Prediction of Amplitude of Solar Cycle 25 using Polar Field Strength at the Cycle Minimum

M.I. Pishkalo

Main Astronomical Observatory, Kyiv, Ukraine

E-mail: pish@mao.kiev.ua

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Abstract Observed strength of the Sun's polar magnetic field is in anti-correlation with relative sunspot number in the 11-year solar cycle. We studied cross-correlation between smoothed monthly sunspot number and modulus of smoothed polar magnetic field strength for different time lags. Maximal correlation coefficient (0.689) is calculated for the time shift of approximately 5.2 years. Using observed strength of polar magnetic field as precursor we have forecasted amplitude of the next solar cycle 25. It was found that predicted amplitude of solar cycle 25 is 116 ± 12 or 130 ± 26 depending on the parameter we used as precursor: 1) maximal value of modulus of smoothed strength of mean polar field near the cycle minimum or 2) modulus of mean polar field strength averaged one year just before the cycle minimum, respectively.

Key words: Sun, solar activity, solar cycle, prediction.

1. Introduction

The 11-year sunspot cycle is the most known characteristic of the solar activity. The 22-year magnetic cycle of the Sun consists of two 11-year cycles. The solar activity variations play an important role in the interplanetary and near-Earth space. In particular, they can disturb the Earth's magnetosphere and affect the operation of many space-borne and ground-based technological systems, *i.e.*, manned space flights, space navigation and aero-navigation, ground power lines, transcontinental pipes, high-frequency radio communication, radars, *etc*. They can also affect the climate and some aspects of the human life. So, it is very important to know in advance the level of solar activity for the nearest years or decades.

The 11-year cycle of solar activity is well consistent with dynamo theory of the Babcock-Leighton type (Babcock, 1961; Leighton, 1969). Toroidal magnetic fields of the Sun, presented by magnetic fields of sunspots, are carried by meridional flows to the poles and form poloidal (polar) magnetic field, which transforms itself into the new toroidal field in the next cycle (see in more details, for example, reviews by Ossendrijver, 2003; Charbonneau, 2010; Petrie *et al.*, 2014, and references therein).

Many methods have been suggested up to date for predicting solar activity (see, e.g., Hathaway, 2009; Petrovay, 2010, and references therein). The strength of polar magnetic field of the Sun in the minimum of solar activity can be considered as a precursor for the solar activity level in the cycle maximum (Schatten et al., 1978). Moreover, it is the physically-based precursor as it is concluded from the dynamo theory. Observed polar field strength (Svalgaard et al., 2004; Pishkalo, 2010) as well as modeled axial dipole component computed from synoptic magnetic maps or using surface flux transport model (Cameron et al., 2016: Wang, 2017; Jiang et al., 2018; Upton and Hathaway, 2018) at the cycle minimum are used to predict maximal sunspot number.

Polar magnetic field reversals occur near the cycle maximum and, as a rule, non-simultaneously in the N- and S-hemispheres (Babcock, 1959; Svalgaard and Kamide, 2013; Pishkalo, 2019).

The aim of this work is to predict the maximal sunspot number in the next solar cycle 25 using measurements of polar magnetic field strengths at the cycle minimum. Scheme of calculations is similar to one which we used for prediction of solar cycle 24 (Pishkalo, 2010).

2. Data

Here for the analysis we used monthly international relative sunspot numbers (since 1975) from the *Sunspot Index and Long-term Solar Observations* (SILSO, *http://sidc.oma.be/SILSO*, Version 2.0) and polar magnetic field measurements at the *Wilcox Solar Observatory* (WSO, *http://wso.stanford.edu*). It should be noted that the polar field strength values, which were determined at the WSO since 1976, are not strength of magnetic field at the poles directly. They represent averaged magnetic fluxes from about the ±55° latitude to the pole for the North and South hemispheres.

It should be also mentioned, when comparing solar cycle parameters in different papers, that the new (revised) version of international sunspot numbers is used in solar physics since July 2015 (Clette *et al.*, 2014).

