LONGITUDINALLY ASYMMETRIC SUNSPOT DISTRIBUTION: A SYSTEMATIC DIFFERENCE BETWEEN THE TWO SOLAR HEMISPHERES

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ABSTRACT

We study the solar cycle evolution during the last 8 solar cycles using a vectorial sunspot area called the LA (longitudinal asymmetry) parameter. This is a useful measure of solar activity in which the stochastic, longitudinally evenly distributed sunspot activity is reduced and which therefore emphasizes the more systematic, longitudinally asymmetric sunspot activity. Interesting differences are found between the LA parameter and the more conventional sunspot activity indices like the (scalar) sunspot area and the sunspot number. E.g., cycle 19 is not the highest cycle according to LA. The separate LA parameters for the northern and southern hemisphere depict a systematic dipolar-type oscillation in the dominating hemisphere during high solar activity times which is reproduced from cycle to cycle. We have analysed this oscillation during cycles 16-22 by a superposed epoch method using the date of magnetic reversal in the southern hemisphere as the zero epoch time. According our analysis, the oscillation starts by an excess of the northern LA value in the ascending phase of the solar cycle which lasts for about 2.3 years. Soon after the maximum northern dominance, the southern hemisphere starts dominating, reaching its minimum some 1.2-1.7 years later. The period of southern dominance lasts for about 1.6 years and ends, on an average, slightly before the end of magnetic reversal.

1. INTRODUCTION

One of the most important properties of solar activity (SA) is that it is often asymmetric between the northern (N) and southern (S) solar hemispheres. It has been shown that a north-south (N-S) asymmetry in SA can be statistically highly significant [1]. Various forms of SA, e.g., sunspots, flares, or sudden disappearances of solar prominences, may have common features in the behavior of their N-S asymmetry [2]. The N-S asymmetry of sunspot groups seems to follow a long-term periodicity of about 80 years [3,4]. Also, it has been recently found that the solar wind speed distribution is systematically north-south asymmetric with respect to the heliographic equator [5]. The N-S asymmetry is important for the topology of the interplanetary space, and it influences both interplanetary and near-Earth space parameters. In particular, it affects the position of the heliospheric current sheet, leading to a difference in the number of away and toward IMF sector days and changing the modulation of the flux of galactic cosmic rays.

In this work we study the sunspot activity in the two solar hemispheres during the last 80 years using the vectorial sunspot number to be called here the LA (longitudinal asymmetry) parameter as a measure of solar activity.

2. THE VECTORIAL SUNSPOT AREA

We calculate the vectorial sunspot area by the polar diagram technique [6,7] which takes into account the area and the Carrington longitude of each sunspot group. The i-th sunspot group on a day k of a Bartels rotation (k=1,2,... 27) in question is presented as a polar vector $\vec{s}_{ik}$ in the heliographic plane whose length equals the sunspot area and whose phase corresponds to the Carrington longitude of the group. Then a vector sum is calculated using all sunspot groups observed during each day of the Bartels rotation under consideration: $\vec{S} = \sum_{i,k} \vec{s}_{ik}$. A sunspot group which lives for several days will be counted equally many times in $\vec{S}$. Thus large, long-lived sunspot groups give the main contribution to the vector $\vec{S}$.

The direction of the vector $\vec{S}$ corresponds to the Carrington longitude which dominates during the given Bartels rotation. Therefore it may be used as a quantitative measure of the longitudinal asymmetry of sunspot distribution during the rotation in question. In particular, $\vec{S}$ is zero if sunspots have no preferred direction in longitude. Hereafter we will

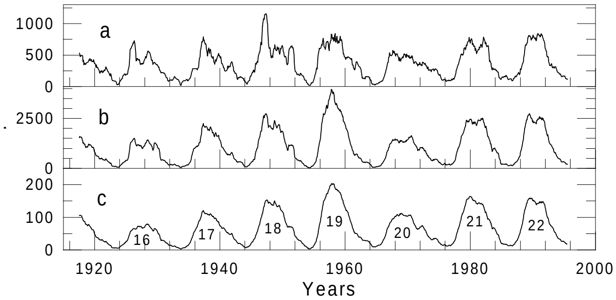

Figure 1. (a) The LA parameter, (b) the sunspot area S_p and (c) the Wolf sunspot number Rz for cycles 15-22. All curves are running means over 13 Bartels rotations.

call the absolute value of the vector $\vec{S}$ the longitudinal asymmetry (LA) parameter of sunspots. Thus LA is a measure of longitudinally asymmetric sunspot activity during one Bartels rotation. Calculating the vector sum of sunspots strongly reduces the stochastic, roughly symmetric sunspot activity which is common in sunspot maximum years. Therefore the LA values will, e.g., experience a smaller cycle variation than the total (scalar) sunspot area.

