Long-term Study of the Solar Activity

Organisers: Bidya Binay Karak (IIT (BHU)), Bibhuti Kumar Jha (ARIES), Dipankar Banerjee (ARIES), Nandita Srivastava (USO/PRL)

Date: 25th March 2022 09:30 — 17:35 hrs

Session 1: 09:30 —11:45 (2 hr 15 min) Chair: Bidya Binay karak (Online)

Internal Dynamics and Long-Term Data

09:30 — 09:55: **Arnab Rai Choudhuri** (IISc) Eugene Parker and his contributions to solar physics
09:55 — 10:20: **S. P. Rajaguru** (IIA) Long-term measurements of solar meridional circulation: temporal variations and connections to rotation and magnetic field.
10:20 — 10:45: **B. Ravindra** (IIA) The synoptic solar observations from the Kodaikanal Observatory
10:45 — 11:00: **Dipankar Banerjee** (ARIES & IIA) Long-term evolution of the Sun's magnetic field during cycles 15–19 based on their proxies from Kodaikanal Solar Observatory

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Coffee/Tea Break
11:00 —11:30 (30 min)

11:30 — 11:45: **Bibhuti Kumar Jha** (IIA & ARIES) Revisiting the Ca-K observation at Kodaikanal Observatory

Session 2: 11:45 — 15:10 (3 hr 25 min) Chair: Sudip Mandal (Online)

Extracting Physics from Long-Term Data

11:45 — 12:10: **Madhulika Guhathakurta** (NASA) Applied Artificial Intelligence for science & exploration enabled by public-private partnerships
12:10 — 12:35: **Susanta Bisoi (**NIT, Rourkela) Long term decline of solar magnetic fields over the past two decades
12:35 — 13:00: **Dibyendu Chakrabarty** (PRL) Long term variation of solar wind helium and suprathermal population.

Lunch Break
13:00 — 14:00 (1 hr)

14:00 — 14:25: **Wageesh Mishra** (IIA) The unusual behavior of CMEs and solar wind in the last two decades that baffles heliospheric physicists

14:25 — 14:40: **Yogesh** (PRL) Helium abundance variation in Interplanetary Coronal Mass Ejections spanning over solar cycle 23 and 24
14:40 — 14:55: **Soumitra Hazra** (Univ. of Massachusetts, Lowell) Variation of solar wind properties over an eleven-year solar cycle
14:55 — 15:10: **Sandeep Kumar** (USO) A parametric study of performance of solar wind forecasting models during 2006 to 2011

Session 3: 15:10 — 16:35 (1 hr 25 min) Chair: Gopal Hazra (Online)

Prediction of solar activity and space weather

15:10 — 15:35: **Dibyendu Nandi** (CESSI) The origin of decadal to millennial scale variability in the solar cycle

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Coffee/Tea Break

15:35 —16:05 (30 min)

16:05 — 16:20: **Pawan Kumar** (IIT, BHU) How early can we predict the solar cycle strength reliably using the polar precursor method?
16:20 — 16:35: **Akash Biswas** (IIT, BHU) Toroidal flux loss due to flux emergence explains why all solar cycles decline in the same way
16:35 — 16:50: **Chitradeep Saha** (CESSI) Periodic behavior driven by meridional circulation during solar grand Minima Episodes
16:50 — 17:05: **Anu Sreedevi** (IIT, BHU) Tracking of Bipolar Magnetic Regions using an automatic algorithm: initial results of tilt, flux and field strength
17:20 — 17:35: **Vindya Vashishth** (IIT, BHU) Modelling the occurrence of grand minima in sun-like stars using a dynamo model

Abstracts

- **The enigmatic meridional circulation of the Sun**

  Arnab Rai Chouduri, IISc, Bangalore

  Abstract: It has been known for about half a century that the plasma at the solar surface keeps moving from the equator to the poles – the maximum speed at mid-latitudes being of order 20 m/s. The theoretical guess that the return flow takes place at the bottom of the convection zone is now confirmed by helioseismology observations. I shall outline the theory of how the meridional circulation arises from a competition between the thermal wind term and the centrifugal term in the fluid dynamical equation of the flow in the meridional plane. I shall end with brief comments about the role played by this circulation in the flux transport dynamo model.

