ASI 2021 Workshop – 4 : Recent Insights into Solar Active Region Dynamics

Abstract Book

Session 1

The Physics of the Solar Dynamo & Sub-photospheric Flows in Active Regions

Shravan Hanasoge, TIFR, Mumbai

Equatorial Confinement of Turbulence in the Sun

Convection in the Sun’s outer envelope generates turbulence and drives differential rotation, meridional circulation, and the global magnetic cycle. We develop a greater understanding of these processes by contrasting observations with simulations of global convection. These comparisons also enhance our comprehension of the physics of distant Sun-like stars. Through helioseismic analyses of space-based observations, I will describe inferences of toroidal flow power as a function of wave number, frequency, and depth in the solar interior. The inferred flows grow with spatial wave number and temporal frequency and are confined to low latitudes, supporting the argument that rotation induces systematic differences between the poles and equator. In contrast, the simulations used here show the opposite trends—power diminishing with increasing wave number and frequency while flow amplitudes become weakest at low latitudes. I will describe how these differences highlight gaps in our understanding of solar convection and point to challenges ahead.

Bidya Binay Karak, IIT (BHU), Varanasi

Dynamo Saturation through the Latitudinal Variation of Bipolar Magnetic Regions in the Sun

Observations of the solar magnetic cycle showed that the amplitude of the cycle did not grow all the time in the past. Thus, there must be a mechanism to limit the growth of the magnetic field in the Sun. We demonstrate a mechanism for this under the Babcock–Leighton dynamo framework which is believed to be the most promising paradigm for the generation of the solar magnetic field at present. Our mechanism is based on the observational fact that the stronger solar cycles produce Bipolar Magnetic Regions (BMRs) at higher latitudes than the weaker ones. We capture this effect in our three-dimensional Babcock–Leighton solar dynamo model and show that when the toroidal magnetic field tries to grow, it starts producing BMRs at higher latitudes. The BMRs at higher latitudes generate a less poloidal field, which consequently limits the overall growth of the magnetic field in our model. Thus, our study suggests that the latitudinal variation of BMRs is a potential mechanism for saturating the magnetic field growth in the Sun.

Sudip Mandal, MPS Göttingen, Germany

Sunspot Area Catalogue: A Tool to Better Understand the Solar Dynamo

Long and consistent sunspot area records are important for our understanding of the long-term solar activity and variability, providing insights to dynamo models. Multiple observatories around the globe, such as Royal Observatory of Greenwich in England, Debrecen Observatory in Hungary, Kodaikanal Observatory in India, etc have regularly recorded sunspot areas, but such individual records only cover restricted periods of time. Moreover, there are systematic differences between them, so that these records need to be cross-calibrated before they can be reliably used for further studies. In this talk, I will present a brief overview of such systematics and how to resolve them to generate a long, consistent and calibrated sunspot area catalogue. Further, I will talk about multiple applications of such a catalogue, e.g. in getting the distribution of individual spots areas, latitude distributions, area filling factor of groups etc, that are important for our understanding of solar (and stellar) dynamos.

Prantika Bhowmik, Durham University, UK

Evolution of the Sun’s Magnetic Field as Governed by Solar Dynamo

Solar variability governs the electromagnetic, radiative, and particulate environment in the heliosphere creating hazardous weather in space through eruptive events such as solar flares, coronal mass ejections. Moreover, modulation in solar output in terms of solar irradiance defines space climate. Both the short and long-term solar variabilities are closely associated with and mostly dominated by the Sun's magnetic field variations. Thus, in the context of space weather studies, understanding and predicting the Sun's magnetic field evolution have gained significant impetus in recent times. The first part of this talk will describe the fundamentals of the dynamo mechanism, which governs the generation and evolution of the Sun's magnetic field within the solar convection zone and on the surface. In the second part of the talk, how recent observational studies and numerical simulations support the dynamo theory and subsequently improve our understanding of variability in solar magnetic cycles will be discussed.

