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Solar Activity Forecasting and North-South Asymmetry

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Abstract

According to the generally accepted theory, the field of local active regions is generated from the poloidal magnetic field. The field in the polar regions, which is measured directly by magnetographs, can be a proxy of the latter. It has been shown that the mean-field dynamo is undoubtedly the main mechanism generating solar activity and the 11-year cycle. However, the magnetic flux generated by the dynamo, being the genetic basis of solar activity, still does not allow unambiguously linking the characteristics of the magnetic field with other indices of solar activity, including the best-known one - the sunspot number. Magnetic fields of active regions and spots are formed from the mean magnetic flux. Its most important properties are the threshold character and the conservation of the total flux. Therefore, a completely reliable long-term forecast of SSN is possible after the occurrence of an equatorial wave approximately 18 months before the maximum. The processes in leptocline play a decisive role in this case.

Keywords: solar magnetic field; solar cycle; forecast

1. Introduction

The basic concept of the solar dynamo is the transformation of the poloidal field into a toroidal field with the emergence of activity in the equatorial zone of the Sun (primarily sunspots) and the reverse process of restoring the poloidal field. This basically correct concept gives rise to several widely held ideas that are in fact not entirely true.

1. The polar field is the main reliable index of the original poloidal field.
2. Since the poloidal field is a primary phenomenon, knowledge of the polar field is sufficient to describe the main properties of the upcoming cycle and, in particular, its height.
3. Solar activity is generally symmetric about the equator, regardless of the characteristic spatial and temporal scales.

2. Is the measured polar field a good predictor of the following cycle?

This view is based on the idea that there is a single mechanism generating solar activity and that once the poloidal field has been established, the sunspot cycle is completely predetermined. This is not the case, or at least not always the case. It is unclear to what extent the solar dynamo is determined by stochastic or deterministic processes (Mininni et al. 2002). Moreover, existing dynamo models deal with the mean-field dynamo. Therefore, the output of any theory is the field structure, not the sunspot number that must be predicted. As a result, attempts based on dynamo models have so far yielded contradictory results (Biswas et al., 2023; Bushby and Tobias, 2007; Kitiashvili and Kosovichev, 2008, 2011; Kitiashvili, 2016; Dikpati, de Toma, and Gilman, 2006; Dikpati and Gilman, 2006; Choudhuri et al., 2007a, b; Upton and Hathaway, Jiang et al., 2018; Bhowmik, and Nandy, 2018; Labonville et al, 2019; Guo et al, 2021; Jiang et al, 2023; Bhowmik et al, 2023). For a detailed review of these publications, see (Nandy, 2021). The current Cycle is indicative in this regard. According to polar field data, one would expect the cycle to be about the same as Cycle 24 or slightly higher.

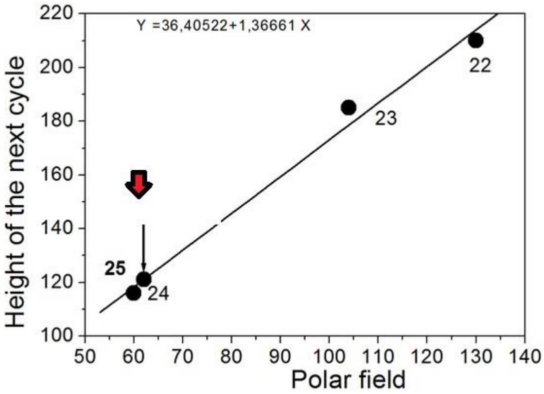

***Figure** 1. Relationship between the polar field measured in mT and the height of the upcoming sunspot cycle. For cycle 25, two values are shown: one is the predicted value based on the polar field (thin arrow), and the other is the value actually reached in October 2024 (thick red arrow).*

In May 2023, the smoothed SSN number reached 123.9 and continued to rise steadily. As shows the arrow in Figure 1, Cycle 25 promised to be at least 10% higher than Cycle 24 (Obridko et al., 2023a, b). But this forecast also turned out to be underestimated. A strong increase in activity in the second half of 2024 changed the course of the cycle, and the smoothed value for March 2024 was 141.3. Actually, the maximum was reached in October 2024 and its height was 160.8.

So, why didn't the forecast of the height of cycle 25 based on polar field data work? First of all, the data available on the WSO website (http://wso.stanford.edu/Polar.html) are not exactly the polar field. The WSO measures the strength of the Sun's polar field daily in the polar-most three-minute apertures. The polar-most aperture measures the line-of-sight field between the latitude of about 55° and the pole. In this case, the longitudinal component is measured directly, i.e. at these latitudes it is close to the meridional one. Even if we assume that the field on the photosphere is radial, at these latitudes it is multiplied by the cosine of the latitude, which is <0.5

In Figure 2, we compare the absolute values of the magnetic field at selected latitudes with the polar field and sunspot numbers.

