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# Latitude Characteristics of the Sunspot Formation Zone and the 11-Year Solar Activity Cycle

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**Abstract**—Using data of the extended Greenwich sunspot catalog for 1874–2006, annual average values of some quantities characterizing the latitude distribution of sunspot activity have been calculated. The quantity describing the width of the sunspot formation zone is closely correlated with the corresponding Wolf numbers. A latitude characteristic has been found that demonstrates in a particular time interval in the fourth year after the maximum of the current 11-year cycle a high correlation with the Wolf number at the maximum of the next cycle. This time interval is characterized by extreme differences between the speeds of the motion of the mean latitude and the upper boundary of the sunspot formation zone. A model displaying good stability and enabling forecasting of the amplitudes of the next 11-year cycles is constructed based on the found correlation. According to these forecasts, the activity of the next (24th) cycle will be 20–30% higher than in the previous one.

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A determining role in the formation and dynamics of solar activity is played by magnetic fields. Sunspots represent one of the most obvious manifestations of local magnetic fields on the Sun. Precisely based on sunspot data, the existence of the 11-year solar-activity cycle was discovered. This cycle was first detected through analyses of sunspot number variations with time, and was called the Schwabe–Wolf Law after the names of its discoverers [1–3].

As early as the 17th century, it was noted that sunspots appear in two latitude zones near the equator, which were later called "royal zones." It is now known [4, 5] that sunspots appear very rarely at heliographic latitudes above 40°. The latitude distribution of sunspots also varies with time cyclically. This phenomenon was first discovered in 1858 by Carrington [6], who noted that sunspots are observed predominantly at heliographic latitudes above ±20° at the beginning of the 11-year cycle, whereas the mean latitudes where they appear are near low latitudes, ±(5°–10°), by the end of the cycle. Somewhat later, Spörer [7], who used a more extensive database, showed that the mean latitude of the sunspot formation zone gradually drifts toward the equator throughout the 11-year cycle. This spatial feature of sunspot formation was called the Spörer law. A vivid illustration of this law is the famous "butterfly diagram," which was first plotted in 1904 by Maunder [8].

It is clear that each of these laws reflects a different aspect of a unified magnetic solar-activity activity. In this connection, searching for correlations between the Schwabe–Wolf and Spörer laws, i.e., between variations in the latitude distribution of sunspots and the solar-activity level, is important for understanding the physical nature of the 11-year cyclicity. In the current paper, we analyze some known correlations between these types of characteristics, and also point out new connections of this kind.

## 1. LATITUDE CHARACTERISTICS OF SUNSPOT ACTIVITY

Widespread indices such as the Wolf number ($W$) and sunspot area summed over the solar disk (SA) are usually used to characterize the sunspot-activity level [5]. The best-known characteristic of the latitude distribution is the mean latitude of sunspot groups weighted with the area of each group (LA). Values of this parameter, together with other characteristics of groups, are given in the famous Greenwich photoheliographic catalog of sunspots, which was begun in 1874 [9].

In 1955, Waldmeier [10] used annual average values of this index to establish a regression relationship linking the mean latitude of sunspot groups at the 11-year cycle maxima ($\mathrm{LA}_{\max}$) and the Wolf number ($W_{\max}$) in these years: $\mathrm{LA}_{\max} = 8.19 + 0.0189 W_{\max}$. The correlation coefficient between these indices is $R = 0.94$, and its reliability (confidence level) exceeds

