On the Possibility to Predict the Next Sunspot Maximum

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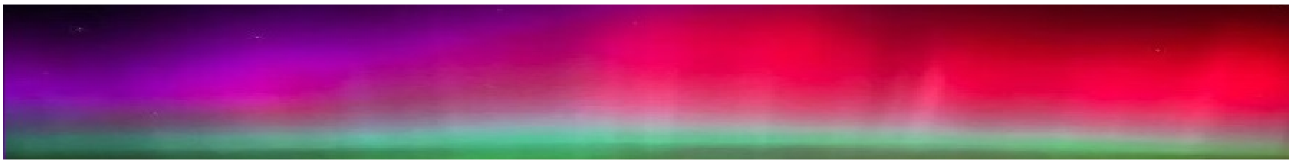

Abstract
In this work, we consider the Earth as a probe immersed in the solar wind, and use the AP index as a characteristic of the solar wind parameters. It has been established that the geomagnetic field reacts to solar coronal mass ejections (CME) and high-velocity solar wind fluxes (HSS). Previously, it was assumed that geomagnetic activity in the sunspot minimum was determined only by the time during which the Earth was under the influence of HSS or CME – in other words, the thickness of the heliospheric current layer. We have established that even in periods without HSS and CME, there is some non-zero geomagnetic activity, and this varies from cycle to cycle. Moreover, this activity depends on the characteristics of the slow solar wind. In this paper, we show that the number of sunspots at the maximum of the cycle is related to the state of the slow solar wind at the beginning of the cycle, and since the parameters of the slow solar wind can be judged by the average AP index for the specified interval, it can be used to determine the upcoming maximum of sunspots.

Keywords: Sunspot Maximum, Solar Cycle Prediction, Geomagnetic Activity, Solar Wind, AP Index

1 Introduction

The prediction of the amplitude for Solar Cycle 25 has generated considerable interest, particularly regarding the use of the Ap index as a precursor predictor. The Ap index, which represents geomagnetic activity, provides insights that are critical in forecasting the upcoming cycle's intensity based on historical data and correlations with previous cycles.

Several studies highlight varying predictive values relating the Ap index or its components to the amplitude of Solar Cycle 25. Miao et al. [5] predicted a maximum amplitude of sunspot activity at 122±33 using a combination of the Ohl prediction method and the aa geomagnetic index, suggesting that geomagnetic activity noted during the solar minimum phase influences subsequent cycle amplitudes [1].

Burud's research corroborates these findings, attributing a predicted amplitude of 99.13 ± 14.97 for Cycle 25, which falls within a collective range of 82 to 140, indicative of a similar intensity compared to Cycle 24 [2]. This predictive accuracy aligns with the principles noted by Upton and Hathaway, who emphasized that the aa-index values are fundamentally linked to sunspot cycles; they highlight the importance of geomagnetic precursors in forecasting amplitude and timing of subsequent cycles [8].

Furthermore, Rajwanshi et al. conducted a comprehensive analysis using Ap index data from solar cycles 17 to 24, applying regression analysis to predict the maximum amplitude for Cycle 25. Their findings indicated that the regression model exhibited a hindcasting precision within 10% accuracy compared to observed amplitudes from previous cycles [7]. This emphasizes the utility of the Ap index not only as a correlational figure but also as an effective predictive tool.

Additionally, Upton and Hathaway discussed the predictive value of the aa index in relation to Cycle 25, postulating a peak sunspot number of around 135 ± 10 based on geomagnetic precursors, with the Ap index being a significant component of their analysis [8]. Similarly, Du remarked on the Ap index's capacity to relate to the maximum amplitude of the upcoming cycle, underscoring its predictive potential [3].

