A NEW PATTERN FOR THE NORTH–SOUTH ASYMMETRY OF SUNSPOTS

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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. We have calculated the separate LA parameters for the northern and southern hemisphere and found a systematic dipolar-type oscillation in the dominating hemisphere during high solar activity times which is reproduced from cycle to cycle. We have analyzed 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 to 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

During the solar cycle the distribution of solar activity (SA) changes over the solar surface. This is true not only for sunspots but also for some other manifestations of SA. The equatorward drift of sunspots at latitudes less than 40° manifests itself as the well known butterfly diagram. On the other hand, at latitudes higher than 40° the poleward migration of polar faculae is observed. Also, the tilt of the neutral line of the Sun's large-scale magnetic field changes dramatically over the solar cycle, with extreme values occurring during the inversion of the global field.

One of the most important properties of SA is that it is often asymmetric between the northern (N) and southern (S) solar hemispheres. The solar cycle evolution of solar activity in the northern and southern hemispheres may differ considerably. It has been shown that such a north–south (N–S) asymmetry in SA can be statistically highly significant (Carbonell, Oliver, and Ballester, 1993). Moreover, when investigating various forms of SA, e.g., sunspots, flares, or sudden disappear-

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ances of solar prominences, it was observed that there are some common features in the behavior of their N–S asymmetry (Vizoso and Ballester, 1990). E.g., during the period of northern sunspot dominance, 78% of solar flares were observed in this hemisphere (Swinson, Shea, and Humble, 1986). However, it was shown by Roy (1977) that the N–S asymmetry of solar flares does not follow the 11- or 22-year cycle of the occurrence of major flares. For the N–S asymmetry of sunspot groups the main period has been found to be about 80 years (Waldmeier, 1957; Pulkkinen *et al.*, 1999).

The N–S asymmetry is important for the topology of the interplanetary space, and it influences both interplanetary and near-Earth space parameters. E.g., it affects the position of the heliospheric current sheet (HCS) and leads to a difference in the number of away and toward IMF sector days (Swinson *et al.*, 1991). Since some mechanisms of cosmic ray modulation depend on the current sheet, the N–S asymmetry of solar activity must be taken into consideration when investigating cosmic ray modulation. Also, it has been recently found that the solar wind speed distribution is asymmetric with respect to the heliographic equator (Zieger and Mursula, 1998; Crooker *et al.*, 1997). This asymmetry changes its direction every solar cycle, thus depicting a connection to the 22-year solar magnetic cycle (Zieger and Mursula, 1998; Mursula and Zieger, 2001).

In this work we study the sunspot activity in the two solar hemispheres during the last 80 years. As the measure of solar activity we use the vectorial sunspot number to be called here the LA parameter which is introduced and discussed in the following Section. In Section 3 we study the total LA parameter and in Section 4 the LA parameter in the northern and southern solar hemispheres separately. Section 5 discusses the difference between the two hemispheres using a superposed epoch method and Section 6 compares the average behavior with the individual cycles. Finally, in Section 7 we discuss our observations and present the conclusions.

2. The Vectorial Sunspot Area

We calculate the vectorial sunspot area by the polar diagram technique (Vernov *et al.*, 1979) 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 ($k = 1, 2, \ldots, 27$) in question is presented as a polar vector $\mathbf{s}_i(s_{ik})$ 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: $\mathbf{S} = \sum_{i,k} \mathbf{s}_{ik}$. A sunspot group which lives for several days will be counted equally many times in $\mathbf{S}$. Thus large, long-lived sunspot groups give the main contribution to the vector $\mathbf{S}$.

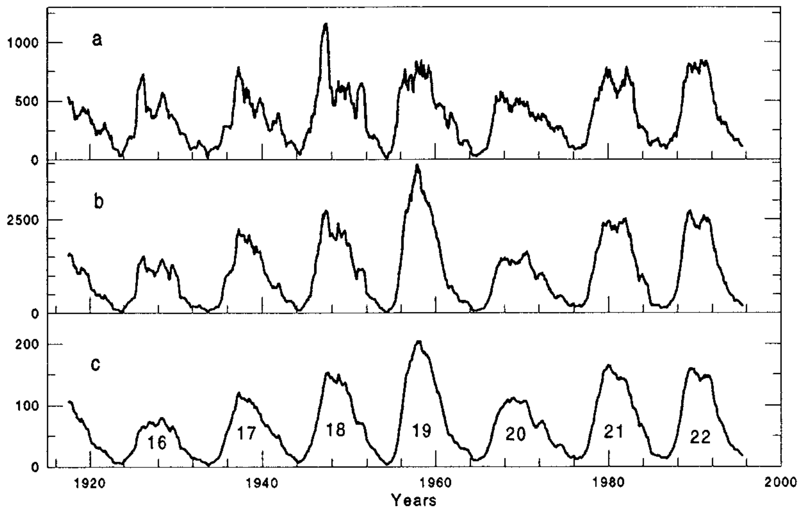

Figure 1. (a) The LA parameter, (b) the sunspot area S_p, and (c) the Wolf sunspot number Rz for cycles 15–22. All curves are running means over 13 Bartels rotations. The solar cycles are numbered in (c).

