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Changes of Solar Magnetic Asymmetry

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Abstract—The results of an analysis of the north–south asymmetry in solar activity and solar magnetic fields are reported. The analysis is based on solar mean magnetic field and solar polar magnetic field time series, 1975–2015 (http://wso.stanford.edu), and the Greenwich sunspot data, 1875–2015 (http://solarscience.msfc.nasa.gov/greenwch.shtml). A long-term cycle (small-scale magnetic fields, toroidal component) of ~140 years is identified in the north–south asymmetry in solar activity by analyzing the cumulative sum of the time series for the north–south asymmetry in the area of sunspots. A comparative analysis of the variations in the cumulative sums of the time series composed of the daily values of the sun's global magnetic field and in the asymmetry of the daily sunspot data over the time interval 1975–2015 shows that the photospheric large-scale magnetic fields may also have a similar long-term cycle. The variations in the asymmetry of large-scale and small-scale solar magnetic fields (sunspot area) are in sync until 2005.5 and in antiphase since then.

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INTRODUCTION

Solar activity is a collective term for the various phenomena and processes associated with the formation and decay of magnetic fields in the solar atmosphere. The best understood manifestation of solar activity is the change in the number of sunspots, which were first observed through a telescope by Galileo Galilei in 1610. Although the physical nature of sunspots had been unclear until the 20th century, astronomers continued observations to obtain a fairly extensive series of sunspot numbers by the mid-19th century. In 1843, Heinrich Schwabe noticed the periodicity of solar activity, and Rudolf Wolf introduced a solar activity indicator, i.e., the Wolf number, in 1848. Today, it is known that, in addition to the main 11-year harmonic, Wolf numbers have a long-period component of approximately 80–90 years (the Gleissberg cycle). The use of radioisotope data helped reveal a periodicity of approximately 205 years (the Suess cycle). In addition to Wolf numbers, there is an index for the surface area of sunspots. This series begins in 1874. These data can provide information on solar activity by hemisphere and on the asymmetry in solar activity.

In 1908, George Hale discovered magnetic fields in sunspots [11]; later, it was found that, during each 11-year cycle, all the leading sunspots in bipolar groups have the same polarity in the northern hemisphere and the opposite polarity in the southern hemisphere [12]. In the next cycle, the polarity of the sunspot magnetic field is reversed in both the northern and southern hemispheres (Hale's polarity law). Thus, the length of the physical cycle of solar activity is 22 years.

Apart from strong fields in sunspots, the sun has a weak (~1 mT) dipole (poloidal) type magnetic field. In 1959, Babcock [5, 6] found that this field reverses its polarity from cycle to cycle and this change occurs at the peak of the 11-year solar cycle. Thus, the complex pattern of solar activity over a large time scale is defined by a superposition of many cycles.

A distinctive feature of solar activity is its asymmetry relative to the northern and southern hemispheres. As early as at the end of the 19th century, Spörer and Maunder noticed an asymmetry in sunspot activity. The first detailed study of this phenomenon was made in [14]. Later, it was found that asymmetry is typical of a wide range of processes associated with solar activity, e.g., the quantity and duration of solar flares [15], photospheric magnetic field rotation [4, 16], etc. The studies focusing on the asymmetry in solar activity pay much attention to the search for and analysis of periodicities, which is important for understanding the nature of this phenomenon. The asymmetry in solar activity was investigated using various statistical methods [8, 9], wavelet analysis [7, 10], and time-series cumulative sums analysis [2, 3]. Now it is clear that the asymmetry is observed over large time intervals rather than randomly. Many of the details of solar activity and its asymmetry are reviewed in [13].

