Flux Emergence Workshop 2013

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Data-Driven Modeling of Emerging Flux and Active Regions

Buoyant Rise of Active Region Flux Tubes in a Solar-like Convective Envelope

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Using a Finite-difference Spherical Anelastic MHD (FSAM) code, we carry out 3D MHD simulations of the rise of active region flux tubes in a rotating, turbulent convective envelope with a solar-like differential rotation. We find that for buoyant flux tubes with an initial field strength of 100 kG inserted near the bottom of the convection zone, the magnetic buoyancy largely determines the rise of the Omega-shaped tubes although strong down flows produce significant undulation and distortion to the shape of the emerging Omega-shaped tubes. The convective flows significantly reduce the rise time for an apex to reach the top. For the weakly twisted and untwisted cases we simulated, the tube apex first reaching the top shows an overall tilt angle consistent with the active region tilts, although the emergence pattern is more complex compared to the case without convection. Near the top boundary at a depth of about 25 Mm, the emerging region shows a retrograde zonal flow of about 200 m/s in the midst of the prograde flow of the banana cells.

Global dynamics of subsurface active regions

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We will present three-dimensional numerical simulations of a magnetic loop evolving in a rotating convective shell. Due to the action of magnetic buoyancy, the loop rises and develops asymmetries between its leading and following legs, creating emerging bipolar regions whose characteristics are similar to those of observed spots at the solar surface. In particular, we self-consistently reproduce the creation of elongated structures called « tongues » around the spot polarities, which can be strongly affected by convection. We want to emphasize the presence of ring-shaped magnetic structures around our simulated emerging regions, which we call «magnetic necklaces » and which were seen in a number of observations before. We show that those necklaces are markers of vorticity generation at the periphery and below the rising magnetic loop. We also find that the typical asymmetry between the two legs of the loop is crucially dependent on the initial magnetic field strength. We will finally show that the tilt angle of the emerging regions seems to be affected both by the convective motions and the presence of a differential rotation. Those results represent another step toward understanding the full process of magnetic field generation and evolution in the solar interior and emergence of large-scale active regions at the surface.

Multi-parametric study of rising 3D buoyant flux tubes in an adiabatic stratification using AMR

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Over the past 30 years a large body of work studying the bouyant rise of magnetic flux tubes through an adiabatic stratification has sheed light on many of the MHD processes depending on the properties of the bouyant flux tubes. We expand the study of the buoyant rise of magnetic flux tubes embedded in an adiabatic stratification in 2D and 3D numerical simulations. We analyze the dependence of flux loss from the main body of the tube and of the tube evolution on the effective Reynolds number and on the magnetic twist and curvature of the tube. This multi parametric study provides great knowledge of the different structures, velocity fields, amount of flux retained within the tube as a function of the different parameters. It gives us a large picture of the impact of the various studied parameters on the flux emergence and let us also to compare the results with the literature. A series of fully compressible magnetohydrodynamics simulations were carried out using FLASH code. The Adaptive Mesh Refinement (AMR) capability implemented in FLASH facilitated 3D simulations at Reynolds numbers comparable to those previously achieved in 2D simulations. In the low magnetic Reynolds number regime, the amount of longitudinal magnetic flux retained inside the tube increases with the curvature of the tube axis. However, this dependence on tube curvature diminishes for sufficiently high magnetic Reynolds number. In addition, the flux retained in the tube increases with twist. Due to the Lorentz force, the two legs of the Omega-loop on either side of the apex gains vorticity of opposite signs. The shedding of vortex tubes with opposite senses from the two legs of the Omega-loop leads to an aerodynamic lift which swings the legs of tube in an antisymmetric fashion.

Flux emergence in the solar global convection calculation with the reduced speed of sound technique.

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We have achieved high resolution calculation of the solar global convection in spherical geometry with higher top boundary. The reduced speed of sound (RSST) is adopted in this study. Compared with the anelastic approximation, the RSST has two major advantages: One is the good scaling in parallel computing. Second is the accessibility to the real solar surface. These enable us to achieve the grid point of 720x1280x3072 and the location of the top boundary is at 0.99Rsun. Since the density ratio exceeds 600 and the pressure scale height varies drastically, our calculation includes multi-scale thermal convection, i.e., 100 Mm scale at the base and 10 Mm scale near the top boundary. This type of the small convection pattern is achieved for the first time in the global convection. In our current calculation, the rotation is not included in order to investigate the local dynamo effect in the global scale. We find that the small scale convection near the surface influences the local dynamo effect in the convection zone. The generated magnetic field in the convection zone rises to the surface. We frequently observe supergranulation scale flux emergence event in our calculation. Its magnetic energy significantly exceeds the local kinetic energy. This results shows that local-dynamo-generated magnetic field contribute the occurrence of the flux emergence to some extent. The detailed process of this type of the flux emergence will be discussed in the presentation.

