Abstract

The Sun's magnetic field exhibits a wide range of variabilities, which can be broadly classified into long-term and short-term. The cause of this magnetic field is believed to be the dynamo process, which operates in the Sun's convection zone. The large-scale magnetic field is responsible for shaping the overall solar activity, including the 11-year solar cycle and the formation of the Sun's polar field. This field exhibits extreme variability and drives space weather, leading to highly energetic events that can have direct or indirect adverse and hazardous effects on Earth's atmosphere and human society in various ways. Therefore, understanding and prediction of the irregular variability of solar magnetic field is essential.

With a renewed focus on researching "*solar magnetic field variability and forecasting*", we have developed and implemented several new automatic techniques and models for extensive data analysis and findings in this thesis. This approach enhances overall consistency and effectively eliminates the potential for human error, which has been common practice in the past. These new techniques and models are used to study the irregularities in the polar field and the solar cycle due to observed fluctuations in Bipolar Magnetic Region (BMR) properties, such as fluctuations in the BMR tilt, flux, emergence latitude, and the time delay between successive BMR emergence. Besides this, we forecast the strength of Solar Cycle 25 using the polar field and the Waldmeier effect. We have used observed data of the polar field (1974–2022) from Wilcox Solar Observatory (WSO), Polar faculae counts (1907–2011), Pulkovo observatory $A(t)$ index (1915–1999), Dipole moment (1976–2017), sunspot number SSN (1749–2022), and sunspot area SSA (1874–2022) along with 2D and 3D dynamo models. We have also explored how the memory of the polar field and the occurrence of grand minimum-like events change with the dynamo super-criticality in Babcock-Leighton-type dynamo models.

The extensive analysis of irregular BMR properties reveals that their cumulative impact sufficiently generates irregularities in the polar field and the solar cycle consistent with observed patterns. Additionally, this analysis indicates that the maximum variability in the polar field and the solar cycle is produced due to scatter in BMR tilt around Joy's law. It is worth noting that many researchers have developed different prediction methods for future solar cycle variability using mathematical and statistical methods. However, most of the time, these methods give diverging results from observations.

For forecasting the irregular solar cycle strength, we utilized the polar precursor method, a widely accepted physics-based approach. In this process, we computed the Pearson correlation coefficient between the previous cycle polar field and peak sunspot number as a function of time. Using this, we predicted the upcoming solar cycle strength after four years of the polar field reversal, typically 2 to 3 years before the solar minimum and about seven years before the predicted maximum. Different utilized dynamo models in this work produce similar results and thus increase the reliability of this result. However, researchers conventionally made the prediction of the next cycle using the polar field as a precursor at cycle minimum. Our prediction for Cycle 25's amplitude, based on the WSO polar field, suggests it will be stronger than Cycle 24 and only deviates from the conventional prediction at the cycle minimum by $3.1 \pm 14.7\%$.

We further show the strong linear correlation between the polar field rise rate of the preceding cycle and the next solar cycle amplitude. This correlation enables us to predict the solar cycle strength 9 years earlier than its maximum. Furthermore, the polar field rise rate of the preceding cycle and the solar cycle rise rate show a strong linear correlation, showing the physical connection between the polar field buildup and the well-known Waldmeier effect.

This forecasting ability comes from the memory of the Sun's polar field and depends on the dynamo super-criticality. An extensive analysis of different Babcock-Leoghton-type

dynamos reveals that when the dynamo operates near the critical region, the polar field can decide multiple cycle strengths (at least three). Furthermore, when the dynamo operates in the supercritical region, the polar field can decide only the next cycle strength. This change in the memory of the polar field is independent of the importance of various turbulent transport processes in the models. We also find that near the critical region, the dynamo produces frequent extended episodes of weaker activity i.e., solar grand minima. The frequency of grand minima decreases with the increase of dynamo super-criticality.

Thus, the Sun's polar field, generated through the Babcock-Leighton process, is used to study the variability and forecasting of the solar cycle. The variability and prediction memory observed in the polar field are contingent upon the inherent randomness and nonlinearity in the BL process, stemming from the irregularities in BMR properties on the solar surface.