and Ca II-H data. The subsurface supergranular patterns have been observed from the initial time-distance analysis. The *Hinode* results show that the solar oscillation spectrum is extended to much higher frequencies and wavenumbers, and the time-distance diagram is extended to much shorter travel distances and times than they were observed before, thus revealing great potential for high-resolution helioseismic observations (Kosovichev and Sekii 2007; Nagashima *et al.* 2007; Sekii *et al.* 2007; Mitra-Kraev *et al.* 2008). Future helioseismology investigations will be based on high-resolution uninterrupted data from the Helioseismic and Magnetic Imager (HMI) of the NASA *Solar Dynamics Observatory (SDO)* space mission scheduled for launch in 2009. The HMI investigation encompasses three primary objectives of the *Living With a Star Program*: first, to determine how and why the Sun varies; second, to improve our understanding of how the Sun drives global change and space weather; and third, to determine to what extent predictions of space weather and global change can be made and to prototype predictive techniques. Helioseismology provides unique tools to study the basic mechanisms of the Sun's magnetic activity and variability. It plays a crucial role in all HMI investigations, which include convection-zone dynamics and the solar dynamo; origin and evolution of sunspots, active regions and complexes of activity; sources and drivers of solar activity and disturbances; links between the internal processes and dynamics of the corona and heliosphere; and precursors of solar disturbances for space-weather forecasts. The SDO mission will provide new unique opportunities for helioseismology studies in combination with data from the other instruments, Atmospheric Imaging Assembly (AIA) and Extreme-ultraviolet Variability Experiment (EVE), and also from various space and ground-based observatories (Kosovichev and Team 2007). New helioseismology data will be obtained also from the *PICARD* mission, a CNES (France) micro-satellite also scheduled for launch in 2009. Its goal is to better understand the Sun and the potential impact of its activity on earth climate by measuring simultaneously the solar total and spectral irradiance, diameter, shape and oscillations. The helioseismology program of *PICARD* aims to observe the low to medium  $l$  p-mode oscillations in intensity and search for g-mode oscillation signatures at the limb (Corbard *et al.* 2008).

## 5. Surface magnetism

### 5.1. Sunspots

Substantial progress in our understanding of sunspot fine structure has been made recently. Interestingly enough, it has been found that a single physical process accounts for the appearance of dark core configurations in both the umbra and the penumbra (in spite of their quite different magnetic field configurations). This magnetoconvective process is clearly responsible for the brightness observed in these sunspot zones. Dark cores, similar to those found ubiquitously in penumbral filaments by Scharmer *et al.* (2002), have been predicted to occur in umbral dots (Schüssler & Vögler 2006) and actually observed with the *Hinode* satellite (Bharti 2007). Comparable dark cores are also observed in light bridges, running parallel to their elongated direction. These dark cores present conspicuous similarities for all three cases, penumbral filaments, umbral dots and light bridges (Rimmele 2008). Careful spectropolarimetric inversions obtained with *Hinode* (Riethmüller 2008) have provided stratifications that show umbral dots to harbor excess temperatures of more than 500 K, fields smaller than their surroundings by 400 G and weak upflows, much in agreement with what is obtained from MHD simulations. To explain these dark cores, it is broadly accepted that magnetoconvective instabilities pile up hot material near the surface giving rise to a cusp shaped magnetic field configuration. The excess densities in these concentrations lift to higher and cooler layers the  $\tau = 1$  surface and thus originate the dark core signature (in depth formulations for the penumbral case can be found in Borrero 2007, Ruiz Cobo & Bellot Rubio 2008). Where there is less agreement is in how much the field strength is reduced in this enhanced density concentrations. According to Scharmer & Spruit (2006), these high density concentrations of hot material would correspond to field free gaps radially aligned with the penumbral direction. The field free configuration in a deep penumbra, sometimes referred as the 'gappy penumbral model, would be originated in a multitube configuration of the sunspot magnetic field below the photosphere. This model has been contrasted to the so called uncombed penumbral model (Solanki & Montavon 1993) where the hot material would flow inside a weakly magnetized tube (see the comparison of the two models in Bellot Rubio 2007). More recent MHD simulations (Heinemann *et al.* 2007, Rempel *et al.* 2008) including grey radiative transport but otherwise realistic atmospheric parameters, suggest some intermediate scenarios whereby magnetoconvective instabilities in inclined magnetic fields initiate hot upflows along reduced but not field free channels. These models are reproducing modern observations of sunspots to levels heretofore never achieved. They also provide some links between yet unsolved problems like the origin of the Evershed flow and the heat transport mechanism in the penumbra.