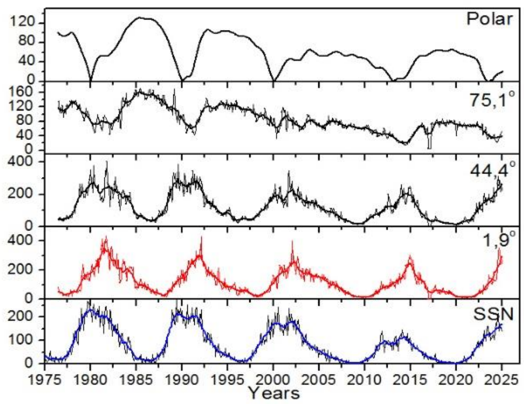

***Figure 2**. Comparison of the absolute values of the magnetic field at selected latitudes with the polar field and sunspot numbers.*

As seen on the top panel, the extrema of the polar field are in antiphase with the sunspot numbers, as it should be according to the basic dynamo model. The field maxima strictly correspond to the sunspot minima, and the dates of the field minima are close to the sunspot maxima. The situation changes starting from latitude ~50°. Now, the field extrema correspond to those of the sunspot numbers. A wave independent of the polar zone appears, moving to the equator.

In the period from 2004 to 2008, the mean-field maximum corresponding to the prolonged decline phase of Cycle 23 is scarcely noticeable. Many observers note an unusual character and a long duration of this phase. The field maximum at mid-latitudes and directly at the equator agrees with the secondary maximum of sunspot numbers. Note that even directly at the equatorial latitudes the mean magnetic field does not fully correspond to the sunspot curve.

The mean field and the sunspots are closely related but not identical phenomena. The general idea is that the mean-field dynamo creates a mean-field toroidal flow, which disintegrates into separate tubes by means of some additional mechanism. The mean magnetic flux forms magnetic fields of active regions and spots. We should emphasize that it is not part of the dynamo process, and no new total flux is generated. This is a fairly complex process, the initial impulse of which is an increase in the magnetic field to a certain threshold value. At this value, the heat influx from below becomes weaker, and thermodynamic processes begin to act. If the region of the increased field is large enough compared to the horizontal optical thickness, a dark feature (a sunspot) appears at the photosphere level.

3. What about NS asymmetry?

The development of the cycles is not synchronous in different hemispheres. In Cycles 12-13 and (less pronounced) in Cycles 14-15, the northern hemisphere was in the lead. In Cycles 16-19, the southern hemisphere was in the lead, and in the last cycles the northern hemisphere was leading again (Figure 3).

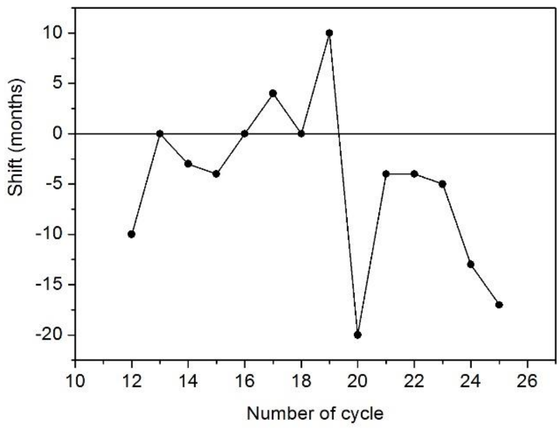

Figure 3. *Shift of thr cycles maxima (Data max N – Data max S).*

Here, we are facing an awkward question: Does the symmetry of the hemispheres indeed exist, or do we see only independent waves of activity in each hemisphere?

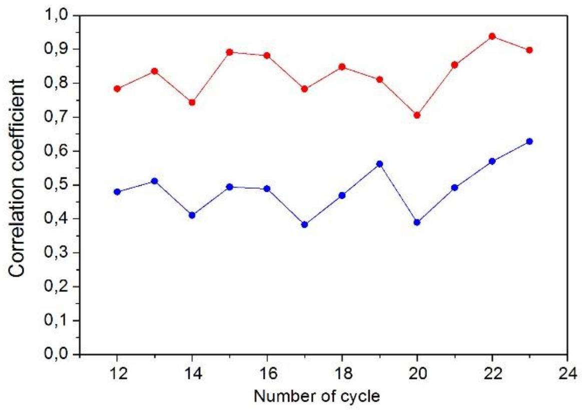

Figure 4. *Correlation coefficient r0 between North and South in sunspot areas (blue line r_0 for unsmoothed data, red line r_0 for smoothed data)*

Figure 4 shows the correlation coefficients separately for the unsmoothed values of the spot areas (blue curve) and the smoothed values (red curve). It turns out that the correlation of the unsmoothed values is quite low, the correlation coefficient for the entire data array is r0=0.526±0.850.

