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Correlations between Time Intervals that Separate Special Points in Neighboring 11-Year Sunspot Cycles

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Abstract—The correlations between series of lengths of intervals that separate special points of sunspot activity, which were determined by toroidal and poloidal magnetic fields in neighbor 11-year cycles, were studied. A high correlation is revealed between the series of lengths of intervals that separate special points of sunspot activity related to the toroidal field. A correlation was calculated between series of the lengths of intervals that separate axial dipole and octupole reversal time points in neighbor cycles. A correlation was revealed between series of the lengths of intervals that correspond to dipole (octupole) reversal time points and series of the lengths of intervals that correspond to special points of sunspot activity. Hence, features of the physical relationships between toroidal and poloidal fields in the current and next 11-year cycles were ascertained.

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1. INTRODUCTION

The 11-year sunspot cycle is basically a magnetic cycle determined (according to the dynamo theory) by evolution, interaction, and mutual transformation of the toroidal and poloidal components of the solar magnetic field; these are usually called the toroidal and poloidal fields (Karak et al, 2014).

Sunspots are considered as good indicators of the toroidal field (Karak et al, 2014), and the 11-year sunspot cycle is naturally divided into phases, which are separated by special time points. Data on these time points allow important properties of cycles to be ascertained (Hathaway, 2010; Miletsky and Nagovitsyn, 2012). Such special points are, in particular, the maximum and minimum points in sunspot activity cycles and special points in cyclic variations in latitudinal parameters of this activity (Miletsky and Nagovitsyn, 2012).

Other type of special points include the time points of polar magnetic field reversals (Makarov and Makarova 1996; Tlatov, 2007), as well as time points of reversals of small-order modes (dipole and octupole) of the large-scale solar magnetic field (Makarov et al., 2003; Tlatov, 2007). It is commonly accepted that this (poloidal) type separates phases of cycle evolution of the poloidal magnetic field.

Special points of the evolution of toroidal and poloidal fields in neighboring cycles are separated by time lags (intervals); a correlation between their lengths can indicate the presence of important features in the relationships between these two types of magnetic fields.

Therefore, our goal was to verify the degree of correlation between lengths of intervals that separate special points in neighbor 11-year cycles.

2. DATA AND THEIR PROCESSING

In this work, the special points of the sunspot activity were determined on the basis of sunspot data from the extended Greenwich–NOAA/USAF catalog (http://solarscience.msfc.nasa.gov/greenwch.shtml) for 1874–2014 (cycles 12–23).

The following data were taken: the annual average and rotation average series of the sunspot group index (G) and other sunspot latitudinal parameters, in particular, the latitudes of the highest (LAH) and lowest (LAL) boundaries of sunspot zone, the latitudinal size of sunspot zone (D = LAH–LAL), and the rate of variation in the latitudinal size of sunspot zone (VD). The series of annual average values of these parameters was used earlier (Miletsky and Ivanov, 2009; Ivanov and Miletsky, 2011).

A smoothed series was formed of the rotation average values of the sunspot group index (G) with the use of a 13-point window with cosine weights. The cycle maxima time points (TGmax) were found for the series (Ivanov and Miletsky, 2014). In this work, we also used a series of rotation average values of the mean sunspot activity index (GM), each term of which is the mean value of G calculated over the number of rotations between the cycle minimum and the current rotation. A series of the mean sunspot activity was formed from the rotation average GM values. It is plotted in Fig. 1 for cycles 20–23; the dates of cycle