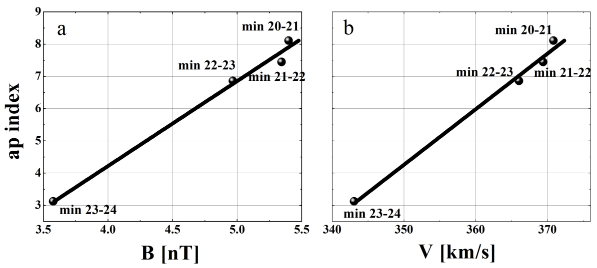

Figure 1: Geomagnetic Ap index as a function of the solar wind magnetic field (a) and velocity (b) of the slow solar wind with $V < 450$ km/s in the last four solar minima.

Thus, the compendium of studies collectively underscores the Ap index's role as a reliable predictor for Solar Cycle 25's maximum amplitude. By harnessing this geomagnetic precursor alongside complementary predictive methodologies, it is possible to develop a more nuanced understanding of solar cycle dynamics, refining predictions on solar activity and its implications for terrestrial systems.

From here, we can conclude that the characteristics of the entire sunspot cycle are determined by the slow solar wind parameters at the beginning of the cycle. Although the direct mechanisms by which to determine the specific parameters of the slow solar wind—such as velocity, density, etc.—at the start of the next sunspot cycle remain unknown, we have seen that there is an indirect indicator for these parameters: the average Ap index at the beginning of the cycle.

Predicting Ap$_{min}$

As clearly seen in Fig. 1a, the variations of the magnetic field of the slow solar wind are associated with similar variations of the average Ap index in the same time interval. This magnetic field is related to the dipole magnetic field of the Sun. The left panel of Fig. 2 shows the Sun's dipole field as a function of time. This composite figure combines 3 studies: the thick grey line is from [4], the thick black line with full black circles from [6], and the thin line from Wilcox Solar Observatory (http://wso.stanford.edu/gifs/DipallR.gif). The right panel of Fig. 2 shows the ap index in the minima between cycles 19–20 to 23–24.

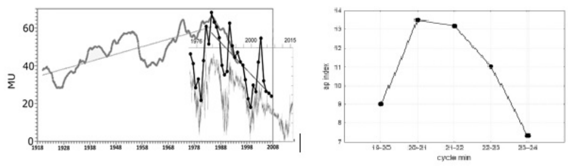

Figure 2: Sun's dipole field (left); Ap index in sunspot minimum (right).

Fig. 2 demonstrates that in 1985, after a prolonged period of rise, the Sun's dipole field began falling. Around the same time, a decline also started in the Ap index measured at the beginning of each solar cycle. The data available to date show that the Sun's magnetic field continues to decline, which is likely to lead to a continuing decrease in the Ap index as well.

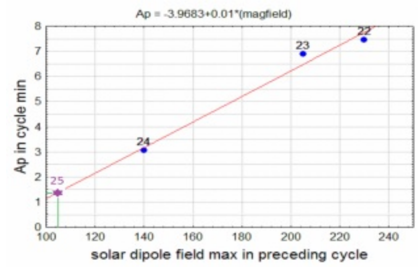

Figure 3: Correlation between the maximum solar dipole field in a cycle and the Ap-index ($V <$ 450 km/s) in the beginning of the next cycle.

Fig. 3 presents the dependence of the Ap index during sunspot minimum periods—when the Earth is not influenced by coronal mass ejections (CMEs) and high-speed streams (HSS)—on the Sun's maximum dipole magnetic field. The data for the Sun's dipole magnetic field are taken from the Wilcox Solar Observatory (http://wso.stanford.edu). The data point for cycle 25 is prognostic and is based on the assumption that the solar dipole field has already reached its maximum in the present cycle 24. Under this assumption, the expected Ap index in the next sunspot minimum will be approximately 1.35.