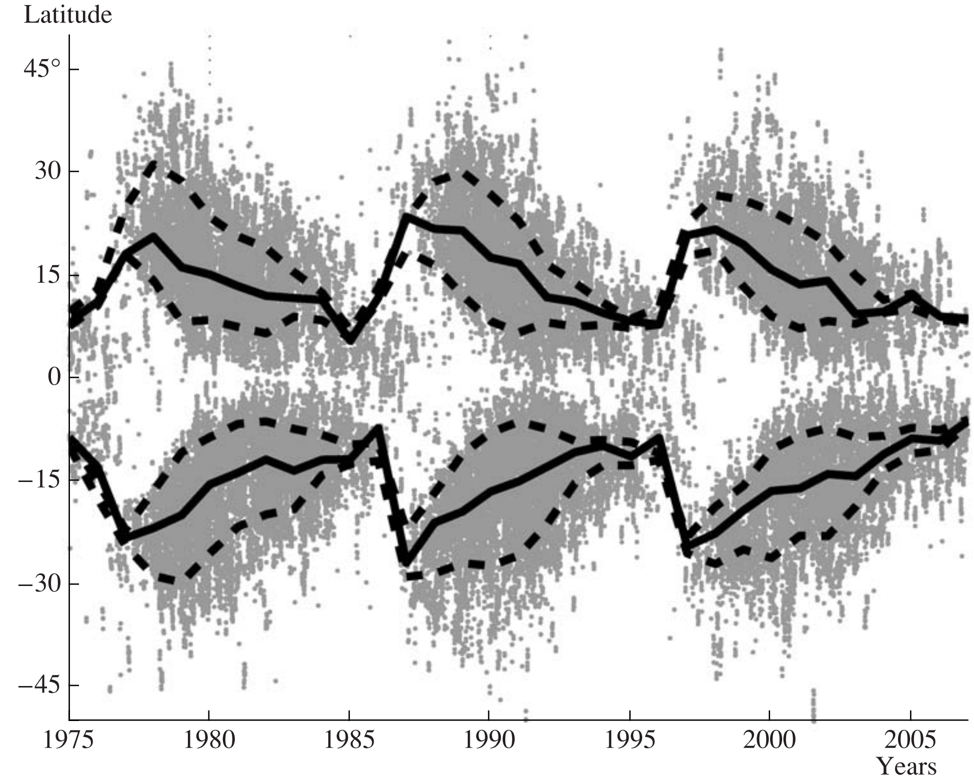


**Fig. 1.** Butterfly diagrams (1930–1976) with plotted average annual sunspot latitudes LA (solid curves), together with the annual average maximum (LAH) and minimum (LAL) latitudes (dashed curves) for each hemisphere.

99.97% ($3\sigma$) (the same is also true of all the correlation coefficients given below). A similar relationship for the sum of the Wolf numbers in a given cycle ($\sum W$) was obtained by Gnevyshev and Gnevysheva [11]: $\mathrm{LA_{max}} = 7.4 + 0.016 \sum W$ ($R = 0.94$). Later, a correlation between the cycle-averaged latitude of sunspot groups ($\mathrm{LA_{cycle}}$) and $W_{\max}$ was established: $W_{\max} = -473.5 + 39.19 \cdot \mathrm{LA_{cycle}}$ ($R = 0.936$) [12]. A recent study of the statistical characteristics of the latitude distributions of sunspots in different cycles [13] found that properties such as the mean sunspot latitude and latitude dispersion in a given cycle are well correlated with each other ($R = 0.96$). However, the correlations between these quantities and other characteristics of the activity level, such as the sum of the sunspot area over the entire cycle, proved to be much lower.