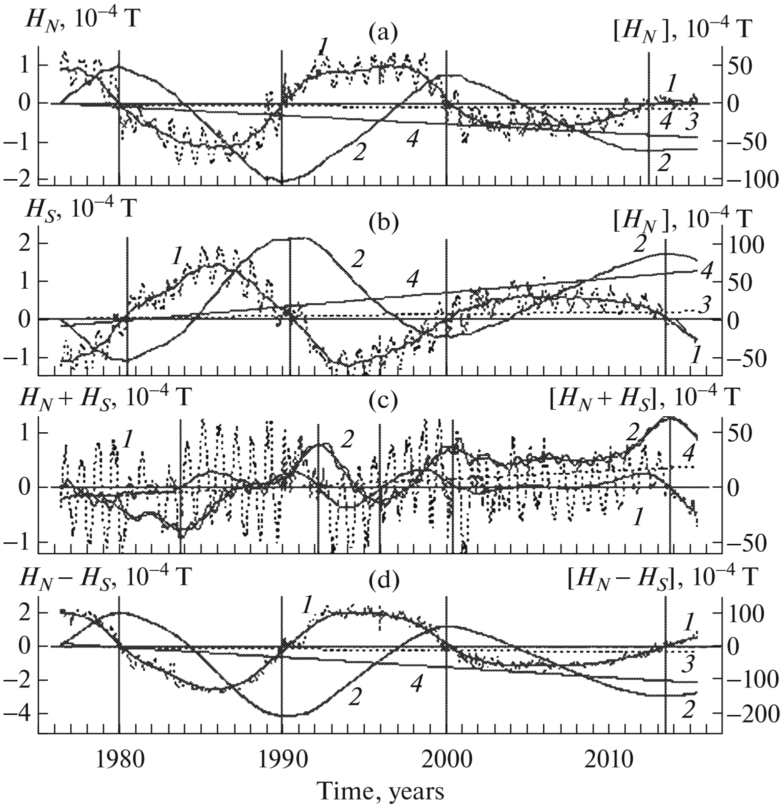

Fig. 1. Time changes of the H_N and H_S of the solar polar magnetic field at the north and south poles and their sum $H_N + H_S$ and difference $H_N - H_S$ (dashed curves; left scale). The thin solid lines show the sliding average; the dashed straight lines show the linear trend. The thick lines show the corresponding cumulative sums of these values (right scale). The thin solid straight lines show the linear trend of the cumulative sums.

This paper, which follows on the research in [2], presents the results of a study of asymmetry in solar activity that were obtained by analyzing time-series cumulative sums for some of the solar activity indices. A cumulative sum analysis for the polar solar magnetic field time series (1975–2015) provides rationale for the use of this method to search for long-term periodicities. A cumulative sum analysis for monthly average sunspot area time-series (1875–2015) is used to study long-term changes of the asymmetry in solar activity. A comparative analysis is conducted of the patterns of the time-series cumulative sums for the sun's global magnetic field (SGMF) and daily values of the surface area of sunspots in 1975–2015.

OBSERVATIONAL DATA AND RESEARCH METHODS

This work uses monthly average and daily sunspot area series by hemisphere (A_N and A_S), daily SGMF series H_0, and polar solar magnetic field series (H_N and H_S).

Sunspots are the most vivid manifestation of magnetic local fields. The total surface area of sunspots across the disk is proportionate to the sunspots' total magnetic flux. The sunspot data (relative Wolf numbers, sunspot areas, etc.) are published on the website http://solarscience.msfc.nasa.gov/greenwch.shtml.

The sun's polar magnetic fields H_N and H_S and its global magnetic field H_0 (SGMF) have been observed at the Wilcox Solar Observatory (WSO) since 1976 (http://wso.stanford.edu). Polar magnetic fields are mean high-latitude near-polar fields at heliolatitudes above ±55°. Polar magnetic fields are at a maximum near solar minima and at a minimum near solar maxima (Fig. 1). The sign of the polar magnetic field is reversed in the epoch of the solar maximum. These changes in the northern and southern hemisphere do not coincide in time.

To find the sun's global magnetic field H_0, which characterizes the magnetic field of the sun as a star, the value of the radial component of the photospheric magnetic field is integrated across the visible solar disk. The value of H_0 is proportionate to the magnetic flux from the visible disk, i.e., the difference between the photospheric magnetic fields of positive and negative polarity (asymmetry). The WSO site provides a time series of daily SGMF values (Fig. 5a).

In our study, we analyzed the time-series cumulative sums for selected solar activity indices. The cumulative function adds the current value of the series being analyzed to all the preceding ones, averages short-period changes, and identifies long-term variations: if the cumulative sum is increasing, there is a dominance of positive values; if it is decreasing, there is a dominance of negative ones.

The properties of the cumulative sum are well demonstrated by the solar polar magnetic field time series. In Fig. 1, the dashed lines *1* show the time change of the polar magnetic field separately for the north and south poles (H_N and H_S) and their sum $H_N + H_S$ and difference $H_N - H_S$; the thin solid lines show their smoothed values; and the dashed straight lines show the trends. The thick solid lines 2 show the corresponding cumulative sums $[H_N]$, $[H_S]$, $[H_N + H_S]$, and $[H_N - H_S]$. (Here and below, the cumulative sum of a value is denoted by enclosing it in square brackets.) The solid straight lines are the linear trends of the cumulative sums. The solid vertical lines denote the times of the reversal of the polar magnetic field at the north and south poles. It is evident that the times of the reversal of the polar magnetic field in all the four panels correspond to the extrema of the cumulative sum.

