Large-scale Structures and their Role in Solar Activity
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Indices of Solar Activity in Minimum of Sunspot Cycles

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Abstract. New indices of solar activity in minimum of sunspot cycles were obtained from the H_α synoptic charts during 1887 - 2004, CaII K observational data of solar disk during 1907 - 1995 at the Kodaikanal observatory in India and observations of the Sun at the Kislovodsk Solar Station in 1950 - 2004. Index Apz determines the area of polar zone occupied by magnetic field of one polarity and the $A(t)$ is a sum of squares of dipole and oktopole magnetic moments. Index $L(t)$ is a general length of magnetic neutral lines on H_α synoptic chart and the $K(t)$ characterizes the complexity of topology pattern of general magnetic field of the Sun. It is determined by inverse number of crossing neutral lines with meridian net on H_α chart. Index $R(t)$ determines correlation factor of polarity of the magnetic field in the latitude zones $\pm 40^o$. Index of solar rotation $SSPD(t)$ is determined by a sum of spectral density of the power of sector structures of the magnetic field. The area of CaII K bright points at the high - latitudes is the index $SK(t)$. It was shown that the 11-year cycles of $Apz(t), A(t), L(t), K(t), R(t), SSPD(t)$ and $SK(t)$ have the maximum in the minimum of sunspot activity and they precede the Wolf number cycles, $W(t)$, for 5 - 6 years.

1. Introduction

In minimum activity the general magnetic field of the Sun is defined by unipolar large-scale structures. The Northern and Southern hemispheres have the magnetic fields of different polarity. Intensity and activity of polar magnetic field is higher than at middle and low latitudes. The corona has the large streamers near equator in this period and the polar corona consists of thin plumes. The inclination of plumes is connected with the magnetic force lines. The indices of the Wolf numbers, sunspot area, CaII K faculae, flare index and radio emission on the wave 10.7 cm are connected with the sunspot active regions and they have practically the same 11-year cycles. This activity is limited by the latitude zone $\pm 40^o$. But it does not take into account an activity at high - latitudes and background magnetic field.

In this paper we considered new indices for the minimum of sunspot activity on a basis of H_α synoptic charts, CaII K bright points at high - latitudes and the solar rotation rate of sector structure of the magnetic field.

2. Observational Data

Authors of this paper have long series of observations in H_α and CaII K lines, and also in white light images of the Sun at all latitudes. More details about the observational data were described in Makarov et al. (2001); Makarov et al. (2002); Makarov et al. (2004).

3. Indices of Background Magnetic Field of the Sun

3.1. Index of the Area of High - Latitude Unipolar Regions, $Apz(t)$

In minimum activity the poles of the Sun have magnetic fields of various polarity. The large unipolar regions near poles can contain coronal holes. The area of high - latitude unipolar regions can be calculated on H_α charts. Figure 1 shows the cycles of the area of unipolar regions at the latitudes more than 35^o, $Apz(t)$, expressed in $10^{16}m^2$. The maximum of an index $Apz(t)$ has been observed in the minimum activity during 1887 - 2003. The greatest area of unipolar regions was observed in the minimum before cycle 19. The smoothed annual index, $Apz(t)$, precede the average annual Wolf numbers, $W(t)$, for 5.5 years. Correlation factor equals $r \sim 0.78$ between $Apz(t)$ and $W(t) = 1.02 \cdot Apz(t + 5.5) - 109$.