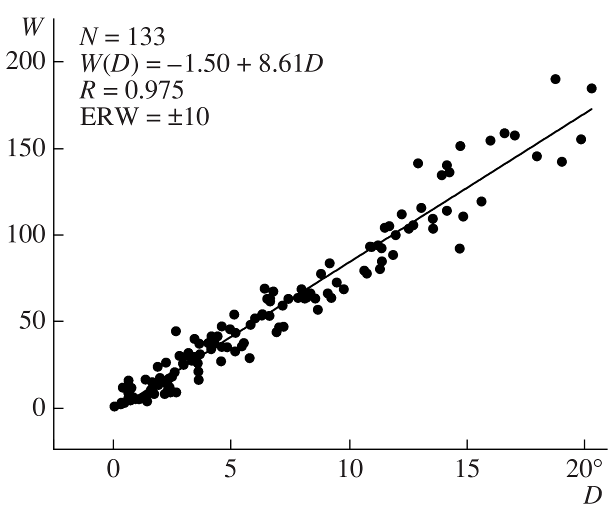


**Fig. 2.** Relationship between the Wolf number ($W$) and the width of the sunspot formation zone ($D$).

We used sunspot data from the Greenwich catalog and its extension (Royal Greenwich Observatory USAF/NOAA Sunspot Data; http://solarscience.msfc.nasa.gov/greenwch.shtml) for 1874–2006 to check the Waldmeier relationship in view of new solar-activity data obtained after 1955. After constructing series of daily, rotation-averaged, and annual average latitudes of sunspot groups weighted with the areas of the groups, we obtained for the annual average indices the relationship $\mathrm{LA_{cycle}} = 9.51 + 0.0577 W_{\max}$ ($R = 0.937$), which testifies that the correlation coefficient has remained virtually unchanged since 1955.

Based on the above relationships, we conclude that latitude indices that are characteristics of

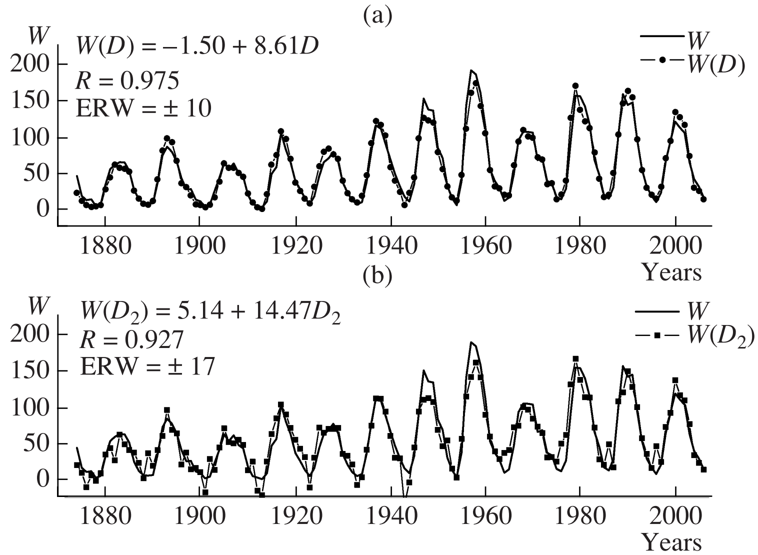


**Fig. 3.** Time variations of annual average values of the (a) Wolf numbers $W$ (solid curve) and model values $W(D)$ (solid curve with circles), and the (b) Wolf numbers $W$ (solid curve) and model values $W(D_2)$ (solid curve with squares).

11-year cycles as a whole are well correlated with the power of these cycles. However, it is important to identify characteristics of the latitude distribution of sunspot groups that are well correlated with the solar-activity level at the same time. One possible such characteristic is the width (latitude extent) of the sunspot-formation zone. In the 1950s, Becker [14] and Gleissberg [15] established that the zone width they introduced as an index, indeed, varies with the phase of the 11-year cycle, reaching its greatest value at the epoch of the cycle maximum. However, they found no dependence of this width on the amplitude of the 11-year cycle or the solar-activity level.

We applied a different technique to calculate the size of the sunspot-formation zone, and then used this together with the Greenwich sunspot data for each day of observations in each hemisphere of the Sun for 1874–2006 to derive the maximum and minimum latitudes of sunspot groups. If only one sunspot group was observed on a given day in a given hemisphere, the maximum latitude was taken to be equal