Probing Emerging Magnetic Flux and the Nature of Detected Pre-emergence Signatures

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It was shown that strong emerging-flux events can be detected by helioseismology in the deep convection zone before they become visible in the photosphere. The detection method is based on computations of cross-covariances between oscillation signals observed at pairs of locations on the solar surface. We present in this talk the results of a helioseismic investigation of emerging magnetic flux in the deep convection zone. First, we present helioseismic measurements which show that the magnetic flux emerged from a depth of 70 Mm to 50 Mm in about 5 hours with an emergence speed of about 1 km/s. The detection of the rising motion of magnetic flux supports our previous studies. We also investigate the physical origin of the detected perturbation signatures. Our results show evidences that these signatures are not associated with flows or wave-speed perturbations but with power variations in the emerging-flux region which change the frequency of the cross-covariance function and cause large phase travel-time shifts at specific peaks. Therefore, the large amplitude of the detected signatures does not contradict theoretical estimates based on the effects of flows and wave-speed perturbations. Last, we analyze numerical simulation data with subsurface static sound-speed perturbations. The results show that although our method is capable of detecting these subsurface perturbations, the static sound-speed perturbation model cannot reproduce all the helioseismically observed properties of emerging-flux regions.

Observations of the Magnetic Flux Approaching the Visible Surface

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We present two characteristic observations of the emerging flux before it appears at the visible surface. According to our previous simulations of the flux emergence from -20 Mm, the rising tube pushes up the plasma ahead of the tube and decelerates in the uppermost convection zone. Such accumulated plasma escapes horizontally around the surface layer before the flux reaches the surface (horizontal divergent flow: HDF). First we report the HDF detection prior to the flux emergence of NOAA AR 11081, which is located away from the disk center. We used HMI Doppergrams to investigate the temporal changes of the flow pattern from the reference quiet Sun. It is found that the HDF of 0.6-1.5 km/s, up to 2.3 km/s, appears before the flux emergence by about 100 minutes. In the second half we present the helioseismic detection of the emerging flux in the uppermost convection zone. We apply six Fourier filters to the MDI Doppler data of NOAA AR 10488 to detect the reduction of acoustic powers at six different depths from -15 to -2 Mm. Up to 2 hours before the magnetic flux first appears at the visible surface, the start times of the power reduction show a rising trend of ~1 km/s with a gradual deceleration. These two observations are well in accordance with the simulation results.

Active Region Emergence, a New Paradigm

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The accepted paradigm is that active regions emerge as a result of a global scale flux tube emerging from the tachocline and rising through the convective zone. To maintain its coherence and to emerge
with the proper orientation and at the correct latitudes such coherent flux tubes must have a field strength of 40-50 kG at the base of the convection zone (Weber 2011). How they are formed with greater than equipartition field strength, stored in and released from the tachocline has long been a mystery. Recent simulations show that another scenario is possible. Global scale magnetic wreaths are produced by dynamo action inside the convection zone which reverse polarity (Nelson 2013). Both these global and also local surface simulations have shown that convective motions produce magnetic loops from these large scale wreaths which rise to the surface and produce active regions. The local simulations of magnetic flux emergence show that the field initially emerges over a confined area with horizontal fields emerging over granules with mixed polarity vertical legs
at their ends in the intergranular lanes. The fields are quickly swept into the intergranular lanes and then collect into separate, opposite polarity concentrations producing pores and spots as a result of the underlying large loop structures. Movies show how this evolution occurs. A tachocline is therefore not needed to explain the origin of active regions and their properties such as the
Hale polarity law. The subsurface structure of magnetic flux concentrations in pores and spots that have formed from the action of magneto-convection without being imposed as an initial condition will
also be presented.