- **Long-term measurements of solar meridional circulation: temporal variations and connections to rotation and magnetic field.**

  S. P. Rajaguru, IIA, Bangalore

  Abstract: Time-distance helioseismology has now inferences on the deep structure and dynamics of meridional circulation (MC) for the last two solar cycles. I will review and summarise the emerging consensus, with a focus on temporal variations and their connections to zonal flows (rotation) and large-scale surface magnetic fields. I will also describe some new findings from an analsysis of the past 11 years of data from the Helioseismic and Doppler Imager (HMI) onboard Solar Dynamics Observatory (SDO), pertaining to the cycle-phase dependent sub-surface cross-equator meridional flows and their connections to magnetic fields. I conclude with a discussion of implications of current helioseismic measurements for models of convection zone dynamics that relate the differential rotation, MC and magnetic fields.

- **The synoptic solar observations from the Kodaikanal Observatory**

  B. Ravindra, IIA, Bangalore

  Abstract: The Kodaikanal Observatory has a legacy of making full-disk solar photosphere and chromosphere observations since 1905. These observations are carried out using the 4-inch telescope for the photospheric and the 12-inch lens for the chromospheric observations. A spectrograph with entrance and exit slit and the instrument's smooth movement recorded the solar chromosphere in Ca-K and H-alpha wavelengths in photographic plates and films. Later in the 20th century, photographic plates were replaced with electronic recording devices. These instruments are still in working

condition, and the interested person can see them when they visit Kodaikanal Observatory. The recent installation of the WARM telescope, Twin Telescope, and H-alpha telescopes continued these observations. This talk will present the digitization of the Kodaikanal photographic data, their calibration, data availability, and some of the recent results obtained. I will also talk about the ongoing activity on sun-chart scanning at the Kodaikanal Observatory.

- **Long-term evolution of the Sun's magnetic field during cycles 15–19 based on their proxies from Kodaikanal Solar Observatory**
  Dipankar Banerjee, ARIES, Nainital & IIA, Bangalore
  Abstract: The regular observation of the solar magnetic field is available only for about the last five cycles. Thus, to understand the origin of the variation of the solar magnetic field, it is essential to reconstruct the magnetic field for the past cycles, utilizing other data sets. Long-term uniform observations for the past 100 yr as recorded at the Kodaikanal Solar Observatory (KoSO) provide such an opportunity. We develop a method for the reconstruction of the solar magnetic field using the synoptic observations of the Sun's emission in the Ca II K and Hα lines from KoSO for the first time. The reconstruction method is based on the fact that the Ca II K intensity correlates well with the unsigned magnetic flux, while the sign of the flux is derived from the corresponding Hα map that provides the information of the dominant polarities. Based on this reconstructed magnetic map, we study the evolution of the magnetic field in Cycles 15–19. We also study bipolar magnetic regions (BMRs) and their remnant flux surges in their causal relation. Time–latitude analysis of the reconstructed magnetic flux provides an overall view of magnetic field evolution: emergent magnetic flux, its further transformations with the formation of unipolar magnetic regions (UMRs), and remnant flux surges. We identify the reversals of the polar field and critical surges of following and leading polarities. We found that the poleward transport of opposite polarities led to multiple changes of the dominant magnetic polarities in poles. Furthermore, the remnant flux surges that occur between adjacent 11 yr cycles reveal physical connections between them.

- **Revisiting the Ca-K observation at Kodaikanal Observatory**
  Bibhuti Kumar Jha, ARIES, Nainital & IIA, Bangalore
  Abstract: Kodaikanal Solar Observatory (KoSO) is one of the oldest observatories observing the Sun in Ca-K (393.3 nm) from the beginning of the 20th century. Earlier, these spectroheliograms (observations) were taken on photographic plates/films with the help of a siderostat, which causes the rotation of the field of view (FOV). It is important to compensate for this rotation of FOV, which was done earlier with the help of tabulated

values and the time of observation. Recently, we have discovered that there are a few issues with the time stamp in the digitized images, which leads to the incorrect orientation of the solar disk and hence, an error in the calculation of coordinates. In this work, we have first used the mathematical relation for the calculation of rotation caused by siderostat. Then, we identified the observations that suffer from incorrect time-stamps and corrected them.

