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Special Points in 11-Year Variations in the Latitudinal Characteristics of Sunspot Activity

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Abstract—It has been indicated that special moments (turning points), when certain characteristics of the latitudinal (equatorward) drift of the sunspot drift zone suddenly change, exist in each 11-year solar cycle. The moment when a sunspot formation low-latitude boundary minimum (T2), coordinated in time with the end of a polar magnetic field polarity reversal, exists has a special place among these points. A conclusion has been drawn that it is impossible to reconstruct polarity reversal moments in the past based on information about turning points T2.

The average velocities of the latitudinal drift of the minimal, average, and maximal sunspot group latitudes have been calculated. It has been indicated that the closeness of the relationship between the first two velocities and the maximal activity amplitudes in the cycles differ substantially for the first (before point T2) and second (after point T2) cycle parts. The corresponding values of the correlation coefficients increase substantially in the second cycle (after point T2).

It has been established that a relationship exists between some velocities calculated in these cycles and the activity amplitudes at maximums of the next cycles.

A model for predicting future cycle maximums has been constructed based on this conclusion. The probable average annual Wolf number at a maximum of cycle 24 has been determined (W(24) = 93).

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1. INTRODUCTION

It is known that different states (phases), separated by moments after which the solar regime activity usually changes substantially, are clearly defined in each 11-year cycle. Such critical moments were for the first time revealed as parameters during studying the behavior of cyclic curves of indices, which characterize sunspot activity, and were called "reference" (Vitinsky et al., 1986), "inflection" (Kuklin, 1992), and "turning" (Badalyan and Kuklin, 2000) points. Thus, the achieved results were analyzed in detail and a list of inflection points in the cycles was presented in (Kuklin, 1992) for the Wolf number.

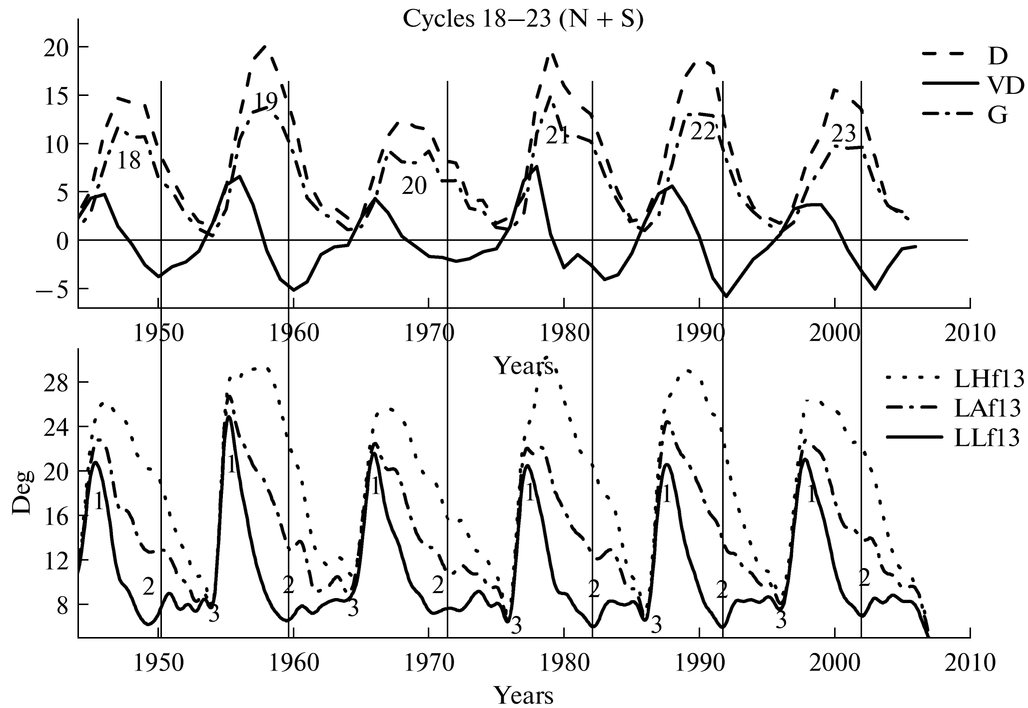
In addition, such turning points were detected in cyclic curves of coronal (in the 5303 A FeXIV green line) (Badalyan and Kuklin, 1993) and global magnetic field (Obridko and Shelting, 1992, 2003) indices.

The performed studies indicate that the positions of turning points (and the duration of the corresponding phases between them) can slightly differ from cycle to cycle. However, the moments of the corresponding turning points are generally close in time for most indices, apparently, because the processes responsible for these indices are common, although the physical mechanisms by which this phenomenon originates are still unclear.