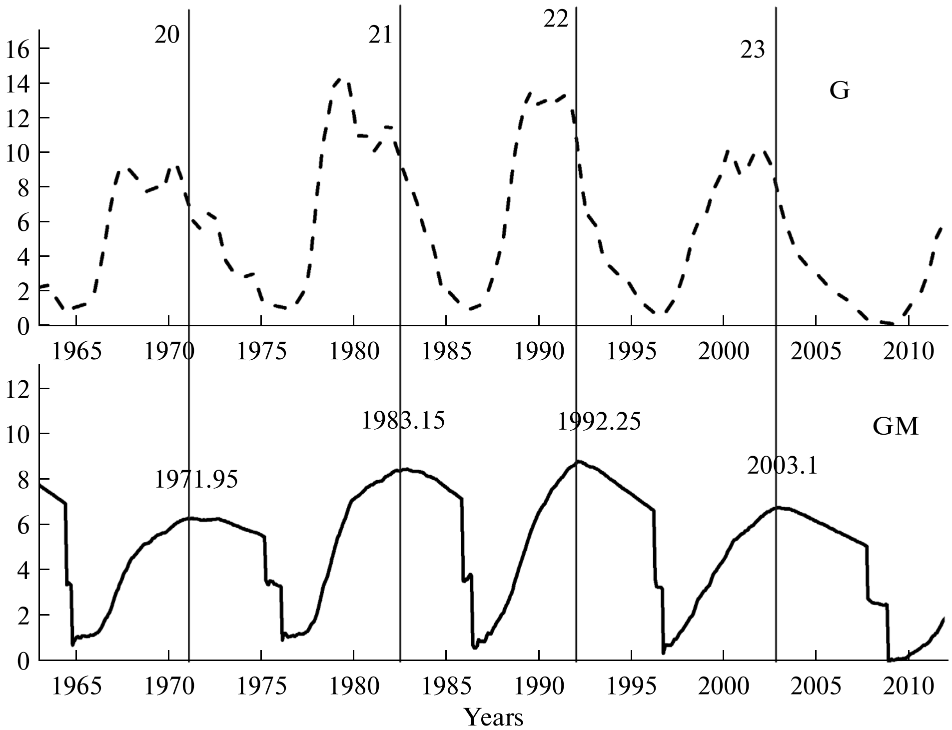

Fig. 1. Variations in the mean sunspot activity index CM (bottom, rotation average values are shown by the solid curve) and the sunspot group index G (top, smooth rotation average values are shown by the dashed curve) for cycles 20–23. The dates of the index G maxima GM are shown.

maxima TGMmax and amplitudes of the maxima GMmax for cycles 12–23 are given in Table 1.

Sunspot special points also include special points revealed in cyclic variations in the latitudinal parameters of the sunspot activity, i.e., the latitude phase reference point (LPRP) (Tst) found from the midlatitude trajectory of sunspot groups in a cycle (Ivanov and Miletsky, 2014; Miletsky and Ivanov, 2014), the time when the smoothed midlatitude curve approaches 15°-latitude sunspots (T15) (Miletsky and Ivanov, 2015), the time point of minimal latitude (TLLmin) of the lowest boundary of sunspot zone (LL) (Miletsky and Nagovitsyn, 2012; Miletsky et al., 2015), and the extreme point (TVDmin) of the rate of decrease in the latitude size of sunspot zone (VD) (Miletsky and Ivanov, 2009; Miletsky et al., 2015).

Dates of maxima points TGMmax and amplitudes of the maxima GMmax of the mean activity index GM from data on cycles 12–23

Cycle	TGMmax	GMmax
12	1885.5	3.58
13	1895.7	5.23
14	1908.9	3.66
15	1919.7	5.21
16	1930.2	5.18
17	1940.2	6.12
18	1950.0	7.79
19	1959.9	9.38
20	1972.0	6.42
21	1983.2	8.57
22	1992.3	8.92
23	2003.1	6.88

Poloidal special points include the point of polar magnetic field reversal (Trev) determined from Hα maps (Makarov and Makarova 1996; Tlatov, 2007; Tlatov, 2009) and points of axial dipole (Tdip) and octupole (Toct) reversals, which are also determined from the Hα maps (Makarov et al, 2003; Tlatov, 2007).

The lengths of intervals determined by these special points that separate similar time points in neighboring cycles with the numbers (n) and $(n + 1)$ were calculated. In particular,