Figure 1 shows the evolution of relative sunspot number and the strength of polar magnetic field since 1975, *i.e.*, in solar cycles 21 to 24. Sunspot numbers and polar fields are plotted in the upper and middle panels, respectively; smoothed values are shown by thick lines. The numbers of solar cycles are indicated in the top panel. Minima of solar cycles are marked by vertical lines in the bottom panel. Minimum of solar cycle is defined (and used hereafter in the text) as minimum at the cycle start.

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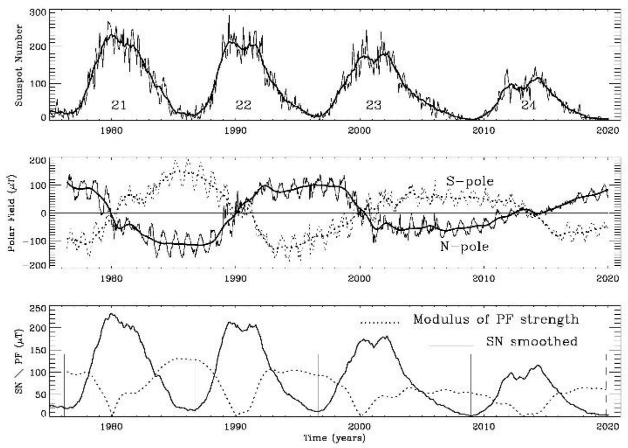

Figure 1. Monthly sunspot number (*top*), strength of polar magnetic fields of the Sun measured at Wilcox Solar Observatory (*middle*), monthly smoothed *sunspot numbers* (SN) and modulus of the smoothed mean *polar field* (PF, *bottom*) with time since 1975. Smoothed values are shown by thick lines (at the *top* and *middle* panels). Minima of solar cycles are indicated by vertical lines in the *bottom* panel (*solid* for solar cycles 21-24 and *dashed* for solar cycle 25).

Smoothed sunspot numbers were calculated here using the running 13-point average. Yearly sinusoidal character of the strength of polar field is caused by the 7.25° inclination of the Earth's orbit to the plane of the solar equator.

One can see from Fig. 1 that the strength of polar field, measured before minima of cycles 24 and 25, are similar. It equals to only a half of the magnitude of polar magnetic field at the minimum of solar cycle 22.

Modulus of mean smoothed polar field and smoothed monthly sunspot number are plotted in the bottom panel. The mean polar magnetic field is defined as (N-S)/2. Polar field strength shows 22-year periodicity, while sunspot number and the modulus of mean polar field show 11-year periodicity.

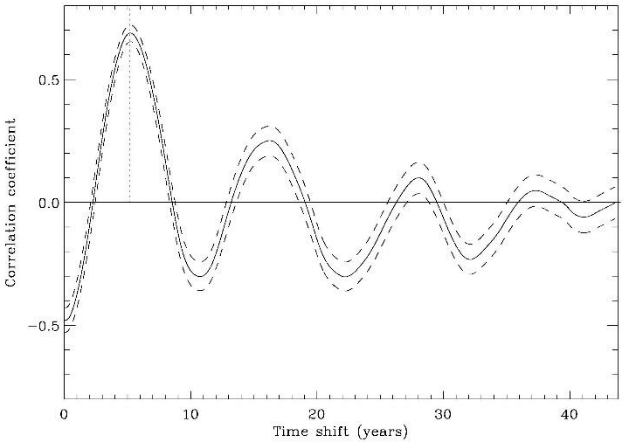

Figure 2. Correlation coefficients (plotted by *solid* line) between smoothed monthly sunspot number and modulus of smoothed mean polar magnetic field strength for different time lag. The 99% confidence limits are plotted by *dashed* lines. The time shift corresponding to the maximal correlation is indicated by vertical dotted line.