Modeling the Origin of Tilt, Twist, Active Longitudes, and More: Buoyant Loops in Global Convective Dynamos

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Global 3D simulations of convective dynamo action in Sun like stars using a variety of numerical codes have shown that strong, coherent «wreaths» of toroidal magnetic field can be created in the bulk of the convection zone and that these wreaths can undergo cycles of magnetic activity and reversals in global magnetic polarity. Using improved subgrid-scale treatments, we have achieved a cyclic wreath building dynamo simulation in which effective diffusion has been reduced by a factor of 30 compared to previous models. These low levels of diffusion lead to increased turbulent intermittency, which can created strong, coherent magnetic flux ropes in the cores of the wreaths which become buoyant and coherently rise through the simulated domain, forming buoyant magnetic loops. Using automated pattern-recognition algorithms, we have identified and analyzed large numbers of these loops and can measure statistical descriptions of their properties such as latitudinal tilt, twist, correlation with mean fields, and longitudinal concentration. We find that our simulated loops mimic the statistical properties of latitudinal tilt and twist observed in sunspots. Loops preferentially arise in longitudinal patches which are somewhat broad in extend, perhaps providing clues to the origin of active longitudes in the Sun. The strength of the axisymmetric toroidal field is not a good predictor of the production rate for buoyant loops or the amount of magnetic flux in the loops that are produced.

Flux emergence in a magnetized convection zone

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We study the influence of a dynamo magnetic field on the buoyant rise and emergence of twisted magnetic flux-ropes, and their influence on the global external magnetic field. We ran three-dimensional MHD numerical simulations using the ASH code and analysed the dynamical evolution of such buoyant flux-ropes from the bottom of the convection zone until the post-emergence phases. The actual flux-emergence episode is preceded by a localised increase of radial velocity, density and current density at the top of the convection zone. During the buoyant rise, the flux-rope's magnetic field strength and density scale as $B\propto\rho^{\alpha}$, with $\alpha\lesssim 1$. The properties of initial phases of the buoyant rise are determined essentially by the flux-rope's properties and the convective flows and are, in consequence, in good agreement with previous studies. However, the effects of the interaction of the background dynamo field become increasingly stronger as the flux-ropes evolve. The threshold for the initial magnetic field amplitude is slightly increased by the presence of the background dynamo field, even if it is on average much weaker than the flux-rope's field. The geometry and relative orientation of the magnetic field in the flux-ropes with respect to that in the background magnetic field influences the resulting rise speeds, zonal flows amplitudes (which develop within the flux-ropes) and surface signatures of magnetic flux emergence. This strongly influences the morphology, duration and amplitude of the surface shearing and Poynting flux associated with magnetic flux-rope emergence, which are key ingredients to the current coronal eruption triggering scenarios. The actual magnetic flux emergence is consistently preceded by strong and localised radial velocity enhancements at the place where the flux rope will emerge. The emerged magnetic flux is in most of the cases studied enough to influence the global surface magnetic field. In some cases, the emergence reinforces the system's global polarity reversal while in some others it inhibits the background dynamo from doing so. The fraction of magnetic flux which remains attached to the flux-rope is slowly spread out in latitude, diffused and assimilated by the background dynamo field.

Magnetic helicity properties of emerging active regions determined from longitudinal photospheric magnetograms.

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We study the emergence of solar active regions (ARs) to determine how their magnetic helicity properties affect the evolution of the photospheric flux observed in SOHO/MDI magnetograms. We characterize the so called magnetic tongues (Luoni et al. 2011, Solar Phys. 270, 45), which are produced by the line of sight projection of the azimuthal component of the magnetic field in ARs formed by twisted emerging flux-tubes. We analyze a set of 25 ARs observed between 2004 and 2010. We only select regions for which the full emergence process is observed on the solar disk. In order to minimize the background magnetic field contribution, we select cases that emerge in areas devoid of remnant flux from older ARs. From the magnetograms we determine and study the evolution of relevant parameters, in particular the tilt angle, the relative direction of the polarity inversion line (defined as the PIL angle), and the magnetic flux of the ARs. Modeling the emergence of twisted magnetic flux-tubes, we demonstrate that the PIL angle is a direct proxy for the evolution of the tongues. To further characterize this evolution we compute and analyze weighted averages of the PIL angle and the magnetic flux. We find that in 22 ARs from our set the presence of magnetic tongues has a direct effect on the evolution of the PIL angle. For these cases, we are able to infer the magnetic helicity sign from the obtained measurements and their computed averages. Since ARs with high contents of magnetic helicity are, in general, the most productive in term of flares and CMEs, the possible determination of their magnetic helicity properties from the very beginning of the emergence can be a powerful forecast tool for solar activity.