Ram A. Maurya, NIT, Calicut

Magnetic Fields and Sub-photospheric Flows of Solar Active Regions

Solar active regions (ARs) are three dimensional magnetic structures extending from the interior below the photosphere to coronal heights. The solar photosphere is an excellent conductor where frozen-in-field condition may be satisfied. Over a period of time, near the photosphere, plasma may evolve with magnetic field lines, and may play crucial role in solar activities. Therefore, one can expect that the near surface plasma and magnetic field lines must show some relationship in their topology. For this, we have studied the topological parameters such as kinetic and magnetic helicities in sub-photospheric flows and photospheric magnetic fields, respectively, over entire areas of several ARs observed during peak to decay phase of the solar cycle 23. We have found the hemispheric trend in the kinetic helicity of sub-photospheric flows averaged over the depth range of 2.5-12 Mms. The kinetic helicity shows a significant signature of the hemispheric trend, as 69%(67%) ARs in the northern (southern) hemisphere show negative (positive) helicity. Further, we derived magnetic helicity parameters for the ARs by using photospheric vector magnetic field observations to examine correlation with corresponding kinetic helicities. We found 68%(67%) ARs in the northern hemisphere with negative (positive) magnetic helicity in agreement with earlier reports. However, we did not find any significant association between the two helicity parameters. We also found that the hemispheric preference of all the parameters increases with the field strength of ARs. The topology of photospheric magnetic fields and near-surface sub-photospheric flow fields did not show good association but the correlation between them enhances with depths, which could be indicating more aligned flows at deeper layers of ARs.

Session 2

Magnetic Flux Emergence and Transport

B. Ravindra, IIA, Bengaluru

Evolution of Net Currents in Active Regions

The three components of the magnetic fields measured at the photospheric level show fine structures at high-resolution. The map of the vertical component of the current density shows salt and pepper-like structures in the sunspot umbra and black & white thread-like patterns in the penumbra of a sunspot at the sub-arcsecond resolution. The vertical current density integration over the whole sunspot called as net current shows the non zero value. The evolution of this net current is different in different active regions. In this talk, I will present the appearance of vertical current density in sunspots and the evolution of net currents in flare productive active regions.

Dattaraj Dhuri, TIFR, Mumbai

Identifying Pre-emergence Magnetic Field Patterns using Deep Learning

Magnetic flux generated within the solar interior emerges to the surface, forming active regions (ARs) and sunspots. Flux emergence may trigger explosive events - such as flares and coronal mass ejections and therefore understanding emergence is useful for space-weather forecasting. Evidence of any pre-emergence signatures will also shed light on sub-surface processes responsible for emergence. In this talk, I will present a first analysis of emerging ARs from the Solar Dynamics Observatory/Helioseismic Emerging Active Regions (SDO/HEAR) dataset using deep convolutional neural networks (CNN) to characterize pre-emergence surface magnetic-field properties. I will show that the trained CNN performs better than a baseline model of discriminant analysis (DA) of only the unsigned magnetic flux, with a True Skill Statistic (TSS) score of ~85%, 3h prior to emergence. I will also show that synthetic magnetograms and network pruning can be used to “open-up” the trained network and interpret the CNN performance to understand the information learned. Using these tools, I will demonstrate that the CNN learns convolution filters that are sensitive primarily to the unsigned magnetic flux and the CNN output peaks for pre-emergence magnetic regions with small-scale and intense fields, possibly a characteristic pre-emergence pattern.

Rahul Yadav, Stockholm University, Sweden

Magnetic Flux Emergence in the Solar Atmosphere

Magnetic flux emergence from the solar convection zone into the overlying atmosphere drives a wide range of solar phenomena associated with solar activity. Recent observations have revealed that flux emergence at the solar surface ranges from the formation of granular scale events to large-scale complex active regions. An important aspect of the flux emergence is the interaction of the newly emerging field lines with pre-existing ones, which give rise to a variety of energetic phenomena such as Ellerman bombs, UV burst, X-ray jets, microflare to large eruptive flares, and CMEs. This also leads to the release of magnetic energy and heating of the solar atmosphere. It is well established that the evolution of flux emergence affects all atmospheric layers, from the photosphere to the corona. Therefore, flux emergence is a key element in understanding the coupling of the solar atmosphere as well as the processes responsible for the magnetic field generation. Thanks to coordinated and multi-wavelength observations of flux emergence regions obtained from various ground and space-based instruments, it is now possible to provide a detailed scenario of flux emerging regions. In this talk, we will discuss the current understanding of a flux emerging region, mainly derived from multi-wavelength observations. We will also discuss the kinematic and magnetic structure of a flux emerging region, inferred from simultaneous high-resolution spectropolarimetric observations, in the photosphere and the chromosphere.