$$\mathrm{TTst} = \mathrm{TTst}(n + 1) - \mathrm{Tst}(n),$$

$$\mathrm{TTmax} = \mathrm{TGmax}(n + 1) - \mathrm{TGmax}(n),$$

$$\mathrm{TTGMmax} = \mathrm{TGMmax}(n + 1) - \mathrm{TGMmax}(n),$$

$$\mathrm{TTLLmin} = \mathrm{TLLmin}(n + 1) - \mathrm{TLLmin}(n),$$

$$\mathrm{TTdip} = \mathrm{Tdip}(n + 1) - \mathrm{Tdip}(n), \text{ and so on.}$$

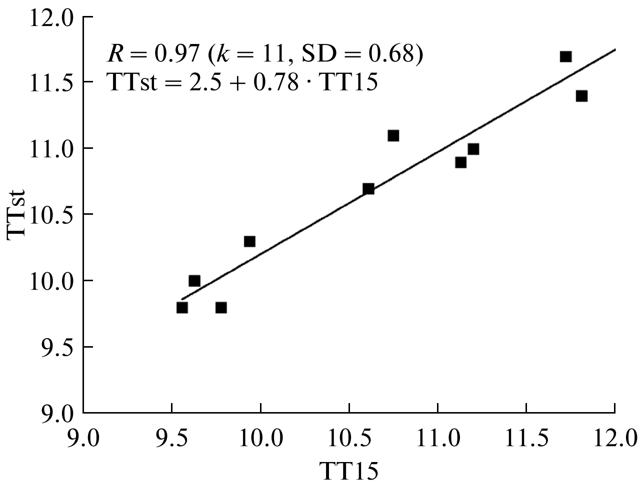

Fig. 2. Scatter plot of the TTst interval lengths versus the TT15 interval length.

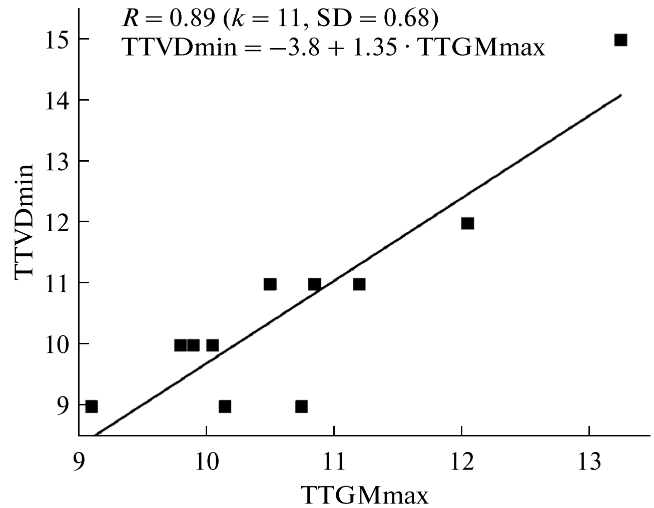

Fig. 3. Scatter plot of the TTVDmin interval length versus the TTGMmax interval length.

The lengths of these intervals in cycles 12–23 form a series that includes similar selected points. The correlation coefficients were calculated for each pair of this series.

3. RESULTS

Let first consider consider the most significant correlations between the sunspot activity points selected.

The correlations (see Fig. 2) between the series of TTst intervals, which separate the LPRP in neighboring cycles, and the series of TT15 and TT20 intervals, which separate the times when the smoothed midlatitude curve approaches 15° (T15) and 20° latitude sunspots (T20), respectively, are the highest (R(TTst, TT15) = 0.97 and R(TTst, TT20) = 0.88). Note that the confidence levels exceed 99.9% (CL > 99.9%) for all correlation coefficients found in this work; therefore, they are omitted below.

The corresponding regression equation for TTst and TT15 is

$$\mathrm{TTst} = \mathrm{A0} + \mathrm{A1} \cdot \mathrm{TT15},$$

where A0 = 2.50, A1= 0.78 ($R = 0.97$, $k = 11$, $SD = 0.69$). Hereinafter, SD is the standard error of the regression equation.

This equation and the known T15 and Tst points in the nth cycle and T15 (or T20) in the $(n + 1)$th cycle (and, hence, corresponding TT15 and TTst intervals) allow calculation of LPRP in the $(n + 1)$th cycle with a high accuracy, without plotting of the corresponding exponent.

A high correlation is also revealed between the series of the lengths of intervals TTLLmin, TTGMmax, and TTVDmin (R(TTGMmax, TTVDmin) = R(TTLLmin, TTGMmax) = 0.89) (Fig. 3).

The results indicate strong correlations between such events as attainment the minimal latitude of the lowest boundary of sunspot zone (TLLmin) in the cycle, the extreme point of the rate of decrease in the latitudinal size of sunspot zone (TVDmin), and the time of cycle maximum of the mean sunspot activity (TGMmax). The corresponding equation for TVDmin and TGMmax is

$$\mathrm{TTVDmin} = \mathrm{A0} + \mathrm{A1} \cdot \mathrm{TTGMmax},$$

where A0 = −3.80 (±2.4), A1 = 1.35 (±0.23) ($R = +0.89$, $k = 11$, $SD = 0.68$).

Again, the most significant correlations were found between the lengths of TTdip, TToct, and TTrev intervals, which separate poloidal time points (Trev, Tdip, and Toct) in neighboring cycles. The highest correlation was revealed between the series of lengths of TTdip and TToct intervals (R(TTdip, TToct) = 0.80); this is evidently explained by the fact that these lengths correspond to the times of axial dipole (Rdip) and octupole (Toct) reversals, which are, in turn, close to the lowest modes in the expansion of the global magnetic field into spherical harmonics.