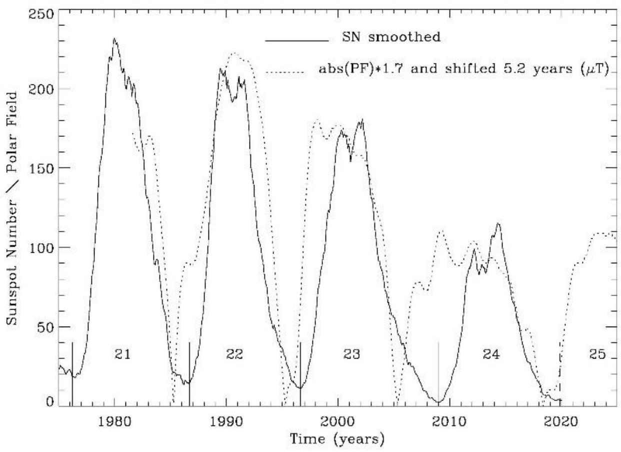

Figure 3. Monthly smoothed sunspot number (*solid*) and modulus of smoothed polar field strength (*dotted*, in *μT*, multiplied by 1.7 and shifted ahead by 5.2 years) for cycles 21 to 24. The numbers of solar cycles are indicated. Minima are marked by short vertical lines.

3. Results and discussion

As one can see from Figure 1, maximal relative sunspot number decreases from solar cycle 21 to solar cycle 24. Magnitude of polar magnetic field decreases from solar cycle 21 to solar cycle 24, too. Magnitude of polar magnetic field of the Sun is in anti-correlation with sunspot number. It is easily seen at the bottom panel. Maximal and minimal polar field strengths are observed at the cycle minimum and maximum, respectively. Moreover, maximal value of polar field strength is observed before the solar minimum, not exactly in the minimum.

At first we quantitatively analyze correlation between smoothed relative sunspot numbers and smoothed mean polar fields. Smoothed sunspot numbers were interpolated to times of mean polar fields, before calculation. Results of cross-correlation analysis are shown in Figure 2. Correlation coefficients for different time lags are plotted by solid line. The 99% confidence limits were estimated by means of the standard Fisher r to z transformation and are plotted by dashed lines.

The correlation coefficient between smoothed sunspot numbers and smoothed mean magnitudes of polar field is equal to -0.478 ($P < 0.001$). Maximal correlation (0.689, $P < 0.001$) is observed when time shift between the parameters equals approximately 5.2 years.

Figure 3 illustrates time evolution of smoothed monthly sunspot number and modulus of smoothed mean polar field strength which was multiplied by 1.7 and shifted ahead by 5.2 years. Sunspot numbers and polar fields are plotted by solid and dotted lines, respectively. One can see that amplitudes of these parameters are similar. From this, one can suppose that amplitude of solar cycle 25 will be similar to or slightly higher than that in solar cycle 24. It should be remembered that maximal smoothed monthly sunspot number in solar cycle 24 was 116.4. So, we can qualitatively suppose that the next solar cycle 25 will be of at least similar or even slightly higher amplitude.

Using observed strength of polar magnetic field near the cycle minimum we can estimate quantitatively the amplitude of solar cycle 25. Of course, we cannot make any serious statistical studying (because data on polar fields are available for small number of solar cycles, from 21 to 24) but some estimations only.

Table 1. Solar cycles 21-25: minima and maxima of smoothed *sunspot numbers* (SN) and *polar fields* (PF) near the minima. Preliminary and predicted values are in brackets.

Number of solar cycle	21	22	23	24	25
Time of SN minimum	Mar 1976	Sep 1986	Aug 1996	Dec 2008	(Nov 2019)
SN in the minimum	17.8	13.5	11.2	2.2	?
Time of SN maximum	Dec 1979	Nov 1989	Nov 2001	Apr 2014	(May 2023)
SN in the maximum	232.9	212.5	180.3	116.4	(116-130)
Maximal PF strength near SN minimum (μT)		131	106	65	(64.5)
Mean PF strength before SN minimum (μT)		128.8	95.7	54.3	(62.8)

We estimate amplitude of solar cycle 25 in two ways: (I) using maximal value of modulus of smoothed strength of mean polar field near the cycle minimum and (II) using mean modulus of polar field strength averaged one year just before the cycle minimum. November of 2019 was used as preliminary minimum of solar cycle 25.