The direction of the vector **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, **S** is zero if sunspots have no preferred direction in longitude. Hereafter we will call the absolute value of the vector **S** the longitudinal asymmetry (LA) parameter of sunspots. (The phase information of **S** will be studied in a separate publication). 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 experience a smaller cycle variation than the total (scalar) sunspot area.

We have analyzed 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. Using the above described method, we have calculated the LA values for the northern and southern solar hemisphere separately.

3. The Total LA Parameter for Solar Cycles 15–22

Figure 1(a) shows the total LA parameter 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 1(b) and 1(c), respectively. The three parameters depicted in Figure 1 are running mean averages over 13 Bartels rotations.

It can be seen in Figure 1 that 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 according to 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.

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. Therefore, the LA parameter can give interesting new information about the long-term development of solar activity.

The LA parameter shows generally a more oscillatory structure than S_p and Rz especially around high solar activity times. This is particularly clearly visible during cycles 17−19. During most cycles large fluctuations in LA are observed around cycle maxima. Thus the maxima are divided into several local maxima, of which the first one is often but not always the highest. As will be discussed later, these maxima are reference points which play an essential part in the development of the solar cycle.

4. Separate LA Parameters for N and S Hemisphere

Figure 2 depicts the LA parameters for the northern (LA_N) and southern hemisphere (LA_S) separately. Again, smoothing over 13 Bartels rotations is applied. 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.

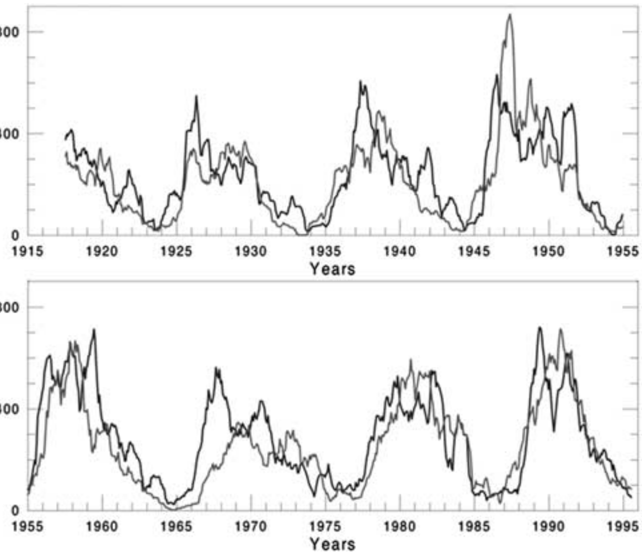

Figure 2. The LA parameter for the northern (*solid line*) and southern (*grey line*) solar hemisphere separately.

The essential difference between the northern and southern LA parameters is confirmed quantitatively by correlation coefficients. Whereas the correlation between the total LA parameter and the total sunspot area (Figures 1(a) and 1(b)) is very high and has a correlation coefficient of 0.93, the correlation coefficient between the northern and southern LA parameters (Figures 2(a) and 2(b)) is only 0.75. Such a considerably lower correlation is due to the fact that, although the overall 11-year cycle is fairly similar for LA_N and LA_S, during high solar activity the two parameters change almost in anti-phase which greatly decreases the correlation coefficient between them. The differences between the two solar hemispheres are also clearly visible in Figure 3(a) which shows the difference $\Delta_{NS} = LA_N – LA_S$. Moreover, Figure 3(b) depicts the relative difference $\delta_{NS} = (LA_N - LA_S)/(LA_N + LA_S)$. The above-mentioned systematic change of the dominating hemisphere around sunspot maxima is seen in both figures but is more clear in the absolute difference Δ_{NS}. (The relative difference δ_{NS} contains additional large peaks during SA minimum times due to the small denominator. These considerably mask the visibility of the pattern at SA maxima.) As seen in Figure 3(a), a positive peak of Δ_{NS} is observed just before or at sunspot maximum during each cycle. These peaks correspond to the first sunspot maximum of the solar cycle, as described by Vitinsky (1992a, b). They 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 behavior in the difference Δ_{NS} around sunspot maximum times.