Photospheric injection of magnetic helicity during AR 11158 emergence

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Magnetic helicity quantifies how globally twisted and/or sheared is the magnetic field in a volume. Previous studies have shown that, magnetic helicity can play a key role in the dynamics and evolution of magnetic flux tubes. To better understand and quantify its role in magnetic flux emergence and evolution, the photospheric distribution of magnetic helicity flux during the lifetime of active regions (ARs) needs to be studied. Most recent analyses of photospheric helicity flux derive a helicity flux density proxy based on the relative rotation rate of photospheric magnetic footpoints. However, such a proxy is not a true helicity flux density because it does not take into account the magnetic field lines connectivity, and hence, is not free from spurious signals. We recently developed a method to compute the distribution of helicity flux by taking into account such connectivity which allows to correct these spurious signals. After introducing this method, we present the results of its application to the NOAA AR 11158. We show that, the distribution of helicity flux is complex, with patterns of real mixed signal of helicity flux related to the specific topology of the AR's magnetic field. Finally, we discuss the implications of our results on the evolution and dynamics of this AR.

Collective Solar Behavior

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The Atmospheric Imaging Assembly (AIA) on the Solar Dynamic Observatory (SDO) together with the Helioseismic and Magnetic Imager (HMI) and the Extreme Ultraviolet Variability Experiment (EVE) allow observations of the entire Sun from 6000 K to 20,000,000 K with arcsecond resolution and a 12 second cadence (AIA), obtain doppler and continuum images at a 45 second cadence and Line of Sight and vector magnetograms (HMI) every few minutes, and integrated solar spectra from 1 to 100 nm on a 2 second cadence (EVE) 24/7. Because of the enhanced thermal and temporal coverage and the high dynamic range available with AIA, it has been able to discovery collective behavior associated with a range of solar events from large flares to quiet sun filament ejections associated with very small GOES flares. Nearly half of the M and X class flares seen with AIA have impact over a solar hemisphere and sometimes nearly the entire sphere. The extent of the events are recognized by using co-temporal STEREO data. The rapidly expanding magnetic structures, speeds between 500 and 2000 km/s, may trigger filament eruptions, CME's, and other flares. The global nature of these events makes flare prediction based upon ONLY local energy build up models less valuable, but suggests that with proper coverage prediction of solar events with potential for Earth impact can be made more reliable. Movies of sample events discovered in AIA together with STEREO and EVE data will be shown.

The role of preexisting magnetic environment with newly emerging flux in flares

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The AR was formed in 24 hours in the trailing polarity of the AR 11121 on November 10-11 2010 observed by SDO/HMI and THEMIS vector magnetographs. AR 11123 is formed by successive emerging bipoles. SDO/AIA (304 A and 171 A) allows us to follow the development of five flares during this one day time involving the eruption of two active region filaments.
The topology analysis shows the existence of 3 null points. One is local and two involved the preceeding active region. Reconnections occur above the filament favouring its eruption. Round-shape ribbons overlay the separatrices and QSLs between the two regions.

Condition for arcade field eruption triggered by a flux emergence event

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An eruption of a plasma associated with a magnetic flux is a dramatic phenomenon leading to flares and CMEs. It is sometimes conjectured that its onset is triggered by a flux emergence event in an active region. We studied such mechanisms by using two-dimensional magnetohydrodynamic simulations to investigate the detailed processes and the criteria of the onset. The initial force-free arcade is deformed by a flux emergence event leading to the magnetic reconnection to detach a magnetic flux rope. The studied criteria is for the magnetic strength and the location of appearance of the emerging event.
Our results may contribute to the prediction of an eruption occurrence by measurements of the amount and the location of emerging flux events.

Structures of Emerging Flux Triggering Solar Eruptions

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Though solar flares and coronal mass ejections are the most catastrophic eruptions in our solar system, their triggering mechanism is still not sufficiently understood, and our capacity to predict the occurrence of them is substantially hindered. In this paper, we tried to solve this problem by systematically surveying the nonlinear dynamics caused by a wide variety of magnetic structures in terms of three-dimensional magnetohydrodynamic simulations. As a result, we determined that two different types of small magnetic structures favor the onset of solar eruptions. These structures, which should emerge near the magnetic polarity inversion line (PIL), include magnetic fluxes reversed to the potential component or the nonpotential component of major field on the PIL. These types of emerging fluxes can trigger solar flares through the eruption-induced reconnection and the reconnection-induce eruption, respectively. In addition, we analyzed several large flares, using imaging data provided by the Hinode satellite, and we demonstrated that they conform to the simulation predictions. These results suggest that forecasting of solar eruptions is possible with sophisticated observation of a solar magnetic field.

Flux emergence and solar eruptive events

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We study the emergence of magnetic flux from the solar interior into the outer solar atmosphere. It is shown that the emergence is followed by (recurrent) eruptions of plasma, mainly driven by reconnection. The condition under which these eruptions may develop into large-scale eruptive phenomena is discussed. The effect of the physical properties of the emerging field on the follow-up dynamic events is also presented.