- **Applied Artificial Intelligence for science & exploration enabled by public-private partnerships**

  Madhulika Guhathakurta, NASA

  Abstract: The recent advances in Artificial Intelligence (AI) capabilities are particularly relevant to NASA science and exploration goals because there is growing evidence that AI techniques can improve our ability to model, understand and predict our environment using the petabytes of data already within NASA archives. In particular this represents a strategic opportunity in Heliophysics, since the need to improve our understanding of space weather is not only mandated by directives such as the National Space Weather Action Plan and the Presidential Executive Order for Coordinating Efforts to Prepare the Nation for Space Weather Events, but also because space weather is a critical consideration for astronaut safety as NASA moves forward leave LEO and return to the Moon. I will also talk about the Frontier Development Lab (FDL) which is an AI research accelerator that was established in 2016 to apply emerging AI technologies to space science challenges which are central to NASA's mission priorities and provide some examples. FDL is a partnership between NASA Ames Research Center and the SETI Institute, with corporate sponsors that include IBM, Intel, NVidia, Google, Lockheed, Autodesk, Xprize, Space Resources Luxembourg, as well as USC and other organizations. The goal of FDL is to apply leading edge Artificial Intelligence and Machine Learning (AI/ML) tools to space challenges that impact space exploration and development, and even humanity. The applied AI projects for heliophysics and space weather that are being undertaken by the Frontier Development Lab (FDL) represent an ideal opportunity for utilization of vast amount of NASA and other data to leverage the public-private partnerships of the FDL program in a manner that is highly complementary to ongoing efforts in space weather research. In this talk I will summarize the latest findings from some of these research topics.

- **Long term decline of solar magnetic fields over the past two decades**

  Susanta Bisoi, NIT, Rourkela

  Abstract: Solar magnetic fields modulate and drive the solar wind, whose interaction with the Earth's magnetosphere at 1 AU, commonly referred to as 'Space Weather'. It is recently one of the main thrust areas of research with mankind's increasingly dependence on space based satellites, which are at risk due to the disturbances in solar cycle activity. The long term study of the solar cycle activity, which is basically a periodic modulation of solar magnetic fields is therefore of utmost importance. A systematic and long term study of solar magnetic field observations over the past few decades have shown a steady and monotonic decline, since around mid-1990's, in solar photospheric magnetic fields along with the observed declining trend in the amplitude of the past four successive solar cycles. In addition, solar cycle 23 displayed the longest and deepest solar cycle minima in the past 100 years and the recently concluded solar cycle 24 showed a significant hemispheric asymmetry in its polar magnetic field reversal pattern. In this presentation, I will discuss a large body of work, carried out over the past decade, of solar cycle variations in solar and heliospheric magnetic fields, their solar wind signatures and effects at 1 AU on the stand-off distances of Earth's bow shock, magnetopause, and terrestrial ionospheric F-region electron densities. I will conclude with forecasting the amplitude of upcoming solar cycle 25 based on solar magnetic fields, and discuss the possibility of the onset of a prolonged diminished solar activity condition beyond solar cycle 25 and its possible impact on the terrestrial climate.

- **Long term variation of solar wind helium and suprathermal population**

Dibyendu Chakrabarty, PRL, Ahmedabad

Abstract: Solar wind consists of ~95 % of protons and 2 - 5% of alpha particles in terms of abundance. The relative abundance of alpha particles with respect to protons is usually expressed as AHe = $(n\alpha/np)$ *100. By systematically analyzing the inter-calibrated AHe data obtained from the first Lagrangian point (L1) of the Sun-Earth system for the last four solar cycles (cycles 21-24), it is shown that AHe variations are distinctively different in solar cycle 24 as compared to the last three cycles. The investigation suggests that the coronal large scale magnetic field configuration started undergoing systematic changes starting from cycle 23 and this altered magnetic field configuration affected the way helium got processed and depleted in the solar atmosphere. In addition, based on two solar cycles' suprathermal particle measurements from the L1 point, it is shown that suprathermal helium and iron behave in a contrasting manner in solar cycles 23 and 24. These results indicate the mass-by-charge and first ionization potential (FIP) dependence of the processes that generate the suprathermal particles in the interplanetary medium. The possible physical mechanisms will be discussed.