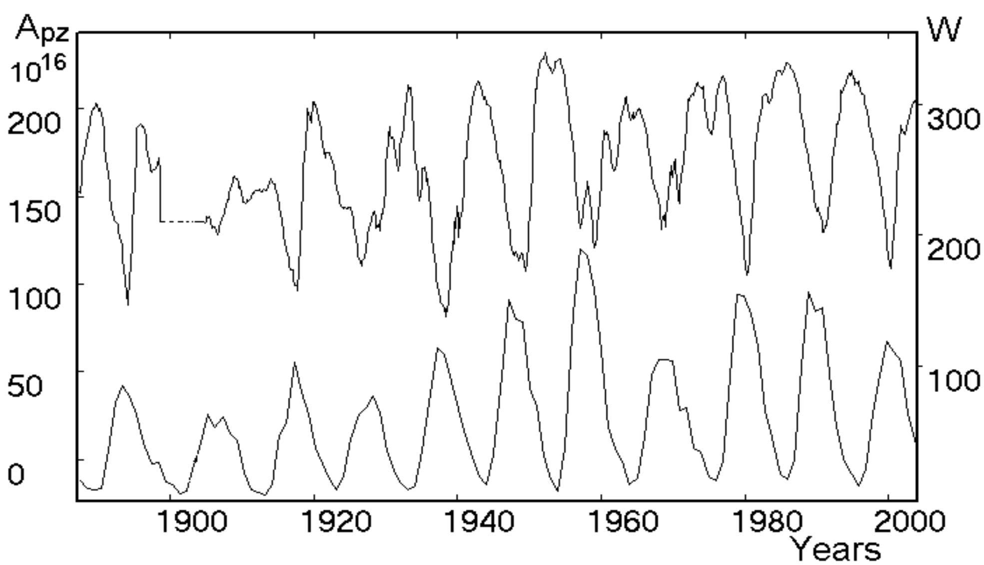

Figure 1. Upper curve: The area of high - latitude unipolar regions, $Apz(t)$, according to H_α charts for 1887-2003. Lower curve: Average annual Wolf numbers, $W(t)$.

3.2. Index of the Dipole - Octupole Magnetic Moments, $A(t)$

The photospheric background magnetic field of the Sun can be represented as a function of latitude and longitude, using decomposition in spherical harmonics. The dipole-octupole index:

$$A(t) = {\mu_1}^2 + {\mu_3}^2/3,$$

demonstrates the 11-year cycles of activity pretty well (Makarov & Tlatov-2000a). Figure 2 shows that an index $A(t)$ precedes the Wolf numbers, $W(t)$, on an average 5 - 6 years. We used dipole and octupole component of background magnetic field only, i.e. modes L = 1 and 3. The even modes L = 2 and 4 have slight intensities. This index can be used for forecast of the solar cycle. The current cycle 23 should be, according to Gnevyshev-Ol rule, higher than the cycle 22. Figure 2 shows that the index $A(23)$ in the maximum of cycle 23 was much lower, than $A(22)$. Therefore the Wolf number in maximum, $W(23)$, was lower compared to $W(22)$ for the cycle 22. The index $A(t)$ for the current cycle 23 was equal to 128 in maximum. It corresponded to the Wolf number 130 ± 10 in maximum activity, $W(23)$. This value corresponds to observational data.

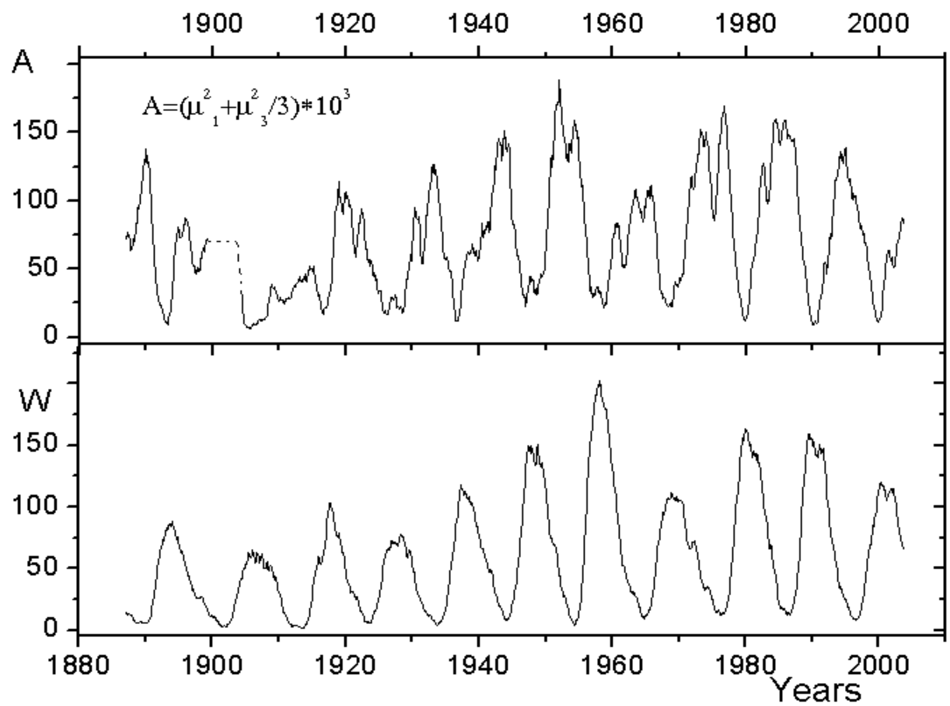

Figure 2. Upper curve: The cycles of background magnetic field of the Sun, $A(t)$, during 1887 - 2003. Lower curve: Average annual Wolf numbers, $W(t)$.