General Discussion

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General Discussion

The Emergence of an Untwisted Flux Rope

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It is of great interest to study the relation between the emergence of a coherent magnetic structure and the amount of twist in the initial flux rope. Here we experiment in our MHD simulations with two types of flux ropes: one initially twisted, and the other one untwisted. In both cases, the flux ropes are placed in the convection zone and fixed horizontally at the lower boundary. By comparison, we examine the role of the twist of the initial flux rope in the convection zone in formation of a coherent emerged magnetic structure at the photosphere and in the corona.

MHD waves generated by flux emergence

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The emergence of a weakly twisted flux tube results in the formation of two bi-polar magnetic regions. The central two bipoles migrate towards the main spots and, in the process, generate MHD waves. These are not gravity waves but appear related to the interaction of the migrating bipoles and the main spots.

Simulation of a full active region life cycle

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We present a numerical simulation of an active region scale flux emergence event covering a total time span of 6 days. We emerge a semi-torus of untwisted magnetic field with $1.7\cdot10^{22}$~Mx flux into our domain at a depth of about 15.5~Mm beneath the solar photosphere. We added within the semi-torus a field aligned flow of 500~ms^{-1} directed from the leading toward the trailing spot, which is expected to occur as consequence of angular momentum conservation during the rise of flux through the solar convection zone. We find the formation of a sunspot pair having about 10^{22}~Mx flux each. The leader spot is more coherent than the trailing spot as consequence of the field aligned flow we imposed. The sunspot formation phase directly transitions into the decay phase, which is driven by convective motions near the bottom of our domain. In the decay phase, fragmentation of the sunspots is a consequence of subsurface convective upflows carving their way through the spots. When such upflows reach photospheric layers of umbral field strengthes, they manifest as light bridges. Persistent upflows that expand laterally leads to the widening of such light bridges and to the eventual fragmentation of the spot into smaller pores. The time scale for decay from sunspot to plage is set by the motions of subsurface flows.

Chromospheric Canopy Fields over a Flux Emerging Region as a Key Condition for Formation of the Sunspot Penumbra

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A presence of a penumbra is one of the main properties of a mature sunspot, and its formation mechanism has been elusive due to a lack of observations that fully cover the formation process. Utilizing the New Solar Telescope at the Big Bear Solar Observatory, we observed the formation of a partial penumbra for about 7 hours simultaneously at the photospheric (TiO; 7057 Å) and the chromospheric (H? -1Å) spectral lines with high spatial and temporal resolution. From this uninterrupted, long observational sequence, we found that flux emergence under the stable chromospheric canopy fields resulted in penumbra formation, while emerging flux under the expanding chromospheric fields appeared as transient elongated granules. Based on these findings, we suggest a possible scenario for penumbra formation in which a penumbra forms when the emerging flux is constrained from continuing to emerge, but rather is trapped at the photospheric level by the overlying chromospheric canopy fields.

High resolution spectro-polarimetric observations of the formation of a penumbra

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We present the results obtained analysing high spatial and spectral resolution data acquired at the Dunn Solar Telescope with the Interferometric Bidimensional Spectrometer during the formation of a penumbra in the Active Region NOAA 11490. We used full Stokes profiles in the Fe I 617.3 nm and Fe I 630.25 nm lines and spectral images in Ca II 854.2 nm taken on May 28, 2012, from 13:39 UT and 14:38 UT. The dataset is complemented by white light (WL) and G-band images that were taken simultaneously to the spectral data by approximately imaging the same field of view. Our analysis is based on a SIR inversion of the Stokes profiles and on the estimation of the line of sight plasma velocity from the spectral data.

The Magnetic Flux History of a Quiet-Sun Supergranular Cell

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In an attempt to understand the origin of internetwork fields, we have observed the quiet Sun at disk center for nearly 25 hours with unprecedented sensitivity (6 G), spatial resolution (0.3 arcsec), and cadence (1.5 minutes). The data were taken by the Narrowband Filter Imager onboard Hinode and consist of longitudinal magnetograms, Dopplergrams, and intensity images. This is the longest uninterrupted sequence of quiet Sun magnetograms ever obtained at such sensitivity, providing the first opportunity to follow the evolution of supergranular cells, from birth to death, at their intrinsic spatial and temporal scales. With the help of a new feature tracking code, we use these measurements to study the magnetic flux budget of a supergranule. In particular, we determine the rates of flux emergence and disappearance as a function of time and radial distance from the supergranular center. We also investigate the processes whereby magnetic flux elements appear and disappear in the supergranule. Our results, some of which are completely unexpected, shed new light on the properties of internetwork fields and how they interact with supergranular convective flows.