The best linear fits for the case I and case II are plotted in Figure 4 by dashed and solid lines, respectively. They can be presented by the equations

$$Y = 1.466*X + 22.141 \quad \text{(case I)}$$

and

$$Y = 1.300*X + 48.948 \quad \text{(case II).}$$

Predicted amplitudes of solar cycle 25 are 116 ± 12 and 130 ± 26 for the case I and case II, respectively. They are shown at intersections of corresponding vertical and horizontal lines in Fig. 4. Naturally, these predictions are slightly different because different initial polar field strengths were used in calculations. When adopting November of 2019 as minimum of solar cycle 25, its expected maximum will be approximately in May of 2023. Some parameters of calculations are shown in Table 1. So, we predict that solar cycle 25 will be of similar amplitude or slightly stronger than the current cycle 24. It seems to indicate that no new deep minimum of solar activity like the known Maunder minimum will take place and that solar activity will probably grow in long-term perspective.

Amplitude of solar cycle 25, predicted in the present study, is in good agreement with some other published predictions. In particular, Pesnell and Schatten (2018) predicted that amplitude of solar cycle 25 will equal 135 ± 25. Jiang *et al.* (2018) obtained that predicted amplitude of solar cycle 25 is 125±32 which is about 10% stronger than the amplitude of solar cycle 24. Okoh *et al.* (2018) predicted that amplitude of solar cycle 25 will be equal to 122.1 ± 18.2. Bhowmik and Nandy (2018) and Cameron *et al.*, (2016) predicted that solar cycle 25 will be similar to or slightly stronger than the current cycle. Wang (2017) predicted that solar cycle 25 will be similar in amplitude to cycle 24. Upton and Hathaway (2018) predicted that amplitude of solar cycle 25 will reach 95-97% of the amplitude of cycle 24.

On the other hand, Covas *et al.*, (2019) reported that the next Cycle 25 will be very weak, with the predicted amplitude of 57 ± 17. Abdusamatov (2007) and Javaraiah (2017) predicted that solar cycle 25 will be weaker than cycle 24. In contradiction, in the previous paper (Pishkalo, 2016) we have studied correlations between several parameters of solar cycle and predicted that amplitude of solar cycle 25 will reach about 167.

4. Conclusions

Solar activity is known to change with about 11-year periodicity. The knowledge of the level of solar activity for the nearest years is very important for some aspects of humanity.

Strength of polar magnetic field of the Sun at minimum of solar cycle can be used as precursor for amplitude of the next solar cycle 25. Polar magnetic fields are maximal in epoch of the solar activity minimum and, *vice versa*, they are minimal in epoch of solar maximum.

We studied cross-correlation between monthly smoothed sunspot number and modulus of smoothed polar magnetic field strength for different time lags. Maximal correlation coefficient (0.689) is calculated for the time shift of approximately 5.2 years. The cross-correlation analysis indicates qualitatively that the next solar cycle 25 will be of similar or slightly higher amplitude than solar cycle 24.

The relation between polar field strength near the cycle minimum and sunspot number at the cycle maximum was found using parameters of solar cycles 22-24. It allows to estimate quantitatively amplitude of the next solar cycle 25 using observed strength of polar magnetic field of the Sun. Predicted amplitude of solar cycle 25 is equal to 116 ± 12 or 130 ± 26 depending on the observed strength of polar magnetic field used as precursor (maximal value of modulus of smoothed strength of mean polar field near the cycle minimum, in the first case, or modulus of mean polar field strength averaged one year just before the cycle minimum, in the second one). It probably indicates that no further deep minimum of solar activity is expected in the upcoming decades.

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