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Solar activity in the following decades

Welcome to the JASTP Special Issue on Expected Evolution of Solar Activity in the Following Decades.

The evolution of solar activity in the following decades is an important question, from both theoretical and practical points of view. Already by the end of the past century, after a period of very high activity, a lot of evidence was accumulated indicating a gradual decrease in the level of solar activity, in particular, in the global field and magnetic fields of sunspots. This may mean that solar activity is entering a period of a secular minimum. A number of papers have appeared claiming that cycle 25 will be lower than cycle 24, and we are on the verge of a period of several low cycles. However, there is no agreement whether this will be a “Dalton-type” minimum like the ones observed every 100–150 years during the recent centuries, or a “Maunder-type” deep minimum like the one in the second half of the 17th century. On the other hand, some researchers believe that the maximum of cycle 25 will be at least not lower than the maximum of cycle 24.

VarSITI (Variability of the Sun and Its Terrestrial Impact – www.varsiti.org) is the current 5-year scientific program of the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). One of its four projects is SEE – Solar Evolution and Extrema. Among the main questions which the project seeks to answer, are: “Are we at the verge of a new grand minimum? If not, what is the expectation for cycle 25? For the next few decades, what can we expect in terms of extreme solar flares and storms, and also absence of activity? Another Carrington event? What is the largest solar eruption/flare possible? What is the expectation for periods with absence of activity?” The answers to these questions are of importance also to the other VarSITI projects dealing with different aspects of the terrestrial impacts of the Sun’s variability.

A forum on “Expected Evolution of Solar Activity in the Following Decades” was jointly organized by the VarSITI SEE project and the International Space Science Institute in Bern, Switzerland (ISSI) in March 2016. This JASTP special issue includes papers based on the presentations at this forum, as well as other contributions related to its topics. Part of the reports (Cameron, Kosovichev, Kitiashvili, Hathaway) by the time of the meeting had already been sent to other publications and could not be placed (In this ssue).

Without claiming to have a complete overview of the results of the discussion at the meeting in Bern, we will only give here briefly our vision of the current state of the matter on the evolution of the solar activity in the nearest 25th cycle.

The problem of forecasting solar activity is a long-lasting one. Actually, this problem occurred as soon as the discovery of the solar cycle itself, but we are still far from a definite solution. Before each sunspot maximum, papers appear forecasting the amplitude of the cycle, but the forecasted amplitude are in quite a wide range (Obridko, 1995; Lantos and Richard, 1998; Hathaway et al., 1999). The last two cycles, 24 and 24, were no exception.

There are basically three types of methods used to forecast the future solar activity.

The simplest way is to rely on the very idea of solar cylicity. Assuming that all cycles are identical, we can forecast the next cycle’s length, and the timing of its minimum and maximum. An average over a number of cycles, or a mathematically modeled cycle can be used for such a forecast (Hathaway et al., 1999). However, in reality cycles strongly differ in terms of duration and amplitude, so these simplest methods do not give satisfactory results. For this reason, various spectral and correlation methods are applied: search for the main periodic processes, expansion in fundamental orthogonal functions, etc. This group of methods is essentially a mathematical extrapolation of the observed numerical series. Here the astrophysics completely gives way to mathematics. The advantage of these methods is the complete absence of any additional assumptions. Each moment of time is characterized by one and only one number. What determines this number is no longer important. Unfortunately, this completely ignores the fact that solar activity is the result of a very complex interaction of many processes. In addition, along this path, particularly stringent requirements are imposed on the length and reliability of the original series. But as the reliable observations only cover about 150 years, the low frequency part of the spectra is calculated with low confidence (Obridko and Nagovitsyn, 2017). Therefore, these “regression” methods are more applicable to short-term (inside the cycle) forecasts, while their results on longer (cycle-to-cycle) time-scales are often quite disputable. An example of this type of predictions is the paper by Popova et al. (In this ssue),who use Principal Component Analysis and forecast that a number of low amplitude cycles follow, and the comments by Usoskin (In this ssue) are an illustration about how questionable such methods are.