The aim of this work is to determine and study the turning points in cyclic variations in the sunspot activity latitudinal characteristics, which were studied in (Miletsky and Ivanov, 2009; Nagovitsyn, 2010; Ivanov et al., 2011; Ivanov and Miletsky, 2011). Note that the parameters of the sunspot formation drift zone depend on the accepted solar cycle model. Therefore, the study of the solar cycle regularity makes it possible to better understand the solar cyclicity character and regularities and, finally, the cyclicity nature.

2. DATA AND THEIR PROCESSING

We used the data on the sunspot characteristics presented in the Greenwich catalog and its continuation NOAA/USAF for 1874–2006 (http://solarscience.msfc.nasa.gov/greenwch.shtml). Based on these data, series of annual values of the following indices for either solar hemisphere were compiled: the sunspot group number (G), average sunspot group latitudes weighed for the sunspot area (LA), and the maximal (LH) and minimal (LL) sunspot group latitudes on a given day. Detailed calculations of these indices are presented in (Miletsky and Ivanov, 2009; Ivanov and Miletsky, 2011). From daily data, we obtained average rotation, as well as average annual, values of these indices. It is clear that the average annual values of the



Top panel presents time variations in a series of the average annual values (cycles 18–23) of the sunspot group number index (G, dot-and-dash line), sunspot formation zone width (D = LH – LL, dashed line), and the velocity of a change in this width (VD, solid line). The bottom panel presents time variations in a series of the average rotational values (moving averaging over 13 rotations) of the sunspot activity latitudinal characteristics (cycles 18–23): maximal (LHf13, doted line), average (LAf13, dot-and-dash line), and minimal (LLf13, solid line) sunspot latitudes.

LH and LL indices characterize the average annual position of the sunspot formation zone at the high- and low-latitude boundaries, whereas the difference in these values (D = LH – LL) characterizes the latitudinal extent of this zone. In addition, from the average annual LA and D values, we obtained the velocities of the average latitude equatorward drift (VLA) and variations in the sunspot formation zone width (VD) by means of finite-difference time differentiation over three points.

3. RESULTS

The bottom panel of figure presents curves demonstrating (for cycles 18–23) time variations in the series (obtained through the transformation of the average rotational values by using the method of moving averages with harmonic weights for 13 rotations) of sunspot activity latitudinal characteristics: average sunspot group latitudes (LAf13), maximal sunspot latitudes (LHf13), and minimal sunspot latitudes (LLf13). It is clear that moments T1, T2, and T3, which are marked with numerals 1, 2, and 3 in figure and can be characterized as special (turning) points of the latitudinal cyclic curves, are clearly defined in each 11-year cycle. In this case, points T1 represent the moments of maximums of the lower and middle latitudes (curves LLf13 and LAf13); points T2, the moments when the lower latitude local minimums are reached (curve LLf13); points T3, the moments when the minimum of all latitudes is reached.

The top panel of figure shows curves reflecting time variations in the average values of the G, D, and VD indices for the same cycles. A comparison of the plots shown in the top and bottom panels of figure makes it possible to conclude that special points T1 are always observed during the 11-year cycle growth phases (curve G) and correspond to the moments when the sunspot zone latitudinal expansion velocity becomes maximal (curve VD). Special points T2 are observed during the cycle decline phases and are located near the moments when the sunspot zone latitudinal contraction velocity is maximal (curve VD minima) and near the moments of polar magnetic field polarity reversals (Makarov and Makarova, 1996; Tlatov, 2007) (vertical solid lines). In addition, point T2 corresponds to the t_{MD} reference point, which is revealed on the Wolf number curve, is observed one to two years after the maximum of this index, and coincides in time with the maximums of the sunspot group power and the number of proton flares and other phenomena characterizing the so-called “secondary” cycle maximum introduced by M.N. Gnevyshev (Vitinskii et al., 1986; Kuklin,1992; Obridko and Shelting, 1992). Singular points T3 are observed near minimums of the 11-year sunspot activity cycles.

Table 1. Correlation coefficients between activity maximums in cycles and the drift velocities of the minimal, maximal, and average sunspot latitudes

N&S	V12LL	V12LA	V12LH	V23LL	V23LA	V23LH
G(n)	0.21	0.08	0.73	0.59	0.44	0.81
D(n)	0.26	0.07	0.78	0.63	0.45	0.83
G(n + 1)	0.18	0.43	0.45	0.10	0.56	0.37

Table 2. Prognostic model parameters and prediction of the cycle 24 maximum

$W_{n+1} = -0.6 + 0.57V23LA_n + 1.7V12LA_n^2 + 1.5V23LA_n^2 + 3V12LA_nV23LA_n$	R(N + S) = 0.83	W(24) = 93

We subsequently calculated the average latitudinal drift velocities (ratios of latitudinal differences to time) of the minimal LL, average LA, and maximal LH sunspot group latitudes (V12LL, V12LA, V12LH, V23LL, V23LA, V23LH) for the time intervals separating points T1, T2, and T3. Table 1 presents the linear correlation coefficients between these values and the average annual values of the G and D indices at maximums of the current (n) and next (n + 1) 11-year cycles (from 12 to 23) based on data for both hemispheres (24 points).