3.3. The Length of Neutral Lines, $L(t)$, as an Index of the Sun's Activity

There are several morphological characteristics to describe a topology of solar magnetic field. One of them is the total length of magnetic neutral lines, $l(t)$, on H_α synoptic chart which has been calculated for 1887 - 2003. It was shown that the value of $l(t)$ changed with 11-year solar cycle and it had a trend during the last 9 cycles. The value of $l(t)$ was increased 1.3 times during 1915 - 1999, (Makarov & Tlatov 2000b). The new index of background magnetic field has been obtained $L(t)$ after subtraction of a trend in the $l(t)$

$$L(t) = l^{-1}(t) - < l^{-1}(t) >$$

It reflects a change of the magnetic field in 11-year solar cycles, Figure 3. The curve of the sunspot numbers, $W(t)$, shows that index $L(t)$ changes in anti phase with $W(t)$ and precede to the 11-year sunspot cycles on an average 5.5 years. An increase of solar activity led to an increase of index $L(t)$ during 1887 -1960, Figure 3. The index $L(t)$ decreases before the solar cycle 20. In the cycles 20, 21 and 22 there is an insignificant increase of sunspot activity, $W(t)$, and index $L(t)$ weakly reacts to this increase. The north-southern asymmetry $\Delta(t) = l_N(t) - l_S(t)$ was calculated, which shows the 55-years quasi-period of background magnetic field in 1915-1990 (Makarov & Tlatov 1997; Kitchatinov et al. 1999). Asymmetry has dominated in the Northern hemisphere at this time. The index $L(t)$ can be used for forecast of the sunspot cycle.

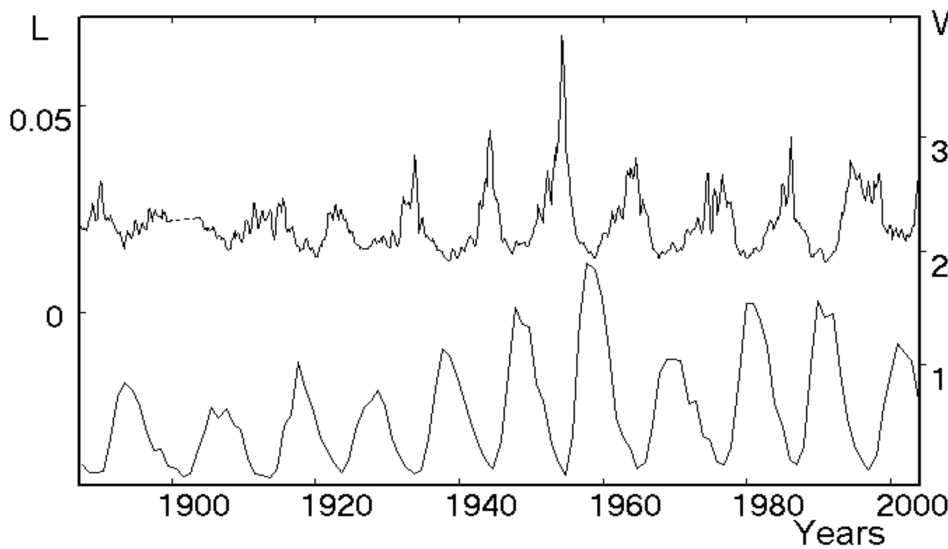

Figure 3. Upper curve: The cycle of an index $L(t) = l^{-1}(t) - < l^{-1}(t) >$ according to the H_α charts for 1887 - 2003. Lower curve: The cycles of average annual Wolf numbers, $W(t)$.

3.4. Index of Complexity of H_α Synoptic Charts, $K(t)$

We use a topological index of complexity of background magnetic field on H_α charts, NCRS. It is the number of crossings of magnetic neutral lines with the longitudes, for example, through 10^o.