High resolution analysis of a magnetic bubble emerging through the solar atmosphere

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We study an intermediate-scale flux emergence event that occurred in NOAA 11024 in July 2009. We observed this event at the highest achievable spatial resolution (0\farcs14) with the CRISP spectropolarimeter at the Swedish 1 m Solar Telescope. Simultaneous full Stokes observations of the photospheric \ion{Fe}{1} 630 nm lines and the chromospheric \ion{Ca}{2} 854.2 nm line, as well as \ion{Ca}{2} H line wing and line core intensity filtergrams, allow us to describe in detail the emergence process across the solar atmosphere. We report on 3D semi-spherical bubble events, where instead of a simple magnetic loop with two footpoints, we find a structure with complex semi-circular feet. Several phenomena occur simultaneously during the emergence process, namely, abnormal granulation, opposite-polarity leg separation and brightenings in the upper layers, as revealed by both the \ion{Ca}{2} 854.2 nm and \ion{Ca}{2} H measurements. A unique characteristic of this event is the appearance of a "dark" bubble in the intensity maps constructed from the wings of the \ion{Ca}{2} 854.2 nm line. There is a clear coincidence between the rise of horizontal magnetic field patches and the formation of the dark bubble in the low chromosphere. As time progresses, we observe the bubble at different positions of the ion{Ca}{2} 854.2 nm line, from the wings to the core, which we interpret as its ascension through the atmosphere. Its average rising speed through the photosphere is 2 km\,s^{-1}. To aid the analysis, we use the Bifrost code to carry out 3D numerical simulations of the evolution of a horizontal magnetic flux tube injected in the convection zone, 2.5 Mm below the photosphere. The computational domain spans from the upper layers of the convection zone to the lower corona. In the modeled chromosphere the rising flux tube produces a large, cool and magnetized bubble. We compare our observed bubble with that given by the numerical simulations.

Signatures of small-scale magnetic field emergence as seen from the New Solar Telescope in Big Bear

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Increased resolution of solar telescopes allow us to study of emerging small-scale magnetic fields in unprecedented detail. First light Hinode magnetograms showed evidence of both horizontal and line-of-sight field being constantly brought to the solar surface by solar convection motion. What are the signatures of these fields in the photosphere, if any? We examine NST granulation and Halpha images co-temporal with SDO, Hinode and BBSO/IRIM vector magnetograms to study the effect that the new small-scale emerging flux induces on solar granulation. We find that emerging flux appears to leave different types of footprint on solar granulation: i) diffuse irregular patches of increased brightness, ii) well defined filament-like structures and accompanied bright points, and iii) bright point-like features that appear inside granules. We suggest that the type of the footprint depends on the intensity of emerging fields. Stronger fields, emerging as a part of large magnetic structure, create on the solar surface a well defined filamentary pattern with bright points at the ends of the filaments, while weak turbulent fields are associated with bright patches inside the host granule. Moreover, the granulation responds to the emerging flux much earlier that it appears in magnetograms. NST granulation images also reveal that various bright points as well as bright granular lanes may form and evolve within a granule.

Small-scale flux emergence from the photosphere to the corona

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We have carried out 3D numerical experiments of the emergence of magnetic flux on small scales through the photosphere, chromosphere and into the corona. We have used the BIFROST code which permits detailed consideration of an important range of radiative and thermal effects. We focus on the emergence of small magnetic tubes at a granular scale, their rise to higher photospheric levels and their interaction with the magnetic field in the corona.

A Detailed Comparison Between The Observed and Synthesized Properties of a Simulated Type II Spicule.

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We have performed a 3D radiative MHD simulation of the solar atmosphere. The simulation shows a jet-like feature that shows similarities to the type II spicules observed with Hinode the Swedish 1-meter Solar Telescope (SST) and other telescopes. Rapid Blueshifted Events (RBE's) on the solar disk are the disk counterparts of type II spicules. Observational results suggest that these jets may contribute significantly in supplying the corona with hot plasma. In the simulated spicule, the chromospheric plasma is ejected as a result of being squeezed by the magnetic tension force as a result of flux emergence. The jet shows evidence of both high velocities in the chromosphere and heating of plasma to coronal temperatures. We perform a detailed comparison of the properties of the simulated jet with those of type II spicules and RBEs. We analyze a wide variety of synthetic emission and absorption lines from the simulations, including lines formed in the chromosphere, transition region, and corona. We compare their synthetic intensities, line profiles, Doppler shifts, line widths and asymmetries with observations from Hinode/SOT and EIS, SOHO/SUMER, the SST, and SDO/AIA. Detailed analysis of the synthetic observables provides insight into how observations should be analyzed in order to derive information about physical variables. I will show that many properties of the synthetic observables resemble the observations. On the other hand, other properties differ from the observations, especially in chromospheric lines. These and other discrepancies gives us suggestive ideas of which mechanisms and physical processes may need to be included in the MHD simulations to mimic the thermodynamic processes of the chromosphere and corona, in particular to reproduce type II spicules.