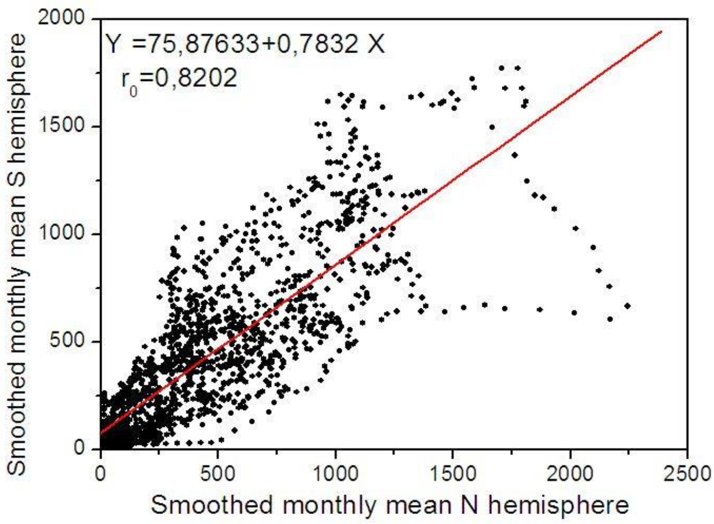

Figure 5*. Correlation of smoothed monthly means data.*

However, if we look at the values smoothed over a one-year window, the correlation improves significantly, r0=0.8202±0.572, (see Figures 4 – red line and Figure 5), and the improvement is achieved mainly due to larger values. It is interesting that in the region of large values, an excess of areas in the northern hemisphere becomes noticeable.

Symmetry of the smoothed data exists!! We have arrived at the conclusion that the 11-year cycles in both hemispheres are virtually identical in their spectral shape. The 11-year oscillations may be slightly offset in time in one hemisphere relative to the other. Other differences in shape have time scales of less than a year and can be considered to be due to processes other than the mean-field dynamo responsible for the main cycle.

Thus, in a fairly average magnetic field, the asymmetry of the hemispheres is not observed. Only the 11-year cycle is clearly visible. Thus, we come to the conclusion that the 11-year cycle is determined for structures of large time scales (more than a year) and is determined by large-scale magnetic fields. Accordingly, as a result, the 11-year cycle is stable and although there is a large shift between the maxima, it never exceeds 10-20 months.

4. What about small-scale structures?

Now, let us turn to the small-scale structures in the data under discussion. We quantify them in terms of the differences between the measured total sunspot areas in the northern (N) and southern (S) hemispheres and their smoothed values (labeled NSM and SSM, respectively).

$$\Delta N = S_N - S_{NSM} \qquad (1)$$

$$\Delta S = S_S - S_{SSM} \qquad (2)$$

We plotted the data for 1697 Carrington rotations. The difference ΔN changed sign 678 times, i.e. on average each 2.502 rotation. ΔS changed sign 715 times, i.e. on average each 2.364 rotations.

Here we come to a very important understanding of fractality and self-organization of solar plasma. The magnetic field as a whole is not described by mean characteristics, and the mean field dynamo reflects only general long-term characteristics. The magnetic field is a not random noise, but it is not a smooth quasi-constant function either.

The statistics of the distribution of positive and negative deviations from the smoothed curve over a time interval of up to one year are shown in Figure. 5. The amplitude of the deviations does not exceed 500 mph.

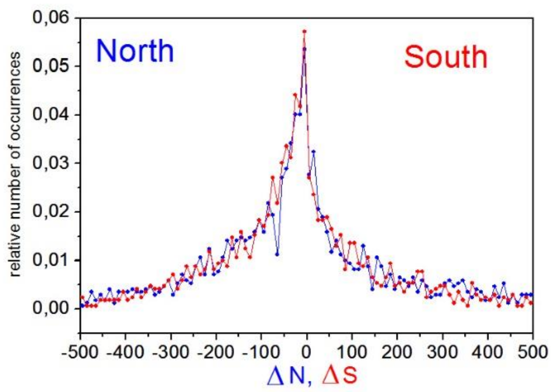

Figure 5. *Distribution of small-scale features, the probability histogram (the abscissa is ΔN –blue, and ΔS (red), the ordinate is the relative number of occurrences.*

We see from this figure 5 that the positive and negative deviations from the smoothed data have a similar probability distribution; however, the positive and negative deviations look independent of each other.