In this context the final fate of the Evershed flow is still a major unknown. An interesting possibility has been suggested by Vargas Domínguez (2007). They found that the moat flow that surrounds mature sunspots, and that is normally associated with some form of a supergranular cell, exits only in sunspots sides with penumbra and is aligned with its filamentary direction. That is, sunspot sides with no penumbra (as seen in irregular spots) show no moat flow and the moat flow is also absent in directions perpendicular to the filaments. This strongly suggest the possibility of a physical link between the Evershed flow and the moat flow surrounding sunspots. This hypothesis would nicely answer at once two unsolved questions such as what does it happen to the Evershed mass flow beyond the penumbral boundary and what is the exact origin of the moat flow. It is interesting to see how the connections between sunspot penumbrae and the moat flow (and fields) is indeed being found in a number of different works using diverse techniques (Balthasar & Schleicher 2008).

5.2. *Quiet Sun magnetism*

The observation of surface magnetic fields based on the Zeeman effect has always suffered an observational bias due to the quadratic dependence on the field strength of the linear polarization signals as compared to the linear dependence for the circular polarization ones. It is thus natural that past studies of solar magnetism have largely dealt with the longitudinal component of the magnetic field. The advent of high sensitive, high spatial resolution observations from the ground and space is changing this picture. One of the most outstanding results obtained by the *Hinode*-SOT telescope has been the discovery of a wealth of transverse fields over substantial fractions of the quiet solar surface, with strengths of 100–200 G and with apparent flux densities that are 5 (!) times larger than their longitudinal counterparts (Lites *et al.* 2008). One way to explain this high ratio between the transverse and the longitudinal fluxes is by assuming a small filling factor of the horizontal component, although the exact factor remains unclear. Lites *et al.* (2008) propose filling factors near 20 %. On the other hand, Orozco Suárez *et al.* (2007) find a ratio more near 2 and filling factors of 40–50 % or so and discuss that the effects of telescope diffraction must be taken into account at this high spatial resolutions (related to the distinction between stray-light and filling factor). In any case, it is clear that more detailed analysis of the superb data obtained by the *Hinode* spectropolarimeter will help consolidate a new picture of the various components of the solar magnetic fields. The same instrument has shown how dynamic these fields are at this small scale, with clear loop-like structures undergoing emergence through the photosphere in the case of quiet regions (Centeno *et al.* 2007) but also for plage areas (Ishikawa *et al.* 2007). Even before *Hinode* revealed the importance of this horizontal component in the photosphere, its presence was suggested from synoptic ground observations using, this time, the center-to-limb variation of the circularly polarized signals (of the same Fe I lines as those observed by the *Hinode*-SP). Using the SOLIS/VSM full disk instrument, another grating spectropolarimeter, Harvey *et al.* (2007) found that the quiet regions of the photosphere must be covered by patches of horizontal field lines with spatial scales of around 10 arcsec typically. The *Hinode* horizontal fields are seen to be distributed at smaller, mesogranular, scales, but a degradation of the resolution from the satellite observations to that obtained on the ground could well explain this difference. Interestingly enough, analysis of existing MHD simulations searching for the presence of the newly discovered horizontal fields has found that, indeed, such fields were present in them, with ratios as large as 5 although this ratio is seen to be strongly dependent on height in the atmosphere (Schüssler & Vögler (2008), Steiner *et al.* 2008). These simulations support the original suggestion by Lites *et al.* (2008) that the physical responsible for the large transverse fluxes is the larger spatial scale of the horizontal field lines as compared to the vertical ones.