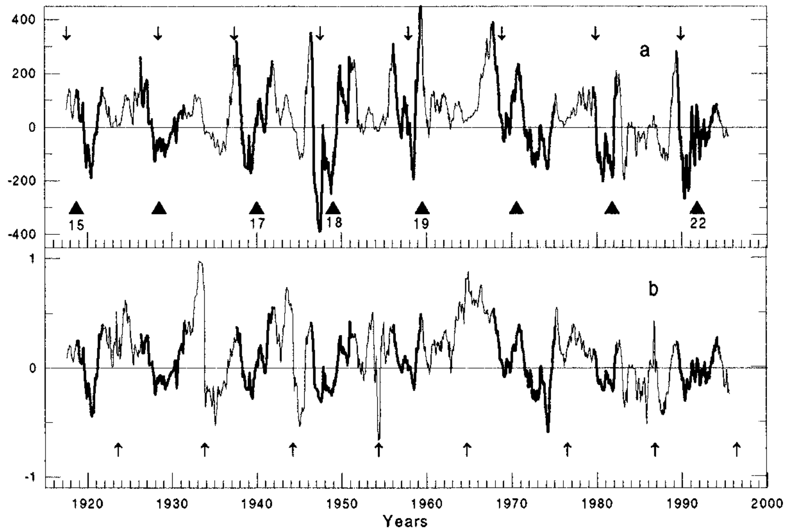

Figure 3. (a) The absolute difference Δ_{NS} and (b) the relative difference δ_{NS} between the LA parameters for the northern and southern hemisphere. The *downward arrows* and *solid triangles* in (a) show the official sunspot maxima and the end times of magnetic field inversion in the southern hemisphere, respectively. The *upward arrows* in (b) depict the sunspot minimum times. The periods of changing dominance of the northern and southern hemispheres around solar maxima are marked *in bold*.

5. The Superposed Δ_{NS} Curve

We have also used the superposed epoch (SPE) method to study the average behavior 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 behavior of polar faculae Makarov and Makarova (1996) showed that a triple reversal of the magnetic field took place in the northern hemisphere for a number of cycles (16, 19, 20), whereas in the southern hemisphere only one single reversal was always found. Therefore we have used the date of the field reversal in the southern hemisphere given in Table I (Makarov and Makarova, 1996) as the zero date in our SPE analysis.

Figure 4 shows the average SPE curve for Δ_{NS} obtained by combining the corresponding curves for cycles 16–22. (Cycle 15 was not included because of the lack of data in the ascending phase.) The average Δ_{NS} has been depicted in Figure 4 for 80 rotations before and 80 rotations after the zero date. It is clear that the behavior of the Δ_{NS} difference is very different before and after the zero date. The most dramatic variations in Δ_{NS} take place, on an average, before the zero date, starting with a positive deflection already some 4–5 years before the zero date at

TABLE I
Polar field reversal time

Solar cycle	S-hemisphere inversion (year)
16	1928.5
17	1940.0
18	1949.0
19	1959.5
20	1970.6
21	1981.8
22	1991.8

time t_1 (see Figure 4) 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 (22 rotations). Note that the significance of the maximum at t_2 is about four standard deviations. (The error is given as a vertical bar in Figure 4.)

The maximum of Δ_{NS} at t_2 is followed by a very sharp decrease, leading to strongly negative values of Δ_{NS}. Figure 4 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 at t_2, 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 the difference Δ_{NS} increases to zero at time t_6 which is quite close to (some 3 rotations before) the date of field reversal (the SPE zero date.) 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. (Thereafter the average Δ_{NS} is mainly positive, depicting a fluctuating pattern with a period of about 20–30 rotations. However, the maxima of these fluctuations are much lower than the peak at t_2, hardly significant statistically.)