It shows the sizes of unipolar regions. One can enter the index of an inverse number of crossings of neutral lines with the longitudes $K(t) = 1/NCRS(t)$. The complexity of magnetic field is less in the minimum activity in comparison with the maximum. Therefore, index $K(t) = 1/NCRS(t)$ in the minimum of the solar cycle reaches the maximum. It is necessary to notice, that index $K(t) = 1/NCRS(t)$ is connected with a change of the longitude-time interval

$\Delta t = 0.003666^o/sec$. Figure 4 shows the behavior of an index $K(t)$ for 1887 - 2003 and average annual Wolf numbers for the same period. The topological index $K(t) = 1/NCRS(t)$ has a maximum in the minimum of solar activity. Figure 4 shows that the index $K(t) = 1/NCRS(t)$ gradually increased during 1887 - 1955 and then has sharply decreased. The index $K(t) = 1/NCRS(t)$ precede the $W(t)$ for the 5.5 years. Therefore, index $K(t) = 1/NCRS(t)$ can be used for forecast sunspot cycle.

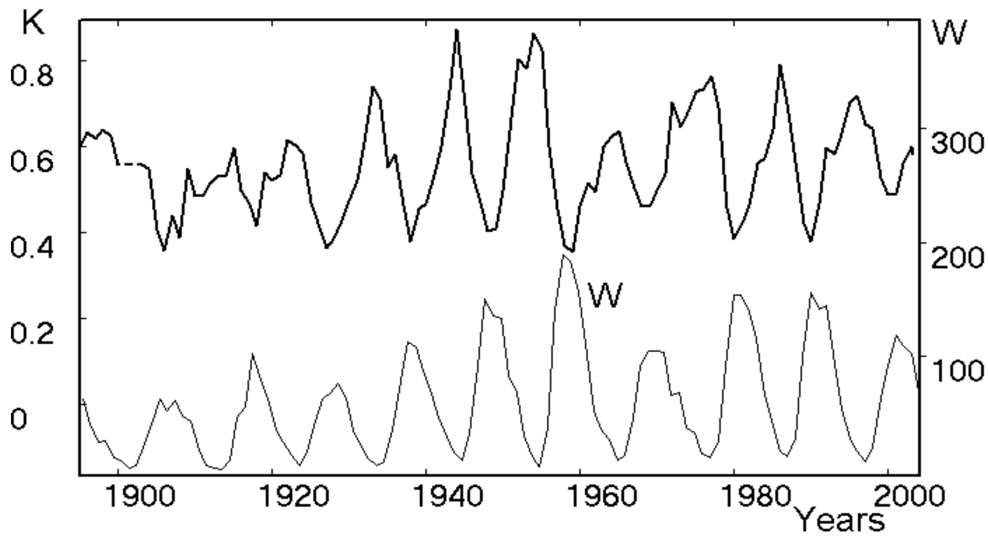

Figure 4. Upper curve: Topological index $K(t) = 1/NCRS(t)$. Lower curve: The average annual Wolf numbers, $W(t)$.

3.5. Correlation between Polarities of Background Magnetic Field in the Northern and Southern Hemispheres of the Sun, $R(t)$.

H_α charts have data on the sign of background magnetic field which was accepted as +1 G or -1 G. Polar regions, as a rule, have the sign of the magnetic field corresponding to polarity of global dipole of solar magnetic field. The magnetic fields have identical or opposite polarities on the same longitudes at middle and low latitudes of Northern and Southern hemispheres.

One can calculate the mean polarity magnetic field, $P(t)$, average in the latitude zone $\pm 40^o$ and in the longitude 10^o. Position of the central meridian is connected with time of solar rotation. The numbers $P(t)$ are function of a time for the Northern and Southern hemispheres $PN(t)$, $PS(t)$ during 1905 - 2003. The index $R(t)$ was calculated in the spectral "window" of width about one year. Then the "window" was displaced along series and calculations were repeated. It appeared that the index $R(t)$ has positive value. It means, that polarity of background magnetic field in the latitude zone $\pm 40^o$ of the Northern and Southern hemispheres have on the whole the same sign. The maximum correlation factor has been found during the minimum activity. Figure 5 shows the behavior of an index $R(t)$ in the Northern and Southern hemispheres for 1905 - 2003.

$R(t)$ reached the largest values in the minimum activity before high-power solar cycles and it distinctly shows the secular cycle. The maximum value for $R(t)$ was observed before the most intensive cycle 19.