Out of the many interesting results obtained with the *Hinode* satellite, one deserves special mentioning. For decades now, a fundamental structure thought to be present in network and plage areas were the so-called flux tubes. These structures were thought to be embedded in intergranular lanes, thus harboring strong downflows outside the field concentration that opens up the field lines with height and displays a canopy like configuration. Lines-of-sights crossing the canopy and entering the field free region would see a sharp change in physical properties, which would naturally produce asymmetric Stokes profiles (Landi Deglincioni & Landolfi, 1983). On the other hand, lines of sight exclusively passing through the central portion of the magnetic concentration would see a slowly varying atmosphere, which only produce symmetric profiles (or perfectly anti-symmetric ones in the case of Stokes V). The asymmetries observed at low spatial resolution (1 arcsec) have long been thought to be the average of the contributions of these

distinct lines-of-sights. Thus, a fundamental prediction of this model was that when the structures were to be resolved, and lines of sight passing through the canopy could be separated from those that go inside the magnetic tube (or sheet), different asymmetries would be observed in them. It is encouraging that *Hinode*-SP observations have provided actually this pattern of asymmetries in the observed Stokes profiles in magnetic concentrations seen at 0.3 arcsec (see Rezaei *et al.* 2007). This is a result originally predicted from theoretical grounds that has received now full observational support and that lends confidence in our understanding of the solar photospheric magnetoconvective processes.

## 6. Future solar telescopes: status of the ATST project (T. Rimmele)

The 4m Advanced Technology Solar Telescope (ATST) located on Haleakala will be the most powerful solar telescope and the world's leading resource for studying the dynamic solar atmosphere and its magnetic environment. As its highest priority science objective ATST shall provide high resolution and high sensitivity observations of the highly dynamic solar magnetic fields throughout the solar atmosphere, including chromosphere and corona. With its 4 m aperture and integrated adaptive optics and located at the best site identified by an extensive site survey, ATST will provide unprecedented resolution of 20 km on the solar surface and thus resolve the essential, fine-scale magnetic features and their dynamics that dictate the varying release of energy from the Sun's atmosphere. The high photon flux combined with careful polarization analysis and calibration and facility class instrumentation will allow high precision polarimetric measurements of magnetic fields as they extend into the upper atmosphere. The ATST has a factor of 64 greater collecting area than the largest existing coronagraph. The coronagraphic site and a design that is optimized for low scattered light will provide the sensitivity needed to measure the illusive weak coronal magnetic fields.

The ATST project is a collaborative effort between US and international partners. The ATST project has been recommended to the NSF Director for construction funding by the National Science Board and has progressed through the National Science Foundation MREFC process and is now ready for construction. The US Senate Appropriations Committee language contained 9.5\$ million of initial funds for the Advanced Technology Solar Telescope in its proposed FY2009 Federal budget. The Environmental Impact Statement process for Haleakala is expected to be concluded at the end of 2008. The ATST construction phase is planned to begin in FY09 following a final baseline review in March of 2009. First light will be achieved by 2014. Commissioning of the initial set of four facility class instruments will take place in a phased manner during 2014–2015. During this time first science operations will be possible but have to be interlaced with significant engineering time. Full science operations will begin in 2016.

The ATST offers tremendous opportunity for the training of students and recruitment of post-docs and faculty in solar physics who will become users of the ATST and the instrument builders and theoreticians of the future. Several US and international graduate and undergraduate students have already participated in ATST development and ATST related engineering and science projects. ATST is establishing strong synergy with the education and outreach programs at the collaborating institutions. The ATST program will continue to actively involve large segments of the US and international solar physics community, helping to strengthen solar astronomy programs at universities and national centers.

## 7. Progress on dynamo theory during 2005–2008 (M. Dikpati)

Large-scale solar dynamo models were first built by E. Parker more than half a century ago, and since then solar dynamo modeling has been an active area of research in solar physics. Much progress has been made specifically over the past two decades, both in the area of mean-field dynamo models and full 3D MHD models.