Prediction of sunspot maximum during cycle 25

We have found that the solar wind parameters at the beginning of a cycle pre-determine the amplitude of that cycle. On the other hand, it is known that these same parameters determine the average Ap index at the beginning of the cycle, during time intervals when the Earth is not influenced by coronal mass ejections (CMEs) and high-speed streams (HSS). Therefore, we studied the relation between this average Ap and the sunspot number at the next cycle maximum, and found a quasi-linear relationship. Using this relationship and assuming an average Ap value of 1.35 in the next sunspot minimum, the expected maximum sunspot number in cycle 25 is estimated to be in the range of 50–55.

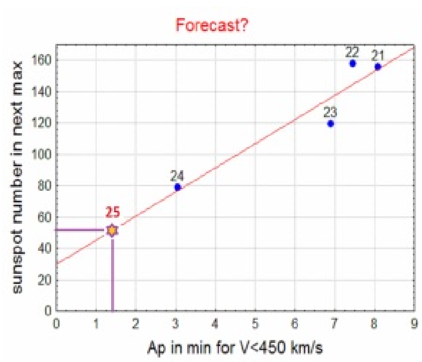

Figure 4: Relation between the average Ap index ($V < 450$ km/s) at the beginning of a cycle and the maximum sunspot number in that cycle.

Discussion

It turned out that during Solar Cycle 25, the maximum sunspot number reached 112 (using the sunspot number version V1), rather than the predicted 50–55. A more detailed analysis revealed that the measured average Ap index for solar wind velocities $V <$ 450 km/s during the solar minimum was 4.82, significantly higher than our previously estimated value of 1.35.

This raises the question of what the predicted maximum of solar activity would have been for Cycle 25 according to our methodology, if an Ap value of 4.82 had been initially adopted.

Fig. 5 is similar to Fig. 4, but includes two additional data points. One represents the measured sunspot maximum and the corresponding calculated Ap, while the other is based on the measured Ap and the resulting calculated sunspot number at maximum.

The analysis shows that for the observed maximum of 112 sunspots, the corresponding Ap should have been 5.3, and for the measured Ap of 4.82, the sunspot number at maximum should have been 103. The differences between measured and calculated values are minor, as clearly illustrated in Fig. 5. Thus, the significant inaccuracy in predicting the Cycle 25 maximum stems primarily from our incorrect forecast of the Ap index at solar minimum for $V < 450$ km/s.

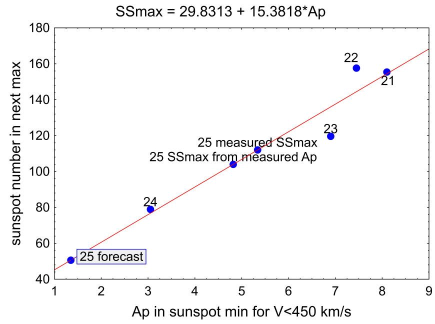

Figure 5: Relation between the average Ap index ($V < 450$ km/s) at the beginning of a cycle and the maximum sunspot number in that cycle, measured and predicted.

We determine the Ap index at the minimum between two cycles based on the preceding maximum of the Sun's magnetic dipole field. As evident from Fig. 4, this method proved reliable for Cycles 22, 23, and 24. Fig. 6 illustrates that these cycles occurred during a continuous decline in the maximum of the Sun's dipole field, followed by a further decline after each cycle's maximum.

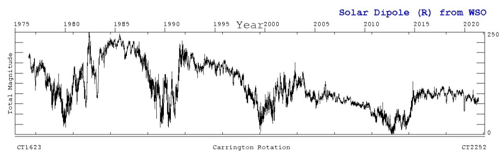

Figure 6: Solar dipole field in (μT) since 1976 from Wilcox Solar Observatory.

However, after the dipole field maximum in 2015, there has been an ongoing plateau in the magnitude of the magnetic dipole, continuing to the present. From this observation, we conclude that the Sun, following the end of the last secular cycle, is entering a different operational regime, which prevents us from applying previously established relationships between the magnitude of the dipole field maximum and the subsequent Ap index at solar minimum. Currently, it appears that the relationship between the Ap index at minimum and the subsequent solar activity maximum remains valid.

Acknowledgements

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