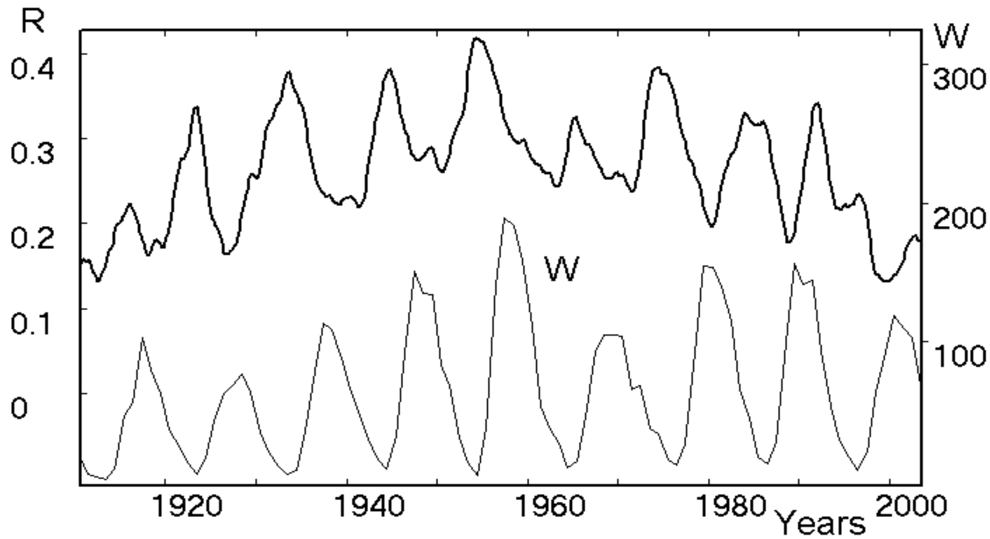

Figure 5. Upper curve: The cycles of correlation factor, $R(t)$, for 1905 - 2003. Lower curve: The average annual Wolf numbers, $W(t)$.

3.6. Index of CaII K Bright Point Areas at High Latitudes, SK

We used daily data on CaII K solar activity using the archive of the Kodaikanal observatory for 1907 - 1980. It was shown that the 11-year cycles of CaII K index at the latitudes $\pm 40^o$ coincide with cycles of Wolf numbers (Makarov et al. 2004). But the CaII K bright points form the polar cycles at high - latitudes between the polar magnetic field reversals. This polar activity shows both 11-year, and 22-year cycles (Makarov et al. 2004). Figure 6 shows that the polar cycles of areas of CaII K bright points at the high - latitudes, SK, precede on an average for 5 - 6 years to the Wolf number cycles. A change of a sign of polar magnetic field occurs through 5.8 ± 0.6 years after the minimum in CaII K activity. Thus, global activity of the Sun has duration of 16-17 years. It develops in two latitude zones divided by the latitude about 38^o. This activity migrates at the high latitudes in beginning of the cycle and then drifts in an equatorial zone after magnetic field reversal.

3.7. Power of Sector Structure of the Magnetic Field

Index of rotation of sector structure of magnetic field, $SSPD(t)$, was determined as the sum of spectral density of power sector structure. The index $SSPD = \Sigma(a \cdot a^* + b \cdot b^*)$ is the sum of all peaks on the spectrum of the chosen periods. It reflects presence or absence of various types of sector structure. Figure 7 shows comparison of index $SSPD(t)$ with an index of the Wolf numbers, $W(t)$, for 1907 - 2000.