The plots of the cumulative sums $[H_N]$ and $[H_S]$ (Figs. 1a, 1b) show a sinusoidal pattern with two maxima and two minima. The protracted minimum of cycle 24 and its low activity also affect the curves of the cumulative sums. The distance between the two maxima and two minima is 20–22 years. The growth and decline phases last approximately 11 years. The maxima of the cumulative sum for the field of the north pole coincide with those of the odd cycles of Wolf numbers; those of the southern hemisphere coincide with the maxima of the even cycles. Thus, the period of the cumulative sum of the magnetic field at each of the poles corresponds to Hale's magnetic cycle and the growth and decline phases correspond to the 11-year solar cycle.

The curves in Fig. 1c have a complex shape. The cumulative sum $[H_N + H_S]$ has five extrema and a plateau of approximately 10 years (2002–2012). The pattern of the extrema is chaotic; they do not coincide with the extrema in the cumulative curves for individual poles. As is evident from Fig. 1c, the plateau corresponds to a time interval during which the polar fields at the two poles were approximately equal in absolute value (the curve of the smoothed values of the total polar field is approximately zero).

It is seen from Fig. 1 that the phase shift of the magnetic fields at the north and south poles is approximately 11 years. The curve of the cumulative sum $[H_N + H_S]$ has such a complex shape, since it is a sum of the cumulative sums $[H_N]$ and $[H_S]$ (Figs. 1a, 1b). Figure 1d shows the difference $H_N - H_S$ for the fields at the north and south poles. In fact, this is a sum of the fields that are phase-shifted by 11 years. Evidently, the cumulative sum $[H_N - H_S]$ corresponds to that of the field at the north pole. (The cumulative sum $[H_S - H_N]$ would correspond to the cumulative sum $[H_S]$ for the south-pole field).

The small linear trends in all the panels are most likely due to the abnormally small values of the polar magnetic field in cycle 24.

We studied the effect of the phase shift between the fields at the north and south poles on the cumulative sum. To this end, we shifted the south-pole time series relative to that of the north pole, summed up the fields, and built the cumulative sum of the resulting series on the combined time interval. The larger the shift, the shorter the combined time interval.

Figure 2 shows the cumulative sums $[H_N + H_S]$ for different phase shifts of the fields at the north and south poles. Curves *1* and *2* are the cumulative sums presented in Figs. 1c and 1d. The other lines of various length are the cumulative curves for the sum of the phase-shifted fields at the two poles. The phase shifts are 500, 1000, 2000, 3000, and 4000 days, or 1.37, 2.74, 5.50, 8.22, and 10.96 years. The shorter the curve, the larger the phase shift. These curves also have a wave-like sinusoidal shape, but their extrema are shifted. Curve *3* for the cumulative sum obtained by shifting the south-pole field relative to the north-pole one by 10.96 years and curve *2* for the cumulative sum of the magnetic field at the north pole are almost the same.

The table shows the times of extrema of the cumulative sums of the series at different shifts. Evidently, the period of all the cumulative sums, regardless of the phase shift (which is not 11 years), is 20–22 years and the growth and decline phases last 11 years.

Thus, the analysis of variations in the cumulative sum of a time series is an effective tool to search for hidden long-term periodicities.

It should be noted that there are different approaches to identify periodicities in time series. The best-known ones are the Fourier and wavelet analysis. However, the cumulative sum of a time series can be used

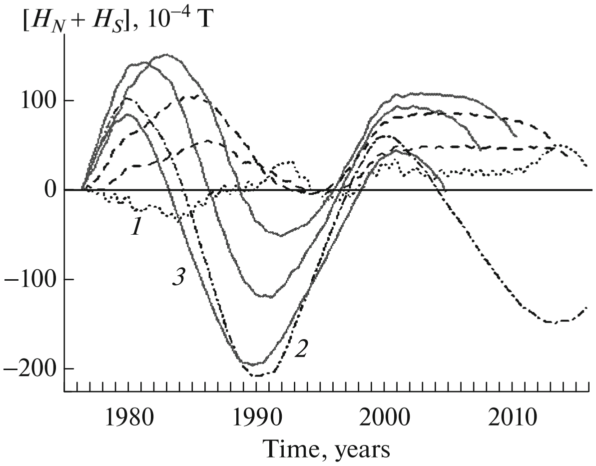

Fig. 2. Shapes of the cumulative curve for the sum of the fields at the north and south poles at different phase shifts. Curves *1* and *2* are the cumulative sums $[H_N + H_S]$ and $[H_N - H_S]$ from Figs. 1c and 1d and curve *3* is the cumulative sum $[H_N + H_S]$ at a phase shift of 10.96 years (see the text).

not only to identify periodicities in the time series but also find the times of minima and maxima of the periodic processes.