Despite the ambiguities in the procedure of detection of the time of polar magnetic field reversal (Trev), the correlation coefficients between the intervals that correspond to Trev and Toct are quite significant (R(TToct, TTrev) = 0.78).

In the next stage, the highest correlations between the lengths of intervals that correspond to poloidal special points and the lengths of intervals that correspond to the sunspot special points selected are considered.

In this case, the highest correlation (Fig. 4) was between the series of the lengths of intervals that correspond to the octupole reversal points (Toct) and the

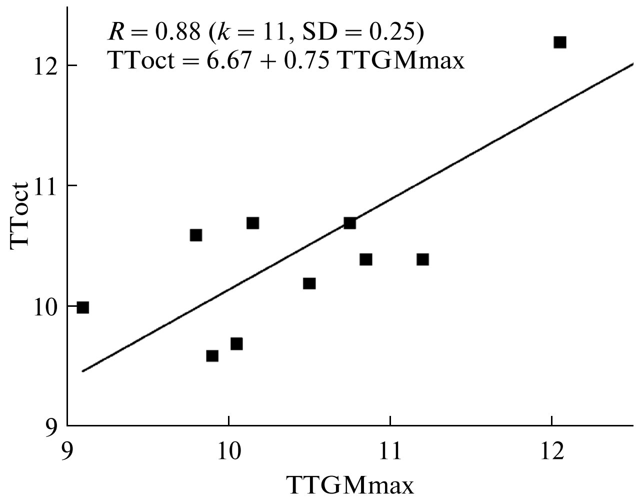

Fig. 4. Scatter plot of the TToct interval length versus the TTGMmax interval length.

lengths of intervals that correspond to cycle maxima of the mean sunspot activity (R(TToct, TTGMmax = 0.88). The corresponding equation for TToct and TTGMmax is

$$\text{TToct} = \text{A0} + \text{A1} \cdot \text{TTGMmax},$$

where A0 = 6.675281 (±0.26), A1 = 0.75(±0.14) (R = +0.88, k = 11, SD = 0.25).

A lower (but also significant) correlation (R(TTdip, TTLLmin) = 0.81) was revealed between the series of the lengths of intervals that correspond to dipole reversals (Tdip) and the series of the lengths of intervals that correspond to the time points of minimal latitude of the lowest boundary of sunspot zone (TLLmin). These results allow calculation of the dipole Tdip(n + 1) and octupole Toct(n + 1) reversal times in the (n + 1)th cycle from data on the length of the 11-year cycle found, correspondingly, from the intervals that correspond to the cycle minima of the lowest boundary of sunspot zone latitude (TLLmin) and the cycle maxima of the mean sunspot activity TGMmax.

The correlations found during this stage between the lengths of intervals determined by toroidal and poloidal fields obviously indicate the presence of physical relationships between these fields in neighboring cycles. This holds promise for the future reconstructions of past time points of axial dipole (Tdip) and octupole (Toct) reversals on the basis of data on special points of the sunspot activity.

4. CONCLUSIONS

1. A high correlation is revealed between the series of the lengths of the TTLLmin, TTGMmax, and TTVDmin intervals that separate special points of the sunspot activity in neighboring 11-year cycles, such as the time of approaching the minimal latitude of the lowest boundary of sunspot zone (TLLmin) in a cycle, the extreme point of the rate of decrease in the latitudinal size of sunspot zone (TVDmin), and the cycle maximum of the mean sunspot activity (TGMmax). This indicates the presence of physical relationships between events (special points) of the cyclic evolution of a toroidal magnetic field in the current and a neighboring cycle.

2. A high correlation is also revealed between the series of the lengths of TTdip and TToct intervals, which separate the axial dipole (Tdip) and octupole (Toct) reversal points in neighboring cycles (close modes of a poloidal magnetic field).

3. The most important result is the significant correlation between the series of lengths of intervals that correspond to the dipole (Tdip) and octupole (Toct) reversal times and the series of the lengths of intervals that correspond to special points of sunspot activity.

The correlations between the lengths of intervals determined by toroidal and poloidal fields reveal features of the physical relationships between these fields in the current and the next 11-year cycles. This can promote the reconstruction of past time points that relate to the poloidal field through the use of data on sunspot activity time points that relate to the toroidal field.

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