The second group of forecasting methods use the known statistical characteristics of the sunspot cycles: the Waldmeier effect (relation between the rise rate of activity in the early phase of a solar cycle to its maximum, and the amplitude of the maximum), the Gnevyshev-Ohl rule: relation between the total number of sunspots during an even numbered cycle and during the following odd-numbered one (Gnevishev and Ohl, 1948), or its better known and widely used modification: relation between the amplitudes of an even numbered and the following odd numbered cycles (Kopecký, 1950), the concept of the “turning points of a cycle” (Kuklin, 1992), etc. The disadvantages of these methods are that a cycle must have already started or even progressed to some point in order to use the relations between its characteristics, and that the statistically established rules connecting consecutive cycles not always hold. Georgieva and Kirov (2011) showed that the Waldmeier rule had the opposite sign during the Maunder minimum, as well as during other grand minima (Georgieva, 2013). Duhau (2003) presented arguments that the ratio of the heights of even and odd cycles changes with time, and one can expect its violation not only in the pair 22–23, but also in the pair 24–25. In the work (Tlatov, 2015) it is shown that the Gnevyshev-Ohl rule changes its sign with a period of about 200 years. It is this inversion that occurred in the pair of cycles 22–23. Accordingly, in the next pair the odd cycle 25 should be below cycle 24 and, therefore, one can expect a low activity in the period 2025–2035. Ahluwalia (In this ssue) reported that the slope of the three-cycle quasi-periodicity (TCQP) found earlier in solar, interplanetary and geophysical parameters turned negative after the minimum of Cycle 21, and predicted decreasing amplitudes of the following cycles.

In the third group of forecasting methods, the future sunspot activity is calculated using other heliophysical data. These methods are known as “precursor methods” in which various parameters observed before the

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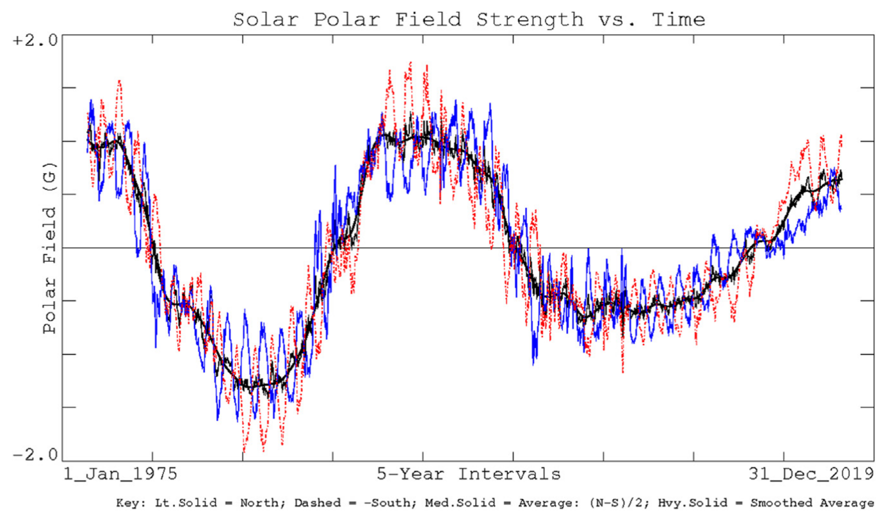

Fig. 1. Solar polar field measured at the Wilcox Solar Observatory (http://wso.stanford.edu/Polar.html).

solar cycle maximum ("precursors") are searched for, and their correlations with spot-formation indices are used to forecast the amplitude of the next cycle maximum. The first such method was proposed by Ohl who noticed that the amplitude of a cycle is correlated with the minimum level of geomagnetic activity in the beginning of the cycle (Ohl, 1966) or with the level of geomagnetic activity during the late declining phase of the previous cycle (Ohl and Ohl, 1979). It may seem quite strange that the variations of the Earth's magnetic field can be a precursor of the solar magnetic field to be observed 5–6 years later. However, this relation is supported by quite high correlation coefficients (up to 0.9–0.97), and in many cases the precursor methods give much more reliable results than the first two types of forecasting methods.

The success of these methods can be explained (Wang and Sheeley, 2009) by the fact that they are based on the operation of the solar dynamo, so an extension of the precursor methods is the construction of solar dynamo models. The advantage of the precursor methods is the attempts for deep penetration into the nature of solar activity. Unfortunately, many additional assumptions can often be made along this path. Solar cycle 24 was the first one for which such dynamo-based predictions were attempted, however with broadly diverging results due to the different additional assumptions. The available suggestions from dynamo theory for predictions of solar cycle amplitude, shape, duration and other parameters as well as the problem of prediction of Grand solar activity minima like the Maunder minimum are summarized by Sokoloff (In this ssue).