RESULTS AND DISCUSSION

Long-Term Variations of the Asymmetry in Sunspot Area (Local Fields). Studies of the north–south asymmetry most often consider the nonnormalized (absolute) index $NSA = A_N - A_S$ and normalized index $NSA_n = (A_N - A_S)/(A_N + A_S)$. It should be noted that the time change of these indices is not identical [1], because one index shows greater change at a minimum of activity while the other one at a maximum. The north–south asymmetry also manifests itself in the different lengths of solar activity processes in the northern and southern hemispheres. For example, the sunspot cycles in the northern and southern hemispheres do not begin simultaneously and their lengths are different [13].

Figure 3 shows the change in the cumulative sum of the time series for the normalized and nonnormalized north–south asymmetry calculated from the monthly average sunspot areas.

Evidently, the curves of the two cumulative sums have a wave-like shape, change approximately in sync, and have two extrema—one minimum and one maximum. It is a part of a quasi-periodic process; the interval between the minimum and maximum, i.e., the growth phase, is a half of the full cycle. From 1875 to 1915 (from the beginning of the interval under study to the minimum), the cumulative sums were decreasing; in 1915–1980, they were increasing; and they were again decreasing starting from the 1980s. This means that there was a dominance of the southern hemisphere in the total sunspot area index in 1875–1915, a dominance of the northern one in 1915–1980, and then again the southern one since 1980. Both of the extrema have two humps of different intensity, the second one being more intensive in both cases. The thick solid vertical lines show the times of maxima of these humps. At a minimum, the first

Times of the extrema of the cumulative sums at different shifts

Phase shift, years	Time of maximum	Time of minimum	Time of maximum
1.37	1986	1994	2006
2.74	1984.5	1994	2006
5.50	1982.5	1992	2003
8.22	1981	1991	2001
10.96	1980	1990	2001
N	1980	1990	2000
N–S	1980	1990	2000

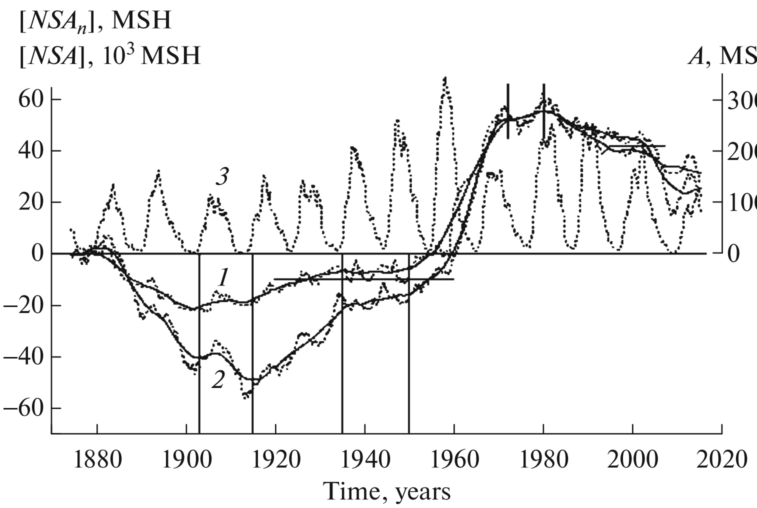

Fig. 3. Time change in the cumulative sum of the time series for the normalized (curve *1*, [NSA_n]) and absolute (curve *2*, [NSA]) solar activity asymmetry (left scale); the solid lines are their smoothed values. The cumulative sums were calculated from the monthly average sunspot areas (curve *3*, left scale).

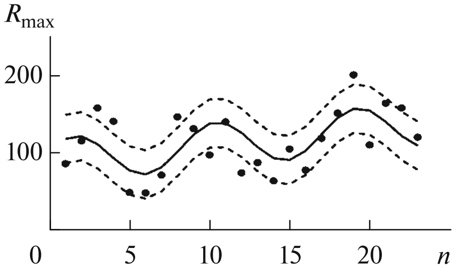

Fig. 4. Gleissberg cycle from the data in [13].

hump is observed in 1900–1903 and the second one in 1912–1915. At a maximum, the first hump is observed in approximately 1973 and the second one in 1980. The distance between the first and second pair of extrema at the minimum and maximum of the cumulative sum is approximately 70 and 65 years. It can be assumed that the full cycle length is 130–140 years.