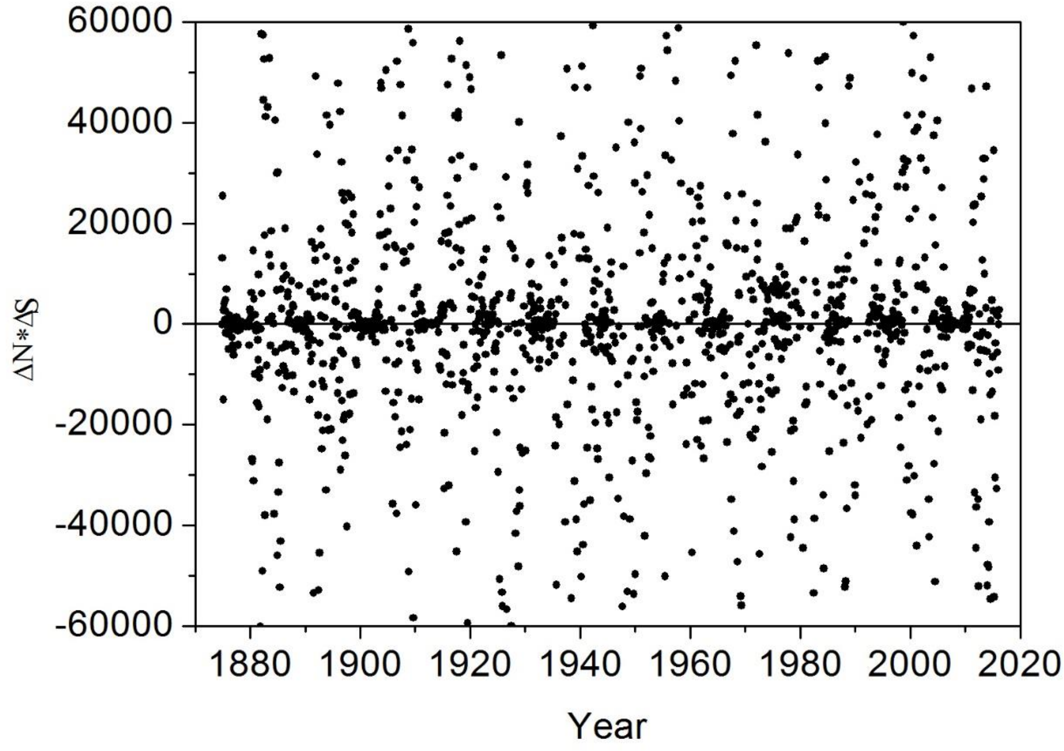

Figure 6. *The dependence of the coincidence index on time.*

To check the degree of coincidence of deviations in the northern and southern hemispheres by sign, the index C (coincidence) = ΔN * ΔS was calculated. Its dependence on time is shown in Figure 6. Obviously, in cases of coincidence of deviations by sign, the value of C is positive and all points should lie above the zero line, in cases of non-coincidence, the points should be below 0. It turned out that out of 1697 points, 881 (51.9%) coincided, and 816 (48.1%) did not coincide, i.e. the number of coincidences was almost equal to the number of non-coincidences, as it should be in the case of independence of two random processes.

Note that such an assessment takes into account only the coincidence or non-coincidence of the signs of the monochrome deviations. Neither the magnitude of the deviation nor its duration are taken into account. To take into account the magnitude and duration, the correlation coefficient of the ΔN and ΔS arrays was calculated. As expected, it turned out to be extremely small and amounted to r0 = –0.0482, which confirms the statistical independence in the northern and southern hemispheres for elements of activity with a lifetime of 2-4 rotations.

5. Conclusions

In summary, we demonstrate that surface magnetic field features such as sunspots and the structure of the mean surface magnetic field behave fundamentally differently in two time intervals, i.e. on time scales shorter and longer than a year. Short-term structures are distributed independently in the northern and southern hemispheres. In contrast, long-term structures are (anti)symmetric about the solar equator and follow the 11-year periodicity. The symmetry is not perfect, but is clearly visible in all data considered.

Thus, the nature of the north-south asymmetry is that it is determined by different processes. In general, the magnetic flux is generated by the global magnetic dynamo and acts equally in both hemispheres, ensuring synchronization of the 11-year cycles. But the spots and groups of spots themselves are created from this flux by a random process that has the same statistical properties in both hemispheres, but acts independently, and therefore the appearance of groups of spots in each hemisphere is not synchronized.

Both observational data and the dynamo model indicate that the immediate subphotospheric layer near the surface plays a key role in the formation of the magnetic butterfly diagram. The role of the leptocline in the solar dynamo has not yet been established. However, this shallow subsurface region is crucial for the formation of sunspots and active regions.

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