- **The unusual behavior of CMEs and solar wind in the last two decades that baffles heliospheric physicists**
  Wageesh Mishra, IIA, Bangalore
  Abstract: The study of evolution characteristics of coronal mass ejections (CMEs) and solar wind is of great significance and is one of the challenging problems in heliospheric physics. The studies on interplanetary CMEs (ICMEs) in the heliosphere over solar cycles 23 and 24 have gathered attention since the observations of the extremely weak and unusually long minimum phase of cycle 23. In my talk, I will begin with an overview of the earlier studies on the solar activity observed over the last two solar cycles. Following this, I will discuss the variation in the mass-loss rate via CMEs and solar wind as a function of solar magnetic variability and the contribution of CMEs to the total solar wind mass flux in the ecliptic and beyond. Further, my talk will highlight the influence of the heliospheric state on the expansion behavior and radial sizes of coronal mass ejections (CMEs) in the last two solar cycles. Also, I will discuss the variation in the charge states and abundances of CMEs and solar wind plasma observed at 1 AU over the solar cycles 23 and 24. Succinctly, my talk aims to summarize the observed solar behavior in the last two decades and discuss the possible causes and consequences of our findings relevant for future studies

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- **Helium abundance variation in interplanetary coronal mass ejections spanning over solar cycle 23 and 24**
  Yogesh, PRL, Ahmedabad
  Abstract: The relative abundance of alpha particles with respect to protons is usually expressed as AHe = $(n\alpha/np)$ *100. AHe is 8-8.5 % in the photosphere. However, AHe varies from 2-5% in the solar wind depending on the solar activity level and solar wind velocity. Interestingly, AHe can increase significantly and reach above 8% in the interplanetary coronal mass ejections (ICME) passing through the first Lagrangian point (L1) of the Sun-Earth system. To explore this AHe variation, we have taken ICMEs from 1996 to 2019 (solar cycle 23 and 24). Although various factors like interplanetary shocks, chromospheric evaporation and “sludge removal” have been separately used to address the AHe enhancements in ICMEs in the past, none of these processes could explain the variability of AHe in ICMEs comprehensively. Based on extensive analysis, we show that there is a solar activity variation of ICME averaged AHe values. We investigate the role of various factors like first ionisation potential (FIP) effect, coronal temperature, chromospheric evaporation, gravitational settling etc. for the variation of AHe beyond 8% in ICMEs. The insights obtained from these investigations will be discussed.

- **Helium abundance variation in Interplanetary Coronal Mass Ejections spanning over solar cycle 23 and 24**

  Soumitro Hazra, PRL, Ahmedabad

  Abstract: We study the behavior and properties of the solar wind using a 2.5D Alfvén wave driven wind model. We first systematically compare the results of an Alfvén wave (AW) driven wind model with a polytropic approach. Polytropic magnetohydrodynamic wind models are thermally driven, while Alfvén waves act as additional acceleration and heating mechanisms in the Alfvén wave driven model. We confirm that an AW-driven model is required to reproduce the observed bimodality of slow and fast solar winds. We are also able to reproduce the observed anti-correlation between the terminal wind velocity and the coronal source temperature with the AW-driven wind model. We also show that the wind properties along an eleven-year cycle differ significantly from one model to the other. The AW-driven model again shows the best agreement with observational data. Indeed, solar surface magnetic field topology plays an important role in the Alfvén wave driven wind model, as it enters directly into the input energy sources via the Poynting flux. On the other hand, the polytropic wind model is driven by an assumed pressure gradient; thus it is relatively less sensitive to the surface magnetic field topology. Finally, we note that the net torque spinning down the Sun exhibits the same trends in the two models, showing that the polytropic approach still captures correctly the essence of stellar winds.