We have analysed the sunspot data for solar cycles 16-21 completely and for cycles 15 and 22 partially using data from Greenwich for 1917-1954, and from Pulkovo for 1955-1995, and calculated the total LA values as well as the LA values for the northern and southern solar hemisphere separately.

3. LA PARAMETERS FOR CYCLES 15-22

Figure 1a shows the total LA parameters for cycles 15-22, taking into account the sunspot groups in both hemispheres. For comparison, the total sunspot area (S_p) and the Wolf number (Rz) are presented in Figures 1b and 1c, respectively. All the three parameters depicted in Figure 1 are running mean averages over 13 Bartels rotations.

The LA parameter changes in the course of the solar cycle roughly in phase with S_p and Rz. Note however that while S_p attains typically values of 2000-3000 for solar maximum times, the LA parameter is only about 700-1000, reflecting the above mentioned partial cancellation of sunspot vectors in LA. Also, while the relative heights of the cycles are nearly the same according to S_p and Rz, they may be clearly different in LA. This is true in particular for cycle 19 whose height is greatly reduced in LA. This further demonstrates that the cancellation of sunspot vectors may be quite dramatic when calculating the vector sum. It also shows that the fraction of stochastic sunspot activity may be different during different cycles. In particular, it shows that the extraneous magnetic flux leading to the record height of cycle 19 according to S_p and Rz has mainly consisted of stochastic sunspot activity whose amount is greatly reduced in LA compared to S_p and Rz. Instead, the longitudinally asymmetric component of sunspot activity is probably related to the relic magnetic field in the solar convection layer [8] for which here is new, convincing evidence since recently [9].

We also note that the relative heights of all cycles included in this analysis (see Figure 1) are quite similar in LA, contrary to S_p or Rz. This demonstrates that the differences between cycles are mainly due to the variations in the stochastic component of the flux, and indicates that the "ordered" asymmetric flux remains roughly the same throughout the 80-year period studied. This observation gives interesting new support for the existence of the relic field.

Figure 2a depicts the LA parameters for the northern (LA_N) and southern hemisphere (LA_S) separately. In the long term, both LA_N and LA_S roughly follow the solar cycle development of the total LA parameter depicted in Figure 1. However, a more careful analysis reveals sizable differences between LA_N and LA_S. Moreover, some of these differences, especially around the sunspot maxima, seem to be repeated systematically from cycle to cycle. For each of the solar cycles 15-22 an excess of LA_N is observed prior to, or at the cycle maximum. After this period, at or soon after the sunspot maximum, a period of LA_S dominance is found, followed again by LA_N dominance before the next cycle minimum. In the different solar cycles the period of this oscillation in the dominance between the two hemispheres varies slightly but the order (N-S-N) remains the same. The systematic change of the dominating hemisphere around sunspot maxima is seen in Figure 2b which shows the difference $\Delta_{NS} = LA_N\text{-}LA_S$. As seen in Figure 2b, a positive peak of Δ_{NS} is observed just before or at sunspot maximum during each cycle. These peaks are followed by a sharp drop to a negative Δ_{NS} and a subsequent rise back to a positive Δ_{NS}, forming a V-type behaviour in the difference Δ_{NS} around sunspot maximum times.

We have also used the superposed epoch (SPE) method to study the average behaviour of Δ_{NS} around sunspot maximum times. Since the dramatic changes in Δ_{NS} occur at the time of the reversal of the Sun's global magnetic field, it is natural to combine the individual solar cycles so as to take the date of reversal as the zero date of the superposed epoch analysis. However, the magnetic field reversal is rather complicated, lasting for 1-3 years and developing rather independently and non-synchronously in the two solar hemispheres. Based on the behaviour of polar faculae it was shown [10] that multiple reversals often take place in the northern hemisphere while the reversal in the southern hemisphere is more simple. Therefore we have used the date of the field reversal in the southern hemisphere [7,10, see also Figure 2b] as the zero date in our SPE analysis.