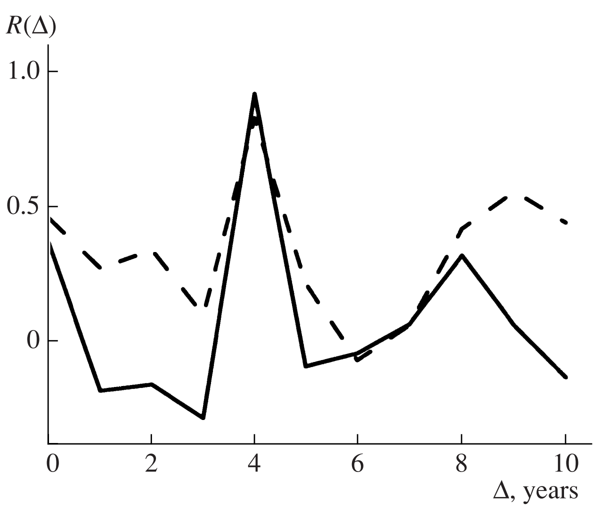


**Fig. 4.** Correlation function $R(\Delta)$ between the Wolf numbers at the cycle maxima and the latitude characteristics $\mathrm{LA}(\Delta)$ (dashed curve) and $\mathrm{LA}(\Delta) - 0.39 \cdot \mathrm{LAH}(\Delta)$ (solid curve) at epochs shifted forward by $\Delta$ relative to the maxima of the preceding cycles.

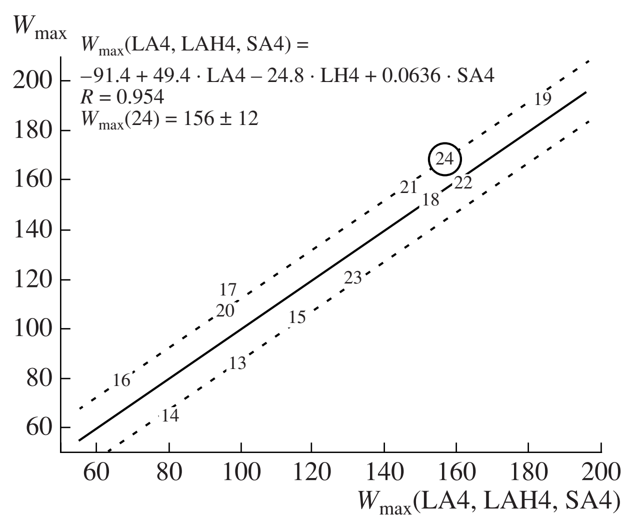


**Fig. 5.** Correlations of the mean latitude (LA4), maximum latitude (LAH4), and sunspot-area index (SA4) in the fourth year of the maximum of the current cycle with the Wolf number at the maximum of the next cycle ($W_{\max}$).

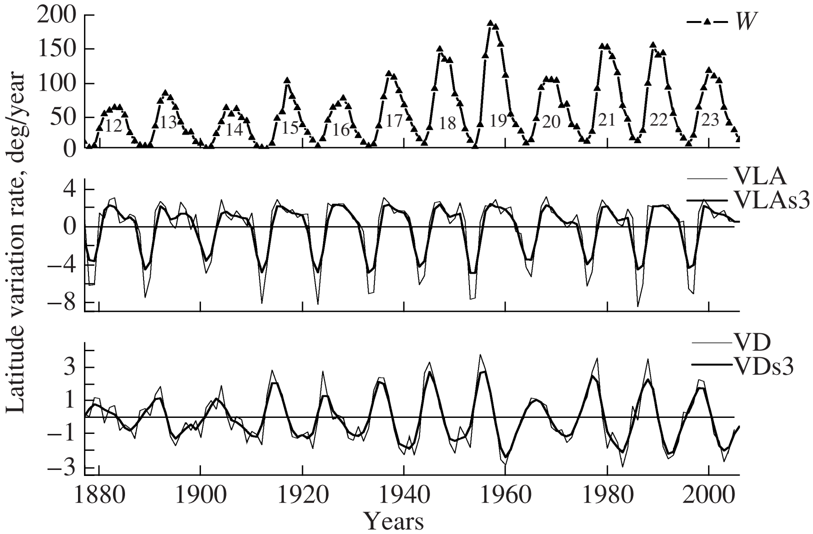


**Fig. 6.** Time variations in the annual average Wolf numbers $W$ (top), the equatorward drift rate of the mean latitude of the sunspot-formation zone VLA (thin curve) and its values smoothed over three years (thick curve) (middle), and the rate of variation of the width of the sunspot-formation zone VD (thin curve) and its values smoothed over three years (thick curve) (bottom). The vertical dashed lines show the fourth year after the maximum in each cycle.

to the minimum. We then obtained the corresponding annual average characteristics based on these daily data (including in the average only days when at least one sunspot group was observed on the solar disk).