On the T1–T2 interval (see Table 1), a correlation between the maximal activity amplitudes in the cycles and the drift velocities of the minimal and average sunspot latitudes (V12LL, V12LA) is almost absent. This agrees with the results achieved in (Vitinsky et al., 1986; Hathaway, 2011); the authors stated that the average drift velocity of the sunspot zone width for an 11-year cycle is independent of the cycle amplitude. However, a substantial and significant (reliability 99.9%) correlation between activity and the maximal latitude drift velocity (V12LH) is found in the same time interval.

In the T2–T3 interval (after a polarity reversal of the polar magnetic field), it turns out that the activity at cycle maximums correlates with the drift velocity of not only maximal (reliability 99.95%), but also minimal (reliability 99%) and even average (reliability 95%), latitudes. Thus, the character of interrelationships between the latitudinal drift velocities of the minimal and average sunspot latitudes and the current activity cycle amplitude changes substantially at point T2.

The value of the correlation between the above sunspot characteristic latitudinal velocities (see Table 1, bottom raw) and the activity at maximums of the next 11-year cycle G(n + 1) made it possible to use these velocities as initial variables when we constructed a model for predicting future Wolf number maximums (W_{n+1}) in these cycles. We found an optimal prognostic model using the Argument Grouped Consideration Method (MGUA or MGDH) (Farlow, 1984; Ivakhnenko and Myuller, 1984; Madala and Ivakhnenko, 1994; Miletsky, 2004; Miletsky and Ivanov, 2006), which makes it possible to select an optimal model from all possible models based on the so-called "external" criteria. Such external criteria can reach a minimum at a gradual sophistication of the model, which makes it possible to select an optimal model. This method makes it possible to avoid any additional sophistication of the model and eliminate variables not bearing additional information.

We sought an optimal model among all possible polynomials, the degrees of which were no higher than 3 for all points from the N and S hemispheres (24 points). As a result, using the MGUA model, we obtained an optimal model, the parameters and accuracy of which (the correlation coefficient between the model and real values R(N + S)) are presented in Table 2. We should note that we selected the drift velocities of the sunspot average latitudes before and after special point T2 (V12LA, V23LA) as optimal model variables.

The last column in Table 2 presents the predicted model value of the average annual Wolf number at the cycle 24 maximum: W(24) = 93. This value corresponds to several predictions, according to which the next cycle will be slightly lower than cycle 23 (Petrovay, 2010).

4. CONCLUSIONS

The performed study indicates that special moments (turning points), when the characteristics of the latitudinal (equatorward) sunspot zone drift change suddenly, are observed during 11-year solar cycles. The moment when a low-latitude boundary minimum of the sunspot formation zone (T2) is reached, which agrees with the end of the polar magnetic field polarity reversal, is of special significance. This indicates that an interrelationship exists between these phenomena and makes it possible to reconstruct special moments in the past (specifically, polarity reversals) in the evolution of the large-scale magnetic field based on information on turning points of latitudinal sunspot characteristics (Nagovitsyn, 2010).

We also determined that the correlation between the latitudinal drift velocities and the activity level at the current-cycle maximum sharply increases in the T2–T3 interval, i.a., during the 11-year cycle decline. This is apparently related to the previously established close relationship between the latitudinal extent of the sunspot zone and the sunspot activity level (Miletsky and Ivanov, 2009; Ivanov et al., 2011; Ivanov and Miletsky, 2011).

We found out that some parameters of the sunspot latitudinal drift velocities in individual intervals between special points (especially in the T2–T3 interval) substantially correlate with the activity amplitude at the next cycle maximum. This agrees with a previously achieved result (Miletsky and Ivanov, 2009), according to which the latitudinal characteristics of sunspot activity during the decline phase can bear information regarding the properties of the next 11-year cycle. We should also note that the velocity value in different intervals between different special points can be differently related to the properties of the next 11-year cycle. This information allowed us to construct a model for predicting maximums in the next cycles.

We can conclude that the results achieved in this work make it possible to better understand the determining properties of 11-year cycles and lead to an increased quality in predicting the future behavior of solar activity.

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