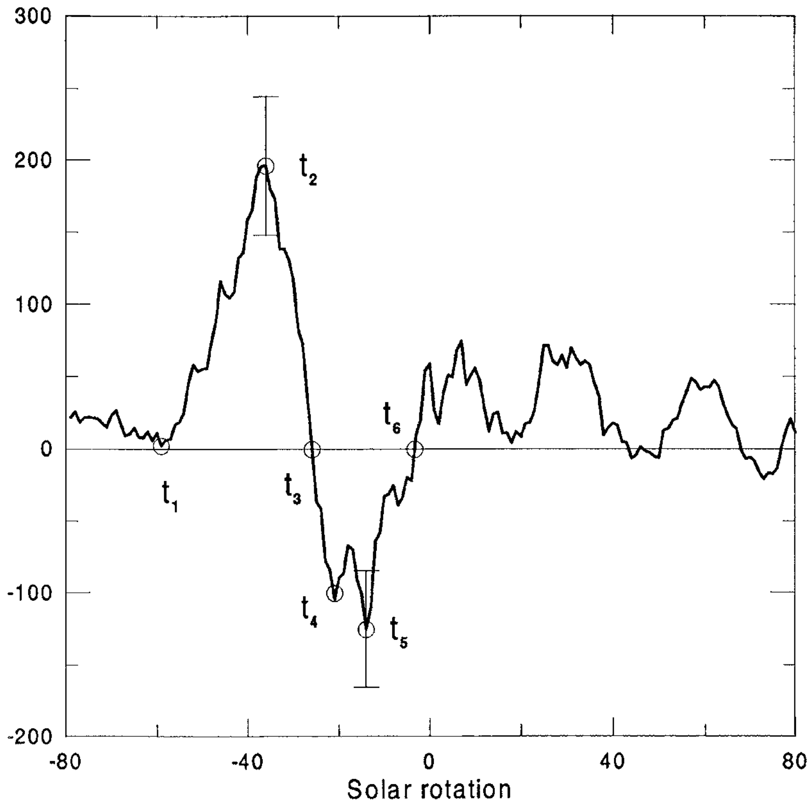

Figure 4. The average superposed epoch curve of the absolute difference Δ_{NS} for cycles 16–22 using the date of the polar field reversal in southern hemisphere as zero time. The times t_1–t_6 are described in the text. Error bars correspond to the statistical distribution of the corresponding extrema.

6. Δ_{NS} for Individual Cycles

The essential features of the SPE Δ_{NS} curve are also visible during most of the solar cycles included in the study. Figure 5 depicts the superposed Δ_{NS} curve together with the individual Δ_{NS} curves for each cycle separately. The zero time of the superposed Δ_{NS} curve was fit to the reversal date of the individual cycle except for cycles 15 and 16 where the superposed Δ_{NS} curve was shifted later. (Note that cycle 16 was quite exceptional among the 8 studied cycles in that the sunspot maximum nearly coincided with the time of field reversal. This property may be an artifact related to problems in determining the field reversal for the early cycles. However, even if it was real, the effect of this time shift is rather small in the superposed Δ_{NS} curve because of the rather low Δ_{NS} for this cycle.) For all other cycles, especially for cycles 17, 20, 21 and 22, the V-type structure of the Δ_{NS} curve is found in a fairly good phase with the superposed Δ_{NS} curve. This observation further supports the significance of the above-mentioned properties of the superposed Δ_{NS} curve