Figure 3 shows the average SPE curve for Δ_{NS} (80 rotations before and 80 rotations after the zero date) obtained by combining the corresponding curves for cycles 16-22. It is clear that the behaviour of the Δ_{NS} difference is very different before and after the zero

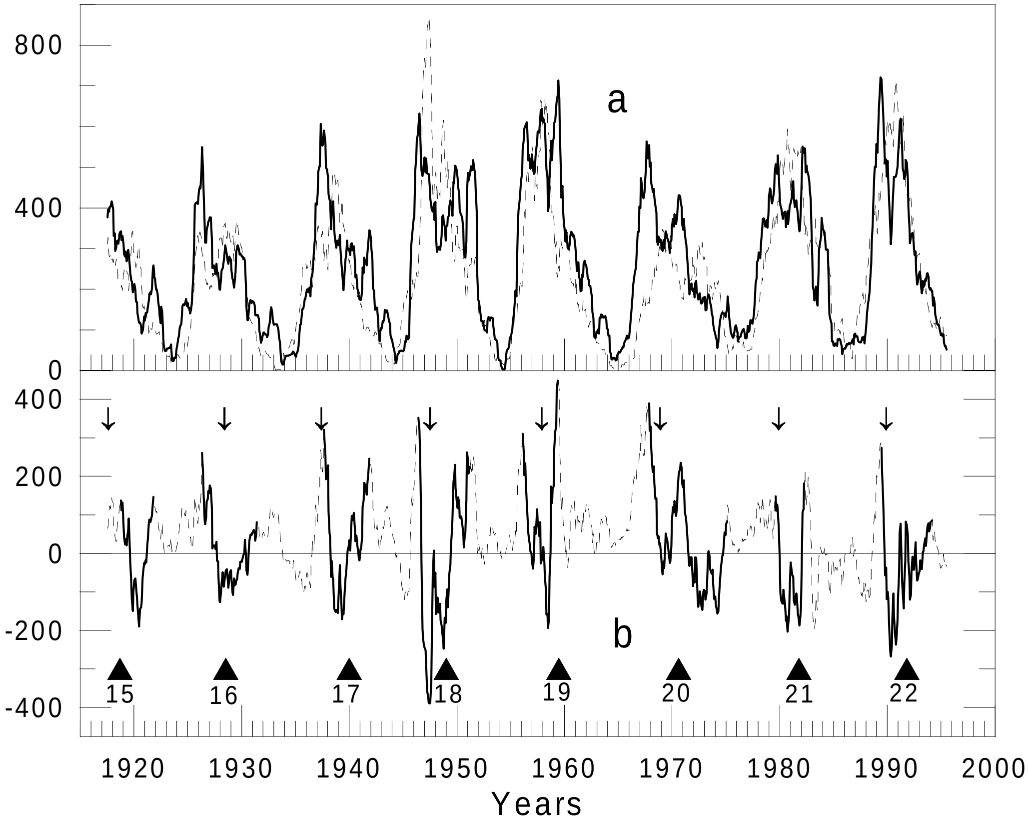

Figure 2. *(a) The LA parameter for the northern (solid line) and southern (dashed line) solar hemisphere. (b) The difference* Δ_{NS} *between the northern and southern LA parameters. The periods of oscillating north-south dominance around sunspot maxima are depicted in bold. Downward arrows and solid triangels show the official sunspot maxima and the end times of magnetic field inversion in the southern hemisphere, respectively. All curves are running means over 13 Bartels rotations.*

date. The most dramatic and systematic variations in Δ_{NS} take place before the zero date, starting with a positive deflection already some 4-5 years before the zero date at time t_1 (see Figure 3) in the ascending phase of the solar cycle. The rising time of Δ_{NS} from time t_1 to the maximum at time t_2 lasts typically about 1.6 years. Note that the significance of the maximum at t_2 is about four standard deviations.

The maximum of Δ_{NS} at t_2 is followed by a very sharp decrease, leading to strongly negative values. Figure 3 depicts some oscillations during the large negative values of Δ_{NS} including two minima, one at time t_4, some 1.2 years (16 rotations) after the maximum, the other at time t_5, some 1.7 years (23 rotations) after t_2. The latter, slightly deeper minimum at t_5 deviates from zero by more than three standard deviations. Note also that even the strongest negative values are, on an average, attained roughly a year before the completion of the magnetic reversal in the southern hemisphere. After t_5 Δ_{NS} increases to zero at time t_6 which is quite close to (some 3 rotations before) the date of field reversal. Note also that the period of positive Δ_{NS} from t_1 to t_3 (some 2.3 years or 32 rotations) is about 50% longer than the period of negative Δ_{NS} from t_3 to t_6 (some 1.6 years or 22 rotations). Similarly, the maximum value of Δ_{NS} at t_2 is about 50% higher than the negative peak value at t_5. These results demonstrate the well-known overall dominance of the northern hemisphere in sunspot activity during the time interval considered. The whole oscillation pattern of Δ_{NS} from t_1 to t_6 lasts about 4.1 years (55 rotations), covering a fair fraction of the ascending phase of the solar cycle, the sunspot maximum time and the early descending phase until close to the completion of the magnetic field reversal.