Major progress in the mean-field dynamo models include the detailed exploration of flux-transport dynamos, which are the so-called  $\alpha$ - $\Omega$  dynamos with meridional circulation. Flux-transport dynamos include three basic processes: (*i*) shearing of the poloidal magnetic fields to produce toroidal fields by the Sun's differential rotation (the  $\Omega$ -effect); (*ii*) regeneration of poloidal fields by displacing and twisting the toroidal flux tubes by helical motions (the so-called  $\alpha$ -effect); and (*iii*) advective transport of magnetic flux by meridional circulation, whereas an  $\alpha$ - $\Omega$  dynamo involves only the first two. Meridional circulation acts as a conveyor belt in this class of models and plays an important role in determining the dynamo cycle period.

Surface meridional flow has been detected by various observational techniques. While helioseismologists are still searching for detecting the subsurface return flow, the past three years (2005–2008) have particularly been the golden era of building theoretical models for understanding the physics of meridional circulation, as well as the exploration of the predictive capability provided by this flow to flux-transport dynamos. Rempel (2005) developed a model using mean-field formalism and showed that the Coriolis force acting on convection creates Reynolds stresses that transport angular momentum toward the equator to create equatorial acceleration. Meridional circulation is then produced through the outward radial velocity created by the Coriolis force on large rotational flow at low-latitudes. Miesch *et al.* (2008) found similar physics behind the generation of meridional flow through direct 3D HD simulation. These models show primarily a large single-cell flow pattern when averaged over 4 months with a flow speed of a few m/s, which is consistent with that obtained from mass conservation.

In the case of oceanic models the Great Ocean conveyor belt carries surface forcing with a certain memory and determines the occurrence of future El Niño events. Dikpati, de Toma & Gilman (2006; see also Dikpati & Gilman 2006) demonstrated that the memory about the Sun's past magnetic field, provided by the solar meridional circulation, can be used to predict the amplitudes and timings of the future solar cycles. A  $\sim 50\%$  reduction in the meridional flow speed during 1996–2003 was found by Dikpati (2005) to be the physical cause of late onset of cycle 24, and this onset-timing prediction has now been validated. Solar cycle predictions using a flux-transport dynamo have been criticized by Bushby & Tobias (2007) arguing that the solar dynamo might be operating in the highly chaotic regime, due to vigorous turbulence in the solar convection zone. But research on investigating the predictive capability of a flux-transport dynamo as well as building more physical models that can assimilate data in order to be able to predict the future cycles also continued (Cameron & Schüssler 2007; Schüssler 2007; Choudhuri, Chatterjee & Jiang 2007; Jiang, Chatterjee & Choudhuri 2007; Brandenburg & Käpylä 2007; Dikpati *et al.* 2007; Dikpati, de Toma & Gilman 2008; Dikpati, Gilman & de Toma 2008).

In view of successes of kinematic flux-transport dynamos in reproducing majority of solar cycle features, questions have arisen whether such a weak meridional flow in such models can sustain the Lorentz force back reaction due to strong ( $\sim 100$  kGauss) spot-producing fields at the base of the convection zone. Rempel (2006) developed a non-kinematic flux-transport dynamo that operates with Lorentz force back reaction on differential rotation and meridional circulation, and showed that the flux-transport dynamos are robust enough to work well for the Sun by sustaining a back reaction on the

solar flow fields as long as the spot-producing fields have the peak-amplitude of  $\sim 30$  kGauss. These models also reproduce solar torsional oscillations.

The limit of  $\sim 30$  kGauss toroidal fields produced at the tachocline by a non-kinematic dynamo, raises another issue of how the spot-producing flux tubes of  $\sim 100$  kGauss can be formed at the base of the solar convection zone. Are 100 kGauss flux tubes formed via some dynamical processes on  $\sim 30$  kGauss broad toroidal fields generated by dynamo action, or are they formed not from the magnetic fields at the convection zone base but rather 3 kGauss spots are directly formed at the photospheric level by a near-surface dynamo action? While the possibility of flux tube formation from a broad toroidal sheet has been investigated in early 2000, recently Brandenburg (2005, 2006, 2007) argued in favor of the near-surface dynamo, which demonstrated efficiency in getting rid of excess small-scale magnetic helicity through coronal mass ejections.