Another feature of the curves is the presence of plateaus where the cumulative sum shows hardly any change. The plateaus are marked by solid thin horizontal lines, and the solid thin vertical lines are the times of their beginning and end: the interval 1935–1950 in the growth phase and 1995–2003 in the decline phase. In these short intervals, there was no dominance of any of the hemispheres in the total sunspot area.

Figure 4 (taken from [13]) shows the Gleissberg cycle. Evidently, the second minimum of the curve corresponds approximately to cycles 14–15 and the subsequent maximum to cycles 19–20. The minimum and maximum in the curve of the cumulative sum also coincide with these times.

Variations in the Asymmetry of the Sun's Large-Scale Field. Figure 5a shows the change in the daily SGMF values H_0, and Fig. 5b shows its sectoral structure. In Fig. 5c, the dots show their cumulative sums; the thick solid line shows the smoothed values of the cumulative sum [H_0]; and the thick dashed line shows the smoothed values of the cumulative sum [S] of the sectoral structure. The straight lines show the respective linear trends. The curves have a different shape, but they are synchronous. Both of the curves have two maxima and two minima. Both of the maxima have two humps; the first minimum has a plateau, and the second minimum shows so far only one hump. The times of the maxima of the humps are shown by vertical lines. In fact, these are the curves of a 22-year cyclic process (equal to Hale's cycle) with 11-year growth and decline phases. It should be noted that the analysis of the SGMF power spectra repeatedly indicated the presence of a strong 22-year peak and a very weak peak with a period of 11 years. However, the trends of these curves are completely different. The cumulative sum of the sectoral structure has

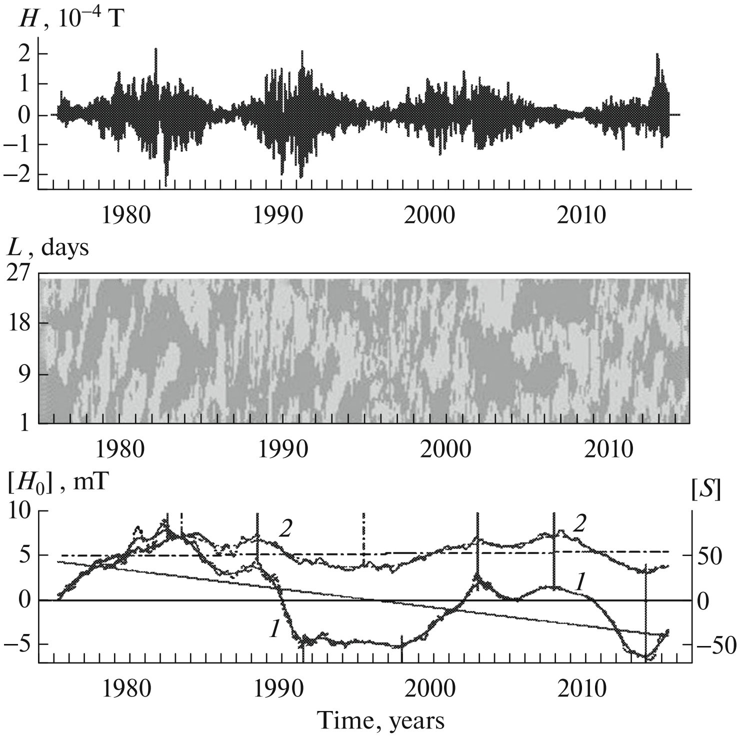

Fig. 5. Time change in (a) the sun's global magnetic field H_0 (SGMF), (b) its sectoral structure L, and the cumulative sums $[H_0]$ (line *1*) and $[S]$ (line *2*). The straight lines are the linear trends of the cumulative sums.

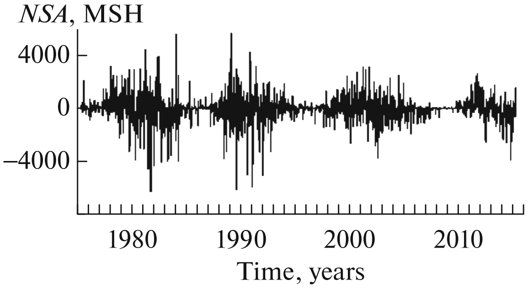

Fig. 6. Pattern of the absolute asymmetry index NSA calculated from the series of daily sunspot areas in the northern and southern hemispheres.

hardly any trend, while the SGMF cumulative sum has a substantial trend. This means that the sectoral structure, which has an approximately 22-year periodicity in the dominance of the area of positive and negative polarity fields, has no cycle of greater length.