4. DISCUSSION AND CONCLUSIONS

We have calculated and studied the vectorial sunspot area, called the LA (longitudinal asymmetry) parameter which is largely purified from the stochastic, longitudinally evenly distributed sunspot activity, and rather emphasizes the more systematic and ordered part of the longitudinally asymmetric sunspot activity. We have shown that while the fraction of stochastic sunspot activity may be quite different during different cycles, the longitudinally asymmetric sunspot activity is fairly constant for the last 8 solar cycles. We noted that this gives new interesting evidence for the existence of relic fields in the

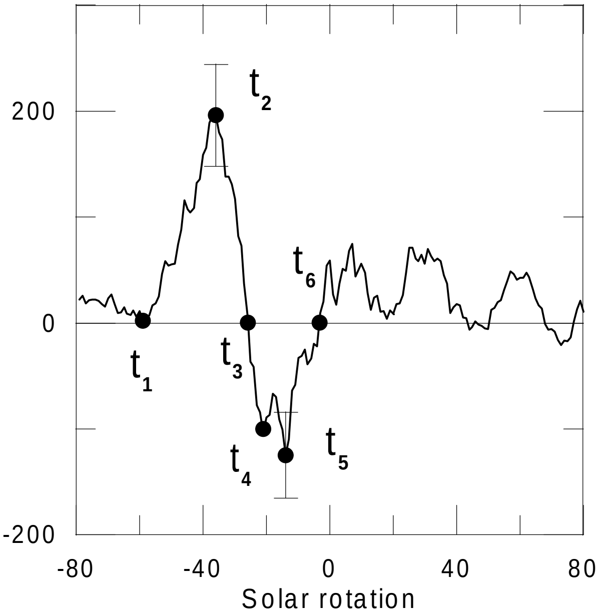

Figure 3. The superposed epoch curve of the difference Δ_{NS} for cycles 16-22 using the date of the polar field reversal in southern hemisphere as zero time. The errors of extremal values are given as vertical bars.

Sun [8,9].

We have found a systematic oscillation in the dominating hemisphere during high solar activity times which is reproduced from cycle to cycle. We have analysed this oscillation by a superposed epoch method for the north-south difference $\Delta_{\mathrm{NS}} = \mathrm{LA}_{\mathrm{N}}$-$\mathrm{LA}_{\mathrm{S}}$ using the date of magnetic reversal in the southern hemisphere as the zero epoch time. According our analysis for cycles 16-22, the oscillation starts by an excess of the northern LA_{N} in the ascending phase of the solar cycle which lasts for about 2.3 years. The maximum of this excess is statistically very significant. After the maximum Δ_{NS} turns negative, reaching the minimum some 1.2-1.7 years later. The period of negative Δ_{NS} lasts for about 1.6 years and ends, on an average, slightly before the SPE zero time.

Related results on the change of the relative role of Sun's two hemispheres have earlier been observed in a number of publications using, e.g., sudden disappearances of solar prominences [11] or distribution of flares [12]. Earlier investigations of the north-south asymmetry of sunspot area and sunspot number [13] found that the northern hemisphere activity displayed a peak about two years after the sunspot minimum. This is in agreement with our finding that the maximum of Δ_{NS} occurs in the ascending phase of the solar cycle, some 3-4 years before the reversal of the global magnetic field. Compared to these earlier studies the results presented here using the LA parameter show a more systematic and consistent pattern, and are statistically more significant, mainly due to the subtraction of the stochastic component of solar activity.

The change of the dominating hemisphere in the various types of solar activity shows the persistent and global character of the solar north-south asymmetries and their changes. Moreover, the existence of a systematic, dipolar-type oscillation in the dominating hemisphere with roughly similar time scales from cycle to cycle implies a new pattern in how the solar magnetic flux is generated. The regular change of dominant activity from the northern to the southern maximum shows that the two solar hemispheres are closely connected with each other. The observed time difference of about 1.2-1.7 years between the maximum northern and southern dominance sets the time scale for this connection. We would also like to note that this time scale is close to the periodicity recently detected at the tachocline at the bottom of the solar convection layer [14], as well as earlier in solar wind speed [15] and other solar and heliospheric variables [16].

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