Recurrent Coronal Jets Induced by Magnetic Emergence

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Three EUV jets recurred in about one hour on 2010 September 17 in the following magnetic polarity of AR 11106. We derive that the jets are above a small emerging magnetic bipole within the following polarity of the decaying AR. The interaction drove the build up of elongated electric currents patterns which disappear later on as observed at the photospheric level with SDO/HMI and THEMIS. For the first time, the high temporal cadence of HMI allows to follow the evolution of such small currents. In the jet region, we found that the integrated absolute current peaks repetitively in phase with the EUV flux evolution observed by SDO/AIA. The photospheric current pattern of the jets is found associated to the quasi-separatrix layers deduced from the magnetic extrapolation. From previous theoretical results, the observed diverging flows are expected to build continuously such currents. We conclude that magnetic reconnection occurs periodically, in the current layer created between the emerging bipole and the large scale AR field. It induced the observed recurrent coronal jets and the decrease of the electric current magnitude.

Jets and eruptions following magnetic flux emergence into the corona

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We analyze in detail the eruptive phenomena following the emergence of magnetic flux from the top of the convection zone into a uniformly-magnetized corona using 3D numerical experiments with a large spatial domain and moderately high numerical resolution. We study the formation of current sheets, reconnection sites and the topology of the field in their neighborhood. The primary reconnection phenomenon leads to the launching of a thin jet of hot plasma, whose internal structure can be disclosed with some detail. We pursue the formation of dense and comparatively cool structures in the early phases, the advanced stages following the emission of the jet, and a number of global quantities characterizing the evolution of the system.

Energy Buildup in Active Regions: A Comparison of AR11158 with a Simulation of Magnetic Flux Emergence

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We present a detailed comparison of an MHD simulation of magnetic flux emergence with observations of a large-scale active region. The simulation (Fang et al. 2012) addresses the buoyant rise of a flux rope through the convection zone into the corona, which spontaneously reproduces several features found in AR11158. We focus our study on the central part of AR11158 from which an energetic CME was observed on 2011 February 15. We examine AIA loops, HMI vector magnetograms, photospheric flow patterns, and convection zone flow patterns to fully characterize the active region and relate its dynamics to basic features found in the MHD simulation. Salient features are the convergence of flux concentrations of opposite polarity and strong shear flows along the polarity inversion line observed prior to and during the CME. We will show that such shear flows are readily explained as a response to the Lorentz force, and the convergence are associated with convective downdrafts that form over the polarity inversion line. We also compare the brightening of coronal loops observed with AIA to tether-cutting reconnection observed in or simulation. Together, these mechanisms explain the buildup, concentration and release of energy necessary for eruptive events.

Evolution of electric currents during active region formation

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It is now well accepted that the energy required to power coronal mass ejections (CMEs) is stored in the corona by current-carrying magnetic fields. Active regions, the main sources of CMEs, carry electric currents of ~ 1 TA. There has been a long-lasting debate whether or not these currents are neutralized, meaning that the "main" or "direct" current flowing in the corona from one active region polarity to the other is surrounded by a "return" current of equal strength and opposite direction. This question is important, for example, for CME models, since the presence of a return current may, in principle, inhibit the eruption of the direct current (i.e., a flux rope or sheared arcade). Both theory and observations are not yet fully conclusive regarding the existence (and strength) of return currents in CME-producing active regions, and numerical simulations of active region formation have so far widely neglected this question.
Here we present our recent study of the evolution of photospheric and coronal electric currents during the formation of active regions. We consider two numerical active region models that describe the two basic mechanisms of current formation in the corona. These are the emergence of a sub-photospheric magnetic flux rope and the twisting/shearing of the active region field by photospheric flows. In both cases, we find a clear dominance of the direct current above the return current given that sufficient shear develops along the polarity inversion line of the model active region. We discuss the implications of this result for theoretical and numerical models of CMEs.

General Discussion

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General Discussion

Magnetic topology, the key to understanding the jets and eruptions following magnetic flux emergence into the corona !?

