Abstract

The 11-year cycle of the Sun's magnetic field is the major driver of the space weather in the Heliosphere. The energetic events like Coronal Mass Ejections (CMEs) or Solar Flares that are driven by the magnetic fields of the Sun pose a great threat to our space and ground-based technologies. Due to the increasing dependence of our society on these technologies, the understanding of the evolution of Sun's magnetic activity and the development of reliable space weather prediction methodologies are crucial to mitigate these threats of severe space weather impacts. The forecast of solar activity and space weather can primarily be divided into two parts. One is the long-term forecast aimed at predicting the strength of an upcoming cycle a few years before its maxima, and in the other case, the short-term forecast which aims at predicting the impact of CMEs or solar flares on space weather conditions in the upcoming few hours or days. This thesis aims to study the long-term solar cycle trend to understand the essential processes in the solar dynamo that drive the observed nature of the solar activity and explores novel methods developed to forecast the aforementioned long-term and short-term forecast of solar cycle and space weather.

Among its many peculiar properties, one of the most fascinating aspects of the solar cycle has been that, in the beginning, the sunspots appear at higher latitudes, and with the progress of the cycle, the activity belts shift towards the equator. What is even more interesting is that different cycles evolve in different manners in their beginning or rising phases depending on their strength. However, all cycles decline in the same way with similar statistical properties. Chapter 2 of this thesis probes the physical process that leads to this behaviour of solar cycles with different strengths and it turns out, that the nonlinear process of toroidal flux loss due to the emergence of buoyant flux tubes that give birth to

the sunspots makes all the cycles have a similar amount of toroidal flux during the end phases of the cycles leading to their similar behaviour.

The reconstruction of the millennia-scale long-term data shows that solar activity has been varying in a wide range throughout the Holocene period occasionally showing very high activity followed by a sharp decline and on the other end it has gone through phases of muted activity followed by a gradual recovery. Questions like why solar activity does not keep growing gradually or why it is not sustained within a particular level, what drives the highly variable nature of solar activity or what leads to its growth from the phases of very low activity, have been explored in Chapter 3 of the thesis. Crucial nonlinear processes and stochastic drivers in the solar dynamo process have been identified that confine the long-term solar activity within the found levels and lead to its highly variable nature respectively.

Prediction of the peak strength of an upcoming cycle has been a challenging yet important task to assess the overall space weather conditions in the forthcoming years. There have been many methods devised for the job, however, the polar field strength at the solar cycle minimum has been a standard indicator of the strength of the upcoming cycle. In Chapter 4, we explore the possibility of extending the time window of solar cycle prediction by utilising the observed correlation of the rising rate of the polar field a few years before the cycle minimum and the peak of the upcoming cycle. We utilise synthetic profiles of solar cycles with the stochastic properties of the bipolar magnetic regions (BMRs) as inputs for the surface flux transport simulations to establish the robustness of this correlation. In this aspect, the polar field reversal timing works as a landmark in calculating the rise rate of the polar field. However, the timing of the polar field reversal has been found to be widely varying for different cycles. In Chapter 5, we probe the role of anomalous properties of BMRs behind the variation in the polar field reversal timing.

The short-term prediction of space weather conditions heavily depends on the solar wind conditions and especially on the impact of CMEs on the Earth's magnetosphere, or on the geoeffectiveness of the CMEs. A tool for forecasting the timing and impact of a CME on near-Earth space weather from the initial properties of the CMEs can have the longest possible time window of a few days. In Chapter 6 we utilise the GCS model to extract the initial parameters of the CME flux rope and deploy an Artificial Neural Network (ANN) Algorithm to forecast the transit time of the CME and the Dst index of the associated geomagnetic storm. The ANN algorithm showed reliable and consistent performance in this study and predicted the transit times with an impressive mean absolute deviation (MAD) of 4.22 hours and a standard deviation of 2.80 hours. The MAD of the prediction of Dst indices is 12.39 nT with a standard deviation of 10.28 nT. These results show that Machine Learning algorithms aided by the forward modelling techniques can be used in forecasting the geoeffectiveness of the CMEs to extend the time window of the space weather forecasts.