- **A parametric study of performance of solar wind forecasting models during 2006 to 2011**

  Sandeep Kumar, USO, Udaipur

  Abstract: There is an increasing need for the development of a robust space weather forecasting framework. It can help us study space weather events, mainly coronal mass ejections (CMEs) consequently their impact on the Earth. State-of-the-art MHD forecasting frameworks for space weather are based upon the Potential Field Source Surface (PFSS) and Schatten Current Sheet (SCS) extrapolation models for the magnetic field using synoptic magnetograms. These models create a solar wind background for the simulations using empirical relations of Wang, Sheeley and Arge(WSA) Model for the CMEs, at the inner boundary of the heliosphere. They have been used to simulate CMEs for specific cases in many earlier studies. Other than those MHD frameworks, there is a Heliospheric Upwind eXtrapolation(HUX) technique that can extrapolate solar wind from inner heliospheric boundaries (2.5 or 5 solar radii) to Lagrangian point L1 and can give a very good estimate of the solar wind velocity at L1 comparable to MHD models but in negligible computational time. We here present an extensive parametric study of the performance of the forecasting framework of PFSS+SCS+WSA+HUX and

PFSS+WSA+HUX of solar wind prediction at L1. We implemented this framework on 61 Carrington rotations (CRs) from CR2047(August, 2011) to CR2107(February , 2011) which includes the declining phase of solar cycle 23 and the ascending phase of solar cycle 24. Our simulated solar wind velocity profiles at L1 show a correlation coefficient (cc) of up to 0.90 with the observed velocity profiles obtained from the OMNI database. We report an unexpected decrease in the framework's performance during the deep minimum phase of cycle 23, which is attributed with the decreased coronal hole area at the low latitudes observed during this period. As cycle 24 begins as expected the decreasing

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- **The Origin of Decadal to Millennial Scale Variability in the Solar Cycle**
  Dibyendu Nandi, CESSI, Kolkata
  Abstract: The solar cycle originates in a magnetohydrodynamic dynamo mechanism in the Sun's interior. The solar dynamo is sustained by plasma flows, and modulated by non-linear feedback mechanisms, turbulent and stochastic fluctuations and other physical processes in the Sun's convection zone that introduce short-to-long term variability, as in evidence in the sunspot record. In this talk, we shall highlight results from dynamo simulations and non-linear dynamical analysis that shed light on the physical causes of solar variability at different timescales.

- **How early can we predict the solar cycle strength reliably using the polar precursor method?**
  Pawan Kumar, IIT (BHU), Varanasi
  Abstract: To predict the strength of an upcoming solar cycle, we usually apply the polar precursor method, which is probably the most robust and physics-based method. It uses the magnetic field concentrated near the poles around the solar cycle minimum. We have done an extensive performance analysis of various such predictors, based on both observational and dynamo model data. We calculate linear correlation coefficients (r) of the predictors with the next cycle amplitude as a function of time measured from solar cycle maximum and polar field reversal. Setting r = 0.8 as a lower limit for acceptable predictions, we find that observations and models alike indicate that the earliest time when the polar predictor can be safely used is 4 years after polar field reversal. This is typically 2 to 3 years before the solar minimum and about 7 years before the predicted maximum i.e. considerably extending the usual temporal range of the polar precursor method. Reevaluating the predictors after 3 years, at the time of solar minimum, further increases the correlation level to r > 0.9. The predicted amplitude of Cycle 25, based on the value of the WSO polar field at the official minimum date (December 2019) is 126 ± 3. A forecast based on the value in early 2017 i.e. just 4 years after the polar reversal would have only

differed from this final prediction by about 3%. trend in the model performance vanishes due to increase in the coronal hole area at the low latitudes.