Rohan Eugene Louis, USO-PRL, Udaipur

Formation of an Atypical Sunspot Light Bridge as a Result of Large-scale Flux Emergence

Light Bridges (LBs) are bright, extended structures within the umbrae of sunspots/pores. LBs are often seen during the early stages of sunspot formation or during the late phase of sunspot decay and are located along lanes where individual spots coalesce or fragment. Their formation is generally regarded to stem from vigorous overturning convection within a sunspot. We explore the above premise in this investigation by analysing the formation, structure, and evolution of an atypical LB in a regular sunspot, using a combination of full-disk data from NASA's Solar Dynamics Observatory (SDO) and high-resolution data from the 76 cm Dunn Solar Telescope (DST) of the National Solar Observatory in New Mexico, USA. Our results indicate that the LB formation is part of a flux emergence event with the LB envelope reaching a height of about 29 Mm before dissolving after about 13 hr. I will describe the events leading to the formation of the LB and its complex 3D thermal structure inferred from spectral line inversions using the DST observations. I will demonstrate that the existence of persistent, large-scale photospheric blueshifts in LBs is the most likely criterion for distinguishing between flux emergence events and overturning convection in field-free umbral intrusions.

Session 3

Solar Eruptions and their Propagation in the Interplanetary Medium

P. Vemareddy, IIA, Bengaluru

On the Evolution of Magnetic Helicity Flux from Solar Active Regions: Our Present Understanding

Magnetic helicity is a parameter to quantify twist and shear of magnetic field and is related to formation of flux rope structure. Understanding the nature and evolution of the photospheric helicity flux transfer is crucial to reveal the role of magnetic helicity in coronal dynamics of solar ARs. The estimations of magnetic energy and helicity flux from a line-tied surface (photosphere) requires velocity and magnetic field distributions in the AR. In this presentation, we will discuss the helicity flux evolution from different active regions and then understand the relation to the eruptive or transient activity from that active region.

Sanchita Pal, University of Helsinki, Finland

Magnetic Reconnection Impacting Solar Eruptions and their Propagations

One of the vast solar eruptions is the Coronal mass ejection (CME) that manifests the expulsion of substantial magnetized plasma from the Sun. The inherent properties of CMEs determine their geoeffectiveness. Therefore, it is worthwhile to determine what controls the geoeffective properties such as kinematics and magnetic properties of CMEs. Although the magnetic flux and nonpotentiality of CME solar sources have contributions to the CME properties, it is observed that the low-coronal magnetic reconnection during a solar eruption is the primary determinant of CME's properties. Being a proxy for the energy associated with eruptions, the reconnection flux drives the CME kinematics. The low coronal reconnection forms twisted CME flux ropes, and it primarily transfers magnetic properties such as magnetic flux and helicity to CME flux ropes. While CMEs propagate through the interplanetary medium, they interact with the ambient solar wind magnetic field (i.e., heliospheric open flux) via magnetic reconnection and lose a substantial amount of their initial magnetic flux. Thus CMEs erode during interplanetary propagation, and the erosion impacts CME geoeffectiveness. A linear relationship between the eroded and open flux uncovers a solar cycle modulation of the eroded flux, thus the associated flux-ropes' geoeffectiveness. Therefore, the origin and propagation of CMEs can be constrained, and better forecasting capabilities of CME geoeffectiveness can be achieved.