Since meridional circulation has been identified as an important ingredient in the large-scale solar dynamo models, but details of meridional flow profiles in the bottom half of the convection zone is not observationally known yet, Bonanno, Elstner, Belvedere & Rüdiger (2005) and also Jouve & Brun (2007) studied the role of multicell meridional flow profiles in the advective transport of magnetic flux. The general conclusion was that the equatorward transport of spot-producing flux is possible via the combination of two flow cells in latitude, but multicells in latitude and radius have strong effect in cycle period as well as in the shape of butterfly diagram. Jouve *et al.* (2008) have done a very important contribution to younger generations of dynamo researchers by producing a mean-field solar dynamo benchmark that used eight different codes.

The prescription of  $\alpha$ -effect in the mean-field, kinematic dynamos is a never-ending issue, particularly when the turbulence is anisotropic. The anisotropy leads to the generation of an electromotive force from the fluctuating flow and magnetic fields, which in turn gives rise to an  $\alpha$ -effect tensor. Kitchatinov & Rüdiger (1992) demonstrated, with a simplified interpretation of the off-diagonal components of the  $\alpha$ -effect tensor as diamagnetic pumping, that it could play an important role in shaping the solar butterfly diagram. Recently Käpylä, Korpi, Ossendrijver & Stix (2006) and Guerrero & de Gouveia Dal Pino (2008) have investigated the effect of turbulent pumping arising from the off-diagonal terms of  $\alpha$ -tensor; both interpreted this pumping as a downward advection effect rather than a diffusive ‘diamagnetic’ effect and showed that this pumping improves the low-latitude confinement of the solar butterfly diagram; along with near-surface shear it also contributes in maintaining the dipolar parity of the large-scale solar magnetic fields.

In reality, dynamo action in the Sun occurs on many space and timescales, from the global down to granulation scales ( $10^{-4}$  of the solar radius), involving many turbulent processes. In order to capture most of these scales and processes, Browning *et al.* (2006) have built 3D global MHD models for solar differential rotation, convection and magnetic fields. These models have so far shown the sustained toroidal fields of  $\sim 4$  kGauss strength at the tachocline region. Using a different approach of including the third dimension in a 2D mean-field kinematic model through the non-axisymmetric  $\alpha$ -effect, Jiang & Wang (2007, 2008) have produced some non-axisymmetric dynamo modes. However, both these approaches are steps toward simulating longitude-dependent solar cycle features in addition to longitude-averaged features.

Investigation of energy cascade and energy transfer across different scales was the subject of many papers. In particular, Mininni and collaborators (Mininni *et al.* 2005; Alexakis, Mininni & Pouquet 2007; Mininni 2007) show that the turbulent velocity fluctuations in the inertial range (which are not dissipated due to eddy viscosity) is responsible for the magnetic field amplification at small scales, whereas the large-scale field is



amplified mostly due to large-scale flows. MHD simulations with helical forcing indicate that the transfer of magnetic helicity is nonlocal, from the forcing scale to the global scale, implying the validity of  $\alpha$ -effect and hence the mean-field generation.

Vögler & Schüssler (2007) showed, by performing a radiative magneto-convection simulation of dynamo action near the solar surface, that this dynamo can be a source of internetwork magnetic flux that was indicated by various observational diagnostics in past. Schüssler & Vögler (2008) have provided further evidence that the ratio of horizontal to vertical components of magnetic fields produced by their local, near-surface radiative MHD dynamo is consistent with the ubiquitous internetwork horizontal fields in the quiet photosphere (Orozco Suárez *et al.* 2007; Lites *et al.* 2008) observed by *Hinode*.

## 8. Quiet corona and solar wind initiation

Measurements of Doppler shifts in coronal emission lines observed in active regions with the EUV imaging spectrometer (EIS) on the *Hinode* satellite show large areas of persistent outflows (Harra *et al.* 2008; Doschek *et al.* 2007, 2008). These features are fainter than the core of the active region and appear to be associated with very long or possibly open magnetic field lines, suggesting that the edges of active regions may be a significant source of solar wind plasma. These results appear to confirm and extend earlier research that suggested that active regions can contribute to the heliospheric magnetic field and solar wind (e.g., Liewer *et al.* 2004).

Valentin Martínez Pillet  
*president of the Commission*

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