- **Theoretical modeling of the properties of the latitudinal distribution of sunspot bands**

Akash Biswas, IIT-BHU, Varanasi

Abstract: At the beginning of the solar cycle, sunspots appear around the mid-latitudes and as the cycle progresses, the activity belt of sunspots gradually migrate towards the equator. At a span of time, the distribution of sunspots over the latitudes show a Gaussian-like pattern. Different cycles begin at different latitudes and reach their maximum strength at different rates following the Waldmeier rule. The stronger cycles reach their peaks at higher latitudes than the weaker ones. However, all cycles decay at the same rates. Thus stronger cycles begin to decay at higher latitudes. The widths of these latitudinal distributions of the sunspots also evolve in a similar fashion. In this work, we present a theoretical understanding of these observational features using a Babcock-Leighton type solar dynamo model. We also put some constraints on the strength of the equipartition value of the magnetic field and the variation of the meridional flow.

- **Periodic Behavior Driven by Meridional Circulation During Solar Grand Minima Episodes**

Chitradeep Saha, CESSI, Kolkata

Abstract: Sunspot observations over the past few centuries reveal that the Sun occasionally slips into quiescent phases, known as solar grand minima. In our dynamo model, we employ stochastic fluctuation in the poloidal source terms to simulate such grand minima episodes. Our simulations detect a gradual decay of the polar field at the onset of a solar minimum followed by a halt in the polar field reversals. But, the large-scale meridional circulation continuously dredges up magnetic fields to the solar surface and advects them further to the polar caps. This eventually builds up polar magnetic fields, strong enough to sustain the regular surface activity again, aiding in the recovery from the grand minimum. Spectral analysis of the hemispheric polar flux time series during simulated grand minima reveals the significant signature of multiple frequencies apart from the 11-year sunspot cycle. In this work, we focus on a ~ 5-year component and establish its causal connection with the meridional circulation characteristic timescale. Our numerical results are in good agreement with the long-term reconstructed solar activity data.

- **Tracking of Bipolar Magnetic Regions using an automatic algorithm: initial results of tilt, flux and field strength**
  Anu Sreedevi, IIT-BHU, Varanasi
  Abstract: Sunspots, seen as dark patches in the white light images of the Sun, are the regions of intense magnetic field on the surface of the Sun. These are essentially the poles of two opposite polarities of a more general feature, called the Bipolar Magnetic Regions (BMR), which can be observed in the full disk, Line of Sight (LOS) magnetograms. The decay and dispersal of BMR is responsible for producing the poloidal field in the Sun and thus plays a crucial role in the solar dynamo models. Hence, long-term study of various properties of BMR like the tilt, magnetic field strength, flux, are important for understanding the working of the solar dynamo. In our work, we are using the full disk LOS magnetogram data from space-borne instruments such as Michelson Doppler Imager (MDI; 1996–2011) with 96-minute cadence and Helioseismic and Magnetic Imager (HMI; 2010–2021) with 12-minute cadence. We use an automatic algorithm to identify and track BMRs for their lifetime or disk passage, starting from their first detection. Here, we present preliminary results of how the tilts, field strengths, and fluxes of the tracked BMRs vary over the course of their lifetimes.

- **Modelling the occurrence of grand minima in sun-like stars using a dynamo model**
  Vindya Vashishth, IIT-BHU, Varanasi
  Abstract: There is some observational evidence that rapidly rotating and young Sun-like stars exhibit a high level of activity with no Maunder-like grand minimum (flat activity) and rarely display smooth regular activity cycles. On the other hand, slowly rotating old stars like the Sun and older have lower activity levels and smooth cycles with occasional grand minima. We want to explain this observational trend using a simple Babcock–Leighton dynamo model. Following previous work (Karak, Kitchatinov & Choudhuri 2014), we build kinematic dynamo models of one solar mass star with different rotation rates and depth of convection zones. We specify the large-scale flows (differential rotations and meridional circulations) from corresponding hydrodynamic models. We include stochastic fluctuations in the Babcock-Leighton source for the poloidal field to produce variable stellar cycles. We observe that the rapidly rotating stars produce highly irregular cycles with strong magnetic fields and rarely produce Maunder-like grand minima, whereas the slowly rotating stars (Sun and longer rotation period) produce smooth cycles of weaker strength and occasional grand minima. In general, the frequency of occurrence of the grand minima increases with the decrease of rotation rate. These results can be explained by the fact that with the increase of rotation period, the supercriticality of the dynamo decreases and the dynamo is more prone to produce extended grand minima in this regime.