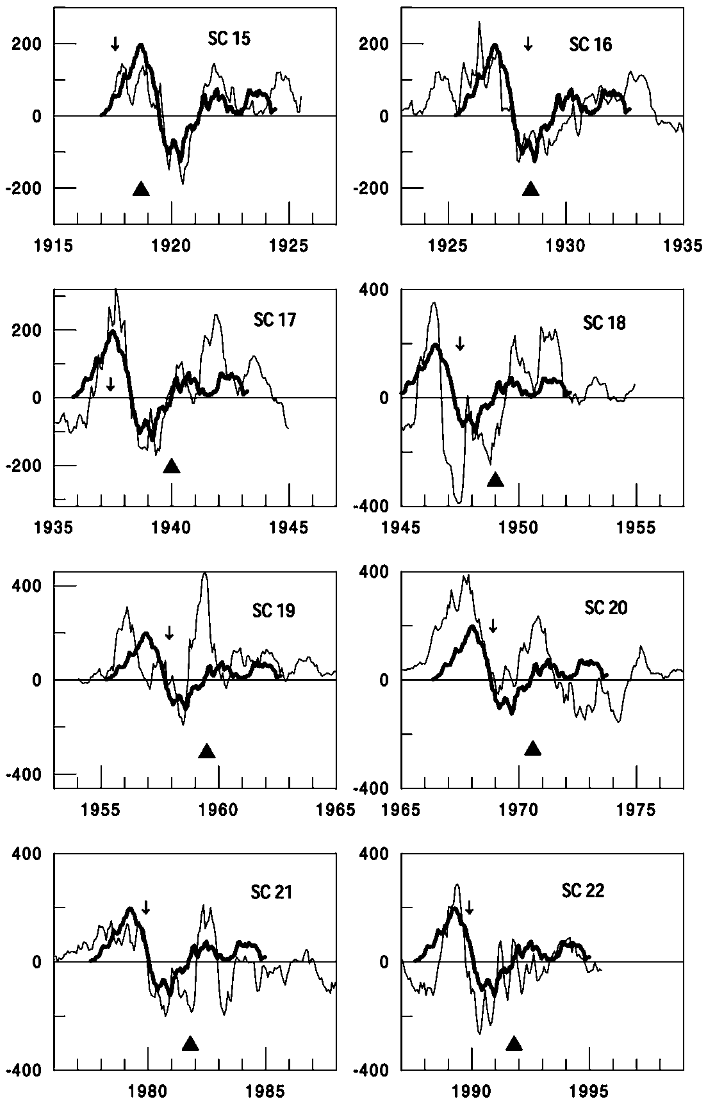

Figure 5. The differences Δ_{NS} for the individual cycles compared with the superposed average Δ_{NS} curve marked *in bold*. The zero time of the average curve is matched with the date of field reversal of the individual cycle except for cycles 15 and 16. Note the different scaling of Δ_{NS} for the three first cycles. *Arrows* and *triangles* are as in Figure 3(a).

and the use of the field reversal in the southern hemisphere as the zero time of the SPE analysis.

Perhaps the most complex behavior of the individual Δ_{NS} curves is observed during the 20th solar cycle. After the positive maximum the values of Δ_{NS} remained exceptionally high and the period of negative Δ_{NS} was exceptionally short. Thereafter, Δ_{NS} reached a very high positive maximum roughly at the time of field reversal and then decreased to strongly negative values which lasted exceptionally long. In fact, the evolution of the Δ_{NS} curve after sunspot maximum during this cycle greatly resembles the average form of the SPE Δ_{NS} curve. However, the timing of this evolution is late from the average behavior by about three years. We would like to note that the 20th cycle was rather extraordinary in many regards. First, cycle 20 had a much lower amplitude (as measured, e.g., by the Rz parameter) than the neighboring high-amplitude cycles. This in turn affected the intensity of cosmic rays which had an exceptionally early recovery and a long, plateau-type maximum (Ahluwalia, 1992). Moreover, the declining phase of this cycle was quite exceptional, including an unusual mini-cycle in the cosmic ray evolution (Webber and Lockwood, 1988; Usoskin *et al.*, 1998) in the same time interval in the early 1970s when the Δ_{NS} curve attained its exceptionally strong negative values.

7. Discussion and Conclusions

We have calculated and studied the vectorial sunspot area, called the LA (longitudinal asymmetry) parameter, for the last 8 solar cycles. The LA parameter is a useful new measure of solar activity which is largely free from the stochastic, longitudinally evenly distributed sunspot activity and which therefore emphasizes the more systematic and ordered part of the longitudinally asymmetric sunspot activity. The typical value of the vectorial sunspot area is about one third of the corresponding scalar value, depicting the scale of significant cancellation.

There are interesting differences between the LA parameter and the other, more conventional sunspot activity indices like the (scalar) sunspot area and the relative sunspot number. In particular, cycle 19 is more reduced in LA than other cycles and is not the highest cycle according to LA. This shows that the fraction of stochastic sunspot activity may be different during different cycles and that the extra magnetic flux leading to the record height of cycle 19 (according to S_p and Rz) mainly consisted of stochastic sunspot activity. Instead, the longitudinally asymmetric component of sunspot activity is probably related to the relic magnetic field in the solar convection layer (Cowling, 1945) for which there is new, convincing evidence presented recently (Mursula, Usoskin, and Kovaltsov, 2001).

We have shown that the separate LA parameters for the northern and southern hemisphere have sizable differences and correlate much more weakly than, e.g., the total LA parameter and the (scalar) sunspot area. However, we have found a systematic oscillation in the dominating hemisphere during high solar activity times which is reproduced from cycle to cycle. We have analyzed this oscillation by a superposed epoch method for the north–south difference $\Delta_{NS} = LA_N - LA_S$ using the date of magnetic reversal in the southern hemisphere as the zero epoch time. According to our analysis for cycles 16–22, the oscillation starts with 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. After the zero time, the northern hemisphere dominates again but less strongly.

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 (Vizoso and Ballester, 1987) or distribution of flares (Yadav, Badruddin, and Kumar, 1980). When investigating the north–south asymmetry of sunspot area and sunspot number, Swinson, Shea, and Humble (1986) 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 maximum to the southern maximum shows that the two solar hemispheres are 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 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 (Howe *et al.*, 2000), as well as earlier in solar wind speed (Richardson *et al.*, 1994) and other solar and heliospheric variables (Mursula and Zieger, 2000).

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