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We have preformed a 3D numerical MHD experiment showing how new emerging flux interacts with a uniform slanted coronal background magnetic field. The general evolution, that is discussed by Moreno-insertis & Galsgaard, shows a number of characteristic evolution stages, where first an Eiffel-tower like jet ejects plasma with high velocity into the corona. As the jet decays, due to lack of continued flux emergence, the magnetic field structure constituting the remaining non reconnected magnetic field provides the basis for a series of "catastrophic" eruptions. Understanding the reasons for this complex behaviour is not easy to obtain from simple data analysis. Therefore, in an attempt to advance out understanding of the reason consequences of the complex evolution phases we have worked on build up a more clear picture of the magnetic field topology and its influence on the evolution. For this we try to determine the magnetic skeleton evolution, by determining the location and type of existing magnetic null points and their associated separator lines.

Time-Dependence of Topological Features of PFSS Models of the Solar Corona

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The topology of the solar coronal magnetic field has engendered much recent interest, due to its importance in determining (for example) the sector structure of the solar wind, the evolution of coronal hole boundaries, and whether the configurations of coronae overlying active regions are unstable and thus possibly eruption-prone. We choose several cases involving eruptive events, and analyze these from a topological perspective, aiming to identify robust topological features in the PFSS models that might represent reality.

Nonlinear force-free extrapolation of emerging flux

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We study the flux emergence process in NOAA active region 11024, between 29 June and 7 July 2009, by means of multi-wavelength observations and nonlinear force-free extrapolation. The combination of these techniques allows us to follow the whole process, from the first appearance of the bipolar axial field on the east limb, until the buoyancy instability could set in and raise the main body of the twisted flux tube through the photosphere, forming magnetic tongues and signatures of serpentine field, until the simplification of the magnetic structure into a main bipole by the time the active region reaches the west limb. At the crucial time of the main emergence phase (taking place on 4 July 2009), spectropolarimetric measurements of the photospheric field are employed to reconstruct the three-dimensional structure of the nonlinear coronal field, which is then used to validate the current understanding of flux emergence processes. In particular, the
knowledge of the coronal connectivity confirms the identity of the magnetic tongues as seen in their photospheric signatures, and exemplifies how the twisted flux, that is emerging on small scales in the form of a sea-serpent, is subsequently rearranged by reconnection into the large-scale field of the active region. In this way, a coherent picture of the emergence process is gained, both in its global properties (helicity, energy, topology), as in some of its observed local reconnection
events.

Estimating flare's free energy using Poloidal-Toroidal Decomposition method.

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The existence of systematic measurements of vector magnetic fields and Doppler shifts allows us to estimate electric field in the photosphere, by solving Faraday's law, using a Poloidal-Toroidal Decomposition (PTD) of the magnetic field and its partial time derivative, as well as incorporating information from Doppler shifts (Fisher et al. 2012). The method is based on solving a set of two-dimensional Poisson equations. We have recently modified the method in the following two ways. First, we improved the speed and accuracy of the Poisson equation solver using the FISHPACK elliptic partial differential equation software developed at NCAR, employing Neumann boundary conditions appropriate for zero electric fields on the vector-magnetogram boundary. Second, we developed a more general procedure which allows us to calculate electric fields from magnetic fields observed at non-zero viewing angles. We apply the improved technique to ANMHD-simulation test case with a known electric field and find that it yields more accurate values of Electric field, Poynting and helicity fluxes than before. We then apply our method to three-days-long HMI data-set centered on AR 11158, which produced an X2.2 flare. We find electric field, helicity and free energy evolutions in AR 11158. We further discuss the errors of the method and its future as a potential tool to estimate flare's free energy and helicity.

A Magnetofrictional Method for Data-driven Simulations of Evolving Solar Coronal Fields

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We present a method for performing data-driven simulations of solar coronal field evolution. The approach is based on magnetofriction, which evolves the induction equation assuming the plasma velocity to be proportional to the Lorentz force. We show that this term in the induction equation has the same form as ambipolar diffusion, which is an agent for current sheet formation. The simulations are driven by temporal sequences of photospheric magnetograms (e.g. from SDO/HMI). In the case of some active region models (e.g. for AR 11158), the data-driven simulations produce flux ropes that are ejected from the evolving AR. One observational feature that is reproduced in such models is the enhancement of the horizontal photospheric field at the polarity inversion line following flux rope ejection. The sequence of time-depedent 3D models of the coronal field allows us to not only study topological changes (e.g. relative helicity evolution), but also the mechanism(s) by which such changes occur. We also present a method for visualizing the model coronal field based on the current density distribution in the computational domain. This method produces mock images that are somewhat reminiscent of EUV images taken by instruments such as SDO/AIA.

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