According to the solar dynamo theory developed by Parker (1955), the sunspot cycle consists of an oscillation between the toroidal and poloidal components, similar to the oscillation between the kinetic and potential energies in a simple harmonic oscillator. Two processes are involved in solar dynamo: the generation of the toroidal field from the poloidal field, and the regeneration of the poloidal field of the new cycle with an opposite polarity from this toroidal field. An overview of the present status of the solar dynamo theory and its application to the prediction of the next solar cycle is given by Choudhury (In this ssue).

The generation of the toroidal field from the poloidal field is considered completely non-controversial. The differential rotation at the base of the solar convection zone stretches in east-west direction the north-south field lines of the poloidal magnetic field predominant at sunspot minimum, thus creating the toroidal component of the field. Due to magnetic buoyancy, the magnetic flux tubes rise through the convection zone and emerge piercing the solar surface in two spots – sunspots. During sunspot minimum periods, the poloidal field is concentrated in the polar regions. As this poloidal field is the seed for the toroidal field resulting in the sunspots of the following maximum, it has been generally recognized that the amplitude of the forthcoming cycle with a high degree of reliability is determined by conditions at the minimum of the cycle and in particular by the values of the polar magnetic field. Therefore, the precursor methods use links between various indicators of the magnetic field at the poles of the Sun, peaking around solar minimum, and the amplitude of the next sunspot maximum.

Direct measurements of the polar magnetic field of the Sun have been performed at Wilcox Solar Observatory since 1976 (http://wso.stanford.edu/Polar.html). In the recent four solar minima (between cycles 20/21, 21/22, 22/23, and 23/24), the peak polar field amplitude has decreased from 1.31 to 0.65 G. During the present minimum between cycles 24 and 25, since November 2017 the polar field has persisted at a plateau with a value of 0.64 G, practically the same as the lowest previous peak of 0.65 G in the solar minimum between cycles 23 and 24 (Fig. 1). This means that cycle 25 is not expected to be much different from cycle 24.

Obridko and Shelting (2009) have shown that the systematic decrease of the polar magnetic field during the last three cycles is due to the fact that the increase in the magnetic dipole moment, observed from 1915 to 1986, was replaced after that by a recession (Fig. 2).The maximum of the magnetic dipole moment precedes the maximum of the polar magnetic field, the sunspot minimum, and the geomagnetic activity minimum, at least in the last four sunspot cycles for which there are instrumental measurements of the solar dipole field. Kirov et al. (In this issue) have shown that the observed value of the solar dipole moment can be used to forecast both the minimum geomagnetic activity a few years later, and the amplitude of the next sunspot maximum. Both are predicted to be lower in cycle 25 than in cycle 24.

Other proxies used for estimating the polar field are the shape of the corona during eclipses, bending of the high latitude polar plumes, the geometry of the heliospheric current sheet, the number of polar faculae (Schatten et al., 1978), etc. Gopalswamy et al. (In this ssue) have shown that the polar microwave brightness temperature can also be used as a proxy to the polar magnetic field strength in predicting the strength of solar cycles. Based on it, they have predicted that cycle 25 will not be much different from cycle 24.

So, if we know the solar polar field around sunspot minimum from direct measurements or from proxies, we can forecast from it the amplitude of the next sunspot maximum. An important question is whether we can calculate the magnitude of the polar field in advance of the cycle minimum. This possibility is represented by flux transport models.

The Babkock-Leighton mechanism (Babcock, 1961 and Leighton, 1964), or the so called flux-transport dynamo explains the regeneration of the poloidal component of the field from the toroidal one. Its basis is the Joy's law: due to the Coriolis force acting on the flux tubes of toroidal field generated at the base of the convection zone during their emergence to the surface, the sunspot pairs appear slightly twisted from the east-west direction so that the higher latitude spot has the polarity of the respective pole, and the lower latitude one has the opposite polarity. With the advance of the solar cycle, the sunspot pairs appear progressively closer to the equator, and in the late declining phase the leading sunspots from the opposite hemispheres diffuse across the equator and cancel each other's flux. The trailing polarity sunspots are carried by supergranular diffusion and poleward large-scale meridional flow to the poles where they first cancel the polar fields of the old cycle, and then accumulate to create the polar field of the new cycle.

Therefore, given the emergence of (tilted) active region magnetic flux,