Ranadeep Sarkar, University of Helsinki, Finland

Active Region Dynamics and their Implications to Space Weather Forecasting

Complex large active regions (ARs) on the Sun are the main sources of large flares and most energetic coronal mass ejections (CMEs) which drive the space weather. Understanding the energy build-up and release processes in the solar ARs is crucial to shed light on the conditions leading to solar eruptive events. Furthermore, the continuous monitoring of spatio-temporal evolution of AR parameters may play an important role to forecast the CME productivity of any AR and the associated space-weather impacts. In this talk, I will present the recent highlights on the active region dynamics that reveal the conditions leading to CME eruptions as well as the recurrent large eruptive events occurred in the same AR. A particular emphasis will be given to the recent studies which address the long-standing unsolved problem in flare physics that, whether the large recurrent events occur due to the continuous supply of free magnetic energy to the solar corona or because not all of the available free magnetic energy is released during a single major flaring event. The space-weather implications of the results as obtained from the above studies will also be presented in the talk. Furthermore, I will discuss the recent techniques which use the information on the AR magnetic field in order to estimate the magnetic parameters of CMEs that provide the important observational constraint to the space weather forecasting models.

Raja Bayanna, USO-PRL, Udaipur

Chromospheric Observations of Solar Activity with MAST

We present details of a narrow-band imaging spectrograph operational at the 50-cm Multi-Application Solar Telescope (MAST) of the Udaipur Solar Observatory. The instrument can provide spectral line profiles that sample the solar atmosphere with a relatively large field-of-view, thus making it ideal for inferring the thermal and kinematic stratification rom photospheric to mid-chromospheric heights, with high spatial and temporal resolution. In this regard, we present recent observations of the solar chromosphere along with the derived temperature stratification and line-of-sight velocities. We shall also discuss preliminary results obtained from our ongoing study.

Sudheer K. Mishra, IIT (BHU), Varanasi

On the Different Phases of the Evolution of Magnetic Rayleigh-Taylor Instability in Eruptive Solar Prominences

The solar prominences shows variety of dynamical plasma processes such as gravity-driven instabilities, waves, turbulence, thin threads, fingers, plumes, oscillation, etc. on different spatio-temporal scales and some of them (e.g., thin thread, turbulence, plumes, vortex, fingers) are related to magnetic Rayleigh-Taylor instability. Recent observations and theoretical calculation suggest that MRT instability develops in the solar prominences. The linear stability theory is used to estimate the theoretical growth rate of MRT instability. However, the estimation of observational growth rate is difficult task as the linear stage of the instability ends when the width of the plume becomes equal to its height. We show a scientific case study in which the high-resolution EUV images of the SDO/AIA provide an opportunity to measure the height of plumes on several heights in an MRT instability driven solar prominence. The estimations exhibit small uncertainties compared to the previous results in the measurement of the observational growth rate. The estimated observational and theoretical growth rate is useful to diagnose the strength of the prominence's magnetic field. Recent theoretical calculations also demonstrate that the observational growth rate of MRT plumes, evolved in prominence, is useful to understand the relationship between magnetic field inclination and propagation direction of the MRT perturbations. Therefore, the detailed multi wavelength observations of the evolution of various stages of MRT instability is significant to provide a deep understanding of the internal dynamics of the solar prominence and its fine structures during unstable phase. The forthcoming high-resolution observational data obtained from Solar Orbiter (spatial resolution is similar to the width of individual prominence thread) and DKIST will be useful to explore the physics of such instability and associated internal dynamics in greater details, and will establish a linkage between various phases of the evolution of MRT instability to better diagnose the eruptive prominence.

Session 4

Numerical Simulations & Machine Learning in Solar Physics

Sushree Sangeeta Nayak, USO-PRL, Udaipur

Magnetohydrodynamics of Solar Transients in Different Reconnection Regimes

Myriads of solar energetics like flares, coronal mass ejections and jets etc occur in the solar atmosphere due to magnetic reconnection where the stored magnetic energy is converted into kinetic energy, heat and fast particle energy in association with rearrangement of magnetic topology. Important to all are the sites of reconnection. We often find these transients are associated with magnetic null points (where the magnetic field vanishes). However, there are other locations like separators or quasi-separatrix layers, where magnetic reconnection occurs and triggers the transients. Sometimes, one kind of topology can be responsible for different energetics. Also, different topologies can compete with each other and then dictate magnetic reconnection further. Considering all, the talk aims to discuss these interesting scenarios using magnetohydrodynamic simulations of some active region transients. Also, notable is the input coronal magnetic field to the numerical simulation which is obtained by a different and novel extrapolation technique called the non-force-free-field extrapolation.