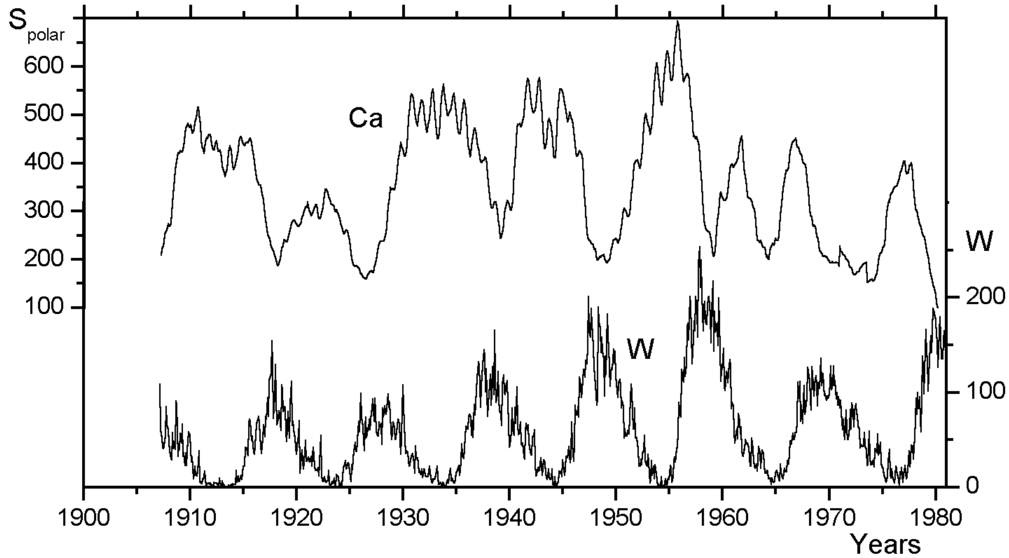

Figure 6. Upper curve: The cycles of area CaII K bright points at the latitudes more than 70^o for Northern hemisphere. Lower curve: The average annual Wolf numbers, $W(t)$, for 1907 - 1980.

It is seen, that the cycles of sector structure of magnetic field, $SSPD(t)$, were displaced for 5 - 6 years and they precede on amplitude and on a phase to the cycles of the Wolf numbers. Similar dependence between the Wolf numbers and rotation rate of two-sector structure of an interplanetary magnetic field has been earlier received (Makarov, Tavastsherna, & Petrova 1990). It means, that the sector structure of the solar magnetic field actively participates in generation of the magnetic field and, hence, is one of the basic types of movements. The indexes $A(t), L(t), K(t), R(t)$ and SK describe topology of global magnetic field of the Sun, but the index of rotation $SSPD(t)$ reflects the rate inside the Sun and essentially differs from above-mentioned. But the index $SSPD(t)$ also precede to the Wolf numbers for 5 - 6 years, (Vasil'eva, Makarov, & Tlatov 2002).

4. Conclusion

New indexes of background magnetic field for minimum activity, $A(t), L(t), K(t), R(t), SK(t), Apz(t)$ and $SSPD(t)$ were studied on the basis of H_α synoptic charts and the data of polar activity. They describe the solar activity in period of minimum and have priority development as regards to the Wolf numbers for 5 - 6 years. The indices $A(t), L(t), K(t), SK(t)$ and $R(t)$ describe the global magnetic field of the Sun, the index of solar rotation, $SSPD(t)$, reflects a rate inside the Sun and by that differs from the above-mentioned indices. But the cycles $SSPD(t)$ also precede to the cycles of Wolf numbers for 5-6 years. It means that the $SSPD(t)$ has the same nature, as indexes $A(t), L(t), K(t), SK(t)$ and $R(t)$. One can note, that index, $< Apz >$, is connected with a secular change

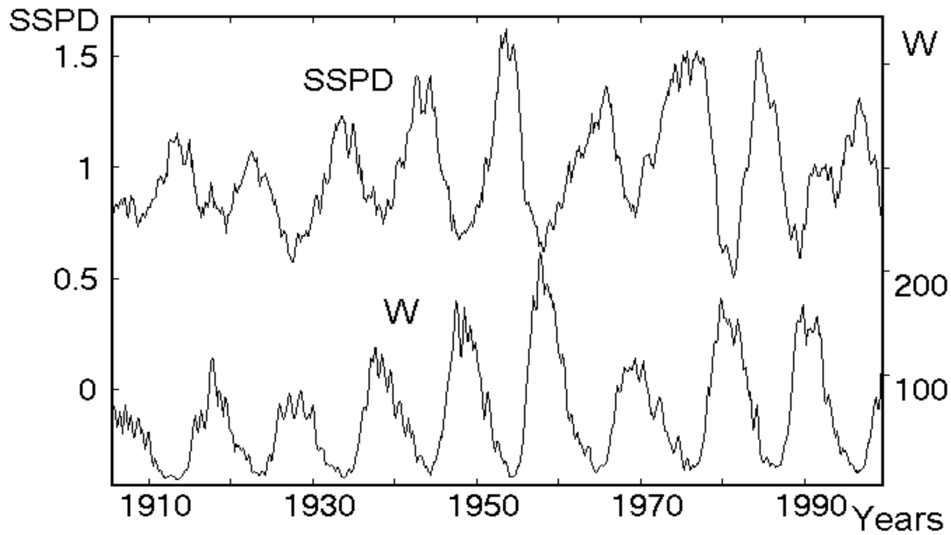

Figure 7. Upper curve: The cycles of an index of solar rotation, $SSPD(t)$. Lower curve: The average annual Wolf numbers, $W(t)$, for 1907 - 2000.

of solar activity and it enables to understand the probable causes of the waxing and waning of the Sun's activity in conditions like Maunder Minimum.

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