Understanding and forecasting the solar cycle variability using the polar magnetic field

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by
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Chapter 6

Conclusions and future outlook

"Every ending is a new beginning" *–Bhagavad Gita (2.22)*

This thesis focuses on the generation, evolution, and significance of the polar field in the aspect of solar magnetism. Undoubtedly, the polar field plays a pivotal and indispensable role in shaping the dynamics of the solar cycle, influencing the solar interior, and impacting the solar atmosphere. Through our research, we have extensively examined various aspects of the polar magnetic field and the solar cycle. This investigation encompasses the assessment of our capability to predict the strength of solar cycles through the analysis of observational data, the utilization of 2D (axisymmetric) Flux Transport dynamo models, and the implementation of advanced 3D dynamo models. Additionally, we have delved into the intricate processes involved in the generation of polar fields, elucidating their origins from the decay and dispersal of sunspots under the Babcock–Leighton process by employing the 3D Flux Transport Dynamo model.

Various aspects of human life and technology-dependent assets are affected by the irregular magnetic field of the Sun. It is noticeable that the extreme irregularities in the solar magnetic field have been well-observed and documented. Chapter 2 of this thesis embarks on an exploration of the underlying causes of this irregularity within the Sun's magnetic field using 3D Flux Transport dynamo STABLE, ultimately pinpointing the pivotal role played by the irregular properties of BMRs. The incorporation of the irregular properties of BMRs within the 3D STABLE model aligns consistently with solar observations. It's worth noting that this model successfully replicates numerous facets of the solar cycle, including key features observed in the SFT model. The irregular properties of BMR contain mainly scatter in tilt, time delays in successive BMR emergence, variation in emergence latitude, and fluctuations in BMR flux. Note that the most substantial variation stems from scatter in tilt, while time delay contributes the least to the observed irregularities. Variations in emergence latitude and BMR flux, on the other hand, wield significant influence over the field's variability. This study suggests that the irregular properties of BMRs are capable of generating some of the observed variability in the solar cycle, aligning with the patterns observed in actual solar observations. There are various mechanisms to explain the solar cycle's long-term variability, like magnetic feedback on the flow, stochastic forcing, and time delays in various processes of the dynamo (Karak, 2023). This chapter only focuses on the aspect of stochastic forcing under the Babcock–Leighton dynamo model.

The inherent irregularity of the solar magnetic cycle poses a formidable challenge to the accurate prediction of long-term variability and its hazardous impact on human society. In Chapter 3, a novel approach to solar cycle prediction is introduced, surpassing the capabilities of previous methods based on polar precursors. This innovative method offers a pathway to enhance the predictability window of the solar cycle. By employing this method, we can forecast the solar cycle amplitude about four years after the polar field reversal. It provides a prediction window that occurs notably earlier than the conventional approach i.e., cycle minimum, and enables us to predict the solar cycle strength about seven years earlier. Both the 2D axisymmetric dynamo models and the 3D models provide robust support for the observed results, although, these models diverge significantly in their underlying physical foundations and the parameter ranges within which they function, including substantial simplifications of different physical processes.

Chapter 4 pushes the boundaries further by demonstrating the capacity to predict cycle strength even earlier than previously achieved. This advancement is accomplished by utilizing the polar field rise rate following the polar field reversal. We show the physical connection of the polar field rise rate with the Waldmeier effect. This enables the connection of the polar field rise rate with the next cycle strength. This novel technique extends the temporal prediction window up to 9 years before the solar cycle maximum. The 9 year window of prediction will give us a great advantage in planning a safe space mission, to protect our space and ground-based technological assets. Moreover, a robust linear correlation is observed between the polar field build-up rate and the subsequent rise rate of the next solar cycle. We explored these observed features in the 2D axisymmetric dynamo model, SFT, and 3D STABLE model, all models produce these robust features.

The Sun's polar field serves as a precursor for forecasting the strength of the forthcoming solar cycle. The question that arises is: How many cycles can we reliably predict using the memory embedded in the polar field? Chapter 5 of this study undertakes a rigorous examination of the factors governing the memory of the polar field in prediction using several 2D Flux Transport dynamos and the time delay dynamo. Through a comprehensive analysis, it is revealed that the memory of the polar field is intricately tied to the supercriticality of the dynamo. When the dynamo operates within the critical regime, the memory of the polar field extends across multiple cycles. Conversely, when it functions in the highly supercritical regime, the memory of the polar field is limited to just a single cycle, effectively limiting the predictive capabilities of the polar field in such conditions.

The work conducted in this thesis has invited many interesting possibilities for further investigations.

Our investigation primarily focused on the variability of the solar magnetic field and prediction of the solar cycle strength. Predicting solar cycle variability with high accuracy has numerous challenges. However, it is essential to forecast solar magnetic field variability, as it is the driver of space weather. There have been various predictions made based on different methods but reliability and accuracy are still a question with a large error range. Therefore, we will focus on **enhancing the predictability of solar activity with high accuracy and reliability using an advanced model based on Flux Transport Dynamo principles and Machine Learning techniques.** We did not consider the back reaction of Lorentz force on the velocity field in our kinematic Flux Transport Dynamo models. We will explore these magnetic features with **non-kinematic Flux Transport Dynamo models and include the back reaction of Lorentz force on the velocity field.** We have been able to predict the long-term variability of the solar cycle up to some extent. However, **we can not predict the observed BMRs (sunspots) emergence time on the solar surface and its associated energetic events. We will try to develop a model to predict these phenomena.** We will try to **make more improvements in the 3D dynamo model to produce the solar photospheric magnetic fields very close to observations.** Achieving a close match between our generated solar photospheric magnetic fields and observational data would enable us to establish a connection between the coronal magnetic fields and the fields generated by the solar dynamo within the Sun's interior. Such a coupling will help significantly to enhance our understanding of the coronal magnetic field and the coronal heating. In the Aditya-L1 mission, a key objective is the measurement of coronal magnetic fields. This measurement will be instrumental in advancing the 3D dynamo model and facilitating the understanding of the linkage between the Sun's interior and its corona.