The substantial negative trend of the curve of the SGMF cumulative sum shows that the field index has a long cycle of change and the available observational interval is in the decline phase of this cycle.

Figure 6 shows the NSA asymmetry index calculated from the daily values of the surface area of sunspots in the northern and southern hemispheres. Evidently, this plot resembles the one for the change in the daily SGMF values (Fig. 5a).

We compared the shape of the curves depicting the cumulative sums $[H_0]$ of the daily SGMF values and the asymmetry $[NSA]$ in the daily total values of the surface area of sunspots in the northern and southern hemispheres over the time interval 1975–2015 (Fig. 7). Despite the different behavior of the cumulative sums, their changes are in sync until 2005.5. Since that time, they change in antiphase. Note that this time coincides with the protracted minimum of cycle 24. Both curves have a plateau at approximately the same time. One can also see that the linear trends of $[NSA] = 399.781 - 0.201487d$, $[NSA_n] = 384.876 - 0.193975d$,

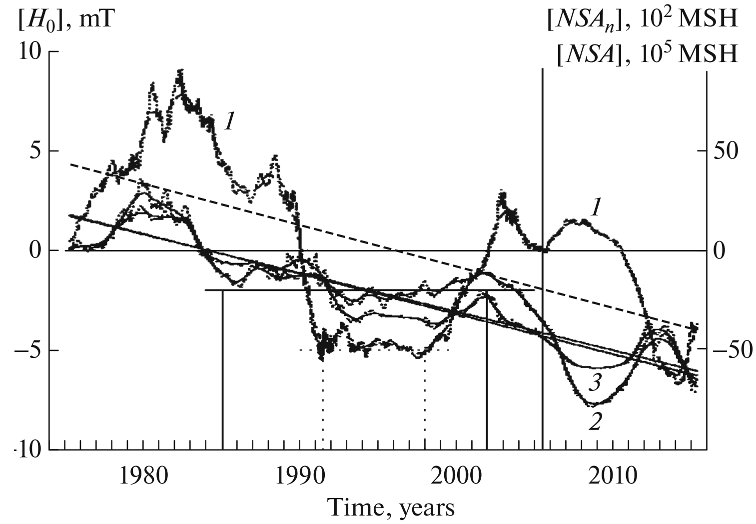

Fig. 7. Variations in the cumulative sum of the SGMF series (line *1* is the daily and smoothed values of $[H_0]$) and the cumulative sums of the sunspot area asymmetry indices (lines *2* and *3* are the daily and smoothed values of $[NSA]$ and $[NSA_n]$). The oblique straight lines are the trends of the cumulative sums.

and $[H_0] = 414.619 - 0.207712d$ are almost parallel. This confirms the above assumption that the north–south asymmetry index of the field strength has a long-term cycle of change, and the available observational interval is in the decline phase of this cycle. Since the trends are parallel, we can assume that this cycle may have the same length as that of the sunspot area asymmetry. It makes sense, because the area of a sunspot is proportionate to its field strength. Therefore, the asymmetry in the strength of both large-scale and small-scale magnetic fields (poloidal and toroidal components) has an approximately 130–140-year periodicity.

CONCLUSIONS

The solar polar magnetic field time series is used to show that the analysis of variations in the time-series cumulative sum gives positive results in the search for cyclic (periodic) variations. The period of the cumulative sum of the polar magnetic field series is equal to the 22-year Hale magnetic cycle and the growth and decline phases are equal to the 11-year solar cycle.

Based on the analysis of the cumulative sum of the sunspot area asymmetry series, we identified a long-term cycle of the north–south asymmetry in solar activity (small-scale magnetic fields, toroidal component) of approximately 140 years.

A comparative analysis of the variations in the daily values of the global magnetic field of the sun as a star and those in the asymmetry in the daily values of the surface area of sunspots over the time interval 1975–2015 shows that the sun's large-scale magnetic field (poloidal component) may also have a long-term cycle of approximately 140 years. The changes of the asymmetry in the sun's large- and small-scale magnetic fields were in sync until 2005.5 and have been in antiphase since that time. This time point corresponds to the protracted minimum of cycle 24.

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