Soumitra Hazra, University of Massachusetts, Lowell

Distinguishing between Flaring and Non-Flaring Active regions: A Machine Learning Perspective

Large scale solar eruptions significantly impact space weather and damage space-based human infrastructures. It is necessary to predict large scale solar eruptions, which will enable us to protect our vulnerable infrastructures of modern society. We aim to investigate the difference between flaring and non-flaring active regions. We use photospheric vector magnetogram data from Solar Dynamic Observatory's Helioseismic Magnetic Imager to study the time evolution of photospheric magnetic parameters on the solar surface. We build a database of flaring and non-flaring active region observed on the solar surface from the years 2010 to 2017 for this purpose. We train the machine learning algorithm by the time evolution of these active region parameters. Finally, we estimate the performance obtained from this machine learning algorithm. We find the strength of some magnetic parameters namely total unsigned magnetic flux, total unsigned magnetic helicity, total unsigned vertical current and total photospheric magnetic energy density in flaring active regions are much higher compared to the non-flaring ones. These magnetic parameters in the flaring active region are highly evolving and complex. We are able to obtain good forecasting capability with a relatively high value of true skill statistics (TSS). We also find that time evolution of total unsigned magnetic helicity and total unsigned magnetic flux have a very high ability to distinguish flaring and non-flaring active regions. In summary, it is possible to distinguish flaring active regions from non-flaring one with good accuracy. We confirm that there is no single common parameter which can distinguish all flaring active regions from the non flaring one. However, time evolution of top few magnetic parameters namely total unsigned magnetic flux and total unsigned magnetic helicity have very high distinguishing capability.

Sahel Dey, IIA-IISc, Bengaluru

MHD Simulations of Solar Swirls in the Regions of Strong Magnetic Fields

Solar swirls are spiraling plasma structures that are ubiquitous in the solar photosphere and higher atmosphere. With the large abundance and high energetics, swirls are suggested to be a significant candidate for transporting momentum and energy fluxes to the solar corona in order to balance radiative losses. Due to limited resolution, understanding of the interaction between small scale swirls and intense magnetic fields is still inadequate yet intriguing. We have performed a series of 3D realistic MHD simulations with strong photospheric magnetic fields to explore these phenomena. The simulated swirls are mostly localized near the intergranular lanes of the photosphere co-spatial with Magnetic Bright Points (MBPs). We find that a large abundance of photospheric and chromospheric swirls are generated due to magnetic tension forces. Swirls in the simulations are also found to be hotter than the ambient plasma, as recently reported in observations.

Suvadip Sinha, CESSI IISER, Kolkata

Classification of Solar Active Regions by Flare Productivity: A Machine Learning Approach

Solar flare releases a huge amount of energy (of the order of 10^{32} erg) in the form of electromagnetic radiation, mainly in extreme ultraviolet and X-ray range. This enormous amount of energy essentially comes from the non-potential orientation of magnetic fields near the localised high intensity magnetic field regions on the solar surface, called active regions. Solar flares are typically known for their influence in space weather and Earth's atmosphere. Recent advancement in machine learning shows the usefulness of photospheric magnetic field data to get prior information of such eruptive events. Using four supervised machine learning models on the HMI SHARP magnetic parameters, we identify active regions that are capable of producing large solar flares in the next 24 hours. The connection between solar flares and the associated active regions are drawn using HINODE XRT flare catalog with one decades of past data, starting from the SDO era. The performance of all four models have been studied in detail and a maximum True Skill Score (TSS) of 0.922 has been achieved by support vector Machine (SVM). We further identify a few important magnetic features which are essential in determining the flaring capability of an active region. These magnetic features include the current helicity, unsigned flux, vertical current, length of neutral line, etc.