Finally, we calculated the arithmetic mean from the two corresponding hemisphere values. We assumed that the resulting annual average values of LAH and LAL characterize the positions of the high-latitude and low-latitude boundaries of the sunspot-formation zone, respectively (Fig. 1). These values certainly do not coincide with the latitudes of the highest or lowest latitude sunspot group observed in a given year. We then calculated their difference $D = \mathrm{LAH} - \mathrm{LAL}$, which is a measure of the width of this zone. Having calculated the difference of the maximum (LAH) and mean (LA) sunspot latitudes, we can determine the analogous characteristic for the upper half-width of the sunspot-formation zone, $D_2 = \mathrm{LAH} - \mathrm{LA}$.

As a result, we obtained from 133 annual average values a regression equation relating the width of the sunspot-formation zone ($D$) with the sunspot-activity level as represented by the Wolf number $W$ (Fig. 2): $W(D) = -1.50 + 8.61D$, with a correlation coefficient of $R(W, D) = 0.975$, and the error of the model $\mathrm{ERW} = \pm 10$, where, by the error of the model ERW, we mean the rms deviation calculated from the observed and model (derived from the equation) series. Note not only the high value of the correlation coefficient, but also the uniform distribution of points along the regression line (Fig. 2). An analogous regression equation, $W(D_2) = 5.14 + 14.47D_2$ ($R(W, D_2) = 0.927$, $\mathrm{ERW} = \pm 17$), was derived to describe the relationship between $W$ and $D_2$.

Using the derived relationship, we can obtain from known annual average values of $D$ model values for the Wolf numbers $W(D)$. A comparison of the latter with the observed values of $W$ (Fig. 3a) demonstrates that the agreement is somewhat poorer near the maxima of the 11-year cycles, while the agreement between the two curves is very good at the phases of increase, and especially of decay, of the cycles. As follows from Fig. 3b, the relationship between $W$ and the upper halfwidth $D_2$ approximates both the maxima and minima of the cycles with lower accuracy. However, on the whole, both relationships reproduce well the observed 11-year cyclicity over the entire interval 1874–2006.

Thus, the obtained relation enables us to judge fairly certainly about the strength of solar (sunspot) activity based on a geometrical characteristic, such as the width of the sunspot-formation zone (calculated from data on sunspot latitudes). The opposite is also true: knowing the sunspot-formation power, we can estimate to good accuracy the width of the corresponding zone. This regularity quantitatively confirms the existence of a deep connection between changes in the latitude distribution of sunspots and the sunspot-activity level.

## 2. LATITUDE CHARACTERISTICS OF SUNSPOT ACTIVITY AS FORECASTING PREDICTORS

Another important question is whether the correlations between the latitude and power characteristics of sunspot activity are conserved if they are separated in time. To answer this question, we studied the dependences between the Wolf number at the maximum of the 11-year cycle and the latitude characteristics of the activity several years before this maximum. We first calculated the correlation between the Wolf numbers at the cycle maxima and the mean sunspot latitude at a time $\Delta$ (in years) after the maximum of the previous cycle as a function of the lag $\Delta$ (dashed curve in Fig. 4).

This dependence has a pronounced maximum at $\Delta = 4$ years. Composing a linear combination of the latitude characteristics LA, LAH, and LAL taken with the same lag and fitting the coefficients of the linear function to get the maximum correlation coefficient, this is achieved with the linear combination $\mathrm{LA} - 0.39 \cdot \mathrm{LAH}$ (solid curve in Fig. 4). This relationship can readily be converted to the form $W_{\max}(\mathrm{LA2}, \mathrm{LAH4}) = -144.6 + 54.0 \cdot \mathrm{LA4} - 21.1 \cdot \mathrm{LAH4}$, which relates the annual values of the mean (LA4) and maximum (LAH4) latitudes in the fourth year after the maximum of the current cycle with the Wolf number in the maximum of the following cycle ($W_{\max}$).

The obtained expression displays a high correlation coefficient between the observed and model Wolf numbers at the maxima, $R = 0.919$, and can be utilized to forecast the amplitude of the next solar-activity cycle. It forecasts for the maximum of cycle 24 an annual average value $W_{\max}(24) = 153 \pm 16$. If we include the total sunspot-area index in the fourth year after the maximum (SA4) in addition to the latitude characteristics among the independent variables, the accuracy of the derived ratio ($W_{\max}(\mathrm{LA4}, \mathrm{LAH4}, \mathrm{SA4}) = - 91.4 + 49.4 \cdot \mathrm{LA4} - 24.8 \cdot \mathrm{LAH4} + 0.0636 \cdot \mathrm{SA4}$) increases considerably ($R = 0.954$). In this case the predicted magnitude of the maximum of cycle 24 is $W_{\max}(24) = 156 \pm 12$ (Fig. 5).

The values we have obtained for the maximum of the Wolf number in cycle 24 are consistent with various forecasts (see, e.g., [16–19]) that predict a higher amplitude for cycle 24 than for cycle 23 ($W_{\max}(23) = 119.6$). A detailed review of various forecasting techniques was written recently by Obridko and Shelting [20]. Previous forecasts of a high amplitude for cycle 24 are based either on the dynamo model [16, 17] or data on "geomagnetic precursors" [18, 19]. In contrast, our approach is based on latitude and power indices of the sunspot activity derived from observations.

The interpretation of the results could be simplified if we can find solar characteristics with conspicuous features near the fourth year after the maximum Wolf number. In the series of annual average sunspot indices ($W$ and SA), the fourth year does not stand out in any way. We attempted to find the desired feature in the latitude characteristics. For this purpose, we calculated the annual average rates of the drift of the mean (VLA) and maximum (VLH) latitudes of the sunspot-formation zone toward the equator, together with their differences (VD = VLA − VLH), which can be interpreted as the mean rate of change in the width of the sunspot-formation zone.

We found that, in each cycle, the fourth year after the Wolf-number maximum (vertical dashed lines) falls close to the epoch of the change in sign of the velocity of the mean latitude (VLA) of the sunspot zone (middle graph in Fig. 6). In other words, at this epoch, the equatorward direction of the mean latitude drift reverses. Furthermore, as a rule, this is one of the years following the VD minimum, which corresponds to the lower extremum of the rate of change in the width of the sunspot-formation zone (bottom graph in Fig. 6). This corresponds to the epoch when the drift velocity of the upper boundary of the sunspot zone (VLH) most exceeds the drift velocity of the mean latitude (VLA). Note also that the VD maxima (bottom graph in Fig. 6) lead the Wolf-number maxima by, on average, two years, and the VD value is already close to zero at the latter maxima.

## 3. CONCLUSION

We have established a correlation between the solar-activity level and some characteristics of the latitude distribution of sunspots. In particular, throughout the 11-year cycle, the characteristic width of the sunspot-formation zone is fairly tightly correlated with the current solar-activity level. This regularity imposes certain constraints on possible theoretical models describing the temporal and spatial features of solar activity.

In addition, we have identified the presence of correlations between the solar-activity level and the latitude distribution of sunspots on various time scales. These correlations can be used to make predictions about the maxima of following 11-year activity cycles. In particular, we have used the latitude characteristics of sunspot groups in the decay phase of cycle 23 to obtain a forecast for the annual average Wolf number for the maximum of cycle 24, which suggests that the activity will be 20–30% higher in the next cycle than it was in the previous one.

The regularity we have found can be used as a diagnostic to identify the most adequate physical models of solar cyclicity.

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